ASSESSMENT OF RAIL TRANSPORT NOISE PERCEIVED BY TRACKSIDE DWELLERS

Submitted in partial fulfilment of the requirements for the award of the degree of

Doctor of Philosophy

By

BODDU SUDHIR KUMAR
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April 2024

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CERTIFICATE

This is to certify that the thesis entitled **"ASSESSMENT OF RAIL TRANSPORT NOISE PERCEIVED BY TRACKSIDE DWELLERS"** being submitted by **Mr. BODDU SUDHIR KUMAR** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Department of Civil Engineering of **NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL** is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for award of any degree.

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APPROVAL SHEET

This thesis entitled **"ASSESSMENT OF RAIL TRANSPORT NOISE PERCEIVED BY TRACKSIDE DWELLERS"** by **Mr. BODDU SUDHIR KUMAR** is approved for the degree of **Doctor of Philosophy**.

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DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **“ASSESSMENT OF RAIL TRANSPORT NOISE PERCEIVED BY TRACKSIDE DWELLERS”** is a bonafide work done by me under the supervision of **Dr. Venkaiah Chowdary**, Professor, Department of Civil Engineering, National Institute of Technology, Warangal, Telangana, India and was not submitted elsewhere for the award of any degree. I declare that this written submission represents my ideas in my own words. I have adequately cited and referenced the original sources where other’s ideas or words have been included. I also declare that I have adhered to all academic honesty and integrity principles and have not misrepresented, fabricated, or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will cause disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

Boddu Sudhir Kumar

Roll No. 718106

Date:

DEDICATED TO

MY PARENTS, WIFE AND BROTHER

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BODDU SUDHIR KUMAR

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LIST OF UNITS AND NOTATIONS

°C	Degree centigrade
cm	Centimeter
dBA	A-weighted decibels
Hz	Hertz
kHz	Kilohertz
km/h	Kilometer per hour
kN	Kilo Newton
L_{eq}	Equivalent continuous sound pressure level
L_{max}	Maximum sound pressure level
L_{min}	Minimum sound pressure level
m	Meter
m/s	Meter per second
mm	Millimeter
sq. km	Square kilometer
U	Flow vector
δ	Path length difference
ΔL	Insertion loss
λ	Wavelength

LIST OF ABBREVIATIONS

AC	Alternative Current with Air Conditioning
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
CFA	Confirmatory Factor Analysis
CFD	Computational Fluid Dynamics
CPCB	Central Pollution Control Board
DC	Direct Current
EFA	Exploratory Factor Analysis
EN	European Standards
EOG	End-On Generator
HCV	Heavy Commercial Vehicle
ICF	Integral Coach Factory
ICF_CBC	Integral Coach Factory – Centre Buffer Coupler
ICSD	International Classification of Sleep Disorders
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LHB	Linke Hofmann Busch
MAPE	Mean Absolute Percentage Error
MEMU	Mainline Electric Multiple Unit
MLR	Multiple Linear Regression
RMSE	Root Mean Square Error
SEM	Structural Equation Model
SLM	Sound Level Meter
SPL	Sound Pressure Level
WAG	Broad Gauge (W) Alternative Current (A) Goods Train (G)
WAP	Broad Gauge (W) Alternative Current (A) Passenger Train (P)
WHO	World Health Organization

ABSTRACT

Unplanned urbanization has led to the settlement of migrants from rural areas close to railway lines, exposing them to the continuous noise levels from the moving trains. These high, intense noise levels annoy and adversely affect the health of individuals living near railway lines. Every ambient noise study employs the source-path-receiver structure to explore the overall behavior of sound. Therefore, noise control techniques are necessary to modify the noise source mechanism, transmission path characteristics, and receiver perception. Among these techniques, eliminating railway noise at the source is the most effective method for mitigating noise. This study evaluated different train types, including various speeds and lengths, to determine their correlation with noise levels. Results showed that train speed had the strongest correlation with noise levels, the driving factor for maximum noise levels. When the train speed increases by 10 km/h, noise levels rise by 2.8 to 3 dBA. In the case of freight trains, the train length is a key parameter in the emission of railway noise when compared to passenger trains. The study also identified the type of trains with the highest noise levels, and a detailed examination of the mechanism responsible for this phenomenon was carried out. Multiple linear regression models for maximum and equivalent noise levels were developed for passenger and freight trains. In addition to source parameters, the current study evaluates a noise pollution hotspot: a railway-level crossing, where several activities related to transportation noise were involved. Train honking, train movement, road vehicles, and pedestrians contribute to the noise level at a railway-level crossing. Train horns are generally blown as trains approach railway level crossings and are mandatorily used to alert road users. However, the train horns are considered a nuisance to the nearby residents. A comprehensive noise monitoring survey was conducted at an access-controlled level crossing. Further, an Artificial Neural Network (ANN) based railway noise prediction model was developed to forecast maximum (L_{max}) and equivalent (L_{eq}) noise levels. Results revealed that train horns produced impulsive sound signals that fall under high-frequency one-third octave bands, causing severe irritation to trackside inhabitants.

Noise levels are affected by changes in distance, intervening barriers, and atmospheric conditions along the transmission path between the source and the receiver. This study explored the variance of railway noise in an urban setting over various measuring distances, including 25, 50, 100, and 200 m, with variables such as air temperature, humidity, and wind conditions. Results showed that the effect of the wind was more significant for larger distances between the source and the receiver. For every 1 m/s increase in wind speed within a distance of 50 m, the average sound attenuation induced by the upwind phenomena was 0.2 dBA. The impact of air temperature changes on received

sound level from a moving source was insignificant within the range of temperatures considered in the study. The effect of humidity was observed to be less at shorter distances but at larger distances, increasingly attenuates noise levels.

Along the transmission path, the presence of a wall between the source and receiver can act as a noise barrier resulting in a reduction in intensity of noise. In urban areas, railway boundary walls are constructed to prevent encroachments of railway lands and to avoid pedestrians trespassing the railway tracks. This study aims to evaluate the effectiveness of such a boundary wall in reducing noise and proposes an improved alternative through Computational Fluid Dynamics (CFD) simulations. Various noise barriers with different geometry, shape, and surface materials were simulated and verified through field study measurements. Noise attenuation was evaluated by measuring railway noise spectra at different positions, including 0.5 m in front and behind the barrier and at the facade of the residential area. Results showed that as barrier height increased, insertion loss also increased, with a maximum attenuation of 17 dBA achieved with a rectangular barrier of height 6 m. The most effective noise barrier for reducing railway noise was a T-shaped barrier with a height of 6 m and a projection length of 2 m, with an insertion loss of 22 dBA. This study recommends constructing the barrier with soft materials on its surface to reflect and absorb sound waves effectively.

In the last phase of this study, the impact of railway noise on the residents living along the railway line at several distances was assessed by measuring the noise inside houses. Additionally, a human perception survey was conducted to investigate the relationship between noise levels and annoyance during daily activities such as working, resting, conversing, eating, talking on the phone, and reading. Structural Equation Models (SEM) were employed to analyze the complex relationships between annoyance, disturbance, and health effects. The outcomes of this study reveal that both passenger and freight trains exceeded the permissible noise limits, with an excess of 36.8% and 15% during daytime and 75.15% and 41.8% during nighttime, respectively. The primary factors contributing to annoyance were identified as the source type and location of noise exposure. The annoyance levels associated with the time of noise exposure negatively impacted disturbances to daily activities and subsequent health effects. This phenomenon suggests a psychological adaptation known as habituation, where residents along railway lines gradually become accustomed to the noise over time. Furthermore, the cumulative impact of disturbances to daily activities can indirectly influence long-term health. Proximity to the railway line amplifies the relationship between annoyance and health effects.

Chapter 1

INTRODUCTION

This chapter introduces the motivation and aim of this research. It highlights the need to evaluate the impact of railway noise on the track-side residents. It emphasizes the importance of possessing an in-depth understanding of railway noise, how it is transmitted, and how the receivers perceive it. The research objectives are defined, and the scope of the current study is detailed. Finally, the chapter highlights the outline structure of the thesis.

1.1 General

Noise pollution is defined as a high-intensity sound that falls within the normal range of human hearing causing harm to humans. Noise pollution can be compared to secondhand smoke as it is also an airborne pollutant, primarily emerging from external sources, and is involuntarily imposed upon the population, often surpassing their ability to control it (Zannin et al. 2006). The historical origins of noise pollution can be traced to the period of the Industrial Revolution, during which urbanization and technological advancements increased noisy machinery, transportation systems, and urban activities. However, in 1972, the World Health Organization declared noise pollution as an environmental pollutant, now considered a critical urban issue affecting human health (Carter 1996). The correlation between prolonged exposure to higher noise levels and its detrimental impact on human well-being has been documented extensively. These effects can be broadly classified into three primary groups: (i) **Auditory effects** such as hearing loss and shift in hearing threshold levels, (ii) **Physiological effects** include increased stress levels, anxiety, changes in metabolism, and hormonal changes, (iii) **Behavioral effects** include population reduction, migration, and habitat loss (Jacyna et al. 2017). Statistics show that 55% of the world's population lives in urban environments, where noise levels increased compared to rural areas (Méline et al. 2013). Within urban settings, the sources of noise pollution are typically classified into four categories: industrial noise, transportation noise, household noise, and noise from public address systems. Figure 1.1 shows several activities leading to noise pollution in an urban environment. According to Meline et al. (2013), industrial and transportation noise accounts for 75% of the total noise pollution within metropolitan regions. Several studies conducted in urban areas revealed that roadway transit noise was the most dominant source, followed by rail transportation noise among various transport modes.

Rail transportation has several advantages over other modes of transport, particularly regarding environmental impact. Railways emit less air pollutants and use less energy per passenger kilometre than air or road travel. Rail transport caters to freight and passengers, irrespective of climate and weather conditions, which has helped several countries' economies. High-speed trains are exceptionally efficient on longer routes and can be a viable alternative to air travel. Additionally, the demand for high-speed trains and freight trains is rising worldwide. Conversely, the drawback of rail transportation is the huge generation of noise and ground vibrations. The noise level generated by a moving train typically ranges between 60 to 90 dBA, depending on factors such as train type, speed, and environmental conditions (Bunn and Zannin 2016). It is important to note that noise levels are typically measured using a logarithmic scale, and an increase of 10 dBA represents 10 times increase in sound intensity level.

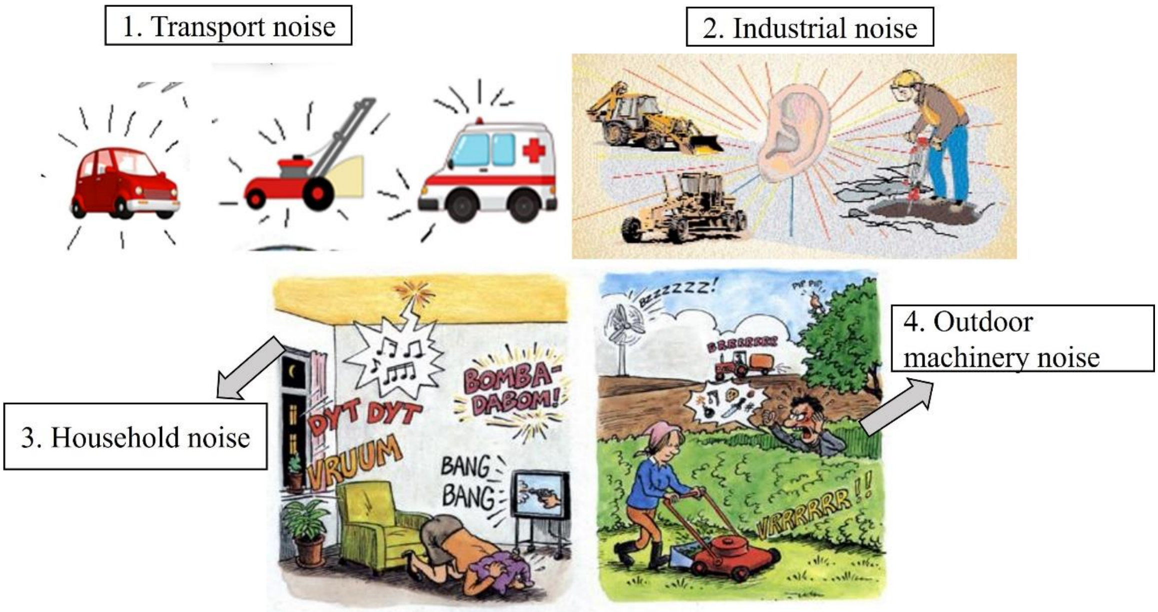


Figure 1.1 Several types of noise sources in an urban environment

As people's living standards increase, they become less tolerant to the annoyance caused by excessive noise. The growth of the population over the past few decades prompted a significant migration of individuals to urban areas, causing a surge in the need for developing infrastructure such as roads, railway networks, and public transportation systems. As a consequence of expanding these transportation networks, there has been an increase in the volume of road vehicles and the frequency of trains, leading to elevated levels of noise pollution. Among several urban environment noise sources, railway noise has emerged as one of the significant contributors, especially in residential areas near railway lines. Recent statistics revealed that about 55% of the world's population (4.4 billion) live in urban areas, and by 2045, it is forecasted that the urban population will increase by 1.5 times (6 billion) (Navarrete-Hernandez and Laffan 2023). Unplanned urbanization has led to the settlement of migrants from rural areas in close proximity to railway lines, exposing them to continuous noise pollution and resulting in a range of adverse effects on their health and well-being (Thorn 2015). Urban planners should consider the influence of railway noise on the well-being of residents living near the tracks when constructing new railway lines or expanding existing ones. They should carefully plan the placement of railway lines to maintain a safe distance from residential areas, ensuring that noise levels within these zones remain within acceptable limits. Hence, there is a need for a comprehensive study to evaluate the impact of railway noise on the track-side residents, focusing on quantifying noise levels from passing trains and proposing requisite measures for noise mitigation.

1.2 Railway Noise

The noise from passing trains is unwanted and considered as a disturbance to the people residing along the railway line. Railway noise refers to the audible emissions produced by trains as they traverse along railway tracks. The primary noise source is the mechanical vibration produced by irregularities at the wheel-rail interface. These vibrations propagate as the sound waves radiate from multiple sources, such as the wheels, rails, bogies, suspension, and sides of rail coaches. The resulting noise travels through the air, affecting the surrounding environment near the railway lines. Effective management of railway noise is becoming important with the anticipated increase in high-speed trains and freight traffic. In order to mitigate these challenges, it is imperative to develop methodologies aimed at attenuating noise emissions to the acceptable levels, thereby fostering a nuisance-free environment along railway corridors. The noise control measures should be implemented through source modification, transmission path treatment, and receiver perception management (Vallin et al. 2018). The current research adopts a source-path-receiver framework to identify and analyze significant parameters in each phase of noise control, as presented in Figure 1.2.

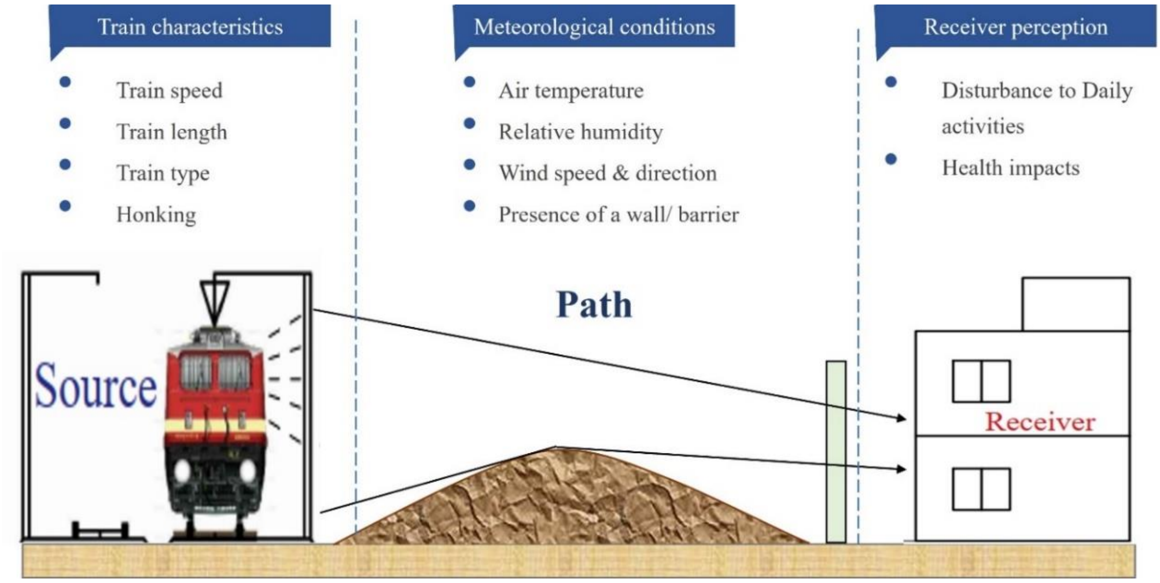


Figure 1.2 The source-path-receiver framework adopted in the current research

Research studies have demonstrated that the dominance of individual sources of railway noise can vary depending on the speed at which the train travels. At speeds lower than 50 km/h, engine noise, propulsion noise, and equipment noise tend to be the most prevalent (Talotte et al. 2003). Rolling noise becomes the primary contributor at speeds ranging between 50 and 250 km/h. Conversely, at speeds exceeding 250 km/h, aerodynamic noise becomes the dominant source of railway noise (Janssens et al. 2006). Different types of trains (passenger or freight) emit different noise levels according to their built-in mechanism. Passenger coaches are made of different kinds of material, body structure, dimensions, arrangement of parts, and internal movement. Freight trains' mechanisms and suspension systems are entirely different from passenger trains. Train length has a significant influence on railway noise; longer trains tend to produce higher overall noise levels and more significant variations in noise levels. Table 1.1 summarises the railway noise source components.

Table 1.1 Source components for railway noise

Rail noise source	Source components
Rolling	Wheel and rail surface condition, impact sound radiation.
Aerodynamic	Pantograph pan and frame, train body.
Equipment	Ventilation or cooling fan, air conditioning, generators.
Propulsion	Motors, gears and brakes, air venting.
Honking	Electric horn.

1.2.1 Rolling noise

Rolling noise is one of the major sources of railway noise caused due to wheel/rail interaction. It is primarily dependent on the speed of the train and the roughness of the wheel/rail. The rolling noise can be further divided into two categories: impact noise and continuous noise. Impact noise is generally caused due to irregularities like wheel flats, crossings, welded or bolted joints, and switches. This type of noise is usually more intense than continuous noise and is generally caused by a sudden change in the contact region of wheel/rail interface.

On the other hand, continuous noise is caused by the constant contact between the wheel and the rail (Kitagawa and Thompson 2006). As shown in Equation (1.1), rolling noise increases with train speed (v), and the A-weighted sound pressure level (L_p) is commonly assumed to be proportional to the logarithm of the speed (Maigrot et al. 2020). This means the faster the train travels, the louder the noise.

$$L_p = L_{po} + \mathrm{N}^* log_{10} \left(\frac{v}{v_0}\right) \quad (1.1)$$

Where L_{po} = sound pressure level at a reference speed (v_o), N = speed exponent (determined by linear regression).

1.2.2 Aerodynamic noise

Aerodynamic noise is prevalent in high-speed train systems, particularly at speeds exceeding 250 km/h. This noise arises from the interaction of the train body with the surrounding airflow, which creates a turbulent boundary layer along the length of the train. This boundary layer is characterized by a thickness of approximately 2 m and a growing profile in the lower region due to ground friction (Iglesias et al. 2017). The primary source for this aerodynamic noise in the trains is the front bogie, pantograph pans, pantograph frame, gaps between the adjacent coaches, and gaps in the train body to install ventilation fans, doors, windows, etc. An empirical equation for measuring aerodynamic noise for a high-speed train moving with a speed ranging up to 500 km/h is shown in Equation (1.2).

$$L_{Aeq} = 64\, log_{20} \left(\frac{v}{100}\right) + 60 \quad (1.2)$$

Where L_{Aeq} is the equivalent to aerodynamic noise, and v is the train's speed.

1.2.3 Equipment and propulsion noise

Equipment noise is emitted from the mechanical components of a train, including the wheels, brakes, and couplings. This noise is primarily attributed to the vibrations during the train's movement on the track. On the other hand, propulsion noise is the acoustic emission produced by the engines or motors that facilitate the train's movement.

1.2.4 Curve squeal

Curve squeal is a form of high-pitched noise that may occur on railway tracks during curvilinear motion. This phenomenon is triggered by the lateral forces acting on the wheel-rail interface, which can instigate wheel slippage and slip-stick movement across the rail, generating a vibration that propagates as a squealing sound. The critical factors governing the onset of curve squeal include the coefficient of friction between the wheel and rail, the geometrical parameters of the contact patch, and the wheel-rail normal and tangential forces (Muller and Oertli 2006).

1.2.5 Interior noise

The interior noise present in trains is composed of two primary constituents: air-borne noise generated by external sources and structural noise, which includes wheel/rail rolling noise, sleeper passing frequency excitation, and aerodynamic effects. The noise generated by the wheel/rail interaction can propagate through the train's interior and result in a loud and persistent noise. The existence of interior noise in trains is a concerning issue that can harm train drivers and passengers.

1.2.6 Honking

The train horn is a powerful audible warning device utilized in high-risk areas, such as railway crossings, bridges, and tunnels, to alert other road users and railway personnel of the approaching train and to ensure wildlife safety. Despite its importance, train horn annoys the people residing along the railway line. The acceptable range for train horns being sounded in urban regions should be between 96 and 101 dBA, depending on train speed, but the measurements taken from the horn installed on locomotives have shown noise levels of 120-125 dBA at a distance of 5 meters from the railway track, which can be more harmful to human hearing (Kalaiselvi and Ramachandraiah 2016).

It is essential to investigate the effects of significant railway noise sources and develop a methodology to identify the specific sub-sources of noise, and suggest necessary mitigation measures. Furthermore, it is also essential to focus on the transmission path features accountable for transferring sound waves from the source to the receiver.

1.3 Transmission Path Characteristics

The transmission path includes the ground, air, and any barriers or reflectors the sound waves encounter. Understanding the transmission path through which sound waves propagate is essential in several domains, such as acoustics, engineering, and environmental science, as it helps in anticipation of the behaviour of sound in different environments and conditions.

Ground characteristics: Several factors, such as the soil type, moisture content, and topography, can impact sound propagation. Sound waves can reflect in the presence of hard surfaces like pavement or rock, leading to echoes and reverberation. Conversely, soft surfaces like grass or sand can absorb sound waves, lowering noise levels. Rough surfaces can scatter sound waves in multiple directions, making distinguishing or detecting the sound challenging. Moreover, temperature or ground surface density changes can cause the sound waves to refract or bend, causing deviations in the sound wave’s direction (Oshima and Li 2013).

Air characteristics: The speed and propagation of sound waves are influenced by various atmospheric factors. Air temperature plays a critical role in determining the speed of sound, with higher temperatures resulting in faster and longer-range sound propagation. The humidity of the air affects sound waves by causing them to be absorbed, leading to a reduction in the range of sound. Wind conditions also impact sound propagation, with upwind and downwind phenomena influencing the movement of sound towards or away from the receiver. Atmospheric pressure also plays a role in sound propagation, with higher pressure leading to increased speed and longer-range noise transmission. Finally, air turbulence can significantly impact the propagation of sound waves, as turbulent air can cause sound waves to scatter and make it difficult for sound to travel long distances.

Barrier characteristics: Barriers, such as walls, trees, and buildings, impact the transmission of sound waves by means of reflection, absorption, or diffraction. For example, sound waves may be redirected towards the receiver by reflective surfaces, causing an increase in noise levels. Conversely, sound energy may be reduced by absorptive surfaces, resulting in a decrease in noise levels. Vegetation can affect sound propagation, especially if it is sufficiently dense and tall to block or absorb sound energy. However, if vegetation is too short, sparse, or distant from the source, it may not effectively reduce noise levels.

It is essential to investigate the propagation of railway noise from the source to the receiver while varying meteorological parameters such as atmospheric temperature, humidity, wind speed, and direction, as well as measuring distance. Furthermore, it is also required to evaluate the efficacy of railway boundary walls for attenuating noise and propose an improved alternative using simulation techniques such as Computational Fluid Dynamics (CFD) simulations. There is also a need to identify effective strategies to mitigate railway noise exposure for individuals residing close to the tracks by modifying the transmission path characteristics.

1.4 Receiver Characteristics

Factors such as age, hearing capacity, previous exposure to noise, and cultural background can influence the perception of noise. The tolerance level towards railway noise can impact an individual’s health and well-being. The railway noise can negatively affect daily activities and lead to adverse health impacts, which are elaborated below:

Sleep disturbance: Railway noise is intermittent and disturbs sleep, resulting in insomnia and sleep deprivation. Research has demonstrated that exposure to railway noise during night hours can cause elevated levels of stress hormones, which can harm physical and mental health. The International Classification of Sleep Disorders (ICSD) has established a framework for describing and categorizing sleep disorders (Tassi et al. 2010). There is a consensus that insufficient sleep, especially sleep deprivation, can significantly impact metabolic and endocrine functions and inflammatory markers and contribute to an increased risk of cardiovascular disease.

Hearing problems: Prolonged exposure to elevated levels of railway noise results in hearing damage or loss. The intense auditory stimuli produced by the passage of trains can give rise to transient or permanent hearing loss. Lokhande et al. (2022) conducted a study to investigate the effects of railway noise on individuals residing near railway tracks. The findings of this investigation indicate that individuals exposed to higher levels of railway noise exhibit an increased incidences of hearing impairment when compared to individuals exposed to lower noise levels. Furthermore, the research highlights a positive correlation between the duration of exposure to railway noise and the risk of developing a hearing impairment.

Cardiovascular diseases: Empirical evidence suggests a positive association between prolonged exposure to railway noise and heightened susceptibility to cardiovascular disease. Investigations reveal that individuals residing close to railway tracks are more susceptible to developing hypertension, a significant risk factor for cardiovascular disease. Studies demonstrate that excessive noise pollution, such as that generated by railways, has been linked to an increased risk of cardiovascular ailments, including hypertension, heart attacks, and stroke (Smith et al. 2013). The precise pathophysiological mechanisms responsible for this relationship are not yet fully elucidated. Further research is warranted to understand the specific impacts of railway noise on cardiovascular health and develop effective strategies to counteract these effects.

Mental health: Living with constant railway noise can lead to anxiety, depression, and other mental health issues. People exposed to high noise levels over an extended period are more likely to suffer from mental health problems than those who are not.

In addition to the aforementioned negative consequences, a household survey is required to collect and analyze data on the impact of railway noise on various activities of different age groups, educational backgrounds, occupations, and exposure lengths. There is also a need to measure the variation in noise levels at specific housing locations in different rooms (such as the bedroom, kitchen, and drawing room) by controlling external factors such as the closure of doors and windows (Kamp and Davies 2013).

1.5 Indian Railway System

The Indian rail network is one of the world's largest and busiest rail networks, totaling nearly 65,000 km, (Indian railways annual report and accounts, 2020). It transports huge volumes of cargo and millions of passengers every day. Figure 1.3 compares the size of the Indian rail network to that of other countries. In India, locomotives are classified by service gauge (broad gauge, standard gauge, meter gauge, narrow gauge), traction used (diesel, electric, hybrid, battery), traffic type (passenger, goods, mixed, shunter) and power/version in a four- or five-letter code which also takes into account the gauge and traffic type (e.g., **WAP 4**, representing broad gauge locomotive for passenger trains with AC power). The number denotes the locomotive's latest model number. Recently introduced WAG 12 locomotive is the most powerful alternative current locomotive (25 kV), developed in 2017 and can move with a maximum speed of 120 km/h. Most of the locomotives are outdated, and the present working locomotives are as follows:

Passenger coach pullers – WAP 4, WAP 5, WAP 6 and WAP 7.

Freight coach pullers – WAG 5, WAG 7, WAG 9, and WAG 12.

Mixed coach pullers – WAM 4.

Locomotives that run using Alternative Current (AC) are quieter than diesel since there is no engine and exhaust noise and produce less mechanical noise. Apart from locomotives, the coaches are mainly of two types: (i) passenger coaches and (ii) freight coaches, also known as wagons. The existing passenger coaches are classified as Integral Coach Factory (ICF), Integral Coach Factory – Centre Buffer Couple (ICF_CBC), and Linke Hofmann Busch (LHB). Similarly, the freight wagons are classified as open, closed, and tank wagons.

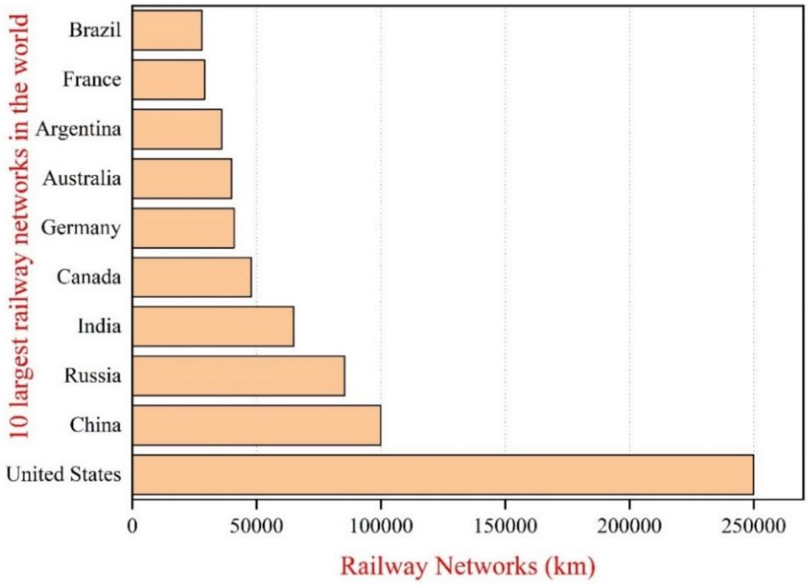


Figure 1.3 Top 10 largest rail networks in the world

1.6 Need for the Study

Extensive research has revealed the adverse impacts of railway noise on the public's well-being, with most research being done in developed nations. However, there is a noticeable lack of research in this area from developing countries like India, despite being the country with the world's fourth-longest rail network and the highest population, surpassing China. Unplanned urbanization has led to the settlement of migrants from rural areas close to railway lines, exposing them to continuous noise pollution and adversely affecting their health and well-being. Furthermore, the issue of noise pollution seems to be receiving less attention in India, as the general population remains unaware of its potentially harmful effects.

Various techniques can be employed to control noise pollution by modifying the source mechanism, transmission path characteristics, and receiver perception. Addressing railway noise at the source is considered the most effective practice among these techniques. To achieve this, it is necessary to investigate the different sources of railway noise and their associated transit mechanisms across different train types and identify the underlying causes of noise generation. Furthermore, the impact of critical factors that influence railway noise must be evaluated.

Sound can travel through various media, including air, water, and solids, and any change in the properties of the medium influences the propagation of sound. During long-distance travel, the atmosphere absorbs some sound and reduces the sound energy. This phenomenon is primarily affected by the frequency, atmospheric conditions, and distance sound waves travel. As railway noise propagates through air, the parameters associated with atmospheric conditions, such as air temperature, humidity, air pressure, wind speed, direction, duration, and turbulence, can positively or negatively modulate sound levels. Therefore, a thorough analysis of railway noise variation requires assessing sound levels at different measuring distances from the source (e.g., 25, 50, 100, 200 m) under various air temperatures, humidity, and wind conditions.

The train horn is a powerful air horn deployed as an auditory cautionary measure in high-risk areas such as railway crossings, bridges, and tunnels (Railway 2008). Train horns are intended to alert other road users of an approaching train, but this can cause significant annoyance to nearby residents. Several activities related to transportation noise are involved at a level crossing, identified as a noise pollution hotspot. Hence, there is a need to investigate the variations in railway noise along with train honking at a railway level crossing.

The presence of a barrier between the source and receiver can attenuate the noise levels based on its shape, material, and dimensions. For example, railway boundary walls in urban areas are constructed to prevent encroachments on railway lands and avoid pedestrian trespassing on railway tracks. Factors that can impact the barrier's ability to reduce noise include its height and size, the distance between the noise source and the receiver, the surface of the barrier facing the railway track, and the noise frequency. Hence, there is a need to evaluate the effectiveness of such a boundary wall for reducing noise and propose an improved alternative.

A human perception survey must be conducted to investigate the relationship between noise levels and annoyance during daily activities such as working, resting, conversing, eating, talking on the phone, and reading. By identifying specific concerns and areas of impact, authorities can implement measures such as noise barriers, sound insulation, or changes in train operations to reduce noise levels and enhance residents' well-being. Several countries implemented regulations on acceptable noise levels in residential zones. There is a need to determine if the railway line noise comply with these regulations. If not, the survey results can be used to contend for making the necessary changes or improvements to meet the standards.

1.7 Research Objectives

The following are the objectives proposed for the research study:

1. To assess the influence of train characteristics, distance of measurement, and meteorological conditions on the noise perceived by the track-side dwellers.
2. To investigate the variation of noise levels at the railway level crossing, which involves noise from different transport sectors.
3. To evaluate the performance of existing encroachment walls to serve as noise barriers along the railway track and to determine the optimal height and shape of the wall.
4. To evaluate the impact of railway noise on exposed residents and establish a noise exposure-annoyance relationship.
5. To develop a practical model suitable for predicting rail transport noise pollution in an urban area.

1.8 Scope of the Work

The present study is limited to trains operating on railway tracks characterized by straight alignments without any curves and signaling systems. Further, the current study evaluates the performance of railway boundary wall located proximate to residential units along the railway line.

1.9 Organization of the Thesis

The thesis is presented in six chapters, and the contents of the report are organized as follows:

Chapter 1: This chapter introduces the motivation and aim of this research. It highlights the need to evaluate the impact of railway noise on the track-side residents. It emphasizes the importance of possessing an in-depth understanding of railway noise, how it is transmitted, and how the receivers perceive it. The research objectives are defined, and the scope of the current study is detailed.

Chapter 2: The assessment of railway noise levels and the exploration of strategies for noise reduction have received significant attention across the globe. This chapter provides a comprehensive overview of the literature collected on multiple noise sources within railway systems, key factors contributing to noise generation, how people perceive railway noise, and effective measures to mitigate railway noise.

Chapter 3: This chapter presents the methodology employed to achieve the defined objectives, along with a comprehensive explanation of the data collection process. This chapter outlines the approach used to measure various parameters related to train sources, such as train speed, length, and type, as well as meteorological factors like wind speed, wind direction, temperature, and humidity. Additionally, it covers the process of evaluating barrier performance and investigating the effects of railway noise on residents living in proximity to the tracks.

Chapter 4: This chapter presents the work carried out to analyse the train source parameters i.e., influence of train speed, length, type and measuring distance on the variation in railway noise. This chapter presents the empirical methods for estimating maximum and equivalent noise levels. In addition, the study results of the train honking levels at the railway level crossing along with the development of an artificial neural network to forecast these noise levels is presented.

Chapter 5: This chapter presents the analysis carried out on variation of railway noise due to transmission path characteristics such as ambient temperature, relative humidity, wind speed and direction. Noise maps are generated for the test site by taking into consideration of the noise source and transmission path characteristics and obtained the ideal distance to construct housing units from the railway line. In addition to this, the noise level variation caused due to the presence of a wall in between source and receiver is presented.

Chapter 6: This chapter quantifies the extent of railway noise within households located along these railway corridors and explores the intricate relationship between noise levels and the resulting annoyance during routine daily activities through a comprehensive questionnaire survey. Structural equation model was developed to analyze the complex relationships between annoyance, disturbance, and health effects and the results are presented.

Chapter 7: This chapter includes a summary of current research work, along with conclusions and limitations. Further, the scope for future work is also presented.

Chapter 2

LITERATURE REVIEW

The assessment of railway noise levels and the exploration of strategies for noise reduction have received significant attention across the globe. This chapter provides a comprehensive overview of the multiple noise sources within railway systems, key factors contributing to noise generation, how people perceive railway noise, and effective measures to mitigate railway noise.

2.1 General

Over the past several decades, researchers worldwide have primarily concentrated on assessing railway noise and its impact on residents living along the railway tracks. Various studies have investigated ways to mitigate the adverse effects of railway noise by targeting noise reduction at the source, transmission path, and receiver end. For instance, numerous countries have implemented train horn policies to enhance the quality of life and improve the health of trackside residents. However, due to the differences in railway systems, rolling stock, track geometry, train speeds, locomotive and wagon types, as well as regulations and standards related to noise levels, countries exhibit unique characteristics that pose a challenge for engineers in achieving a noise-free environment for residents living along railway tracks. In addition to source characteristics, transmission path features such as atmospheric pressure, temperature, humidity, wind speed, and direction, and the presence of objects or vegetation further contribute to the complexity of creating a noise-free environment for trackside residents. Therefore, conducting a comprehensive study on the variability of noise levels with changes in train characteristics, transmission path, and receiver characteristics is imperative to analyze the impact of railway noise on trackside residents.

Trains with varying speeds and lengths while transporting both passenger coaches and freight wagons exhibit different noise emissions. This necessitates a comprehensive investigation into the various sources of railway noise, the transit mechanisms involved in each train type, and a summary of the causes of noise generation. A railway level crossing is a significant source of noise pollution due to various transportation-related activities, including train horn usage, train movement, road vehicles, and pedestrians, all contributing to increased noise levels. Train horns are generally blown as they approach railway level crossings and are mandatorily used to alert roadway users. However, the train horns are considered a nuisance to the nearby residents. A detailed evaluation of train horn effectiveness is essential in the contemporary environment. In addition, it is necessary to quantify the noise produced by the railways and its effects on residents' perception to implement noise mitigation strategies. Hence, a human response survey must be conducted to comprehensively understand impact of noise on individuals. This chapter discusses the studies available in the literature on various environmental noises, factors affecting railway noise levels, principal noise sources responsible for higher noise levels, several transmission path characteristics, train honking, noise barrier characteristics, receiver perception characteristics, and noise abatement measures.

2.2 Negative Impacts of Noise Pollution

Noise pollution causes several ill effects on human life. The impact of noise on human life is mainly divided into auditory effects, physiological effects, and behavioural changes. A comprehensive list of noise sources and their effects is presented in Figure 2.1. Transport vehicle noise contributes to approximately 55% of all environmental noise sources (Singh et al. 2018). The sources of noise pollution in any urban area are classified as follows: industrial noise, transportation noise, household noise, and noise from public address systems. Among all these sources, industrial and transportation noise constitute 75% of overall noise in any urban environment system (Feng et al. 2015). Several studies conducted in urban areas revealed that road transport noise is the primary source of noise pollution, and next to it is rail transport noise among various modes of transportation.

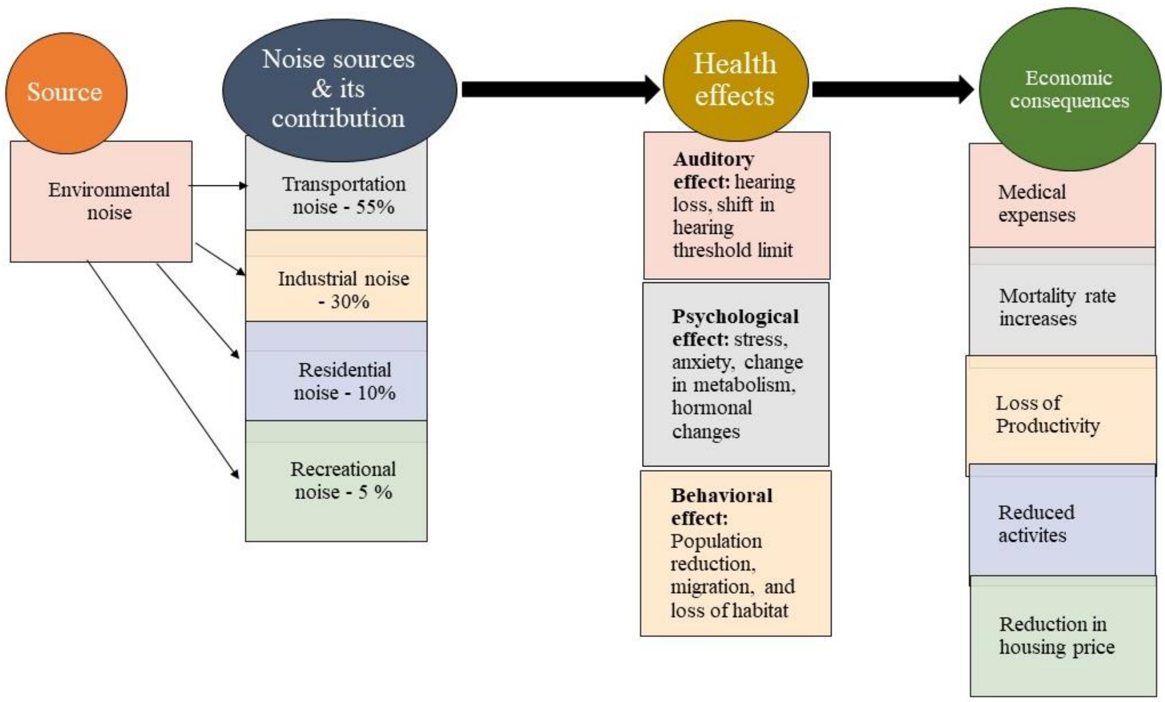


Figure 2.1 Environmental noise sources and their impacts.

Moreover, noise pollution harms the environment by disrupting wildlife habitats and diminishing biodiversity. According to a study conducted by the European Environmental Agency (EEA), exposure to noise pollution has been associated with an increased risk of sleep disturbances and insomnia. Furthermore, the World Health Organization (WHO) has emphasized that over 1 billion young individuals worldwide are at risk of developing hearing impairments due to the effects of noise pollution (Clark and Stansfeld 2007). A research study by Grubliauskas et al. (2014) established that exposure to traffic-related noise is linked to a heightened susceptibility to heart attacks and strokes. Similarly, research from the University of California, Berkeley, has demonstrated that noise pollution can elevate cortisol levels, a stress-related hormone contributing to anxiety and depression (Vincent 2000).

2.3 Studies on Transportation Noise

Transport noise, particularly from road traffic, aircraft, and railways, significantly contributes to noise pollution in urban areas. In the European Union, approximately 89.8 million people were exposed to annual noise levels exceeding 55 dBA in 2007, with 11.7 million affected by railways and 4.3 million affected by air traffic (Neitzel et al. 2013). A recent report from the European Union indicates that despite efforts to mitigate noise levels, the population exposed to noise levels exceeding 55 dBA has risen to 113 million for road traffic, 22 million for railways, and 3 million for air traffic. In the United States, approximately 104 million individuals are impacted by noise levels primarily generated by road traffic exceeding 70 dBA (Gidlöf-Gunnarsson et al. 2012). These statistics highlight the significance of implementing strategies, policies, and regulations to mitigate the impact of transportation noise on the affected population in some developed countries.

In urban areas, noise levels from the transport sector often exceed 85 dBA, which is unacceptable for most residents. Developed countries typically possess well-established transportation systems, consisting of highways, railways, airports, and urban transit networks, which contribute to elevated transportation noise levels compared to less developed countries. In Europe, approximately 25% of the population is subjected to transportation noise levels exceeding 75 dBA. Transportation-related noise affects nearly every individual in the United States. Chevallier et al. (2009) conducted a study in Italy investigating several sources of urban environmental noise pollution, including industrial, transport, and commercial activities and concluded that transportation noise is the primary contributor. The major components of several transportation noise sources, ill effects, and mitigation measures are detailed in Table 2.1.

Table 2.1 Comparison of noise from different urban transport sectors

Description	Road traffic noise	Railway noise	Aircraft noise
Source of noise	○ Engine noise ○ Tyre pavement interaction noise ○ Aerodynamic noise	○ Engine noise ○ Rolling noise ○ Aerodynamic noise ○ Ground vibration	○ Mechanical noise ○ Aerodynamic noise ○ Aircraft system noise
Ill effects	It causes irritation, annoyance, cardiovascular disease, risk of heart strokes, and hypertension.	Causes sleep disturbance, increased awakenings throughout the night, and temporary or permanent impairment.	It causes community annoyance, negatively impacts children's cognitive skills, such as reading and memory, and causes wakefulness and difficulty sleeping.
Mitigation measures	By creating more gaps between roads and buildings, using sound insulation walls, and constructing quiet pavements wherever necessary.	Installation of trackside noise absorbing barriers, grinding of wheel and rail, utilisation of porous material as damping proof along the track.	Soundproof the windows, doors, walls, roof, etc., fly aircraft at higher altitudes in residential areas, and develop and adopt quieter aircraft.

Promoting sustainable mobility by regulating noise pollution necessitates a complex array of policies. These policies demand substantial financial investments and will require an extended period for their full implementation. The proposed remedies include avoiding residential zones, educational institutions, and medical facilities near noise-emitting transportation hubs. Additionally, there is a pressing need for rigorous enforcement of pertinent noise control regulations. Currently, urban planning often overlooks the issue of transportation noise, but it should be considered in future planning endeavours. The ongoing legislative efforts are focused on investigating the feasibility of creating an integrated transportation noise prediction model. Such a model could account for the cumulative impact of noise generated by various transportation modes, including aircraft, highways, and railways, especially in areas where residents are exposed to the combined noise emanating from multiple transportation sources.

Negative monetary impacts of transport noise

Measuring the financial impact of transportation noise can be challenging because it does not cause direct financial loss but indirectly affects the public and the government. One negative effect is the loss of well-being of people consistently exposed to transport noise, which can be quantified in terms of money spent on things like sleeping pills, stress-reducing pills etc. (Chen et al. 2020). A European study found that the social cost of road traffic noise above 55 dBA is 35 billion euros/year, while the social cost of railway noise is 3.5 billion euros/year. Most social costs are from road traffic, primarily passenger cars and heavy vehicles (Chan and Lam 2008). Lowering speed and traffic volume can reduce social costs, but it comes at the cost of increased travel time.

Transportation noise can also impact the housing market, resulting in monetary loss for houseowners and developers. This phenomenon can be seen by evaluating how much people are willing to pay to live in a quieter environment. A study on the impact of transportation noise on independent houses found that houses near roads with heavy traffic noise can lose up to 30% of their value. Another study showed that an increase in noise by one decibel could reduce the value of a house by 0.20% (Bellinger 2006). These studies indicate that transportation noise can significantly impact the housing market and lead to a loss of property value. Figure 2.2 compares the cost-effectiveness of road and rail transport noise. The financial expenditure on road accidents often surpasses that allocated for noise-related concerns. However, the scenario differs in railways, where the costs associated with noise pollution outweigh those attributed to accidents. This underscores the prominence of noise pollution as a critical issue within the railway sector compared to road transportation. Thus, policymakers must identify abatement measures to reduce the ill effects caused by rail transport noise.

Figure 2.2 Cost-effectiveness of road and rail transport noise (Pronello 2003)

2.4 Rail Transport Noise

Railway noise refers to the audible emissions produced by trains as they traverse along railway tracks. These emissions can encompass many different sounds, including engine noise, wheel/rail interaction noise, horn sounds, and brake sounds. The major dominant railway noise sources include engine noise, propulsion noise, equipment noise, rolling noise, aerodynamic noise, and honking. Research findings indicate that the primary contributors to railway noise can differ based on the train's speed. When operating at lower speeds, engine, propulsion, and equipment noise tend to be the dominant sources. However, rolling and aerodynamic noise are major sources of railway noise at higher speeds (Lee et al. 2021).

2.4.1 Rolling noise characteristics

The rolling noise, also called wheel-rail or rolling contact noise, is generated due to the interaction between the wheels and the rails as a train moves along the tracks. The variation in the roughness of both the train's wheels and the rail can lead to variations in rolling noise levels. Impact rolling noise occurs when the train's wheels come in contact with the joints or irregularities on the track, and it is more noticeable at lower speeds. Continuous rolling noise, on the other hand, emanates from the vibrations and resonance produced when train wheels move over the smooth track surface. This type of noise is predominant at higher speeds and lower frequencies. The key factors influencing rolling noise include the shape and condition of the wheels and rails, track alignment and geometry, track surface quality, train speed, design of train wheels and suspension systems, and the presence of moisture on the track, all of which can affect the level of rolling noise.

2.4.2 Mitigation measures for rolling noise

Various steps can be taken to reduce rolling noise, some essential methods are described below.

1. **Reduction of rail roughness:** Rail corrugation with a wavelength of 3-7 cm and amplitude of 0.1 mm frequently occurs over the railheads and this phenomenon leads to the roaring noise. The process of grinding reduces the roughness of the rail. Rotating grinding stones are conventionally used for rail grinding.
2. **Change in the braking system:** Several studies revealed that by changing the train braking system from cast-iron block brakes to disc brakes, there is a noise reduction of 10 dBA. If cast-iron brakes are used, the risk of wheel corrugation is high, whereas disc brakes give a smooth surface finish to the wheel.
3. **Modifying the wheel shape:** Wheel shape significantly influences rolling noise, and wheel diameter and web play a crucial role. The axial movement of the web and the radial motion of the wheel emits the rolling noise. These two radial and axial motions are coupled together; reducing this action reduces most of the noise. This is achieved by changing the web shape and reducing the wheel diameter.
4. **Introducing damping material:** The damping elements can be introduced to both wheel and rail. The damping element is a thin layer of visco-elastic material between the wheel and the constraining plate. This arrangement can reduce the rolling noise up to 2.5 to 5 dBA and can be achieved by introducing damping elements to the rail (Sadeghi and Hasheminezhad 2016).
5. **Trackside barriers:** Installation of trackside barriers is widespread in many countries. This barrier creates a shadow zone, which does not allow the noise to propagate. Trackside vegetation also acts as a natural sound barrier if the trunk and leaf sizes are large enough to absorb the noise (Hartung and Vernersson 2003).

2.4.3 Train honking noise

A train horn or whistle, which is a powerful air horn, serves as an audible warning device for railway guards, staff, and train passengers at railway stations. Unfortunately, the train horn can significantly disturb those living beside railway lines or working near railroad crossings. The adverse effects of this honking noise are improper sleep structure, causing congenital disabilities, increased heart rate, and cardiovascular diseases. Locomotive use horns as per strict controls and rules, not as per their whims and fancy. The general code of practice detailing the usage of train horns suggests the scenarios needed for applying train horns, such as the intensity, duration, and repetition required based on the conditions. Figure 2.3 shows the primary purpose of blowing a horn along the railway line, and these horns should be loud enough to be heard from a considerable distance.

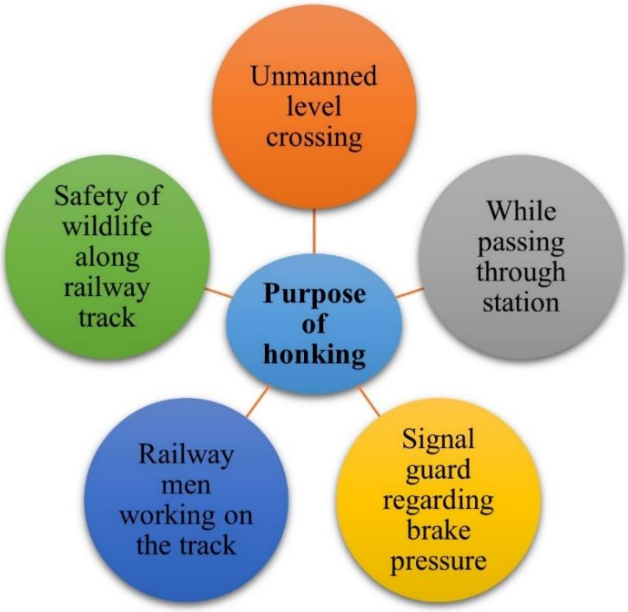


Figure 2.3 The primary purpose of blowing a train horn (Dolan and Rainey 2005)

The train horn or whistle has a pattern that has a specific meaning in certain scenarios. According to Indian Railways, there are eleven distinct horn patterns, each with distinctive sound patterns, as shown in Table 2.2.

Table 2.2 Train horn pattern and its significance

Pattern of horn	**Significance of the horn**
One short horn.	Before taking the train into the yard for cleaning.
Two short horns.	Signalling the guard to change the railway signal for starting the train.
Three short horns.	Loco pilot lost control and signals the guard to pull the vacuum brake.
Four short horns.	Train not moving ahead due to technical issue.
One long and short horn.	Signalling the guard to set the brake pipe system before starting the engine.
Two long and two short horns.	Signalling the guard to take control of the engine.

A continuous horn.	Train passing non-stop through many stations.
Two horns with two pauses.	Alert the passersby while passing through a level crossing.
Two long and one short horn.	While the train is changing the tracks.
Two short and one long horn.	Any passenger has pulled a chain or the guard has pulled a vacuum brake.
Six short horns.	It's a trouble signal when the train is in a dangerous situation.

Several countries have implemented various train horn policies to improve the standard of living, thereby improving the health of trackside residents. Table 2.3 shows the detailed train horn policies and control strategies practiced in various countries. However, train horn policies must be formulated specifically to protect people's health depending on their lifestyles in nations with populations over one billion, such as India and China. The influence of noise on public health depends on the intensity of the noise and the duration of its exposure. As the intensity of noise increases, the permissible limit of exposure decreases, and as the intensity of noise decreases, the allowable limit of exposure increases. For instance, impulse noise, defined as a brief and sudden noise, can harm human health if its intensity exceeds 125 dB (Lokhande et al. 2022). Hence, it is necessary for the Governments in various countries to establish noise limits in residential areas based on the intensity of the noise and the exposure duration.

Table 2.3 Train horn policies and control strategies being practiced in various countries.

Country	**Train horn policy**
Australia	Train horn decibel limit in urban areas is 95 to 100 dBA, and in non-urban regions, the minimum decibel restriction is 106 dBA.(Daly 2016)
Canada	Train horns are prohibited in the silent zones between 10 p.m. and 6 a.m. if automatic gates are installed at the level crossing. (Russo et al. 2003).
United Kingdom	Imposed quiet zones from 11 p.m. to 7 a.m. in which train drivers must use the low horn at whistle boards. (Meister et al. 2000).
United States	Train horn restrictions were placed on track sections depending on the time of day. The maximum level for the train horn is restricted to 110 dBA, but the minimum sound level remains 96 dBA.(Votano et al. 2004)

2.4.4 Railway interior noise characteristics

Interior noise in trains is a cause of concern that can negatively impact train drivers (locomotive pilots) and passengers. Feedback from railway passengers indicates that good comfort and a sound environment inside trains are crucial factors affecting train comfort. Long-term exposure to interior train noise can also negatively impact people's moods and health. The interior noise in trains comprises two main components: air-borne noise generated by external sources and structural noise, which includes wheel/rail rolling noise, sleeper passing frequency excitation, and aerodynamic effects. A study conducted by Thompson (1993) highlights wheel/rail roughness as a significant contributor to interior noise excitation, mainly when the rail is corrugated. The primary sources of interior noise in trains include:

1. **Rolling noise:** Rolling noise from a train can significantly impact the interior noise. The noise generated by the wheel/ rail interaction can penetrate the train's interior and cause a loud and persistent noise.
2. **Aero-acoustic noise:** Aero-acoustic noise from a train refers to the noise generated by the interaction of the train's motion with the surrounding air. It can also be caused by other moving parts of the train, such as the pantographs, roof-mounted equipment, and doors.
3. **Mechanical noise:** Mechanical noise from a train refers to the noise generated by the movement and operation of various mechanical components, such as engines, compressors, fans, and other systems.
4. **Impact noise:** Impact noise from a train refers to the noise generated by sudden, sharp impacts between the wheel and the rail. Various factors, including rough tracks, misaligned wheels, and uneven rail joints, can cause this type of noise (Thompson et al. 2000; Kitagawa and Thompson 2006).

Additional factors, such as the frequency of sleeper passages, vibrations induced by the passage of sleepers, and their cumulative effects, become more pronounced when the bogie axle spacing is a multiple of the sleeper spacing. This alignment can lead to a prominent peak in the A-weighted noise level, particularly under specific conditions. These vibrations are transmitted internally through structural pathways. Moreover, there is potential for aeroacoustics excitation at the frequency of sleeper passages in particular scenarios. Sound from external sources, such as the train's wheels and engine, can enter a running train's interior through air-borne and structure-borne paths.

2.5 Railway Noise Measurement Procedures

Following particular procedures and guidelines while conducting railway noise measurements is crucial to ensure precise and comparable results. A few standards mentioned below can provide a valuable reference for evaluating and mitigating train noise more consistently and reliably.

ISO 3095-1975: According to ISO 3095-1975, the following steps should be taken when conducting train noise measurements:

1. **Site selection:** Select a suitable location for the railway noise measurement that is representative of the typical operating conditions of different train types. The location should be free from obstructions and reflecting surfaces, as such objects' presence will significantly impact measured sound levels.
2. **Selection of equipment:** When selecting a Sound Level Meter (SLM) for sound measurement, it is vital to ensure that the equipment meets the requirements of the applicable standard. Several international standards, like the International Electrotechnical Commission (IEC) 61672-1 and American National Standards Institute (ANSI) S1.4, define the measurement range, frequency weighting, and accuracy requirements for SLMs.

   When choosing the microphone for a SLM, it should be calibrated and meet the required standards. The microphone should have a flat frequency response and low self-noise to ensure accuracy in sound measurement. Depending on the application, the type of microphone, such as an omnidirectional or directional microphone, has to be appropriately chosen.
3. **Test setup:** The microphone is to be placed at a specified height above the track and a certain distance from the track in accordance with the standard. A specific set of guidelines, such as the IEC or the ANSI, has to be referred for sound measurements.

   According to IEC 61672-1, a sound level meter should be positioned at the height of 1.6 m (5 feet 3 inches) above the ground and at least 2 m (6 feet 7 inches) from the nearest reflecting surface. This is referred to as the free field measurement condition and is used for measurements in outdoor environments.
4. **Measurement procedures:** This defines the duration of time, frequency weighting, and other factors for conducting sound level measurements. The resulting data is used to

determine the average sound level and other relevant parameters, such as the frequency spectrum of the sound.

5. **Data analysis:** The sound level data collected using SLM must be organized into datasheets correctly for more straightforward calculation. Statistical methods can be used to calculate the average, minimum, and maximum sound pressure levels using spreadsheets.

Selecting a suitable SLM for railway noise measurement requires careful consideration of several technical factors. First and foremost, the SLM should comply with relevant standards, such as Type 1 or Type 2, which are defined based on the desired level of accuracy in noise measurement. Additionally, the SLM should possess the necessary features, including an appropriate frequency range, typically between 20 Hz and 20 kHz, a suitable measurement range, and various time-weighting options, such as fast, slow, and impulse. In addition, it is essential to ensure that the SLM is calibrated and maintained regularly to ensure accurate measurements. Several types of SLMs generally used for railway noise measurements are mentioned below:

1. **Class 1 and Class 2 SLM:** These are the most commonly used SLMs for railway noise measurement, which were standardized in accordance with IEC 61672. Class-1 SLM is more accurate than Class-2 in measuring railway noise.
2. **Integrating SLM:** These are most suitable for measuring railway noise as they can measure noise generated by passing trains and ambient noise levels. These types of SLMs measure sound pressure levels over a period of time and average the sound levels over that period.
3. **Handheld SLM:** These portable and user-friendly devices can measure railway noise at various locations quickly and easily. These SLMs are commonly used for preliminary noise evaluations and identifying potential hotspots.

When selecting an SLM for railway noise measurement, it is essential to consider a few requirements like accuracy and precision, frequency range, measuring distance, and measurement duration.

2.6 Factors Affecting the Railway Noise

Within the train system, the noise is primarily determined by the type of train, train speed, train length, measuring distance, meteorological conditions, the running train’s braking system, coupling type, axial load, suspension system, and load transfer mechanism.

2.6.1 Train speed

The speed of the train primarily determines the influence of various noise sources. When the train operates at speeds below 50 km/h, engine and traction noise are the dominant noise sources (Zhang 2010). On the other hand, when the train runs between 50 km/h and 250 km/h, rolling noise becomes the primary contributor to noise levels (Degrande and Schillemans 2001). The level of rolling noise is significantly correlated with the speed of the train (V, km/h), increasing at a rate of 30 log (V), corresponding to nine decibels increase in noise levels when the train's speed is doubled. At speeds exceeding 250 km/h, aerodynamic noise emerges as the dominant noise source, exhibiting an exponential increase with train speed. The rate of increase in aerodynamic noise ranges from 60Log (V) to 80Log (V), resulting in an 18 dBA to 24 dBA increase in noise level when the speed of the train is doubled (Noh et al. 2014). Hence, train speed is a pivotal factor significantly contributing to railway noise levels.

2.6.2 Train type

Different types of trains (passenger or freight) emit different noise levels according to their built-in mechanism. In the Indian Railways, passenger trains are broadly classified into three categories depending on the type of coaches and coupling: ICF (Integral Coach Factory) train, ICF-CBC (Integral Coach Factory – Centre Buffer Couple) train, and LHB (Linke Hofmann Busch) train. It is important to note that the old ICF coaches consist of screw coupling, whereas all the new ICF coaches consist of CBC. The old-generation ICF coaches would be retrofitted with CBC by replacing the screw coupling in a phased manner. However, the LHB coaches are equipped with CBC. Locomotives are categorised by service gauge (broad gauge, meter gauge, narrow gauge), traction used (diesel, electric, battery), traffic type (passenger, goods, and mixed), and power/version in a four- or five-letter code (e.g., WAP 4). The number refers to the locomotive's most recent model. Alternative Current (AC) locomotives are quieter than diesel because there is no engine or exhaust noise, and they produce low mechanical noise (Dittrich and Janssens 2000). Apart from locomotives, train coaches are mainly of two types: (i) passenger coaches and (ii) freight wagons. The detailed mechanism in each train type is discussed in subsequent sections.

2.6.3 Train length

The noise generated by trains is greatly influenced by the length of the train and the type of coaches it carries. The length of trains is a measurable factor affecting noise production, with longer trains generally producing higher noise levels than shorter ones. This is because longer trains cause increased track vibration and more sound from additional coaches/wagons. Table 2.4 shows the standard lengths of various types of passenger and freight coaches/wagons, and Table 2.5 shows the standard lengths of various types of locomotives available in Indian railways.

Table 2.4 Type of coaches and their lengths

Passenger coach	**Coach length (m)**	**Freight coach**	**Wagon length (m)**
ICF	22.28	Open wagon	10.71
LHB	24.70	Closed wagon	15.43
ICF_CBC	21.70	Tank wagon	12.42
MEMU	20.73	Brake van	13.54

Table 2.5 Type of locomotives and their lengths

Locomotive type	**Length (m)**	**Locomotive type**	**Length (m)**
Passenger coach carrier		*Freight wagon carrier*	
WAP 4	18.79	WAG 5	17.16
WAP 5	18.16	WAG 7	20.93
WAP 6	18.79	WAG 9	19.28
WAP 7	19.28	WAM 4	18.85
		WAG 12	38.40

Since sound can travel through air, water, and solids, any factor that affects the state of the medium influences sound propagation. The atmospheric conditions, such as air temperature, humidity, air pressure, wind speed, direction, duration of the wind, wind turbulence, etc., can dampen or enhance sound levels (Klop and Ivantysynova 2008).

2.6.4 Effect of wind speed and direction

The variation in wind speed and the distance from source to receiver results in the upward or downward bending of the sound waves. This phenomenon can significantly impact sound levels at the receiver end. Tanaka and Shiraishi (2008) conducted a study evaluating the effects of wind on noise propagation and concluded that a constant wind flow has very little effect on sound propagation. However, a shift in wind direction or speed can generate sound level changes of 10 to 15 dBA over a short period. Wind speed profiles are affected mainly by the intensity of sunlight, meteorological conditions, and the nature of the ground surface. The relative speed is calculated by adding the sound speed (c) and the wind speed (u), i.e., c+u (down-wind condition) or c-u (up-wind condition).

Sound traveling in the direction of flow is referred to as downwind. Near the ground, air flow generally increases with increasing height. This effect causes the sound waves to refract towards the earth’s surface, increasing the intensity of sound propagation. Wind direction is generally reported by the direction from which the wind originates. The flow vector (U) gives information regarding the magnitude and direction of the airflow. As shown in Figure 2.4, path 1 shows the sound propagation when no wind occurs. The sound waves travel through vegetation, ground, plants, and boundary walls, wherein these obstacles absorb some part of the sound energy. Path 2 shows the downwind phenomenon in which the sound waves travel upwards into the sky and bend towards the earth. In this situation, the sound waves pass above the obstacles, yielding higher sound levels at the receiver. The downwind phenomenon is generally preferred by acoustical engineers as there is less variability, and the results are considered the “*worst-case*” (Öhlund and Larsson 2015).

Upwind sound waves travel in the opposite direction of the flow and are refracted from the ground surface. The sound intensity at the receiver is reduced due to this phenomenon. As seen in Figure 2.5, strong upwind can create a shadow zone, and the shadow zone distance from the source can be determined if the wind speed profiles are known accurately. Ocker and Pannert (2020) estimated the shadow zone for noise emanating from a wind turbine and reported a 3 to 5 dBA reduction in noise due to upwind conditions.

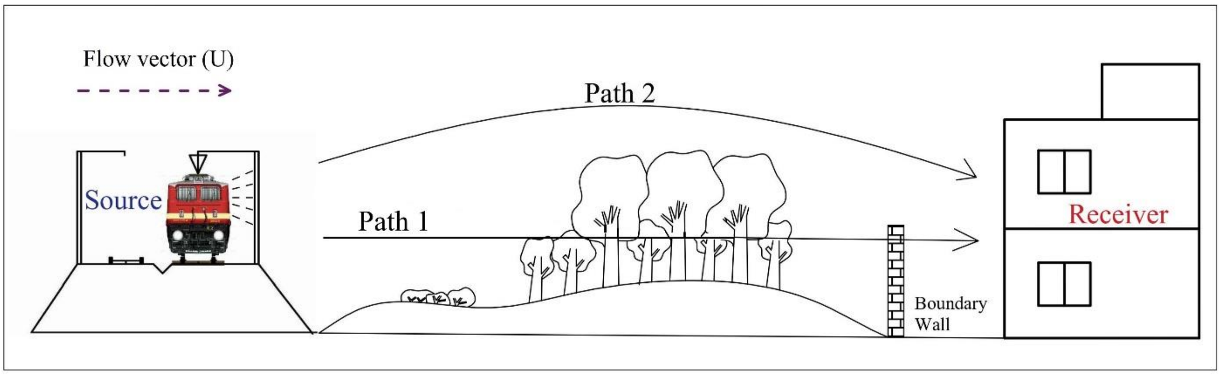


Figure 2.4 The phenomenon of downwind sound propagation

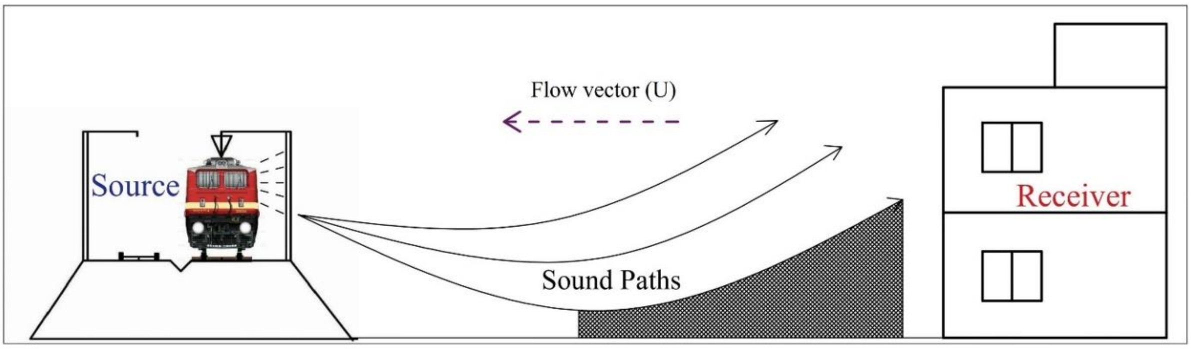


Figure 2.5 The phenomenon of upwind sound propagation

2.6.5 Effect of air temperature

Temperature influences the density of air, which in turn affects the speed of sound. A constant temperature change with altitude does not affect sound propagation. However, the temperature gradient, similar to the wind gradient, can bend sound waves upwards or downwards. When the temperature rises, the air molecules gain energy and vibrate faster. As a result, sound waves traveling through this medium can travel at a faster rate. According to Chen et al. (2021) sound waves are bent downwards due to the influence of air temperature in the upper atmosphere. The noise levels at the receiver have been observed to increase when the sound source is at a higher altitude than the receiver due to temperature inversion, even when the receiver is far from the source.

2.6.6 Effect of humidity

According to a study by Hornikx et al. (2018), 50% humidity in the atmosphere causes sound attenuation of less than one decibel per 100 m for frequencies below 2500 Hz. As a result, humidity attenuation is considered only when the wind speed is low and the sound frequency is high. In another study by Wong and Embleton (1985), the impact of atmospheric humidity on railway noise transmission will depend on the noise frequency, the distance between source and receiver, and local atmospheric conditions. In a study conducted by Cheinet et al. (2018), the effects of atmospheric absorption variation on sound propagation were investigated. The research was carried out using a single omni-directional sound source operating under static climatic conditions. However, in urban environments, climatic conditions change dynamically over time, which can considerably impact sound transmission.

2.6.7 Effect of distance from source to receiver

The distance from the source to the receiver is crucial in understanding the propagation and perception of sound. Several factors influence the effect of distance on sound, including divergence, absorption/diffusion, and shielding. These mechanisms are discussed below in more detail:

Divergence: The phenomenon occurs when sound spreads out and gets quieter as it moves away from the source. Railway noise divergence happens for several reasons, including the inverse square law. This law states that sound gets weaker as you move further away from it. As sound waves travel away from the railway line, they spread out over a larger area, which makes them quieter (Godin 2008).

Absorption: Sound absorption is the conversion of sound energy into alternative forms of energy, notably heat, when it interacts with different materials. When sound waves propagate through the atmosphere, they come into contact with surfaces and objects that possess the ability to absorb, reflect, or transmit sound energy. Regarding railway noise, sound absorption can transpire through various mechanisms such as ground absorption, absorption facilitated by vegetation, atmospheric absorption, and absorption resulting from the presence of obstacles or buildings (Pàmies et al., 2014).

Shielding: Railway noise shielding encompasses a range of strategies implemented to diminish or alleviate the auditory disturbances produced by trains during their passage through the atmosphere. Among the prevalent techniques employed for this purpose are acoustic barriers, which serve to absorb or deflect the noise emitted by trains; earth berms consisting of natural or artificial elevations of earth or soil erected parallel to the railway tracks; and noise walls that bear a resemblance to acoustic barriers but are typically taller and specifically engineered to obstruct the direct line of sight between the railway tracks and regions sensitive to noise (Harris 1969).

2.7 Noise Barriers

The sound transmission from source to receiver varies with obstacles like vegetation, encroachment walls, buildings, and natural hills. Their height and distance from the track influence the noise perception. Natural hills covered with bushes, trees, grass, etc., help to absorb the noise. In the free-field condition, sound propagation is influenced by reflecting, absorbing, or reverberating ground surfaces (Koussa et al. 2013).

Noise barriers have proven effective in reducing noise emissions globally. These barriers act as solid obstacles and reduce noise levels without completely blocking sound energy. They are typically long and continuous structures constructed between the railway line and areas sensitive to noise. Various materials can be used to construct noise barriers, including brick, concrete (cast in place or precast), timber, metal, recycled, transparent, composites, and proprietary materials. Its shape and construction materials determine the acoustic performance of a noise barrier. Additionally, a top-mounted element can influence a noise barrier's effectiveness. Designing efficient noise barriers requires considering the barrier's aesthetics, cost, effectiveness, maintenance, and acceptability (Reiter et al. 2017; Jin et al. 2021).

Low-height noise barriers (LHNB) are increasingly used to mitigate railway noise. These barriers are designed to reduce noise and are typically between 85 and 110 cm tall above the rail surface. LHNB is positioned near the tracks to lessen the impact of rolling noise from the rail-wheel collision. Their effectiveness is measured by the insertion loss, which compares sound pressure levels before and after installing the LHNB. Unlike regular noise barriers, LHNBs are provided close to the tracks and have lower heights, making them less obstructive to train passengers' views. They are also typically more expensive to construct. Some of the noise barriers for protecting residents from railway noise in different countries are shown in Table 2.6. (Hothersall et al. 2000; Wang and Wang 2019).

Table 2.6 Types of barriers used in different countries to protect residents from railway noise

Type of barrier	Significance	Country
Precast concrete barriers, metal panels, transparent acoustic walls, and vegetative barriers	Durable, long-lasting, and effective	United States
Concrete, steel, and timber barriers	Local availability of materials to ensure cost-effectiveness and sustainability	Canada
Polycarbonate or acrylic, metal panels, and masonry walls	Provide aesthetic background	United Kingdom
Concrete barriers, steel, glass or plastic barriers	Vegetation can be grown over these barriers to increase efficiency	Germany
Concrete barriers, steel barriers, and transparent barriers	Based on location and cost-effectiveness	Japan

The literature review showed that the effectiveness of a noise barrier is determined by its geometry, material, and design (Morgan et al. 1998). Factors that can impact the barrier's ability to reduce noise include its height and size, the distance between the noise source and the receiver, the surface of the barrier facing the railway track, and the noise frequency (Ekici and Bougdah 2003). Additionally, the properties of the ground and meteorological conditions also play a role in the barrier's performance. Table 2.7 summarises the review findings of significant research works on the noise barrier's acoustic performance for various shapes and materials from different noise sources, but not specifically for railway noise.

Table 2.7 Review of acoustic performance of noise barriers with different shapes and materials

Authors	Type of source	Shape and material	Remarks and Conclusion
May and Osmans 1980	Point source	T, cylindrical, Y, arrow shape and inclined	Higher noise reduction for wide-topped surface barriers.
Hothersall et al. 1991	Point source	T, Y and Arrow shape (reflective material)	The Y and arrow profiles often perform less effectively than the T profile.
Ishizuka and Fujiwara 2004	Line source	T shape and cylindrical edge barrier (rigid, absorbing and soft material)	The most efficient design is a T-shape with a soft upper surface.
Greiner et al. 2010	Fixed point source	Y-shaped	The methodology proposed in this study increased the insertion loss efficiency by 15 to 30%.
Naderzadeh et al. 2011	Point source	T, A, Y, Z, L-shaped	Those with a 10° L-shape were the most effective among all types of barriers.
Tokunaga et al. 2016	Line source	Vertical reflective, T-shaped, multi-edge barriers.	Compared to conventional barriers, simple shapes offer higher attenuation of 2 to 3 dBA.
Sun et al. 2018	Line source	T and Y-shaped	The Y-shaped noise barrier's ability to reduce noise is most influential and improves as the vertical length increases.
Laxmi et al. 2019	Point and line source	Rectangular, T, cylindrical, Y and Arrow shaped. (Rigid, absorbing and soft material)	Noise reduction is known to be effective with T-shaped barriers that have a soft top surface.
Song et al. 2022	Line source	Low height inverted L and Y shaped (absorbing material)	The inverted L-shaped was observed to be slightly more effective than the Y-shaped.

Concept of noise propagation through a noise barrier

The noise barrier is designed to reduce the level of sound that reaches the receiver by blocking the direct path of sound energy. A noise barrier's effectiveness depends on various factors, including its height, width, and distance from the noise source. When sound energy from the source reaches the barrier, a portion of the energy is reflected towards the source, another portion is diffracted and sent to the receiver side, and the barrier absorbs a portion. The amount of energy absorbed, reflected, and transmitted depends on the barrier's shape, top surface, and material properties (Pultznerová et al. 2021). Figure 2.6 illustrates the entire process of sound energy dissipation in the presence of a barrier.

The acoustical performance of a vertical barrier is affected by the path length difference (δ) and the wavelength of the sound energy (λ). The path length difference of a noise barrier refers to the difference in the distance that sound waves travel to reach a listener's ear, with and without the presence of the noise barrier. This difference can affect the perceived loudness of the sound and can be used to measure the effectiveness of the noise barrier in reducing noise pollution. This concept is illustrated in Figure 2.7. The formula for path length difference is given in Equation (2.1).

$$\delta = A + B - C \tag{2.1}$$

Where A = distance of the source from the barrier top,

B = distance of the receiver from the barrier top, and

C = distance of the source from the receiver.

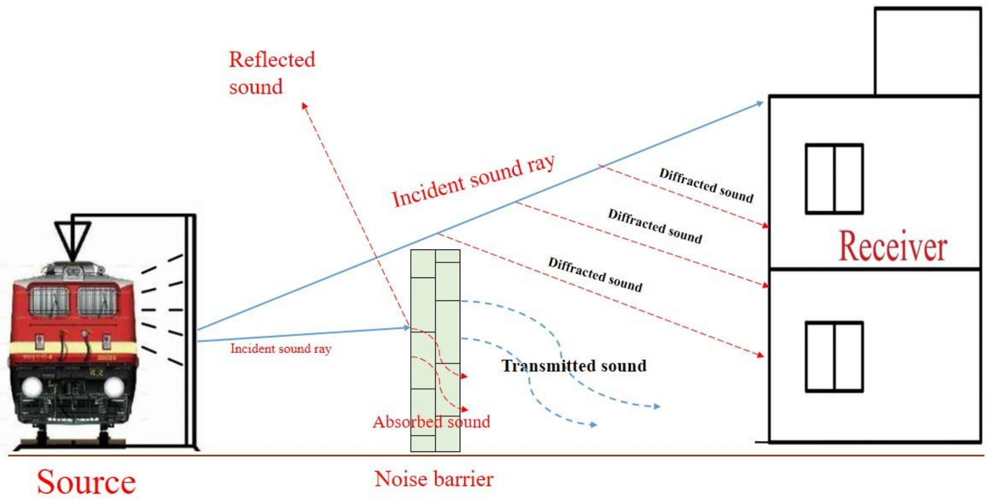
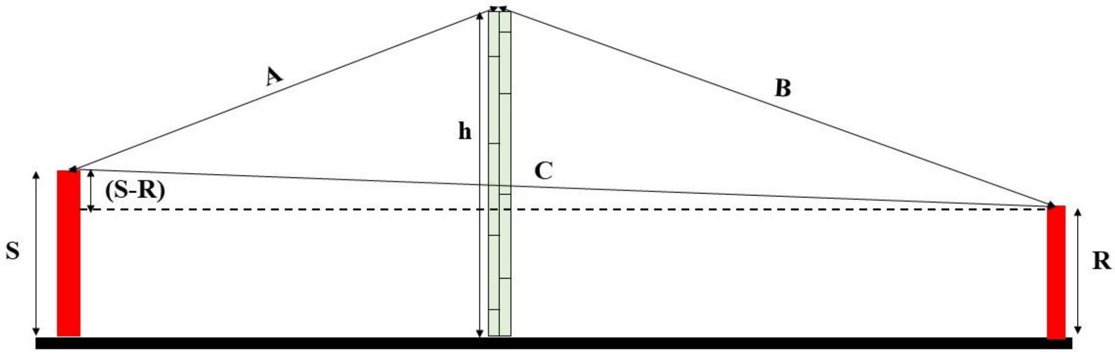


Figure 2. 6 Phenomenon of noise propagation through the noise barrier



S – source height, h- barrier height, R- receiver height, (S-R) difference in the height of source and receiver.

Figure 2.7 The concept of path length difference (δ)

The path length difference and wavelength of the sound energy (λ) combine to give the Fresnel number (*N*), which is shown in Equation (2.2). Fresnel number is a non-dimensional parameter that is commonly used in simplified models to quantify the effectiveness of a barrier.

$$\text{Fresnel number (N)} = \frac{2\delta}{\lambda} \tag{2.2}$$

The wavelength (λ) depends on the frequency of the 1/3rd-octave-band centre.

In addition to Fresnel number (N), noise attenuation and insertion loss are two other parameters that are widely being used to quantify the effectiveness of the noise barrier. Noise attenuation measures how much sound energy the barrier absorbs or blocks. It is the difference in sound pressure level between the sound just before the barrier and far sides.

Noise attenuation (dBA) = SPL before barrier - SPL after barrier.

Equations (2.3) and (2.4) give the formulae to evaluate noise attenuation and insertion loss.

$$\text{Noise attenuation} = -\,20\log\left|\frac{\emptyset_{Total}}{\emptyset_{Free-field}}\right| \tag{2.3}$$

Where, $\emptyset_{Total}$ = sound pressure due to geometrical spreading with ground and barrier present.

$\emptyset_{Free-field}$ = sound pressure at the receiver due to the same free field source.

$$\text{Insertion loss } (\Delta L) = 10\log(2+5.5\,N), \text{ when } (N>1)$$

$$\Delta L = 15\log\left[\frac{\sqrt{2\pi N}}{\tan h(\sqrt{2\pi N})}\right] - 10\log\left(2e^{\frac{-h}{2\lambda}}+1\right) + 5, \text{ when } (N<1) \tag{2.4}$$

Where, $\emptyset_{Ground}$ = sound pressure at the receiver due to the same source in the presence of ground.

Both noise attenuation and insertion loss are a function of the barrier's design, materials, and location, as well as the frequency and direction of the sound source. It is essential to consider both parameters to understand how well the barrier reduces the noise.

2.8 Receiver Perception

Railway noise can have a significant impact on the well-being and health of trackside dwellers. The noise of trains, as they move, can disrupt daily activities, except for occupational noise. While it is rare for railway noise to cause permanent hearing damage, most people in urbanized areas and some in rural areas are somewhat exposed to it. The main impacts of this noise source include annoyance, interference with speech, and sleep disturbance. Research has indicated that individuals exposed to higher railway noise levels may experience non-auditory physiological health issues such as hypertension, cardiovascular problems, and digestive disorders. However, various factors can influence these reactions, and currently, there is no definitive link between a specific noise level description and particular physiological effects. Noise perception varies significantly from person to person based on hearing ability, age, previous exposure to noise, personal preferences, psychological factors, and cultural background (Smith et al., 2013).

2.8.1 Socio-demographic and economic factors affecting the noise perception

The impact of gender on perceptions and experiences of environmental stressors, including noise, has been studied in the past. However, results are inconclusive, with some studies finding no significant gender difference in annoyance levels and others suggesting that women may be more prone to experiencing severe noise annoyance. Miedema and Oudshoorn (2001) found that men and women did not differ in their annoyance levels when exposed to noise. However, recent studies point to women being more susceptible to serious noise annoyance. These findings highlight the need for further research to understand the complex relationship between gender and noise stress and develop effective interventions considering gender-specific differences.

Multiple scientific studies have investigated the correlation between age and noise annoyance. The findings consistently indicate an inverse U-shaped relationship, with the lowest annoyance levels observed in the youngest and oldest age groups. This relationship has been explained as a result of the high workloads and social demands faced by middle-aged individuals, which make them more susceptible to the adverse effects of noise exposure and contribute to their higher levels of annoyance. For instance, a study by Golmohammadi et al. (2007) found that the age group with the most significant noise annoyance was between 40 and 60 years old. Additionally, a study by Gidlöf-Gunnarsson et al. (2012) showed that middle-aged individuals are more prone to sleep disturbances caused by noise exposure than younger and older age groups. These findings emphasize the significance of considering age when studying noise perception.

The relationship between educational attainment and noise annoyance has been established as positive, suggesting that individuals with a higher education level tend to view noise as a more significant threat to their health. However, the strength of this relationship is often considered weak and varies across studies. Another study found that individuals with higher levels of education tend to view noise as a more significant threat to their health, but the strength of this correlation was weak. Scientific research has concluded that the relationship between education level and perception of environmental noise pollution is complex and can vary depending on the methods and indicators used to measure social status (Erkaya et al., 2015).

The following are some means through which railway noise can affect people:

1. **Sleep disturbance:** Railway noise disturbs sleep, resulting in insomnia and sleep deprivation. Research has demonstrated that exposure to railway noise during night hours can cause elevated levels of stress hormones, which can harm physical and mental health. The International Classification of Sleep Disorders (ICSD) has established a framework for describing and categorizing sleep disorders. There is a consensus that insufficient sleep, especially sleep deprivation, can significantly impact metabolic and endocrine functions, and inflammatory markers contribute to an increased risk of cardiovascular disease (Němec et al., 2020).
2. **Hearing damage:** Prolonged exposure to elevated levels of railway noise results in hearing damage or loss. The intense auditory stimuli produced by the passage of trains can give rise to transient or permanent hearing loss. Tassi et al. (2010) conducted a study to investigate the effects of railway noise on individuals residing near railway tracks. The findings of this investigation indicate that individuals exposed to higher levels of railway noise exhibit an increased incidence of hearing impairment when compared to individuals exposed to lower noise levels. Furthermore, the research highlights a positive correlation between the duration of exposure to railway noise and the risk of developing a hearing impairment (Szwarc et al., 2011).

3. **Cardiovascular diseases:** Empirical evidence suggests a positive association between prolonged exposure to railway noise and heightened susceptibility to cardiovascular disease. Investigations reveal that individuals residing close to railway tracks are more susceptible to developing hypertension, a significant risk factor for cardiovascular disease. Studies demonstrate that excessive noise pollution, such as that generated by railways, has been linked to an increased risk of cardiovascular ailments, including hypertension, heart attacks, and stroke. The precise pathophysiological mechanisms responsible for this relationship are not yet fully elucidated. Further research is warranted to understand the specific impacts of railway noise on cardiovascular health and devise effective strategies to counteract these effects (Li et al. 2019).
4. **Mental health:** Living with constant railway noise can lead to anxiety, depression, and other mental health issues. People exposed to high noise levels over an extended period are more likely to suffer from mental health problems (Laxmi et al., 2022).

2.8.2 Building location characteristics

Due to rapid urbanization, many high-raised buildings are frequently constructed along major traffic routes, adjacent to railway tracks, or near airports. Individuals residing in such accommodations experience continuous exposure to high-intensity noise, which can result in various adverse effects. The noise levels increase from 3.5 to 4.2 dBA when buildings are positioned at heights ranging from 10 to 15 m and at distances spanning 15 to 30 m. Another study indicated that noise levels decrease with an increase in building height. There is a reduction of 6 dBA for the initial 50 m of height and a maximum reduction of 4 dBA for heights exceeding 50 to 150 m (Benocci et al. 2020). Additionally, the perception of noise levels is influenced by the angle between the building's front facade and the railway line, referred to as the sound's directional characteristics.

2.9 Noise Mapping

Noise mapping is a methodological approach to represent noise levels in a designated geographical location visually. This process involves noise measurements at multiple points and generates a map or model exhibiting noise propagation and variance over the region. These maps are used to identify locations with excessive noise above acceptable levels. Several popular software tools, as shown below, are used to perform noise mapping (Garg et al. 2017, 2019):

- **CadnaA software:** This software is used to calculate, assess, and present environmental noise like industrial noise and transport noise, which includes road and railway noise, household noise, etc. The main features are that it can handle mapping large areas quickly, integrate with other tools like GIS and work efficiently, and work for noise control strategies like analysis and designing noise barriers.
- **SoundPLAN software**: This is a popular noise modelling software developed in 1986. The main features are used for calculating noise levels of indoor and outdoor environments; it is interlinked with Google Maps/ Google Earth and retrieves ground elevations. Used for developing noise control measures by analysing and modelling building interior and exterior noise, it can produce 3-dimensional maps.

Several other software like ArcGIS desktop software, IMMI software, SPM9613 Community Noise Prediction software, CUSTIC software, Predictor-LimA Software Suite Type 7810, etc., can be used for noise mapping.

Noise mapping strategy and implications

Noise maps provide policymakers and urban planners with valuable information to make informed decisions on mitigating noise pollution and encouraging the creation of liveable environments. This may necessitate implementing noise reduction techniques, such as erecting sound barriers, restricting activities that generate noise during designated periods, or advocating for quieter technologies. Noise mapping can be conducted for specific noise sources such as road traffic, railways, aircraft, industries, etc., or in conjunction with all noise sources within a studied region to present a comprehensive noise profile of the area. The following are the benefits associated with noise mapping:

- **Quantification and noise impact analysis:** The noise from primary sources is measured and analyzed, including the areas with the highest noise levels. This will involve creating visual representations of noise exposure and scenarios. Additionally, mapping will include assessing the potential impact of increased noise levels on the local population, particularly in areas with high noise levels. Finally, this will analyze the expected noise impact of proposed new infrastructure, such as an airport runway, elevated transit train corridor, or industrial units. Predictions of future noise levels will also be made in this analysis.
- **Noise abatement and control:** It investigates the effectiveness of noise control action plans and their overall effects on reducing noise levels. Various noise abatement measures will be

examined to determine their potential for mitigating noise pollution. The best practicable and economical option will be formulated based on the findings. Furthermore, installing noise barriers across sensitive receptors will be explored as a potential solution for reducing noise levels.

- **Policy formulation:** Facilitating development and enforcement of noise control policies, particularly at the regional and national levels. Importance of enforcing established plans for noise control and creating guidelines for new projects, such as new runways or industrial facilities, to minimize noise pollution.

2.10 Summary of Literature

From the literature, it was observed that noise pollution is considered unwanted and can negatively impact human health and quality of life. WHO declared noise an environmental pollutant, now regarded as one of the most serious urban issues affecting human health. Out of all environmental noise sources, transportation noise contributes nearly 55% of the overall noise. In most of the urban areas, when a railway line is passing through different land zones, the noise levels emitted by a passing train cross the permissible noise levels. Due to increased demand for rail transport, new railway lines have been proposed throughout the world, thereby leading to increased movement of number of trains and their frequency, leading to increased railway noise. The major factors identified from the past literature regarding train source are train type (Locomotive: diesel or electric, carrier coach: freight or passenger), rolling stock characteristics, train transit conditions, topographic characteristics, track equipment, and meteorological characteristics. The railway level crossing was identified as a noise pollution hotspot, where several activities related to transportation noise were involved. Train honking, train movement, road vehicles, and pedestrians contribute to the noise level at a railway-level crossing. The transmission path characteristics are crucial in elevating or abating the noise levels. Wind speed, direction, turbulence, air pressure, air temperature, and humidity were the major factors influencing sound transmission in the atmosphere. In addition, a detailed study was made on several noise abatement measures and performance analysis of noise barriers with various shapes, dimensions, materials, and acoustical conditions. The effectiveness of a noise barrier is determined by its geometry, material, and design. The factors that can impact the barrier's ability to reduce noise include its height and size, the distance between the noise source and the receiver, the surface of the barrier facing the railway track, and the noise frequency. Finally, several studies have provided valuable insights into the percentage of individuals sensitive to railway noise, the health effects of exposure to noise, attitudes and behaviour towards the noise, and other factors.

2.11 Gaps in the Literature

Based on the reviewed literature, the current study identifies several gaps in the existing body of literature, and the detailed list is outlined as follows:

- Noise abatement techniques can be applied at the source, transmission path, and receiver. But among all these techniques, reducing noise at the source is identified as the best practice. The literature review has revealed that less research has been done on eliminating railway noise at the source.
- Most of the studies considered vehicle characteristics such as type of trains (passenger or freight), speed of train, acceleration, braking mechanism etc., but the influence of train length (number of coaches), type of coaches/wagons were not considered, which also play a crucial role in noise variation levels.
- Several research studies have suggested that the influence of meteorological characteristics on noise propagation is negligible. However, some of the studies showed clear evidence that meteorological conditions greatly affect noise propagation. Thus, it is very much essential to carry out a comprehensive study to evaluate the effect of meteorological characteristics on railway noise.
- Most of the research has been conducted on noise emitted from a stationary point source; meteorological effects on more realistic time-varying line sources, such as railway noise, have received little attention in the literature.
- The research showed that the train honking is an impulsive sound ranging between 100 to 110 dBA (L_{eq}), which has a strong negative health impact. However, no study has quantified the noise levels at a railway-level crossing, where several activities related to transportation noise are involved.
- Most of the research studies focussed on quantifying the variation of sound levels with distance which followed the inverse-square law. However, no research work focussed on identifying a safe distance from the railway track to construct houses such that people residing in those houses are subjected to lower noise levels that are well within the prescribed limits.
- Numerous research works on noise barriers for different types of noise sources show a noticeable gap in the literature regarding the effectiveness of railway boundary walls to

function as potential noise barriers. This is due to the fact that railway noise possesses unique characteristics that distinguish it from other types of noise.

- Extensive research has revealed the adverse impacts of railway noise on the public's well-being, with most research being done in developed nations. However, there is a noticeable lack of research in this area from developing countries like India, despite being the country with the world's fourth-longest rail network and the highest population, surpassing China.

Chapter 3

METHODOLOGY AND DATA COLLECTION

This chapter presents the methodology employed to achieve the defined objectives, along with a comprehensive explanation of the data collection process. This chapter outlines the approach used to measure various parameters related to train sources, such as train speed, length, and type, as well as meteorological factors like wind speed, wind direction, temperature, and humidity. Additionally, it covers the process of evaluating barrier performance and investigating the effects of railway noise on residents living in proximity to the tracks.

3.1 General

In accordance with Chapter 1, the objectives of the present study respond to critical gaps identified during the literature review presented in the preceding chapter. The current study adopts the source-path-receiver framework to achieve these objectives for quantifying and analyzing railway noise. Applying noise control techniques necessitates modifying the source mechanism, transmission path characteristics, and receiver perception. Among these techniques, abating it at the source is the best practice to mitigate railway noise. The cost comparison for decibel noise reduction using this technique is one-tenth of the cost of installing a noise barrier (Schulten et al. 2015; Sarikavak and Boxall 2019). Thus, if the noise is not controlled at an acceptable rate at the source, further efforts should be made in the transmission path or at the receiver end. Based on the past literature, the source parameters considered for evaluation in the current study includes the type of train, train speed, train length, measuring distance, and honking.

A railway-level crossing has been identified as a hotspot for noise pollution, consisting of various transportation-related activities. This includes the emission of noise from the passage of trains, including train horn usage, the presence of road vehicles, and pedestrians. The train horns are blown while approaching a level crossing especially to alert road users. However, this huge impulse sound from the train horns is considered as a disturbance to the nearby residents. In light of the contemporary environmental context, it is imperative to conduct a comprehensive assessment of the effectiveness of train horns. The current study measures the noise levels emanating from train horns at a level crossing with due consideration to train types and climatic conditions.

Sound consists of vibrating particles that collide with each other, and these particles require a medium for their transmission because they are incapable of propagating through a vacuum. Given that sound can traverse through various mediums, such as air, water, and solids, any modification in the medium's condition can influence the propagation of sound waves. The surrounding atmosphere absorbs a fraction of the sound energy during its transmission over long distances. This phenomenon defines the damping of sound energy and is primarily affected by frequency, atmospheric conditions, and the distance traveled by the sound waves. Consequently, the variation of railway noise with changes in meteorological factors, such as air temperature, relative humidity, wind velocity, and direction, were evaluated in this study. Additionally, the presence of physical barriers or vegetation can significantly influence the transmission of noise from its source to the receiver. In urban settings, constructing railway boundary walls serves the dual purpose of preventing encroachments on railway lands and avoiding pedestrian trespassing on railway tracks. The current study aims to evaluate the effectiveness of such a boundary wall in mitigating noise and proposes an improved alternative through Computational Fluid Dynamics (CFD) simulations.

The growth of the population over the past few decades prompted a significant migration of individuals to urban areas, causing a surge in the need for developing infrastructure such as roads, railway networks, and public transportation systems. Among several urban environment noise sources, railway noise has emerged as one of the significant contributors, especially in residential areas near railway lines. Unplanned urbanization has led to the settlement of migrants from rural areas in close proximity to railway lines, exposing them to continuous noise pollution and resulting in a range of adverse effects on their health and well-being. The current study quantifies railway noise by measuring the noise inside houses along the railway line and conducts a human perception survey to investigate the relationship between noise levels and annoyance during daily activities.

Thus, the entire study is divided into three parts: the first part deals with the influence of railway source parameters on noise levels, the next part discusses the variation of railway noise with changes in meteorological parameters, and the final part evaluates the receiver perception towards railway noise.

3.2 Flowchart of the Methodology

The flowchart shown in Figure 3.1 summarises the research methodology used in the current study.

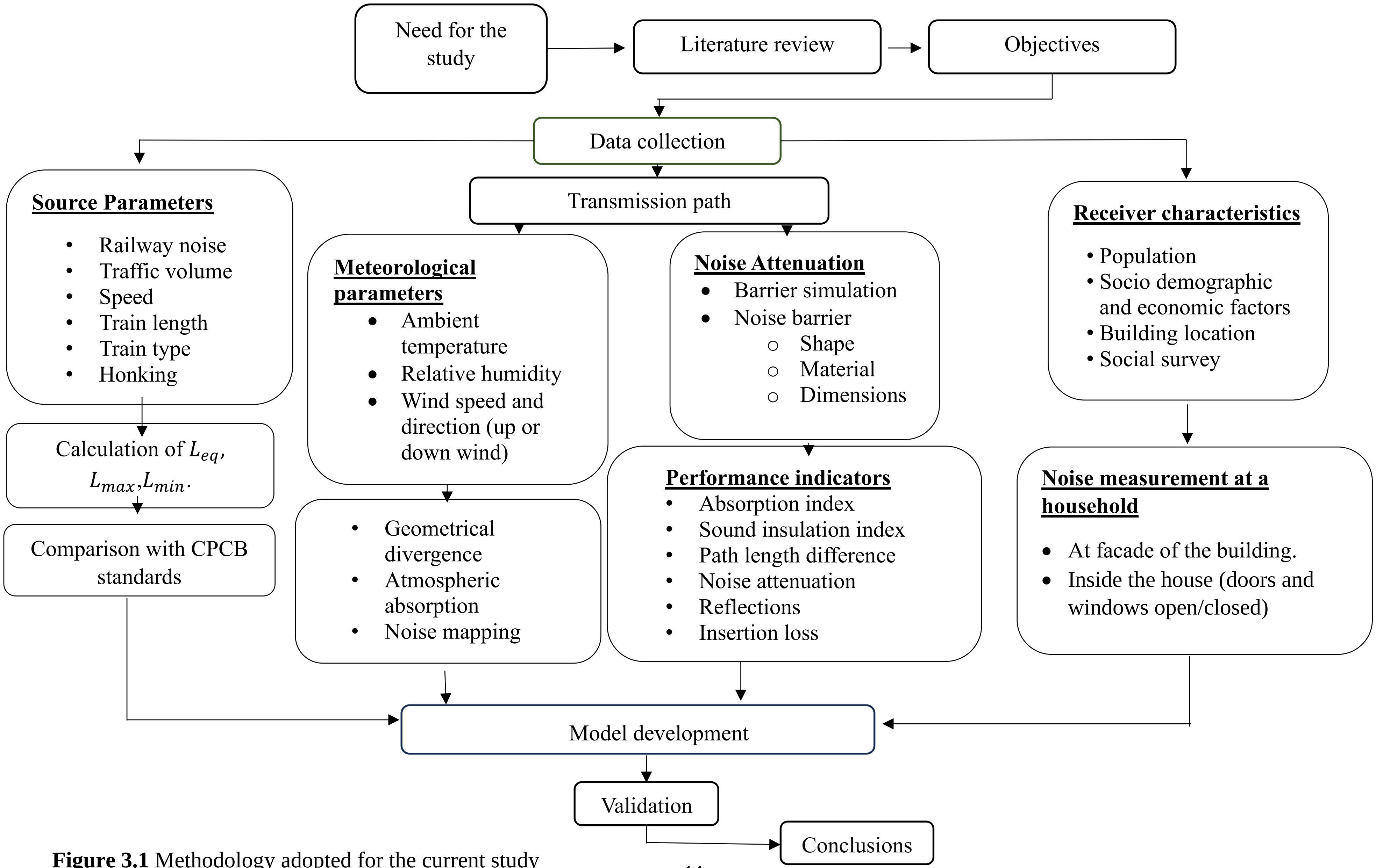


Figure 3.1 Methodology adopted for the current study

3.3 Study Area Characteristics

Warangal city was selected as the study area due to the high railway activity, with approximately 100 trains, both passenger and freight, passing through this section daily. The south-central railway operates this railway network within Warangal city, located in Telangana, India. The city features three major railway lines converging near Kazipet junction—one from Secunderabad, another from Nagpur, and a third from Vijayawada. The city has an area of 407 sq. km. and is rapidly growing in educational, commercial, trading, and industrial sectors. According to the 2011 census, the city's population was 6.27 lakhs, which increased to 9.37 lakhs by 2019 (Handbook of Urban Statistics 2019). Due to the rapid increase in population and unplanned urbanization, most migrants from rural areas are constructing their dwelling units very close to the railway lines. Approximately 25 to 30% of the city's residents are exposed to railway noise and train horn sounds, posing significant health risks to those near the tracks (Sahu et al. 2020). The chosen study area's geographical characteristics closely resemble many other urban areas in India, rendering it a nationally representative location for conducting the study. Figure 3.2 depicts a detailed overview of the study area and the locations for data collection.

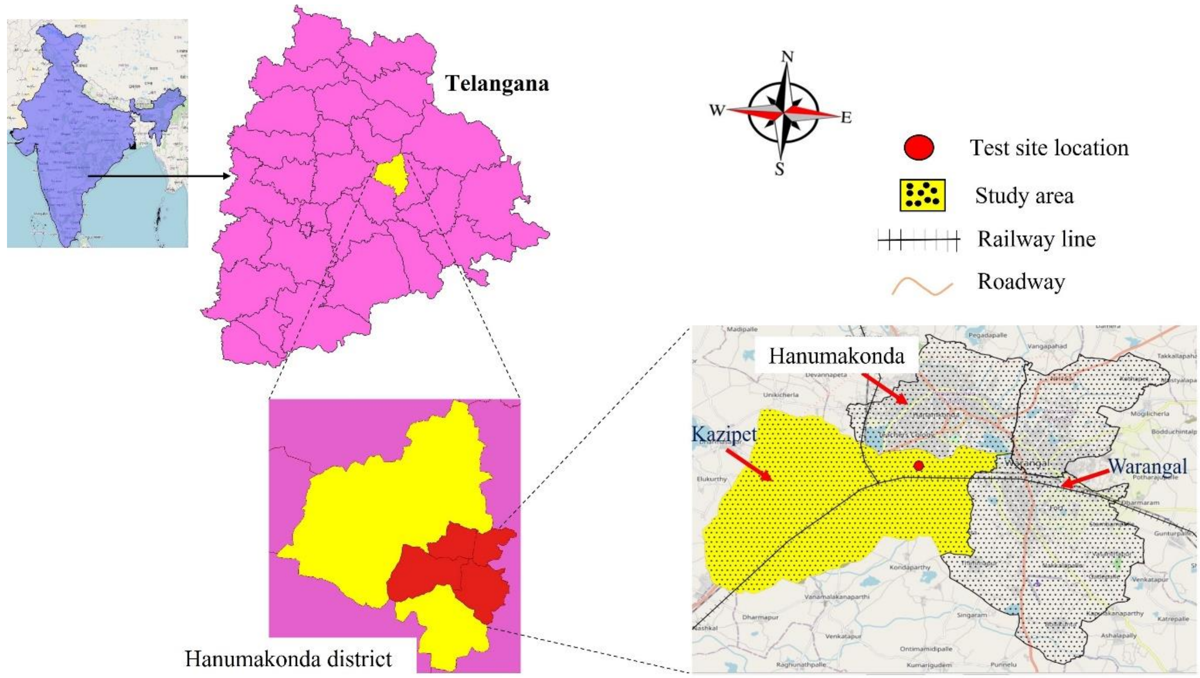


Figure 3.2 Map showing the location of the study area and railway noise measurement test site.

Atmospheric conditions at the test site

To quantify the impact of meteorological parameters on the variation of railway noise, it is essential to examine the atmospheric conditions at the study site. The tri-cities of Kazipet, Hanumakonda, and old Warangal put together are well known as Warangal or Orugallu. Even though the study area is in Kazipet, hereafter it would be referred to as Warangal. Warangal is situated in the semi-arid region of Telangana, experiences a predominantly hot and arid climate. The year is primarily categorized into three seasons: summer, monsoon, and winter. Summer spans from March to May, with average temperatures reaching 42°C. Monsoon, occurring from June to September, brings an average rainfall of 550 mm. The winter season extends from October to February, characterized by low humidity and average temperatures ranging from 20 to 23°C. The region maintains an annual average humidity level of 56%, with August being the wettest month and April the driest. From December to April, strong winds prevail, while the period from July to October is marked by calm winds. The annual average wind speed ranges from 4 to 6 m/s (AccuWeather 2023). Data were collected during months of extreme temperatures and wind speeds to evaluate the potential adverse effects of temperature, humidity, and wind on noise levels. Table 3.1 summarises the weather conditions recorded during the data collection period.

Table 3.1 Atmospheric conditions at the test site during the pass-by of trains

Atmospheric conditions	Minimum	Maximum	Mean
Air temperature (°C)	20	40	31
Humidity (%)	40	80	55
Wind speed (m/s)	0.75	6.25	4.1
Wind direction (up or down)	Down	Up	Up

3.4 Methodology Adopted for Quantifying Railway Noise Source Parameters

The study area was selected meticulously to minimize interference from other noise sources. Noise measurements were recorded from 6:00 a.m. to 6:00 p.m. The noise measurement process started when the train passed the line of alignment and stopped when the last coach or wagon crossed the line of alignment. At the test site, the railway track system was constructed over a 1.5 m high embankment, and the test setup was placed at a distance of 25 m and 50 m from the nearest track centre. The centre-to-centre distance between the two adjacent tracks is 3 m. Electric traction was used with ballast deposited along the track. Figure 3.3 shows the schematic representation of the test location and instrument setup. The trains operating on this section of the track were propelled by Direct Current (DC) Electric Locomotives.

The noise levels were measured using two Class-1 SLMs with a data logging precision of one-tenth of a second in fast weighting. The SLMs were installed on tripods at the height of 1.5 m to simulate field acoustics, with distances between the two SLMs from the centre of the nearest railway line being 25 m and 50 m, respectively. These two measuring points were used to investigate the geometrical influence of railway noise. A windscreen protected the SLM and was calibrated before and after each measurement. When calibration values deviated by more than 2 dBA, noise measurements were repeated. A digital video camera was synchronized with the SLM during the measurement time to measure the train length, and a radar speed gun was used to measure the train speed.

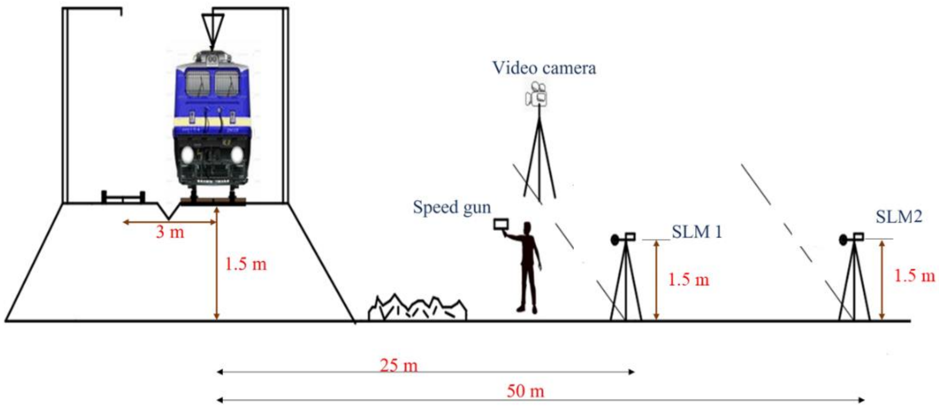


Figure 3.3 Schematic representation of the noise measurement procedure

3.5 Methodology Adopted for Quantifying the Influence of Meteorological Conditions on Railway Noise

The experimental setup and noise measurement process to quantify the influence of meteorological conditions on sound propagation were meticulously carried out with due consideration to the points listed below:

- To assess noise propagation characteristics, the primary acoustic source considered was train noise, with sound levels exceeding the background noise. The power of train noise was calculated to anticipate the distance up to which meteorological conditions could influence the propagation of railway noise.

- According to ISO – 1996: 2 (2007), guidelines suggest that the influence of weather conditions is minimal on sound propagation when the distance between the source and receiver is short. As a result, sound propagation is affected by the source's height, the receiver's height, and the distance between the source and the receiver. If $\frac{h_s + h_r}{r} \geq 0.1$, the meteorological influence is minimal.

  Where, h_s= source height,

  h_r= receiver height, and

  r = distance between source and receiver.

- Under these conditions, meteorological conditions play a minor role in measurements taken at distances of 25 m and 50 m. However, their influence becomes more significant at distances of 100 m and 200 m. Thus, this study quantifies noise levels at 25 m, 50 m, 100 m, and 200 m to examine sound wave propagation, both with and without the influence of meteorological conditions. In this study, the receiver height is 1.5 m, whereas the source height, which includes the embankment's height and the train's height, is 5.5 m.
- To ensure accurate measurements, the noise measurement points along the railway corridor were carefully selected to ensure that there is a clear line of sight between the source and the SLM. Additionally, care was taken to prevent vegetation or small structures from obstructing the train noise propagation.
- Before each noise measurement, the SLM was calibrated, and measurements were repeated if the calibration results exhibited differences exceeding 2 dBA.

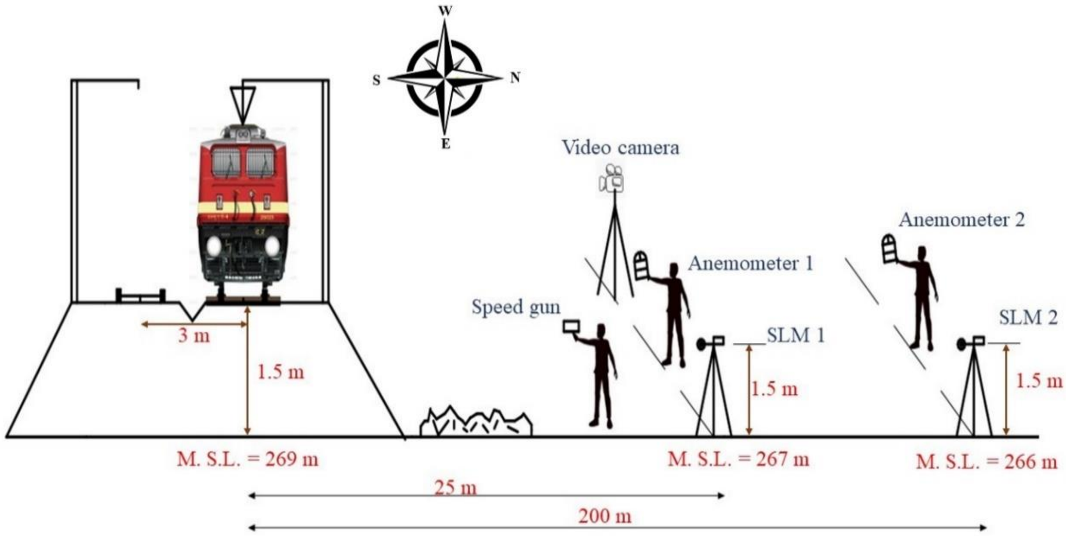


Figure 3.4 Instrument setup at the test site to quantify the train and meteorological parameters

Handheld rotating vane thermo-type anemometers were employed in the current study to measure relative humidity, ambient temperature, and wind speed. Figure 3.5 illustrates the specific anemometer utilized in this study. Within this instrument, a rotating vane quantifies wind speed while a digital screen displays relative humidity and ambient temperature readings. These anemometers were positioned at different distances from the railway track within the test site, adjacent to the SLMs. To determine wind direction, a wind vane was used to identify the orientation of wind as North, Northeast, East, Southeast, South, Southwest, West, or Northwest. The arrow of the wind vane indicates the prevailing wind direction. These measurements were recorded along with other meteorological parameters while collecting train noise data, resulting in a total of 106 data samples.

Figure 3.5 Anemometer with its distinct components and respective functions

3.6 Methodology Adopted for Quantifying Noise Levels at the Level Crossing

Indian railways employ a square yellow board displaying the letter 'W' or 'W/L' to signal train operators to blow the whistle, also known as the horn. 'W' signifies a general whistle alert, while 'W/L' indicates the need to whistle specifically for a level crossing. These square boards featuring the letter 'W' are typically positioned ahead of curves where people or animals may not be able to see the approaching trains, necessitating the use of honking to alert them. The 'W/L' signboard is strategically placed 250 meters in advance of a level crossing (Trackside Indicator Boards and Signages 2020).

Field investigations were conducted at unmanned level crossings to quantify the overall noise generated by train movement, train honking, road vehicles, and pedestrians. To accomplish this, four distinct scenarios were taken into account at the level crossing, and noise measurements were obtained for each situation. The four scenarios are as follows: (i) level crossing in open condition where there is a smooth flow of vehicular and pedestrian traffic, (ii) closed condition where there is an accumulation of vehicular and pedestrian traffic, (iii) passage of train with and without honking, and (iv) gate opened after the passage of the train where the drivers tend to accelerate their vehicles. The SLMs were positioned at a distance of 1.5 m from the road and 4.5 m from the railway line.

This placement was determined to be a safe distance for measuring noise emanating from both the roadways and the railway line throughout field observations. The data collection process at the level crossing can be seen in Figure 3.6.

The selected level crossing is one of the most heavily trafficked access-controlled level crossings. Occasionally, these crossing experiences the simultaneous passage of two or three trains with minimal time intervals between them. Consequently, the level crossing remains closed for lengthy periods, constantly causing significant noise from the road vehicles, leading to traffic congestion. Such situations contribute to additional noise at the level crossing, ultimately posing long-term health risks for residents living in proximity to the railway line.

The selection of the level crossing for data collection was informed by the Divisional Engineer responsible for the specific track section within the south-central railway. Subsequently, essential data regarding rail traffic, such as the number of daily train movements, the track condition at the crossing, and the train arrival timetable, was obtained from the concerned authorities. The research team conducted vehicle volume counts at the crossing while the gate was open and counted vehicles waiting at the crossing when the gate was closed. A total of 167 train movements were observed, recording 194 train horns, including two horn sounds from 27 trains. The time intervals between two consecutive trains moving in the same direction with the shortest gap were observed to be 2.5 minutes, and the longest time gap was 15 minutes.

(a) (b)

(c)

(d)

Figure 3.6 Noise measurements for (a) level crossing in open condition, (b) level crossing in closed condition, (c) passage of train with and without honking, (d) gate opened after passage of the train.

At the test site, three research teams were assigned the task to monitor field observations and collect data while ensuring proper safety measures along the roadside. The first team was positioned at the level crossing and held responsibility of operating SLMs to collect data on railway noise, including horn and train movement noise. The second team collected data on the train speed using the radar gun, the train length was estimated using a videographic camera, and the weather data was captured using an anemometer. The third team conducted manual counts of road traffic volumes when the level crossing gate was open and categorized the vehicles waiting at the closed gate. Vehicle volumes on both sides of the railway level crossing were counted. The number and type of vehicles that kept their engines running while waiting at the closed-level crossing gate were also recorded. Noise levels were measured both in the presence and absence of passing trains. In the absence of the train, background environmental noise levels were recorded, which could later be used to estimate the additional noise generated when a train passed through the level crossing.

3.7 Methodology Adopted for Quantifying the Efficiency of Railway Boundary Wall to Abate Noise

Field observations were carried out to investigate the acoustic properties of a stone masonry boundary wall with cement mortar constructed adjacent to a railway line in a residential area. Noise measurements followed European standards EN 1793-6 (2012) at three specific distances from the boundary wall. These distances include (i) 0.5 m in front of the barrier (referred to as point A), (ii) 0.5 m behind the barrier (referred to as point B), and (iii) 6 m behind the barrier (referred to as point C). The dimensions of the wall are 2.75 m in height, 45 cm in thickness, and 110 m in length, and it is located at a distance of 11 m from the center of the railway line, which serves as the primary source of the noise. Figure 3.7 shows a detailed schematic representation of the experimental setup used for the field measurements. Measurements were taken during the passage of each train, and environmental conditions such as mean air temperature of 31°C, humidity 55%, and wind speed of 3.5 m/s were recorded using an anemometer. A detailed schematic of the field measurement test setup, including the site location and test configuration, is illustrated in Figure 3.8.

Three separate teams were stationed at designated locations A, B, and C to ensure safe and effective field observations and data collection. Each team utilized SLMs to capture railway noise while adhering to essential trackside safety precautions. In addition to measuring railway noise, the teams also recorded background environmental noise during train absence, enabling them to estimate the additional noise produced when trains pass by.

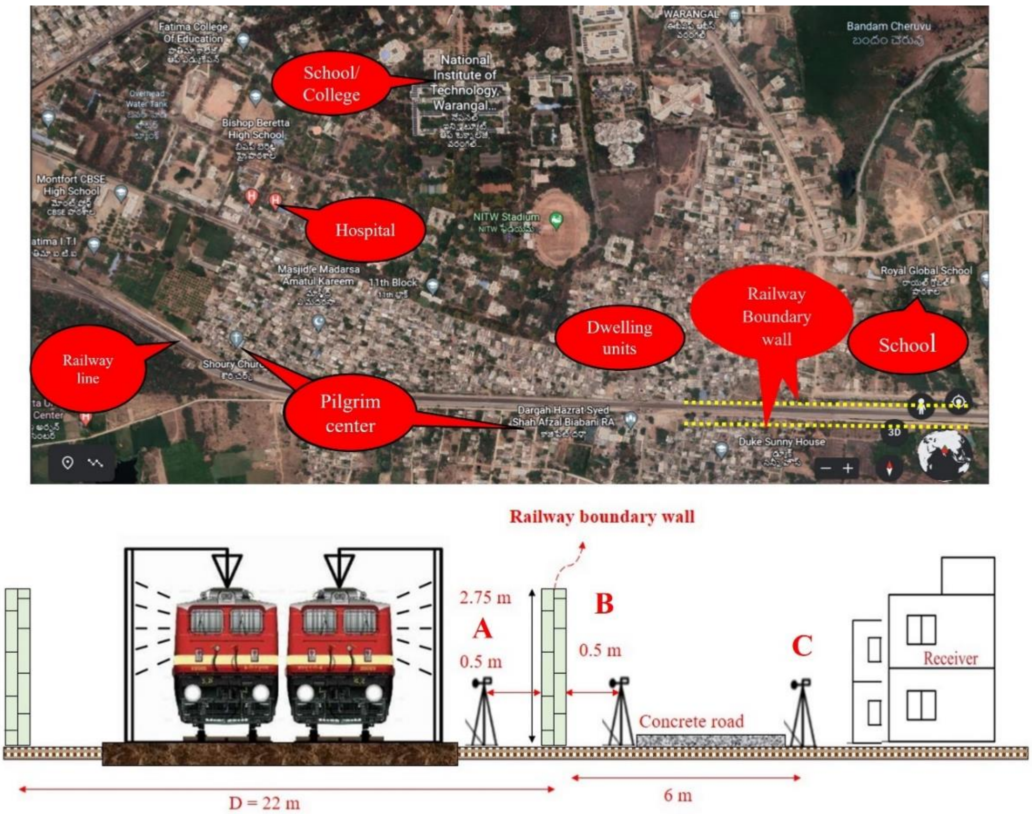


Figure 3.7 Location of boundary walls along the railway line in the map and schematic representation of the instrument set up at the test site.

(a) (b) (c)

Figure 3.8 Noise measurement at: (a) 0.5 m ahead of the barrier, (b) 0.5 m behind the barrier, (c) 6 m behind the barrier.

3.8 Methodology Adopted for Quantifying the Impacts of Railway Noise Pollution on Residents' Health and Well-being

In the current study, ISO 3095: 2013 is adopted to evaluate the impact of noise on trackside residents. This standard provides a systematic approach for assessing and describing railway noise, which is crucial for understanding its effects on people and implementing noise mitigation strategies. According to ISO 3095: 2013, to determine the impact of railway noise on human annoyance, it is imperative that the study area satisfy a set of precise criteria. Firstly, it should be close to the railway line and have residential areas nearby. Additionally, it should be easily accessible to install noise measurement equipment and feasible to conduct surveys on human perception. It is also essential that the study area has a homogenous population density and building types to ensure that noise levels and human annoyance perception are comparable across the region. Moreover, the study area should have no significant noise sources besides the railway line, which could influence the results. Lastly, the study should include a representative sample of residents from different age groups, genders, and occupations to increase the generalizability of the results.

Figure 3.9 illustrates the study area, and the dwelling units located at several distances (50, 100, 150, and 200 m) on either side of the railway track are developed using QGIS 3.32.2. These dwelling units in each cluster were selected randomly to conduct a study on railway noise quantification and human perception. These houses are chosen based on the proximity to the railway line and the existing infrastructure. Table 3.2 shows the data of the number of respondents and L_{eq} noise levels in each cluster zone (ranging from 0 to 50 m, 50 to 100 m, 100 to 150 m, and 150 to 200 m), respectively.

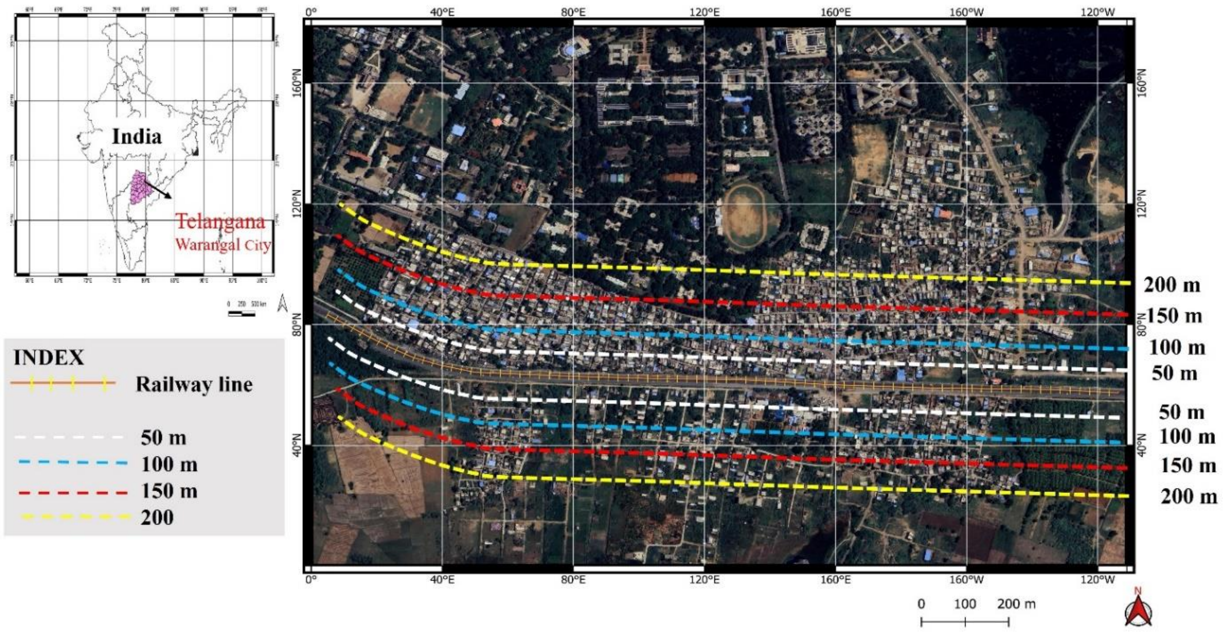


Figure 3.9 Study area location and cluster zones selected adjacent to the railway track.

Table 3.2 Number of dwelling units in each cluster zone and corresponding L_{eq} noise levels

Location of the dwelling units (m)	No. of dwelling units	No. of respondents	Average L_{eq} noise level in the zone (dBA)
Zone I (0 to 50)	54	94	73.6
Zone II (50 to 100)	58	110	68.2
Zone III (100 to 150)	39	67	61.5
Zone IV (150 to 200)	31	45	57.5

3.8.1 Noise measurement at the residential units

In the current study, data was gathered from a total of 182 households located on either side of the railway line, as mentioned previously. The data collection includes the measurement of noise levels and human response to noise in these households at various distances from the nearest railway track. The noise measurements were obtained using SLMs placed both externally (at the facade) and internally within each household, with the doors and windows in open and closed condition. Closing the doors and windows provided a degree of sound insulation, thereby reducing the intensity of noise entering the house from the outside. Three Class-1 SLMs with a data logging precision of one-tenth of a second in fast weighting were used to measure the noise levels. The SLMs were installed on tripods at a height of 1.5 m to simulate field acoustics. Three teams were formed to collect data: one team measured noise levels at the front of the building, another team measured noise levels inside the house with doors and windows closed, and the final team measured noise levels inside the house with doors and windows open. This analysis is to check if there is a significant difference in noise levels inside a house when the doors and windows are opened and closed.

3.8.2 Study population and survey procedure

The research sample comprises individuals residing in Warangal along the railway line, ranging in age from 5 to 65 years, who have a known home address and GIS location of their dwelling unit. Previous studies have used telephone and email surveys to collect social data from residential areas based on listed addresses. However, the current study employed a one-to-one interactive questionnaire for the social survey, enabling participants to provide their responses directly. The questionnaire assessed the level of annoyance caused by railway noise using a 5-point categorical scale: strongly disagree - 1, disagree- 2, neutral - 3, agree - 4, and strongly agree- 5.

A population size of 316 respondents was selected based on statistical considerations to represent the diverse residents living along the railway line. The information collected from these respondents is presented in detail in Table 3.3. Factors such as age, gender, proximity to the railway line, duration of stay, education, and occupation of the respondents were considered for developing the exposure-response relationship. The questionnaire covered topics such as noise exposure, perception of noise levels, annoyance levels, impact on daily activities, sleep disturbance, overall well-being, and any other relevant factors for establishing the exposure-response relationship. An exploratory factor analysis was performed to explore the inherent structure within the questionnaire data. Confirmatory factor analysis was performed to assess the goodness-of-fit between the observed data and the hypothesized factor structure. Structural equation model was developed to examine the structural relationships and hypotheses of the model.

Table 3.3 Main demographic factors of the interviewees

Demographic information		**Percentage** (%)
Gender	Male	45
	Female	55
Age (years)	≤ 15	20
	16 to 25	10
	26 to 45	30
	46 to 60	25
	> 60	15
Marital status	Single	60
	Married	40
Education	Primary	20
	Secondary	30
	Degree	20
	Illiterate	30
Occupation	Government	05
	Private	20
	Self-employed	40
	Unemployed	35
Length of stay	5 and below	45

(years)	6 to 10 years	15
	11 to 15 years	25
	16 to 25 years	15

Before conducting the survey, a pilot study was conducted with a small group of participants to ensure the clarity and relevance of the questionnaire. Based on the outcomes of the pilot study, a few adjustments were made to the final questionnaire based on the feedback received. Confidentiality and sensitivity to participant responses were maintained, and consent from each participant was obtained before proceeding with the survey. Participants were encouraged to provide detailed qualitative data by elaborating on their answers. The data sheets accurately recorded the responses and upheld data integrity throughout the survey. The detailed step-by-step procedure of the current study methodology is shown as a flowchart in Figure 3.10.

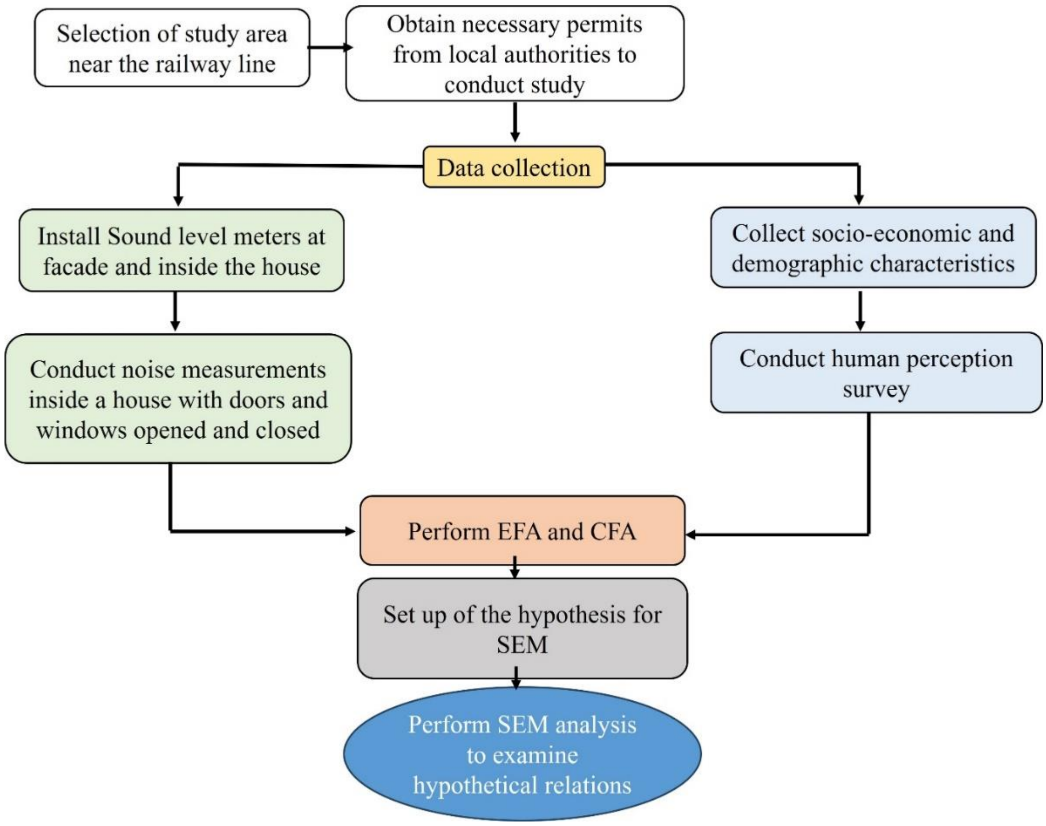


Figure 3.10 Flowchart representing the methodology adopted in assessing noise inside residential units and receiver perception.

Chapter 4

INFLUENCE OF TRAIN SOURCE PARAMETERS ON RAILWAY NOISE

This chapter presents the work carried out to analyze the train source parameters, i.e., the influence of train speed, length, type, and measuring distance on the variation in railway noise. This chapter presents the empirical methods for estimating maximum and equivalent noise levels. In addition, the study results of the train honking levels at the railway level crossing and the development of an Artificial Neural Network to forecast these noise levels are presented.

4.1 General

A conventional noise control strategy targeting the noise source can be pursued upon recognizing the detrimental effects of railway noise on trackside residents. To achieve this, it is essential to identify the specific sources of the noise, which requires a comprehensive understanding of the underlying mechanisms driving these sources. Application of noise control strategies at the source is more economically beneficial than at the receiver end or through the transmission path. Additionally, reducing noise at the source can improve safety, making it easier for workers to communicate and decreasing the risk of accidents, such as on construction sites. This chapter analyses the influence of train source parameters such as train speed, length, type, and distance between the source and receiver on the railway noise and the honking noise. A railway level crossing was chosen to quantify the honking noise levels within the study area.

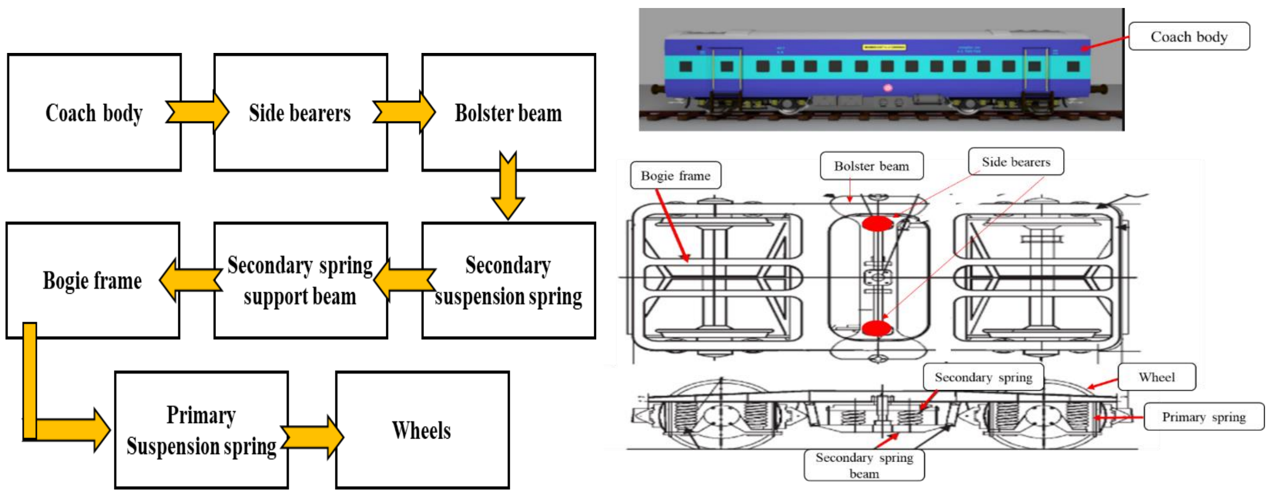
4.2 Influence of Train Type on Railway Noise

The passenger trains are broadly classified into three categories depending on the type of coaches and coupling: ICF (Integral Coach Factory) train, ICF-CBC (Integral Coach Factory – Centre Buffer Couple) train, and LHB (Linke Hofmann Busch) train. The Passenger coaches possess diverse attributes in material composition, body structure, dimensions, component arrangement, and internal dynamics. A thorough examination of the specifications and mechanisms of these coaches is critical in identifying the sources of noise production within the system. Control measures can be integrated during the design phase if the noise source is determined. Consequently, a detailed examination of the mechanism of each train type is presented below.

4.2.1 Mechanism involved in ICF trains

These are conventional coaches designed to transport passengers and are widely used on most Indian railway lines.

1. The coach's body is made of fabricated mild steel, and most connections are made by riveting and bolting. The tare weight of a coach is 45 tonnes, and the load-carrying capacity is 16 tonnes.
2. ***Load transfer mechanism***: The payload (passengers and luggage) and the coach's body weight are transferred to the two side bearers on the bolster beam. The secondary suspension spring supports the beam, and the load is transferred to the bogie frame by steel hangers attached to the secondary suspension spring. The bogie frame rests on a primary suspension helical spring attached to the wheel axle. Figure 4.1 illustrates the load transfer mechanism.



(a) (b)

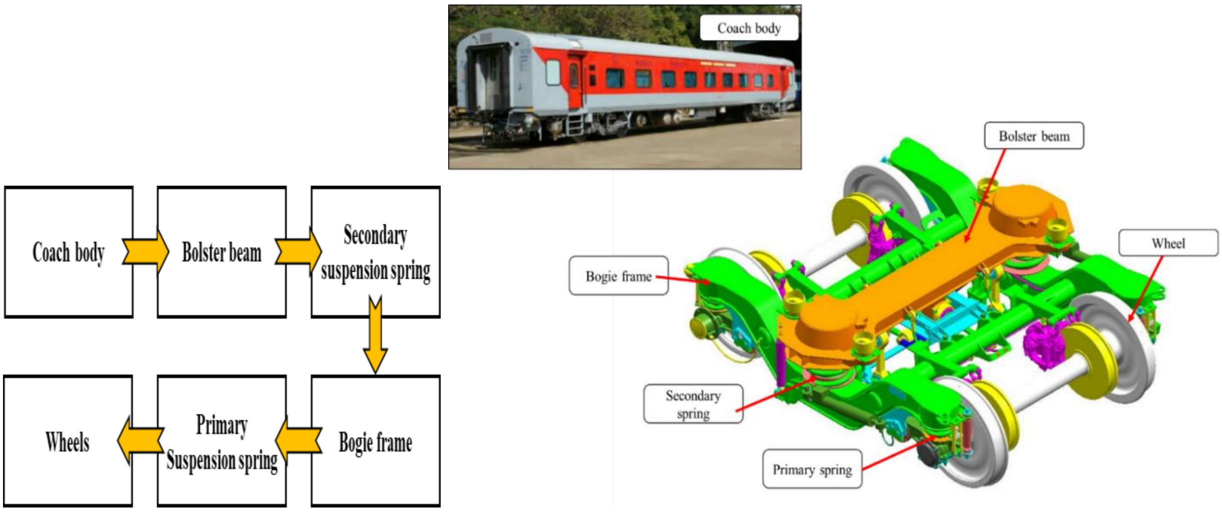
Figure 4.1 (a) Load transfer mechanism (b) ICF coach and corresponding configurations.

4.2.2 Mechanism involved in LHB trains

LHB coaches are another type of passenger coach developed by a German manufacturing company in the year 2000 for Indian Railways.

1. The material used for the coach body is low-corrosive stainless steel, which is beneficial for structural construction. This coach's tare weight is 40 tonnes, which is lower than ICF coaches despite their length being 2 m longer (Dzambas et al. 2014).

2. ***Load transfer mechanism:*** The transfer of the payload (comprising of passengers and luggage) and the weight of the coach takes place through a Y-shaped beam known as the "bolster." The secondary suspension spring passes this load to the bogie frame. The primary suspension spring, which is connected to the wheel axle, supports the bogie frame.
3. The insulation material "*Bary Skin V60*" is used as a primer in the coach shell interior to absorb structure-borne sound. These coaches have exceptional ride quality, with the coach producing minimal vibrations during movement. Figure 4.2 illustrates the load transfer mechanism.



(a) (b)

Figure 4.2 (a) Load transfer mechanism (b) LHB coach and corresponding configurations.

A coupling system is a mechanism used for linking train coaches with one another. It is centrally located at both ends of a train coach and can transmit tensile and compressive forces. The coupling system used in ICF trains is a screw couple with dual buffers. The coupling system used in LHB trains is center buffer coupling. ICF-CBC trains are made of ICF coach bodies and interconnected using a center buffer couple. This type of train is a composite of ICF and LHB specifications.

The specifications of the Centre Buffer Coupling (CBC) are mentioned below:

- Tensile load carrying capacity: 1000 kN, Compressive load: 2000 kN.
- Maximum Horizontal and Vertical swing angle of the coupler: ± 17.85° and ± 7°.
- Maximum permissible slack: Limited to 3.5 mm.

The screw coupling with dual buffers offers the following load capacities:

- Operating Load Capacity: 36 metric tonnes.
- Proof Load Capacity: 70 metric tonnes.
- Breakage Load Capacity: 130 metric tonnes.

The train bogie is an essential train component that plays a vital role in rolling noise generation. A train bogie is located beneath the coach body, typically consisting of wheels, axles, and suspension systems. Two types of bogies are primarily used in passenger trains. FIAT (Fabbrica Italiana Automobili Torino) bogie is used in LHB, and ICF bogie is used in ICF trains. The differences between these two bogies are shown in Table 4.1. These specifications help in identifying the source of rolling noise in the train.

Table 4.1 Comparison of FIAT bogie and ICF bogie

Features	**FIAT bogie**	**ICF bogie**
Potential speed (km/h)	160	120
Ride index	2.75	3.5
Weight of bogie	6.3 ton	6.5 ton
Axle box	Free movement	Rigid
Lateral stoppers	Rubber	Metal
Bearings	Taper	Spherical
Dampers	Hydraulic dampers	Dashpot
Rubber components	Many	Very few
Body length	23.5 meters	21.3 meters

4.2.3 Mechanism involved in freight trains

A freight train is a group of cargo wagons inter-connected by one or more locomotives. Unlike passenger trains, which are designed for the comfort and safety of passengers, freight trains are specialized for transporting goods and commodities. Freight trains' mechanisms and suspension systems are entirely different from passenger trains. To provide a clear understanding of the differences between these wagon types, a comparison is made in Table 4.2.

Open wagon mechanism: These wagons are designed for transporting iron ore, coal, and minerals. Non-transition center buffer couplers are used in these wagons. The braking system adopted is a single-pipe graduated-release air brake. The bogie's underframe is reinforced to withstand point loads of iron/steel cargo, and the frame is built of mild steel to prevent corrosion of the wagon body.

The design includes a total of 24 springs. Bolts and screws form the majority of the body connections.

Closed wagon mechanism: These wagons are manufactured to transport food grains, fertilizers, and other goods packaged in bags. To reduce the wagon's tare weight, these are made up of stainless steel and Cold Rolled Formed (CRF) sections. Rivet and welded connections are used throughout the construction. The design includes a total of 28 springs.

Tank wagon mechanism: These wagons are designed to transport kerosene, crude oil, other petroleum products, and milk. The mechanism involved in tank wagons is similar to that in closed wagons, but the wagon's body is thicker to prevent fluidic product leakage. The design has a total of 30 springs.

Load transfer mechanism: The payload (goods) and the bodyweight of the wagon are transferred to the two side bearers and the center pivot situated on the bolster beam. The bolster beam is supported by the coil spring, which transfers the load to the bogie frame via steel hangers. The bogie frame is directly attached to the wheels without any suspension springs. Figure 4.3 shows the load transfer mechanism.

Table 4.2 Freight train specifications

Features	**Open wagon**	**Closed wagon**	**Tank wagon**
Total gross weight (ton)	90-100	80-90	80-85
No. of wagons fitted to a locomotive	58/59	45-55	30-40
No. of springs per wagon	24	28	30
Type of bearings	Roller	Roller	Roller
Permissible speed	70 to 75 km/h	75 to 80 km/h	65 km/h

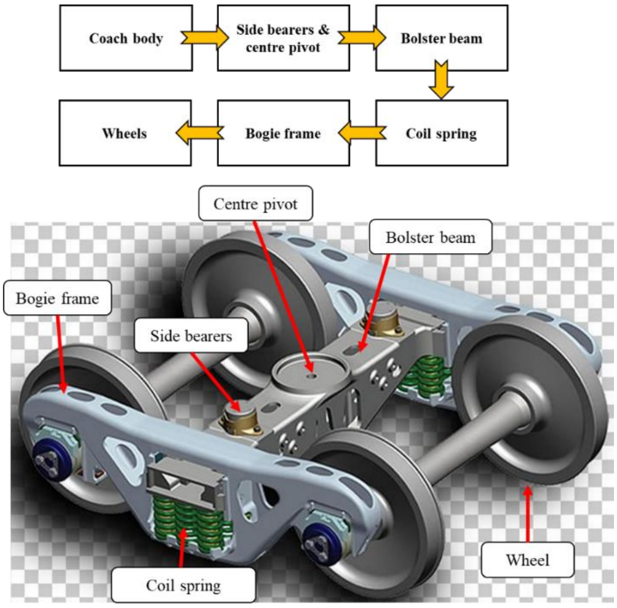


Figure 4.3 Load transfer mechanism in freight trains

Equivalent continuous noise levels (L_{eq}) and maximum noise levels (L_{max}) were used to quantify the captured railway noise levels. The L_{eq} is defined as the equivalent noise levels the moving train produces over a certain period of time. This time period was referred to as pass-by time. The time period was measured when the train's front face just entered the line of sight of the SLM, and the train's rear end passed the SLM. It mainly depends on the train length and train speed. If the length is long, the pass-by time is more; if the speed is high, the pass-by time is less. In the current study, the average pass-by time ranges between 16 to 60 seconds. L_{max} is the maximum noise level the moving train produces during the specified time period. The equivalent noise levels were calculated using Equation (4.1).

$$L_{eq} = 10 \log \frac{1}{T} \int_0^T \left(\frac{P_A^2}{P_{ref}^2} \right) dt \text{ dBA} \qquad (4.1)$$

Where P_A = instantaneous sound pressure level measured

P_{ref} = reference sound pressure (20µ Pa)

T = measured time period (seconds).

The equivalent noise level data corresponding to 124 trains was collected and analyzed to study the influence of train type on railway noise. According to the data obtained, passenger trains travelled at speeds ranging from 58 to 106 km/h, producing (L_{eq}) noise levels of 67.5 to 91 dBA. The LHB train emitted the maximum noise (91 dBA) while traveling at a speed of 106 km/h, whereas the ICF train emitted the minimum noise (67.5 dBA) while traveling at a speed of 58 km/h. The scatter plots in Figure 4.4 show the equivalent noise levels for different passenger trains when measured at 25 m from the centre line of the nearest railway track. The graph displays the best curve fit equations for the scattered data set of each train type.

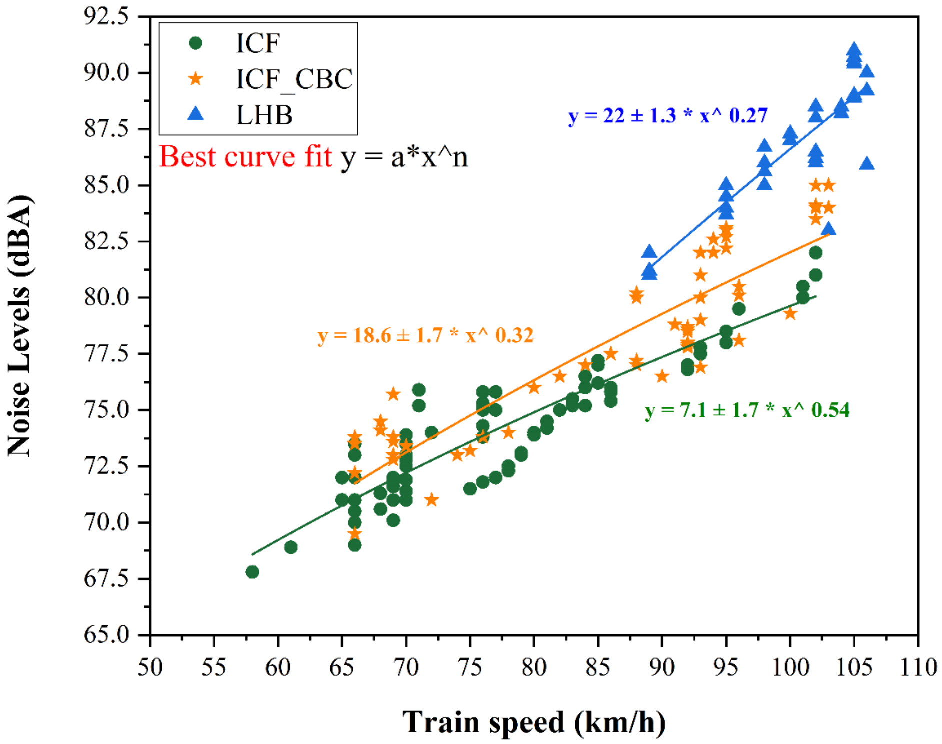


Figure 4.4 Variation of L_{eq} noise levels for passenger trains measured at 25 m

Even though LHB coaches are built using the latest technology, which provides comfort to commuters in terms of riding, interior noise, and vibrations, they still produce the highest exterior noise compared to other train types. In LHB trains, to supply electricity for train lighting, air conditioning, and other equipment operations, the End-On Generation (EOG) system is used since LHB trains lack a self-generation system. The EOG coaches produce significant noise when they are in operation. Along with this noise, the centre buffer coupling system used in LHB coaches produces uncomfortable jerks due to the absence of side-on dual buffers. These jerks produce extra noise during acceleration or deceleration of the train.

The noise sources identified in ICF trains include higher tare weight of ICF coach and higher number of metallic components. Thompson et al. (2018) studied several railway noise sources and concluded that rolling noise is due to the load acting on the rail. The higher the load at the wheel-rail interface, the higher the rolling noise. Generally, a single ICF coach is nearly five ton of weight higher than LHB coaches, producing high rolling noise. Further, ICF trains consist of a higher number of connections and joints. Bolts and rivets constitute the majority of these connections. Due to poor maintenance, these connections wear out over time, and the banging sound is emitted during transit (Dittrich and Janssens, 2000).

A single train coach consists of four axles, and each axle consists of two wheels. Due to the clogging effect during transit conditions, one or more wheels may move slower than others. Due to this effect, higher noise is produced when skidding of the wheel occurs. Thus, LHB coaches use a special arrangement called "*wheel slide protection*". Hence, ICF trains may adopt this technology to reduce transit noise. According to this study, on average, LHB trains emit 8.5 dBA higher noise than ICF trains and 5.5 dBA higher noise than ICF_CBC trains within a 90 to 102 km/h speed range. The sound level increment follows a logarithmic trend, and even one dBA increment leads to ten times increase in sound energy level (Viscardi et al. 2017). Hence, a 5.5 to 8.5 dBA increase in noise can significantly impact the health of dwellers near railway tracks.

The data revealed that the freight trains travelled at speeds ranging between 25 to 70 km/h and emitted L_{eq} noise levels of 56 to 76 dBA. Figure 4.5 shows the noise level variation of different freight wagons under loaded and unloaded conditions. Open wagon trains, on average produced 8 dBA higher noise under loaded conditions than unloaded conditions, based on the best fitting equations. This is due to the higher load at the wheel-rail interface, which produces more rolling noise. The other possible reasons for open wagons include the unsatisfactory working of air brake cylinders and possible brake pipe leakages. The roller bearings are worn out quickly due to heavy loads. Open wagons are generally humped during loaded conditions, and a considerable impact is created due to wheel/rail interaction at its interface (Mellet et al. 2006).

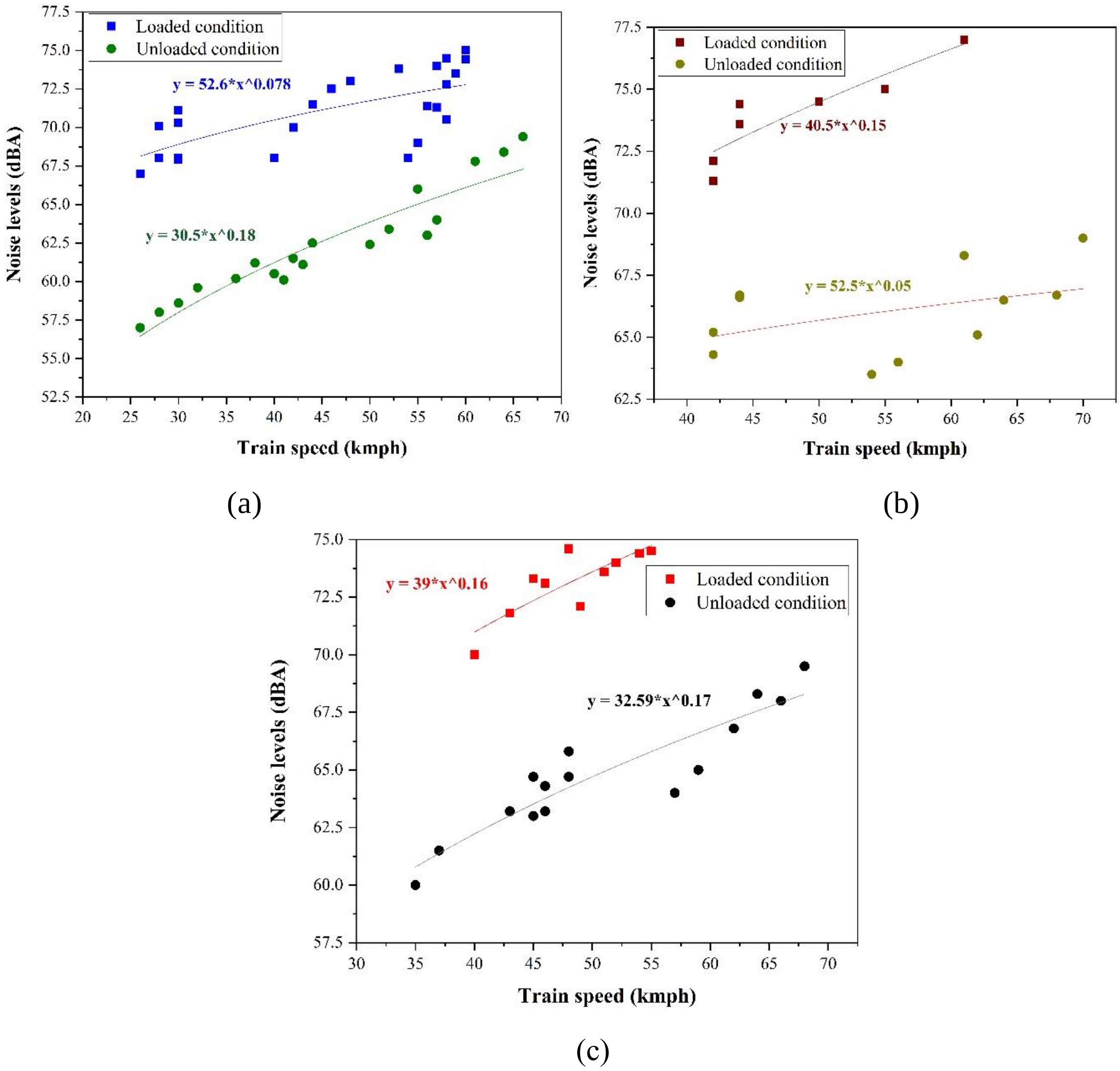


Figure 4.5 Variation of L_{eq} noise levels for freight trains under loaded and unloaded conditions: (a) open wagon, (b) tank wagon, and (c) closed wagon.

On average, closed and tank wagons produced 9 dBA and 7 dBA, respectively, higher noise under loaded conditions than unloaded conditions. When comparing the noise levels produced by the three types of wagon trains, open wagon trains emitted higher noise levels. As shown in Table 4.2, the total gross weight carried by each open wagon is 10 to 20 tonnes higher than the other two types of wagons. As a result, a higher magnitude of rolling noise was emitted from open wagons.

The air brake system in freight trains pushes the brake blocks onto the running wheel surface. When the train applies the brakes, this causes significant friction. Brake blocks are manufactured using cast iron. These blocks gradually make the wheel's running surface rougher. The rough wheels running on the rails generate higher noise and vibrations, which result in higher pass-by noise. Replacing the cast iron blocks with composite brake blocks reduces the pass-by-noise levels by 10 dBA (Tuler and Kaewunruen 2017).

A thorough analysis of each train type specification and the mechanism was carried out to identify the possible sources of noise in passenger and freight trains to identify the possible reasons for higher noise levels. All the identified noise sources could be redesigned and modelled so that the rolling stock and suspension systems can absorb most of the vibrations and noise levels.

Some control measures required to minimize railway noise include regular maintenance of springs and replacing old springs with new springs whenever necessary. Inspection of bogie frame alignment and pivots for welding defects or cracks due to wear is another control measure. Replacement of old connections with new ones and lubricating them with graphite flakes regularly, examining the brake gear levers for worn-out components, and lubrication of brake cylinders, strainers, horizontal levers, hand brakes, and gears frequently are the essential control measures as significant heat is produced at the joints/connections (Yoon and Pyo 2019).

4.3 Influence of Train Length on Railway Noise

Figure 4.6 illustrates the time-history curve of the equivalent sound level measured at 25 m and 50 m distances from the nearest track. It can be seen that, after two seconds of measurement time, the train enters the SLM's line of alignment. The train has a total length of 450 m, with an Electric Locomotive and 17 ICF coaches. During a single pass of an ICF train traveling at 100 km/h, there are 19 peaks in the noise levels. The peak appears at the exact location at both measuring distances (25 m and 50 m). The first peak corresponds to the train head (Locomotive) entering SLM's line of alignment, while the last peak corresponds to the train tail exit. The high noise level at the train's entrance was caused by aerodynamic noise at the front coach, while low noise occurred at the train's tail. When the videographic data overlapped with the time history curve, the peaks in the graph were observed at the train bogie level. The study conducted by Bangjun et al. (2003) showed that wheel/rail rolling noise, gear noise, and bogie aerodynamic noise were all generated by the bogie. The current study shows maximum noise levels are due to the rolling noise generated from wheel-rail interaction and the noise radiating in the axial directions from the bogie. The 11^{th}, 12^{th}, and 13^{th} peaks in Figure 4.6 are higher than the rest of the peaks due to the presence of air conditioning (AC) coaches. The specifications detailed that the tare weight of the AC coach is 5 tonnes greater than a standard coach, resulting in higher rolling noise. A sharp peak was also observed at the interface of the pantograph frame and the pan due to "*electromagnetically induced acoustic noise*".

In Figure 4.7, the length of the LHB train is 400 m, including the length of the electric locomotive and 15 LHB coaches. There are 17 peaks during a single train pass at 100 km/h. The intermediate maximum noise levels were due to the presence of a diesel generator and pantry car, which produces significant mechanical noise. Figure 4.8 shows that the train length is 460 m, with 17 LHB coaches and 19 peaks during a single pass. The maximum noise was caused due to the end-on generator located at the train end.

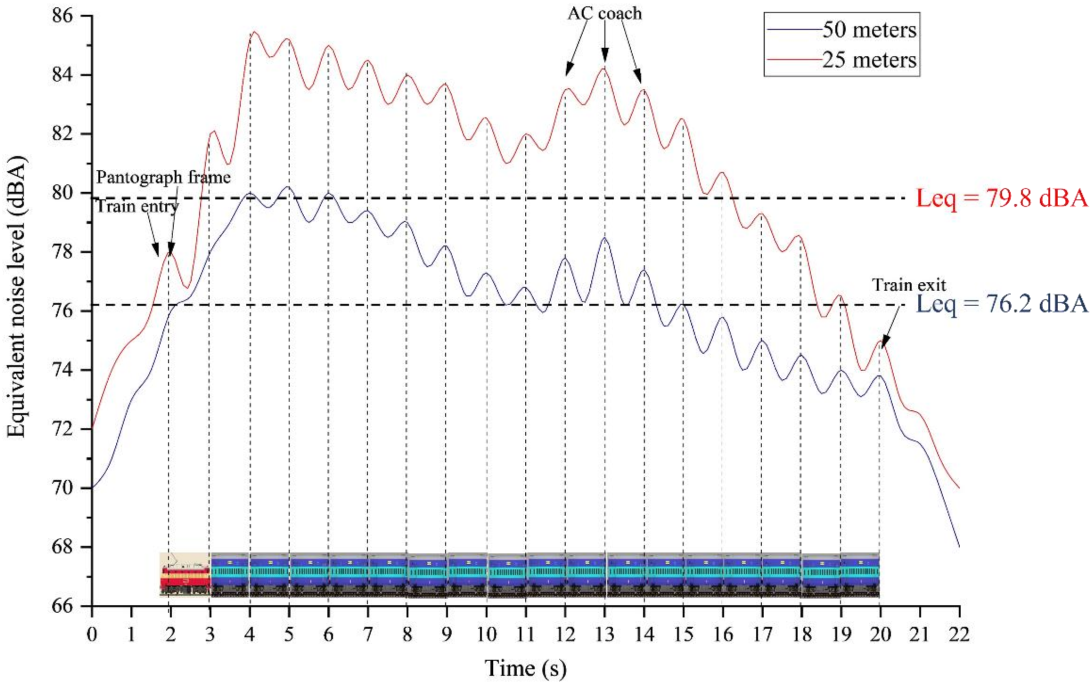


Figure 4.6 Time-history graph of equivalent noise levels of an ICF train at 100 km/h

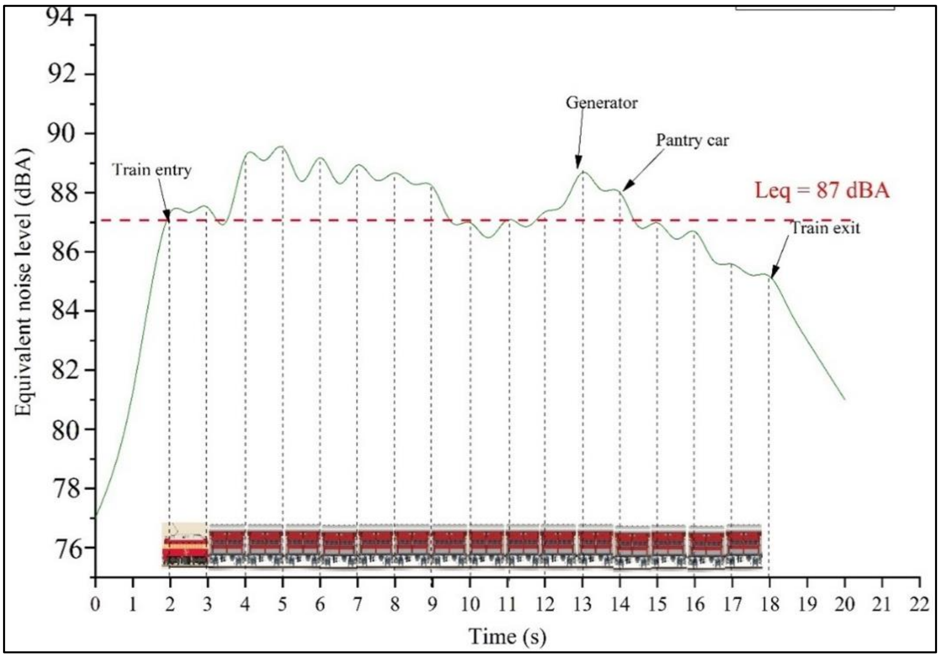


Figure 4.7 Time-history graph of equivalent noise levels of a LHB train when the generator is in the middle.

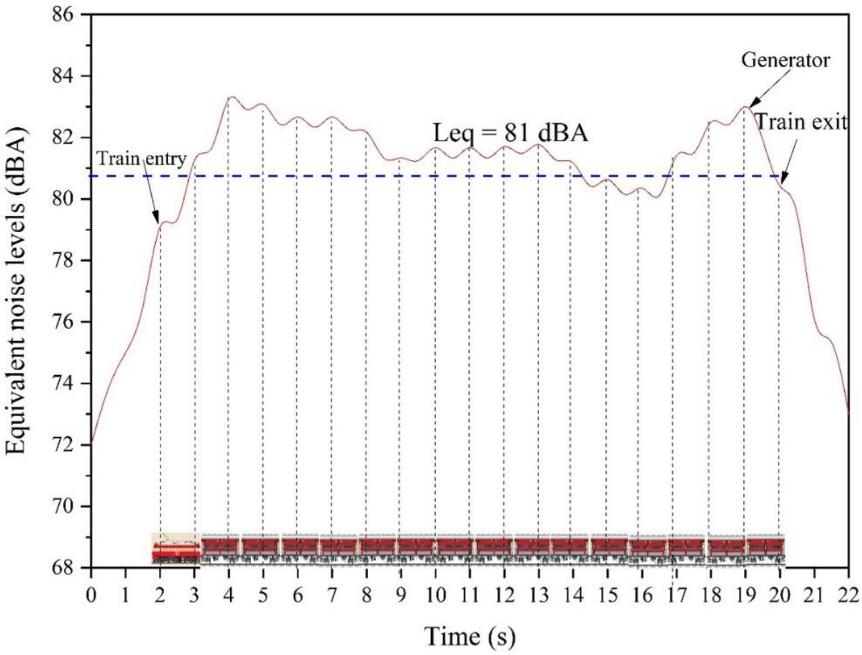


Figure 4.8 Time-history graph of equivalent noise levels of an LHB train when the generator is at the end.

4.4 Influence of Train Speed on Railway Noise

Passenger trains produced higher noise levels than freight trains. The reason might be the speed of passenger trains, which is the driving factor for high noise. The maximum allowable speed for freight trains varies from 65 to 70 km/h, irrespective of the wagon type.

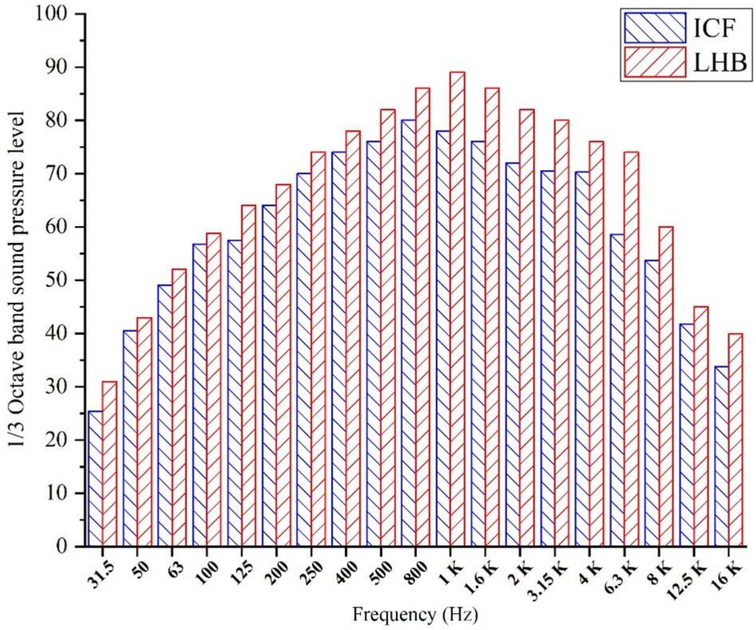


Figure 4.9 Frequency analysis of L_{eq} noise levels for ICF and LHB trains

Frequency analysis was performed, and the 1/3 octave sound pressure variation for ICF and LHB trains measured at the same speed of 95 km/h is shown in Figure 4.9. For LHB trains, the noise spectrum peaks at 1000 Hz, with an associated noise level of 89 dBA, while for ICF trains, the noise spectrum peaks at 800 Hz, with a corresponding noise level of 80 dBA. The sound pressure levels corresponding to each frequency band vary as the train type changes. This might be due to various modifications to each train's mechanism, particularly those involving the coach bogie, coupling arrangement, and damper types. In the current study, by considering the noise levels from different train types and across all speed ranges, noise levels increase by 2.8 to 3 dBA when the train speed is increased by 10 km/h.

4.5 Influence of Measuring Distance on Railway Noise

Geometrical spreading decreases noise levels as the distance between the source and the receiver increases. The geometrical spreading of sound is independent of noise frequency but depends on the distance between the source and receiver. The sound waves travel in a spherical form for a point source, and the reduction rate is 6 dBA per doubling the distance from the source to the receiver. In the case of the line source, the sound waves travel in a *cylindrical form*, and the corresponding reduction rate is 3 dBA. The railway noise is generally considered as the line source, and its spreading depends mainly on the length of the train. In the present study, the average attenuation caused by geometrical spreading when measured at 25 and 50 m ranged between 2.5 and 4.5 dBA. The attenuation caused due to atmospheric and ground effects was not considered while evaluating the influence of train source parameters. Meteorological conditions like air temperature, humidity, and wind speed of the surrounding atmosphere are assumed to be constant.

4.6 Statistical Analysis of Noise Source Parameters

Statistical analysis was done to identify the relation between dependent and independent variables, along with the development of a railway noise prediction model. Table 4.3 summarises the variables' statistical characteristics, such as mean, standard deviation, skewness, and kurtosis. For the data collected, the noise levels vary for different train types, having lower values of standard deviation ranging from 2.18 to 3.14 dBA for L_{eq} and 4.3 to 5.1 dBA for L_{max}. These values suggest that there exists uniformity in the measured L_{eq} and L_{max} noise levels.

Table 4.3 Statistical characteristics of evaluated variables

Train parameters	**Mean**		**Std. deviation**		**Skewness**		**Kurtosis**	
	(L_{eq})	(L_{max})	(L_{eq})	(L_{max})	(L_{eq})	(L_{max})	(L_{eq})	(L_{max})
Passenger coach								
ICF	74	80	2.18	4.25	+0.25	+0.32	1.8	2.6
ICF_CBC	76	82	2.53	4.31	+0.27	+0.36	2.3	2.9
LHB	80	86	3.04	5.14	+0.22	+0.29	1.5	2.3
Freight coach								
Open wagon	68	72	2.32	4.52	+0.33	+0.35	2.5	2.2
Closed wagon	66.5	69	2.98	4.85	+0.38	+0.39	2.4	2.3
Tank wagon	63	67.5	3.24	5.07	+0.4	+0.42	2.6	2.5
Train speed	70 km/h		10.5 km/h		+0.26		1.88	
Train length	580.85 m		145.08 m		+0.35		2.12	

The present study uses Karl's Pearson coefficient of correlation, and coefficient values are represented by 'r'. From Figure 4.10, all the correlation values were observed to be positive, which shows that if the value of one variable increases, then other variables also follow a similar pattern and vice versa. As the proportion of each train type, speed, and length increased, the L_{eq} and L_{max} noise levels increased. In the case of passenger trains, the correlation values were observed to be stronger than that of freight trains. The reason might be the speed of passenger trains, which is the driving factor for higher noise levels. In the case of freight trains, the train length has a strong correlation (greater than 0.5), indicating a significant effect of train length on the emitted noise levels. However, in the case of passenger trains, the train length has a weak correlation. These correlation values indicate that the influence of train type, speed, and length is significant on the noise levels.

"R" values	L_{eq}	L_{max}	ICF	ICF_CBC	LHB	Open wagon	Closed wagon	Tank wagon	Speed	Length
L_{eq}	1									
L_{max}	0.75	1								
ICF	0.63	0.75	1							
ICF_CBC	0.68	0.72	0.7	1						
LHB	0.72	0.76	0.65	0.67	1					
Open wagon	0.61	0.68	0.64	0.7	0.71	1				
Closed wagon	0.58	0.7	0.6	0.48	0.68	0.75	1			
Tank wagon	0.56	0.65	0.58	0.6	0.62	0.65	0.47	1		
Speed	0.85	0.76	0.78	0.77	0.8	0.56	0.57	0.55	1	
Length	0.52	0.45	0.41	0.38	0.35	0.53	0.56	0.54	0.83	1

0.35 0.45 0.55 0.65 0.75 0.85 0.95 1

Figure 4.10 Pearson correlation matrix for noise source parameters

Table 4.4 Multicollinearity diagnosis using variance inflation factor analysis

	ICF	ICF_CBC	LHB	Open Wagon	Closed Wagon	Tank Wagon	Speed	Length
ICF								
ICF_CBC	1.96							
LHB	1.73	1.81						
Open Wagon	1.69	1.96	2.02					
Closed Wagon	1.56	1.30	1.86	2.29				
Tank Wagon	1.51	1.56	1.62	1.73	1.28			
Speed	2.55	2.46	2.78	1.46	1.48	1.43		
Length	1.20	1.17	1.14	1.39	1.46	1.41	3.21	

Multicollinearity is a common issue in regression analysis where independent variables are highly correlated with each other. This can lead to inaccurate estimates of the coefficients and inflated standard errors, making it difficult to interpret the significance of individual predictors. One method for diagnosing multicollinearity is through the Variance Inflation Factor (VIF) analysis. The variance of an estimated regression coefficient is increased due to multicollinearity. A high VIF indicates that the associated independent variable is highly collinear with the other variables in the model. Table 4.4 shows the VIF values for the developed Pearson correlation matrix. If any VIF is greater than 10, there is high multicollinearity. VIF values between 5 and 10 indicate moderate multicollinearity. VIF values below 5 are usually considered acceptable, indicating low multicollinearity (Weaving et al. 2019). In the current study the vales are less than 5 signifying low multicollinearity and the values are acceptable for developing the model.

Multiple linear regression analysis was performed to identify the strength of the relation between the variables, to estimate the change in the dependent variable with the change in independent variables, and to predict future trends in the noise levels. Equations (4.2) and (4.3) can be used to estimate L_{max} and L_{eq} for passenger trains, and Equations (4.4) and (4.5) correspond to freight trains.

$$(L_{max}) = 60.8 + 1.14*(ICF) + 6.89*(ICF\_CBC) + 16.27*(LHB) + 0.2*(speed) + 0.015*(length)\ [R^2 = 0.825] \quad (4.2)$$

$$(L_{eq}) = 61.2 + 0.75*(ICF) + 6.89*(ICF\_CBC) + 16.27*(LHB) + 0.1*(speed) + 0.0075*(length)\ [R^2 = 0.851] \quad (4.3)$$

$$(L_{max}) = 60.4 + 0.68*(Open\ wagon) + 4.5*(Closed\ wagon) + 4.1*(Tank\ wagon) + 0.15*(speed) + 0.005*(length).\ [R^2 = 0.813] \quad (4.4)$$

$$(L_{eq}) = 60.7 + 0.52*(Open\ wagon) + 4.6*(Closed\ wagon) + 3.8*(Tank\ wagon) + 0.12*(speed) + 0.002*(length).\ [R^2 = 0.832] \quad (4.5)$$

The coefficient of determination (R^2) for these models are 0.825, 0.851, 0.813, and 0.832, with significance values (p) as 0.003, 0.001, 0.005 and 0.006. In all the equations, the values 60.8, 61.5, 60.4, and 60.7 dBA denote possibly the background noise at the test site while measuring the railway noise. From the developed model, out of all the variables, the train speed and proportion of ICF_CBC and LHB trains significantly contribute to L_{max} and L_{eq} as they bear higher coefficient values. Nourani et al. (2020) concluded that the influence of traffic volume classification into different categories enhances the performance of the noise prediction model concerning acoustical performance. Similarly, the present study classifies train traffic into several categories, and models have been developed, which resulted in better coefficient of determination (R^2) values.

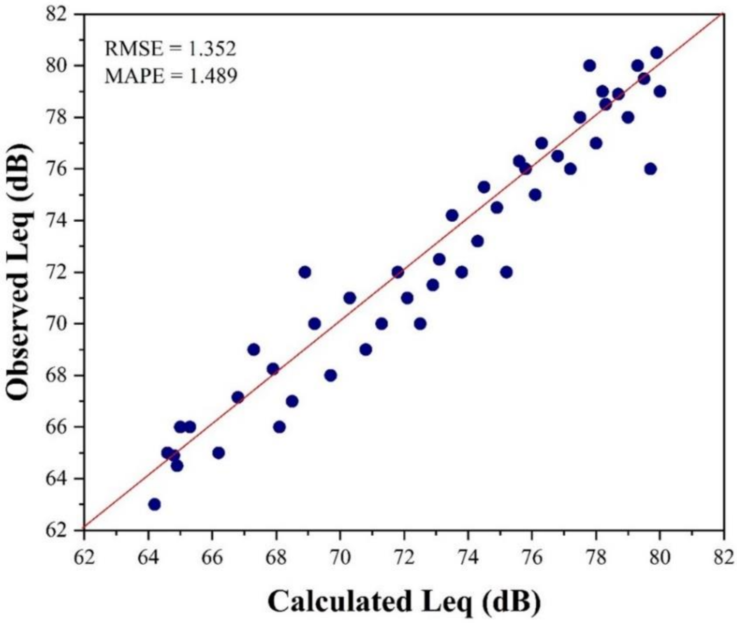


Figure 4.11 Observed vs Calculated noise levels of L_{eq} for the model.

The models developed were validated using 47 observations, including all train types, speeds, and lengths. From Figure 4.11, the Root mean square error (RMSE) obtained is 1.352, and the mean absolute percentage error (MAPE) is 1.489% for the predicted model. The R^2 obtained for this analysis is 0.75, and these results suggest that the parameters significantly forecast railway noise levels in urban scenarios. However, more research into factors such as rail and wheel roughness characteristics, ballast properties, and sound transmission path characteristics like temperature, wind speed, humidity, and train honking characteristics are expected to enhance noise level estimation.

4.7 Assessment of Train Horn Noise at a Railway Level Crossing

A level crossing is an intrusion where a railway line crosses a roadway at the same level. Generally, level crossings on less important roadways or railway lines are frequently open or unregulated, and they pose a severe safety risk to road and rail users. As a result, level crossings on major highways are equipped with a railway gate, which is operated by a gate person. On the Indian rail network, there are 31,846 level crossings, of which 18,316 are access-controlled, and 13,530 are uncontrolled (Mishra 2018). It has been noticed that road vehicle drivers and pedestrians waiting at the level crossing misjudge the speed of an approaching train as the human reaction time is 2.5 seconds, which is just enough to coordinate reflexes against speeds of 60 to 70 km/h. But, most Indian trains travel at speeds of around 100 to 120 km/h, which necessitates a longer reaction time. Even when the train is visible and approaching, the pedestrians, bicyclists, and motorcyclists continue to cross the tracks, resulting in level crossing crashes. In these situations, the loco-pilot uses extra horns to alert these trespassers to avoid crashes but it causes an additional nuisance to the people living near the level crossings.

A train's capability to react to sudden intrusions on railway lines is severely limited and delayed, and train drivers can only slow down, apply brakes, and sound the train horn to warn people against the danger of collision. Whistle boards are typically placed ahead of high-risk zones to inform train drivers to blow horns. The usage of train horns has safety benefits at railway-level crossings. The collisions between trains and road vehicles are uncommon at level crossings. However, those involved are more likely to get seriously injured or even killed when they occur. Hence, the deployment of train honking reduced the road vehicle and train collision rate by 70% (Votano et al. 2004).

Most studies on train horn evaluation in proximity to trackside residents are limited and primarily focused on US policies, which differ from those in other countries (Brach and Brach 2010; Fraszczyk et al. 2016). As rail networks and rail traffic expanded over the years, sirens rang at level crossings for extended periods. These scenarios raise the overall noise levels and duration at railroad crossings, making the trackside residents more irritated by the noise. There is currently no study on how train horns are used in practice or if they are beneficial to road users' safety or harmful to trackside dwellers. As a result, this study determines the impact of train horns on trackside residents by measuring the train honking noise levels at unmanned level crossings for various train speeds, train lengths, and weather conditions. In the Indian context, most of the scenarios at the level crossing are similar, and the analytical model developed for a single site may also be transferable to other sites (Givargis and Karimi 2010). In the current study, the residents living along the railway line who are continuously exposed to high levels of noise from the railway line were taken into consideration, and an ANN model along with linear regression was developed to forecast the equivalent continuous noise level (L_{eq}) and maximum noise level (L_{max}). Finally, the mean errors for the two developed models (ANN and regression) were identified by comparing the forecasted railway noise levels with the measured values.

Table 4.5 illustrates the statistical values for the collected data, with the maximum noise (104 dBA) coming from train honking and the lowest noise (65 dBA) from the ambient when there is no train movement. The equivalent noise of 82 dBA represents the average noise produced by the train movement without honking. Along with the train's data, the volume of road traffic waiting at the closed railway gate was also recorded. During the noise measurement period, the largest number of vehicles waiting at the level crossing when the gate was closed per single train movement was 105. The level crossing gate was closed 54 times during the survey period from 6:00 a.m. to 6:00 p.m. During this duration of the day, a total of 4,300 vehicles were halted at the level crossing gate.

Table 4.5 Statistical values of the noise levels and the input parameters

Railway noise levels (dBA)			**Train speed** (km/h)		**Train length** (m)		**Wind speed** (m/s)	
L_{eq}	L_{max}	L_{min}	*Mean*	*Standard deviation*	*Mean*	*Standard deviation*	*Mean*	*Standard deviation*
82	104	65	80	± 5.1	425	±103	4.2	±1.3

The noise levels are compared in Figure 4.12 for the four scenarios considered at the level crossing. Among all the scenarios considered at the level crossing, the noise levels emitted during the train honking were observed to be the highest. In the first scenario, i.e., when the level crossing was opened to road traffic, the maximum noise produced was 80 dBA due to Heavy Commercial Vehicles (HCV) and Light Commercial Vehicles (LCV) movement. During the traffic volume survey, it was observed that two-wheelers were the most common vehicle category in terms of volume, generating an equivalent noise level of 72.5 dBA while moving when the level crossing gate was open.

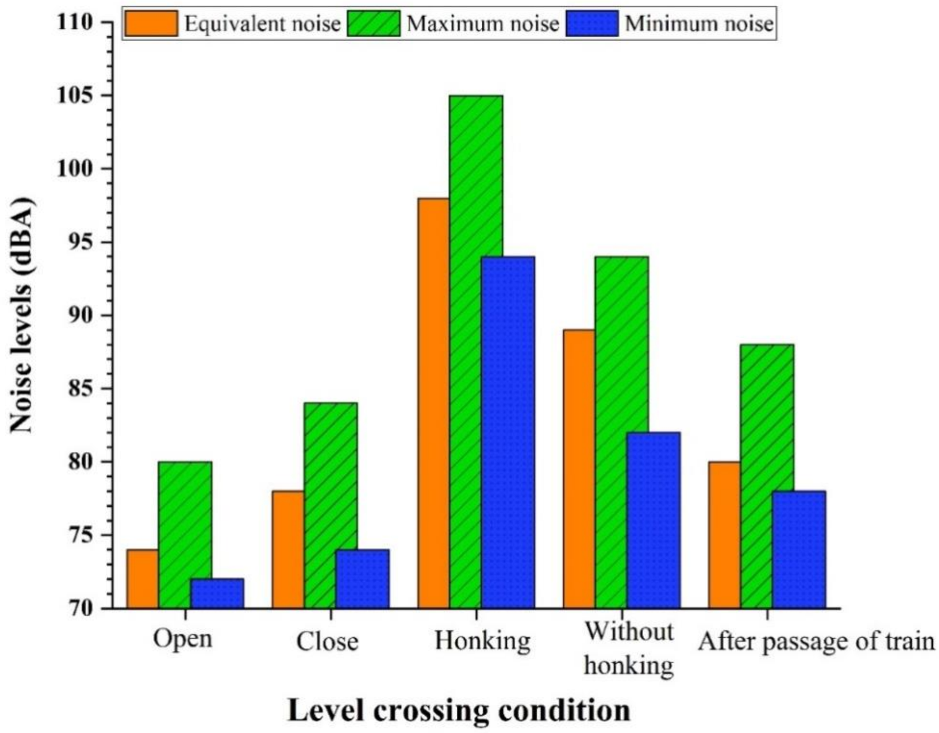


Figure 4.12 Comparison of noise levels in all the scenarios at the level crossing

The maximum noise produced in the second scenario was 85 dBA due to the accumulation of road traffic and pedestrians when the level crossing gate was closed. It was observed that most of the vehicles' engines were not turned off while waiting at the level crossing. The HCVs and cars were observed to keep their engines ON among all vehicle categories for the maximum duration of time. The number of vehicles with engines ON at the closed level crossing gate, including the vehicle category and the total number of vehicles under each category, are shown in Figure 4.13. According to the study conducted by Aditya and Chowdary (2020), the engine propulsion has a considerable impact on road traffic noise along with the tire-pavement interaction noise. The current research observed that when the vehicle's engine was not turned off during the waiting period, the equivalent noise level increased by 10 dBA. Hadley et al. (2019) observed that the number of people present at any event significantly impacted the overall noise. Similarly, the presence of pedestrians in high volumes at the railway gate in the current study resulted in an additional L_{eq} noise of 2 to 3 dBA.

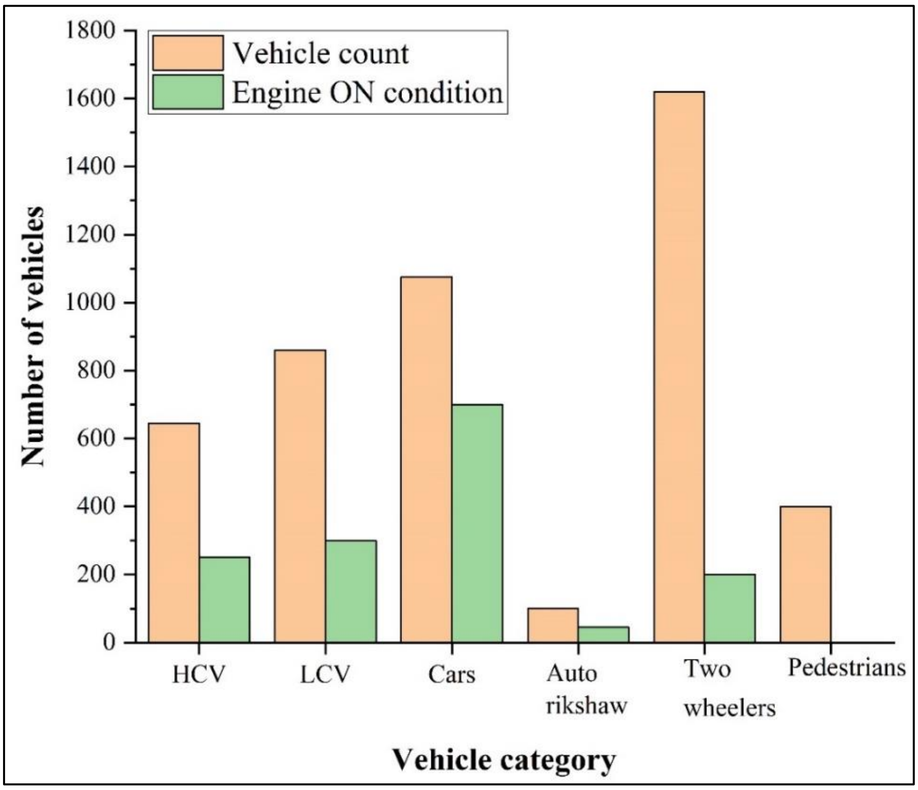


Figure 4.13 Traffic volume, the proportion of different vehicle classes, and the number of vehicles switched on their engines.

The third scenario produced a maximum noise level of 104 dBA, associated with train movement and honking. A detailed analysis of honking, along with frequency analysis, is presented in the subsequent sections. In the last scenario, it was observed that most of the vehicles accelerated at the moment the railway gate was opened to roadway traffic. A study conducted by Lelong and Michelet (1999) revealed that frequent acceleration or deceleration of the vehicle significantly impacted noise levels and depended on acceleration rate, the gear ratio, and the engine speed. The present study observed that the acceleration of vehicular traffic produced an extra noise of 5 dBA. As a result, it can be concluded that the highest noise will be produced at a railway-level crossing owing to train movement and honking, apart from the presence of vehicles with their engines on.

4.7.1 Analysis of honking noise

The sound signals measured with SLM, which could distinguish 1/1, and 1/3 octave frequency zones, were pre-processed using a series of frequency analytic methods generally used to assess the sound levels heard by humans on acoustic signals (Kattis et al. 1999). As the human auditory system is sensitive to low frequencies, all the measurements were first filtered using human ear sensitivity using an A-weighted frequency filter. The A-weighted sound level was considered as a standard measuring unit for quantifying the harmfulness of the noise to public health. The final step was to reduce the error in noise measurement due to disturbance caused by the microphones (Garg et al. 2019). The detailed steps to reduce the error in noise measurement due to disruption caused by the microphones are listed below:

- **Use of high-quality, low-noise microphones:** These SLMs can reduce measurement errors caused by microphone disturbances.
- **Shielding the microphone:** Shielding the microphones from environmental noise sources and vibrations can reduce measurement errors.
- **Selecting an appropriate measurement location:** Selecting a location isolated from disturbance sources can reduce measurement errors.
- **Usage of multiple microphones:** Multiple microphones can help to average out measurement errors caused by microphone disturbances and increase measurement accuracy.
- **Calibrating the microphone:** The cumulative impact of numerous small errors that occur during noise measurement using a microphone can be reduced by calibrating the microphone to a recognized standard before conducting the measurement. This is referred to as minimizing the "*pooled error*" (Garg and Maji 2014).

Figure 4.14 depicts a graph for a single train passage showing the variation in SPL with time while blowing the horn. This graph resembles an impulse sound signal subjected to a short exposure time. The noise measured before the train horn is shown by the negative values of time for 2 seconds. The train's horn is blown for the first time at zeroth seconds and continues for two seconds. The video camera recordings aided in determining the length of time when the train horn is activated. The average L_{max} of 102 dBA was recorded when the train horn was blown, whereas the L_{max} noise level measured before blowing was 72 dBA. The train horn noise levels were extracted within the identified peak of the graph for maximum A-weighted SPL. As per the standard noise limits set by the Central Pollution Control Board (CPCB) of India, the maximum permissible noise in residential areas is 55 dBA during the daytime and 45 dBA at night (The Noise Pollution Regulation and Control, 2000).

Two horns with two pause patterns were used at the level crossing, as shown in Table 2.2. For most of the train horns, the noise levels resulting from the first horn ranged between 63 to 85 dBA, whereas the second horn ranged between 89 to 104 dBA. The second horn was observed to be 21 dBA higher than the first horn. On average, train horns were 30 dBA higher than the ambient noise. Such higher noise levels can have a significant effect on human health. That is, for every 3 dB increase in sound level, the impact on hearing health loudness gets doubled (Garg et al. 2016). Most of the train horns ranged between 10 to 41 dBA above the background environment noise, indicating significant variation. When the first horn was sounded, there was no significant difference between the train horn and background environment noise with a *t*-value of 0.02 and '*p*' of 0.92, and the loudness difference was 15 dBA. The second horn had a significant difference with background noise ($t = 3.25$, $p = 0.002$), with the loudness difference being 35 dBA.

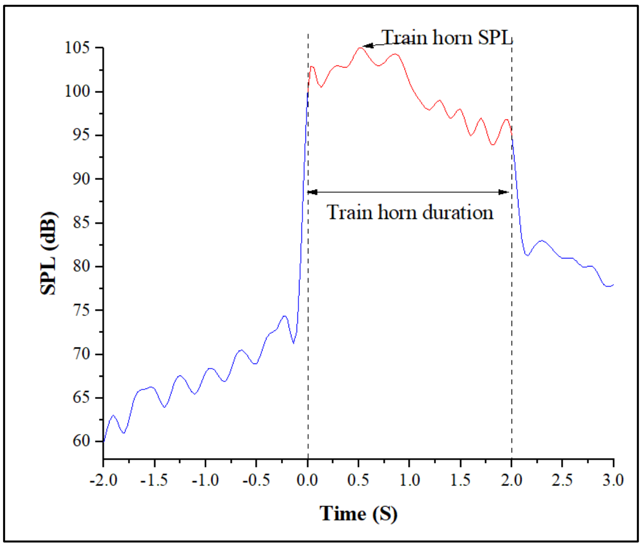


Figure 4.14 Sound signal during the train horn (red line) showing the duration and peak SPL

4.7.2 Frequency analysis of L_{eq} noise levels with changes in train speed

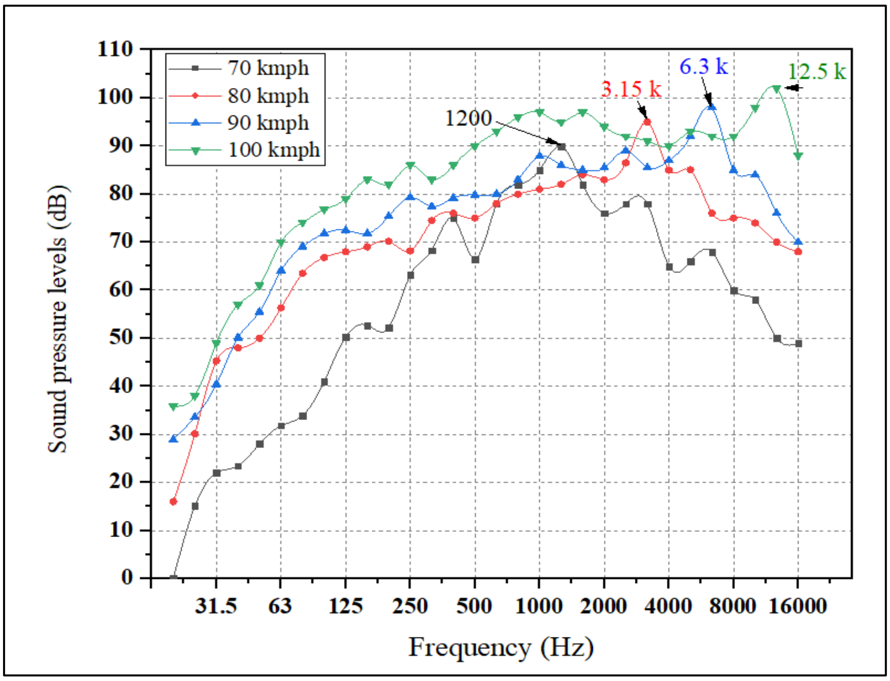


Figure 4.15 Frequency analysis of L_{eq} noise levels including honking noise for different train speeds

Figure 4.15 depicts the 1/3 octave frequency variation of sound pressure levels for various train speeds and honking. The frequency spectrum shifts from 1200 Hz to 12.5 kHz as the train speed increases from 70 km/h to 100 km/h. The shift in SPL from 90 dBA to 104 dBA was observed due to the increase in train speed from 70 km/h to 100 km/h. This increase in noise level was primarily caused by rolling noise, and the shift in frequency band was due to honking. In general, if there is no train honking, changing the train speed from 70 to 100 km/h results in a shift in the frequency spectrum from 500 to 1250 Hz, but the presence of honking results in a much larger shift in the frequency spectrum (Zhan et al. 2021). Figure 4.16 shows that if the noise intensity is the same (85 dBA), but the frequency band is high (1000 Hz), the people who are exposed to the noise are more irritated (Zvolenský et al. 2021). As a result, honking is a great annoyance to those who live near the railway tracks.

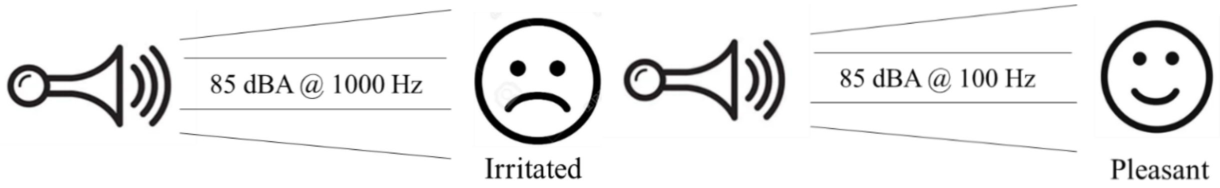


Figure 4.16 Differences in human perception of noise at various frequency bands.

4.7.3 Modelling of honking noise

The railway noise prediction models substantially aid urban planners in getting access to and monitoring the noise impact on railway infrastructure projects. These mathematical models serve as a tool for rigorous analysis, hypothesis generation, and event prediction. However, developing a mathematical model is difficult as disparate domains of knowledge are often required in mathematics and engineering. Several studies have been carried out throughout the globe to develop a model that can accurately forecast railway noise levels. Much of the research has been published on environmental noise modelling for a variety of urban areas, with the hope of applying it to noise prediction in several other countries. Moehler et al. (2008) conducted a study in the central Europe region using the results of the "*Schall 03*" prediction methods. This study took into account the number of trains as well as the types of trains. Another study by Thompson et al. (2018b) demonstrated that while engineering techniques for simulating the generation of rolling noise were well established, they still required some simple model hypotheses to calculate the noise levels radiated by the wheel and the track. Van Leeuwen (2000) conducted a study to develop generic railway noise prediction models by considering sound propagation path characteristics, source conditions to be monopole and dipole, meteorological conditions, reflections, etc. Another study was conducted at a railway-level crossing by Larue et al. (2021) to assess the impact of train horns on the safety of motorists and pedestrians. All these models assumed that the variation in railway noise level was linear as a function of several parameters. Since the relationship between noise levels and railway traffic density, average train speed, and other parameters may be non-linear, other approaches, particularly soft computing techniques, should be examined compared to the regression-based approach.

Artificial neural networks are nonlinear statistical modelling algorithms that offer a novel approach to logistic regression, the most extensively used method in engineering for creating predictive models for discrete outcomes. Kumar et al. (1998) developed a road traffic noise prediction model using an ANN and regression approach. Even with limited data, the ANN approach was found to be satisfactory. Kuznetsov et al. (2022) conducted a study on railway noise by considering train speed and distance from the centre of the track. This study attempted to develop an Emotional Artificial Neural Network (EANN) model and compared the results with linear and logarithmic regression models. Test results showed that the prediction accuracy of the EANN model was 95.6%, the linear regression method was 82.6%, and the logarithmic regression was 88.9%.

Most developed countries like Australia, the United States, the United Kingdom, etc., developed their prediction models by considering several train and rail parameters like wheel and rail roughness, train aerodynamics, curve squeal, train speed and type, sleeper characteristics, etc. Based on 25 input variables, Genaro et al. (2010) built an ANN-based model to forecast urban environmental noise in terms of L_{eq}. The results of ANN have been proven to be satisfactory even with a tiny database. However, the authors emphasized that more work is required to develop and evaluate train honking noise levels to develop complex heterogeneous models. ANN models developed in other countries may not necessarily be applicable to the Indian scenario.

The accuracy of an ANN model depends on several factors, one of them being the quality and representativeness of the data used for training the model. Other critical factors include the condition of the railway system, which comprises the track geometry, train speed, and train type. These conditions can vary significantly between countries and can have a significant impact on railway noise levels. In addition, environmental conditions such as humidity, temperature, wind profiles, terrain, population density, and land use patterns can affect noise propagation and vary across countries. Hence, to ensure the accuracy and reliability of ANN models, it is recommended to carefully evaluate and calibrate these models for railway noise prediction in the Indian scenario. With these complexities, the accuracy and reliability of ANN models across different countries can be improved by collecting additional data, adjusting model parameters, or developing new models that can better reflect the unique conditions and characteristics of the railway system and environment. Thus, the current study focuses on applying the ANN approach to model train honk decibel levels compared to developing an analytical model regarding train speed, train length, and climatic conditions. Compared to conventional mathematical and numerical methods, the advantages of ANN are rapid, precise, and accurate computation of multiple variables with non-linearity and complex algorithms.

Multiple Linear Regression (MLR) models

The Multiple Linear Regression (MLR) analysis was used to identify the strength of the relation between the variables and to estimate the change in the dependent variable when there is a change in the independent variables such that future trends in the noise levels can be predicted. In the present study, the MLR model was developed for L_{max} and L_{eq} with input variables such as train speed, length, and wind speed. Equations (4.6) and (4.7) show the empirical relationships for predicting L_{eq} and L_{max}.

$$L_{eq} = 72 + 1.27*(\text{train speed}) + 0.85*(\text{train length}) + 0.60*(\text{wind speed}) - 1.55. \quad [R^2 = 0.67] \quad (4.6)$$

$$L_{max} = 95 + 1.62*(\text{train speed}) + 0.91*(\text{train length}) + 0.82*(\text{wind speed}) - 2.61. \quad [R^2 = 0.72] \quad (4.7)$$

Table 4.6 Linear Regression results for L_{eq}

L_{eq}	Coefficients	Std. error	t-stat.	p-value
Intercept	72	1.3214	52.93	1.2365E-2
Train speed (km/h)	1.27	0.00857	26.52	0.0853
Train length (m)	0.85	0.00325	5.64	0.0065
Wind speed (m/s)	0.60	0.00152	1.67	1.717E-21

Table 4.7 Linear Regression results for L_{max}

L_{max}	Coefficients	Std. error	t-stat.	p-value
Intercept	95	2.4785	60.32	0.8723E-2
Train speed (km/h)	1.62	0.00258	20.54	0.0745
Train length (m)	0.91	0.00987	3.65	0.0032
Wind speed (m/s)	0.82	0.00619	2.87	1.525E-23

The regression analysis findings are shown in Tables 4.6 and 4.7, which include regression coefficients, standard errors, t-statistics, and p-values. For example, the regression coefficient value of 1.27 in Table 4.5 indicates that if the independent value changes by one unit, the dependent variable will vary by 1.27 units. The *t*-values are the regression coefficients divided by the standard error, and all three parameters have a *p*-value of less than 0.05, indicating that all three variables significantly impact the predicted model.

4.7.4 Development of artificial neural network model

ANN is one of the soft computing techniques used for forecasting mathematical models that were inspired by the human brain. They predict the complex nonlinear relationships between the dependent and independent variables. The neural network can calculate outputs for a given set of inputs once it has been "trained", but the links between the inputs and outputs are not easily recognized (Garg et al. 2015). The Back-Propagation (BP) algorithm is the simplest and most extensively used technique for training a neural network, and the present study uses this back-propagation algorithm for updating weights and bias variables according to the Levenberg-Marquardt optimization technique. The Levenberg-Marquardt algorithm combines the steepest descent method and the Gauss-Newton algorithm, inheriting the speed advantage of the latter and the stability of the former (Debnath et al., 2022). As the information is propagated feed-forward, these ANNs are known as feed-forward networks. There are two types of ANN: single-layer and multi-layer neuron networks. The latter has the advantage of dealing with non-linear functions (Tomić et al. 2016). Thus, a neural network consists of interconnected artificial neurons organized in several layers (input layer, one or more hidden layers, and output layer), as shown in Figure 4. 17.

The ANN model used in this study incorporates several key architectural components to facilitate accurate noise level predictions. The learning rate, which governs the rate of weight updates during training, was carefully chosen to balance convergence speed with stability. The optimization algorithm employed is the back-propagation algorithm with the Levenberg-Marquardt optimization technique, enabling efficient weight and bias adjustments to minimize prediction errors.

In addition, regularization techniques were applied to prevent overfitting and enhance the model's generalization ability. Specifically, L1 or L2 regularization methods were employed to penalize overly complex models and encourage simpler solutions. The number of training epochs required to achieve satisfactory results varied depending on the dataset and model complexity, with early stopping criteria utilized to prevent overfitting.

The choice of activation function, particularly the sigmoid (logistic) function, was motivated by its ability to introduce non-linearity into the model and facilitate the learning of complex relationships between input and output variables. The selection of model parameters and techniques, including learning rate, optimization algorithm, regularization, and activation functions, was informed by careful consideration of the dataset characteristics and desired performance metrics, ensuring optimal model performance across various scenarios (Paneiro 2018).

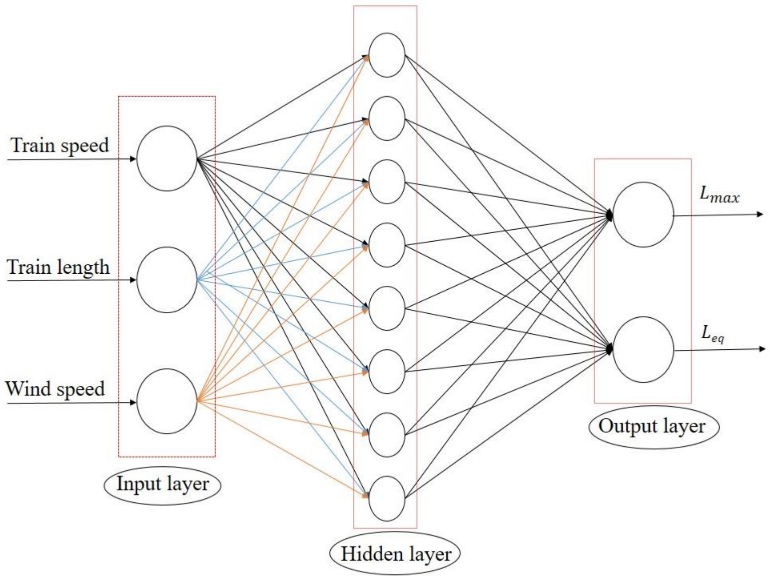


Figure 4.17 Schematic representation of ANN model with three inputs and two outputs developed for L_{max} and L_{eq}

Structure of a neural network

The inputs from three variables supplied to the node from one end can be seen in Figure 4.18. The circle element is referred to as a node, and it is divided into two portions. The summation function is on the left, and the activation function is on the right. X_1, X_2 and X_3 are the input signals and w_1, w_2 and w_3 are the corresponding weights of the three input signals. When all of these signals enter the node, the summation function calculates the weighted sum of all of the inputs (i.e., $\Sigma x_i w_i$). Later, the activation function determines whether or not a neuron should be activated and generates an output based on the supplied input. The sigmoid (logistic) function is the most commonly used activation function. By iteratively adjusting the weights, a neural network can be taught to map a set of input data. The input and output data in the training dataset are read by ANN, which then modifies the weight of the link to reduce the difference between the forecasted value and target values. The prediction error is minimized across multiple training cycles (epochs) until the performance requirement is reached. This study used the MATLAB Neural Network Toolbox to create an ANN model.

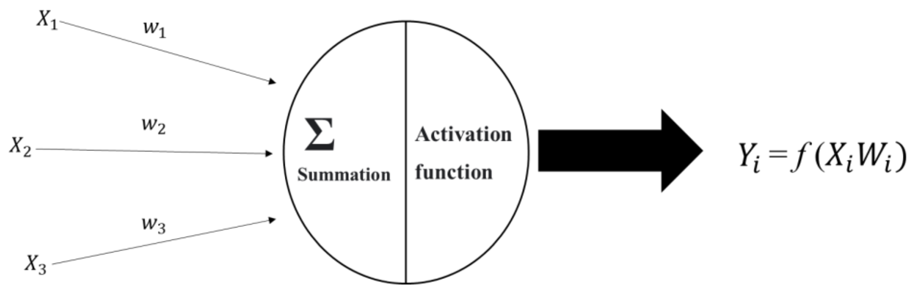


Figure 4.8 The schematic approach of the ANN model

The separation of data into training, validation, and testing datasets is critical for determining the model's accuracy. The training data set contains samples for learning, such as fitting weights for intended output, the validation data for tuning network parameters, and the testing dataset for evaluating performance after learning (Nedic et al. 2014). The number of hidden layers in a network is difficult to determine, but normally in many cases, one hidden layer was utilized. The network is subjected to a series of trials in which the number of neurons in the hidden layer is varied. The number of neurons in the hidden layer that achieves the performance criterion of Mean Square Error (MSE) and correlation coefficient (R) between measured and predicted data is chosen (Kumar et al. 2014). As a result, using the test dataset, the constructed and validated network may be employed to deliver credible predictions. If the MSE is smaller than the limiting error, the neural network training would have been completed, and the network is suitable for prediction. Otherwise, the values are modified till the desired error level is reached.

Each training pair of ANN consists of input parameters such as train speed, train length, and wind speed and target parameters such as L_{max} and L_{eq} noise levels. Table 4.8 compares training and testing sample data for a single hidden layer with neurons ranging from 4 to 20. Among all the tested results, a single hidden layer with 8 neurons yielded the best results for minimum mean square error and good correlation coefficient for training and testing data sets. As a result, the optimal neural network structure is 3-8-2, as illustrated in Figure 4.17, which connects the 3-input and 2-output parameters through the 8 hidden layers.

The present study considers 70% of the data for training the neural network and the remaining 30% for testing. After deciding on the number of neurons, the next step is to test the ANN's prediction abilities. The testing data are not used for training but rather to assess the predictive accuracy of the trained ANN model.

Table 4.8 ANN architecture for training and testing data set

Hidden Nodes (*N*)	Training				Testing			
	R		***MSE***		***R***		***MSE***	
	L_{eq}	L_{max}	L_{eq}	L_{max}	L_{eq}	L_{max}	L_{eq}	L_{max}
4	0.9984	0.842	0.1211	9.24	0.9958	0.853	0.0078	7.85
8	**0.9989**	**0.875**	**0.1389**	**1.67**	**0.9941**	**0.895**	**0.2227**	**1.34**
12	0.9953	0.866	1.3392	4.67	0.9909	0.886	0.4386	3.65
16	0.9991	0.800	0.0098	1.24	0.9688	0.823	0.7753	1.05
18	0.9974	0.832	0.3422	2.36	0.8870	0.854	0.6630	3.21
20	0.9793	0.891	2.4104	3.98	0.9564	0.912	2.3431	4.36

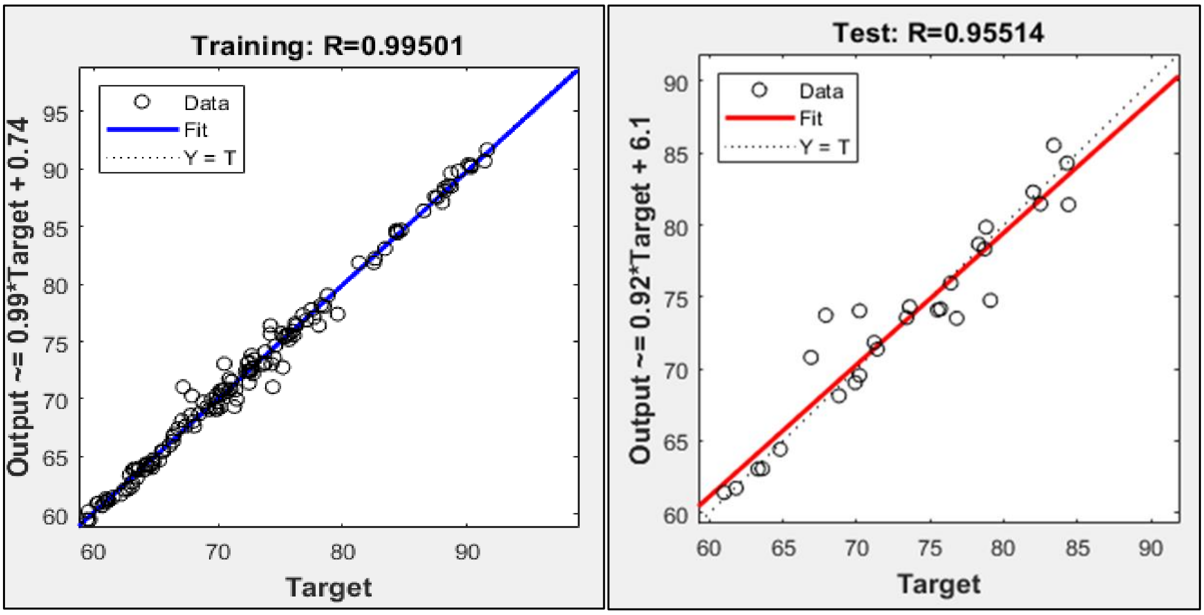


Figure 4.19 Comparision of the results for training and testing data set

Figure 4.19 shows the measured values versus forecast values for both L_{eq} and L_{max}. In the case of training data, the dotted line and the thick line overlapped one over the other, which shows that the error is less. However, there is a slight difference between the measured and predicted values in testing data. This difference can be noticed with the generated "*R*" values which are 0.99 for training and 0.95 for testing.

It was also observed that higher values of "*R*" are observed for ANN rather than MLR. This indicates that ANN is successful in characterizing the problem, and the estimated output error is lower than the acceptable limits. This model always guarantees a higher precision than the suggested regression model.

Sensitivity analysis

A sensitivity analysis was performed to test the impact of each parameter on the variation of noise levels. In this process, the standard deviation of each input parameter was computed, and the variations in each input around the mean values were utilized to derive the output changes. The model's sensitivity was determined by the standard deviation of output values for each input variable. The relationship between changes in model output values and changes in input variables (within standard deviation) illustrates the model's trend. The results are shown in Figure 4.20, with train speed having the most significant impact on railway noise generation, followed by train length, and wind speed.

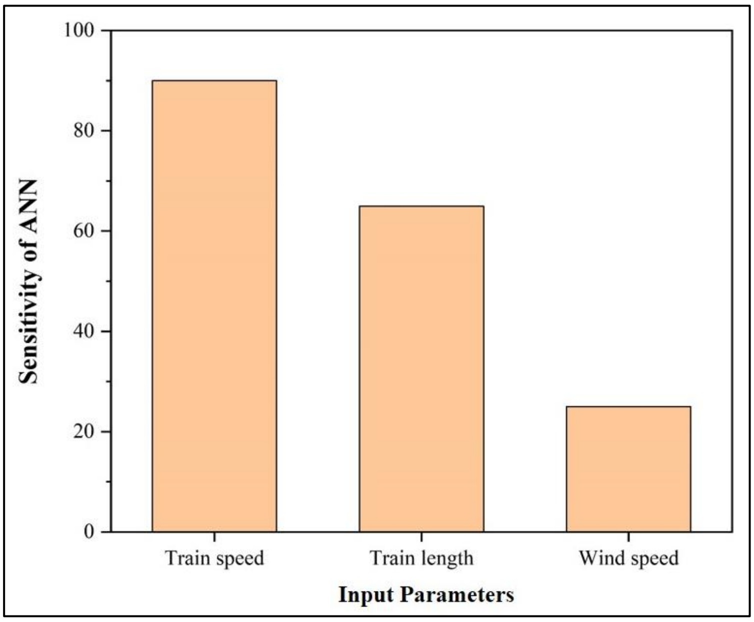


Figure 4.20 Results of the sensitivity analysis of ANN.

4.7.5 Comparison of MLR and ANN model

The suitability of ANN and MLR models for predicting railway traffic noise in an urban area was investigated by comparing the two models. Table 4.9 shows the comparison of L_{eq} and L_{max} values for the measured and models' predicted data. Randomly, a few data points were taken out, and error values for the two models were calculated. In the case of the MLR model, on average, there is a variance in L_{eq} and L_{max} noise levels by 2.92 dBA and 2.68 dBA, respectively. The ANN model has an average deviation of 0.82 dBA in L_{eq} and 0.58 in L_{max}. Hence, the ANN model outperforms the MLR model in terms of mean-squared error and coefficient of determination between measured and predicted data. Additionally, ANN models are more versatile and better at forecasting extreme noise levels, but MLR models perform better at capturing the linear pattern of time series data. MLR models are limited in their adaptability, and correction factors are required to capture extreme values. As a result, it is clear that current ANN models can be utilized to make accurate railway noise estimates and forecasts.

Table 4.9 Comparison between measured and models' predicted results

Testing trial	**Results**						**Error-values**			
	Measured		***Regression***		***ANN***		***Regression***		***ANN***	
	L_{eq}	L_{max}	L_{eq}	L_{max}	L_{eq}	L_{max}	L_{eq}	L_{max}	L_{eq}	L_{max}
1	72.5	88.6	75.6	91.1	72.9	88.4	-3.1	-2.5	-0.4	0.2
2	75.6	92.5	79.3	95.2	74.9	93.1	-3.7	-2.7	0.7	-0.6
3	74.8	91.3	72.3	88.1	75.8	92.1	2.5	3.2	-1	-0.8
4	73.2	93.4	75.1	96.2	71.7	93.1	- 1.9	-2.8	1.5	0.3
5	74.6	90.8	71.2	88.6	75.1	89.8	3.4	2.2	-0.5	1.0

Chapter 5

INFLUENCE OF TRANSMISSION PATH PARAMETERS ON RAILWAY NOISE PROPAGATION

This chapter presents the analysis of the variation of railway noise due to transmission path characteristics such as ambient temperature, relative humidity, wind speed, and direction. Noise maps were generated for the test site by considering the noise source and transmission path characteristics and obtaining the ideal distance to construct housing units from the railway line in the absence of a noise barrier. In addition, the noise level variation caused due to the presence of a wall between the source and receiver is presented.

5.1 General

The previous chapter presents a complete analysis of the railway noise source parameters and the development of prediction models. This chapter presents a detailed analysis of the transmission path characteristics, i.e., ambient temperature, relative humidity, wind speed, and direction, along with the presence of an obstacle between the source and receiver. Since sound can travel through air, water, and solids, any factor that affects the state of the medium influences sound propagation. Two types of noise sources are point source and line source. Railway noise is considered both a line source and a moving source because it is generated continuously along the length of the track as a train moves. A line source can differ from a point source regarding noise distribution, directionality, and sound intensity and may require unique engineering and control measures.

5.2 Influence of Wind Speed and Direction on Noise Propagation

The wind rose diagram shown in Figure 5.1 represents the direction, speed, and wind duration corresponding to the time the train is present at the test site. Each color bar length represents the proportion of share for a specific range of wind speed. The legend is used to interpret the color bar, and the frequency of wind is depicted in ascending order of circles. The small circle in Figure 5.1 was used as a reference in the analysis, with the prevailing wind above the red line being regarded as upwind and below it being considered as downwind.

It was observed that the dominant wind directions are from south-west and north-west. The red dots in Figure 5.1 indicate the orientation of the sound level meters, which are perpendicular to the direction of the railway track. The railway track is along the East-West direction. The observed wind direction was mostly upwind, reducing SPL's intensity from source to receiver. The maximum wind speed recorded was 6.25 m/s, which prevailed in the southwest direction. This wind rose diagram assists in determining whether the wind is blowing upwind or downwind, as well as the wind speed.

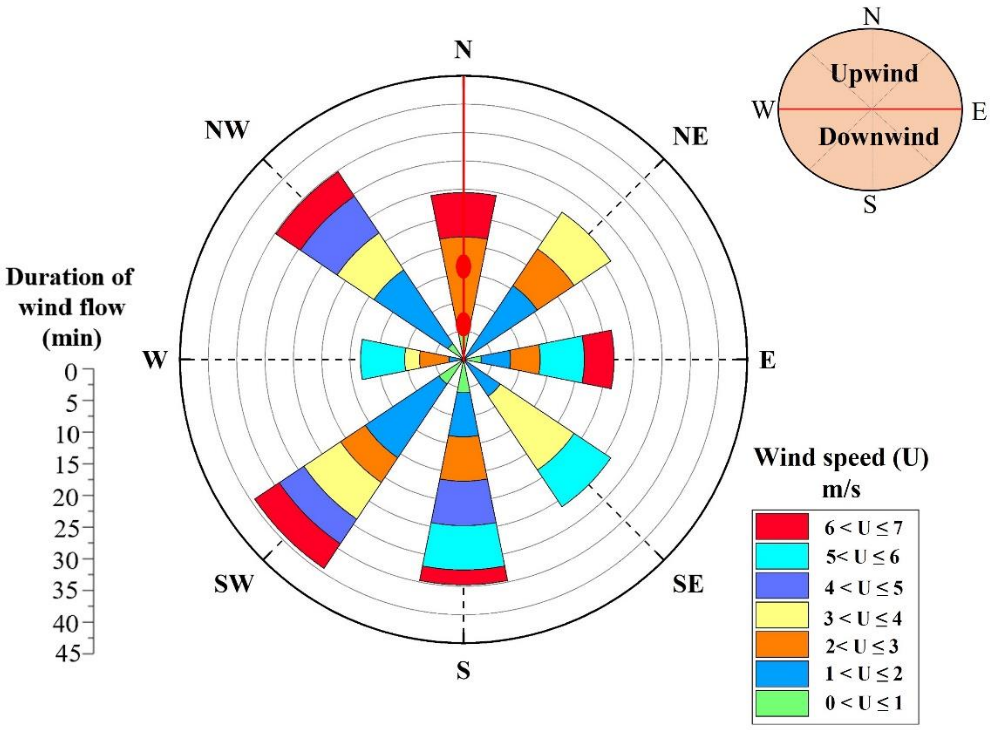
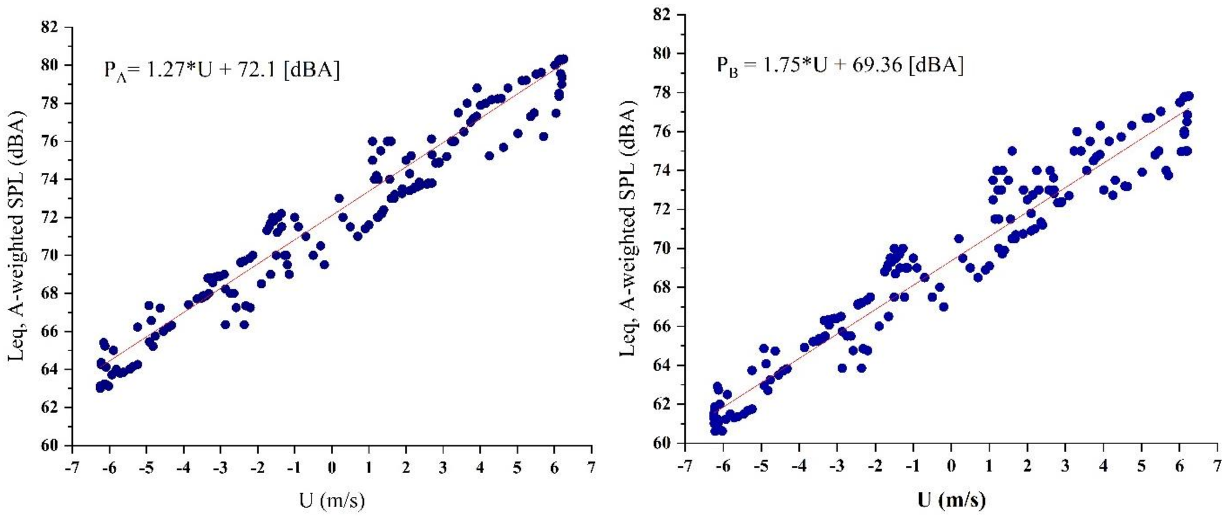


Figure 5.1 The wind rose diagram showing the wind speed and direction

Sound pressure levels over wind velocity

The scatter plot of A-weighted sound pressure levels obtained at 100 and 200 m from the nearest railway line is shown in Figure 5.2. Each dot represents a single L_{eq} sound pressure level measurement unit related to a certain wind speed. Negative values on the x-axis represent the upwind direction, whereas positive values represent the downwind direction. The solid line represents the SPL regression equation obtained through the least square fitting approach. The noise level measuring points P_A and P_B correspond to 100 and 200 m distances, respectively.

Noise levels were found to be lower for upwind. For instance, at a downwind speed of 4 to 5 m/s, noise levels were observed to be 78 dBA, but at the same upwind speed, the noise levels were observed to be 65 dBA. Hence, when the sound levels were measured in two opposite wind directions, a difference of 13 dBA was observed. Table 5.1 shows the average noise level difference for various wind speeds, and it is observed that for every 1 m/s change in wind speed, there is a 7.8 dBA difference in sound level for upwind and downwind directions. The variability in L_{eq} sound pressure levels is primarily caused due to the influence of wind speed and direction, showing a strong dependency of sound pressure level (SPL) on the parameter 'U'. Apart from wind conditions, the variations in L_{eq} sound pressure levels can also be attributed to factors including varying train speed and propagation path characteristics, such as ground absorption and atmospheric absorption. It should be noted that wind conditions hold paramount significance as the primary causative factor, while the variables mentioned above assume a secondary role in modulating these fluctuations.



(a) (b)

Figure 5.2 Scatter plots showing the variation of SPL with change in wind speed and direction: (a) measurements taken at 100 m, and (b) measurements taken at 200 m

According to the coefficient of regression line equation at points A and B, the influence of wind on SPL at position B has 1.75 dBA per unit wind velocity, which is higher than 1.27 dBA at point A. As a result, when the distance between the sound source and the receiver is greater, the wind effect on the SPL becomes more significant.

Analysis of variance (ANOVA) was carried out at a significance level of 95% ($p = 0.05$) to determine if the uncontrolled factors (train speed, ambient temperature, and relative humidity) had any statistically significant effects on the residuals observed in the graph depicted in Figure 5.2. The results indicated that train speed had a more significant impact among these factors compared to ambient temperature and relative humidity. To mitigate the influence of variations in train speed, the data points corresponding to specific ranges of train speeds (such as 50 to 60 km/h, 60 to 70 km/h, 70 to 80 km/h, etc.) were segregated and analyzed to assess the variations in wind speed and direction within each of these speed ranges.

Table 5.1 Average noise level difference for various wind speeds

Wind speed (m/s)	**Noise level, dBA**		**L_{eq} sound level difference** (dBA)
	Upwind	*Downwind*	
0<U ≤1	71	72	1
1<U ≤2	70	73	3
2<U ≤3	69	74	5
3<U ≤4	67	76	9
4<U ≤5	65	78	13
5<U ≤6	63.5	79.8	16.3
6<U ≤7	62.5	80.3	17.8

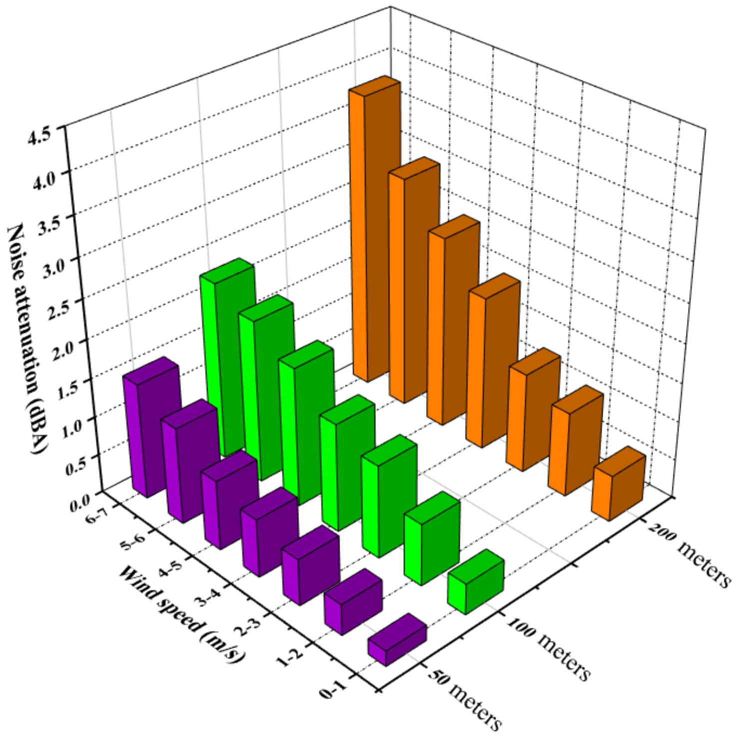


Figure 5.3 Noise attenuation is caused by upwind phenomena at different wind speeds and measuring distances

Later, the sound attenuation induced by the upwind phenomena was investigated, and it was observed that sound attenuation increased with distance from the source and wind speed. Figure 5.3 shows the impact of wind speed on noise attenuation. When the wind speed was 6.2 m/s, the maximum attenuation at 50 m was 1.4 dBA; at 200 m, it was 3.75 dBA. The minimum noise attenuation was observed as 0.15 dBA at 50 m when the wind speed was 0.75 m/s. Hence, at a 50 m measuring distance, there is an average noise attenuation of 0.2 dBA with an increase in wind speed by 1 m/s. Maximum attenuation of 2.1 dBA and 3.75 dBA was found at 100 and 200 m, respectively. Finally, from this analysis, it can be inferred that for the upwind blowing at a high intensity, the shadow zone distance from the receiver becomes easier to forecast.

5.3 Influence of Measuring Distance and a Moving Source on the Noise Propagation

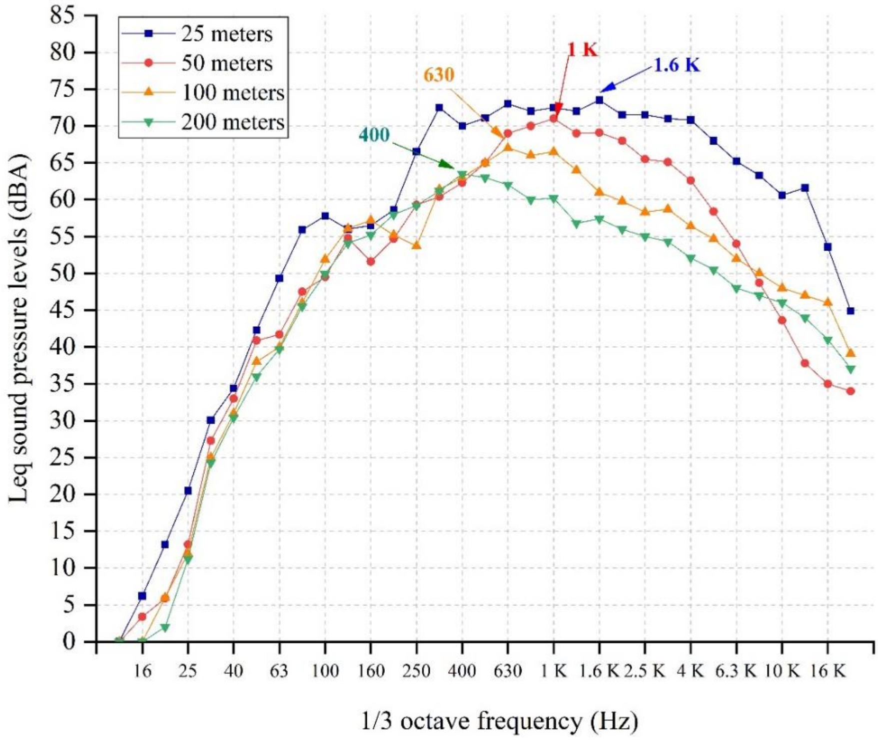


Figure 5.4 Sound pressure (dBA) variation with frequency for a single pass of a train

When sound travels through air, geometrical spreading states that the sound level decreases as the distance between the source and receiver increases. The frequency of sound and the atmospheric conditions are the most important factors in sound propagation in the air (IS 9613-1 (1993)). For a stationary line source, sound waves travel in the form of cylindrical waves. According to the inverse square law of acoustics, doubling the distance from the source results in a 3 dBA drop in sound level. Railway noise is commonly regarded as a moving line source, and its impact on sound propagation is assessed in the current study.

Figure 5.4 shows L_{eq} sound pressure versus 1/3 octave frequency measured at various distances from the railway line, assuming steady weather conditions and a train speed of 60 km/h. The meteorological parameters recorded during the observation period included a temperature of 30°C, relative humidity of 55%, wind speed of 4 m/s, and a downwind direction from the Southwest. For the noise levels measured at a distance of 25 m, the highest frequency band was 600 Hertz, and the equivalent sound pressure level was 73.5 dBA. The highest frequency measured at 50 m was 1000 Hertz, with a sound pressure level of 71 dBA. The sound frequency was high in both the cases, and there was a 2.5 dBA difference in sound level between 25 m and 50 m, which can be attributed to geometrical dispersion. Similarly, a 3 dBA variation in noise intensity was found between 50 m and 100 m.

When noise levels were plotted for 100 and 200 m measuring distances, the highest frequency bands were 630 and 400 Hertz, with sound pressure values of 68 and 64.5 dBA. As the distance from the source increased, the frequency band and sound levels decreased. The difference in sound levels measured at 100 and 200 m was 3.5 dBA, owing to geometrical sound propagation and the effect of weather conditions.

The average difference in sound intensity increased by 0.5 dBA due to geometrical spreading and the doppler effect caused by a relative motion between the source and the receiver. The anemometer observations revealed a minute variation in wind speed during the train pass-by-time, with variation in train speed being the cause of the difference. Hence, considering the line source to be moving, the sound waves fluctuate in a wider range.

The noise generated by the fierce interaction of airflows with the front face of the train's locomotive increases in proportion to train speed. The fast-moving train causes a disturbance in the constantly flowing wind, causing it to change direction. As a result, the influence of train speed on the minimal variation in noise levels caused by passing trains is plotted in Figure 5.5. The present study assumes all atmospheric conditions to remain constant over time and observes the variation of sound pressure levels for different train speeds.

There is a 0.16 dBA fluctuation due to train aerodynamics for train speeds ranging from 51 to 60 km/h, and these sound levels increased predominantly with increasing train speed. The aerodynamic noise fluctuation caused by train speeds ranging from 101 to 110 km/h was observed to be a maximum of 0.72 dBA, as shown in Figure 5.5. This analysis revealed that a fast-moving source can generate additional sound pressure levels by creating a disturbance in steady atmospheric conditions.

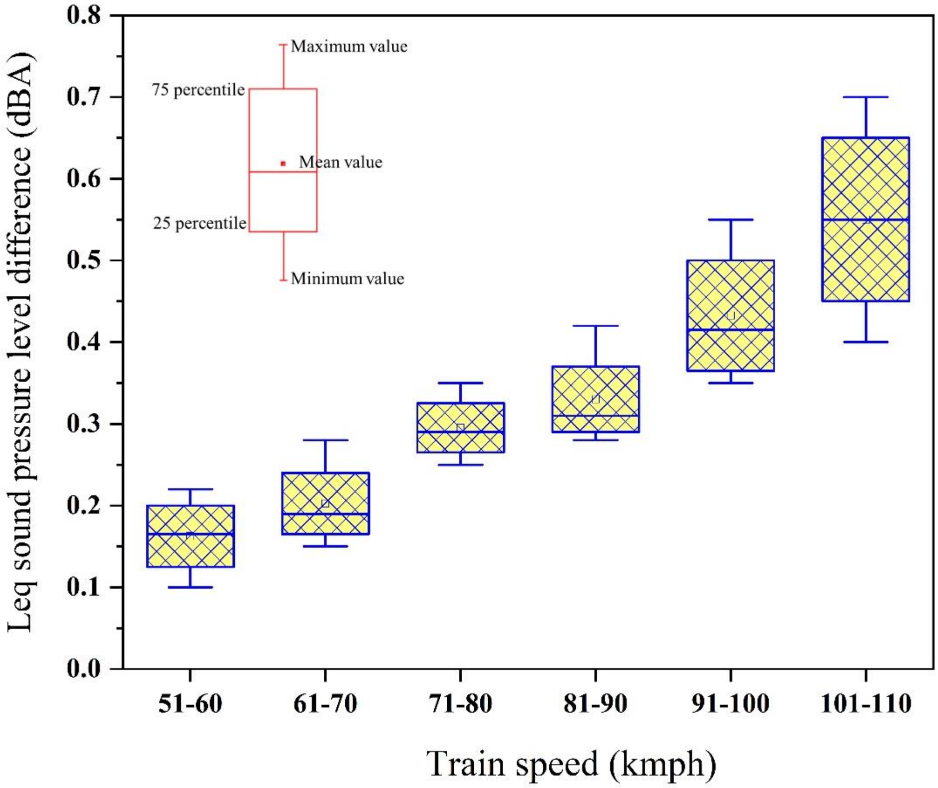


Figure 5.5 Box plots showing L_{eq} sound level variation caused by train speed.

5.4 Influence of Atmospheric Temperature on Noise Propagation

Considering train speed, wind speed and direction, and humidity conditions as constants, the sound level variation with atmospheric temperature was plotted at various measuring distances in Figure 5.6. The trend shows that as the air temperature rises, so do the sound levels. The minimum sound levels were 70 to 71 dBA at 20°C for all four measuring distances. When the measuring distance was 25 m, and the temperature was 40°C, the maximum sound level was 80 dBA. Similar trends were observed from the studies on variations in railway noise caused due to the change in air temperature, where field measurements over a temperature range of 0°C to 35°C resulted in an increase in noise levels by 3 to 4 dBA (Broadbent et al., 2009 and Squicciarini et al., 2016).

The sound waves in air move at a constant speed proportional to the ambient temperature's square root. Sound waves propagate through the air by transferring momentum and energy between air particles. As the temperature of the air molecules increases, the rate of molecule interaction and the mean speed of molecular motion increases. Hence, the speed of the sound wave depends on the ambient temperature, and an increase in temperature causes a slight increase in sound speed. When the temperature around the air molecules is low, these air molecules are inactive, and moving these molecules requires more energy. However, the air molecules are already active at higher temperatures, requiring less energy to move the molecules further. From the current study, regardless of the measuring distance, there is an average increase in sound level of 0.51 dBA with an increase in air temperature by 1°C. Therefore, a rise in temperature causes sound waves to propagate more rapidly, making it more difficult for sound to be attenuated.

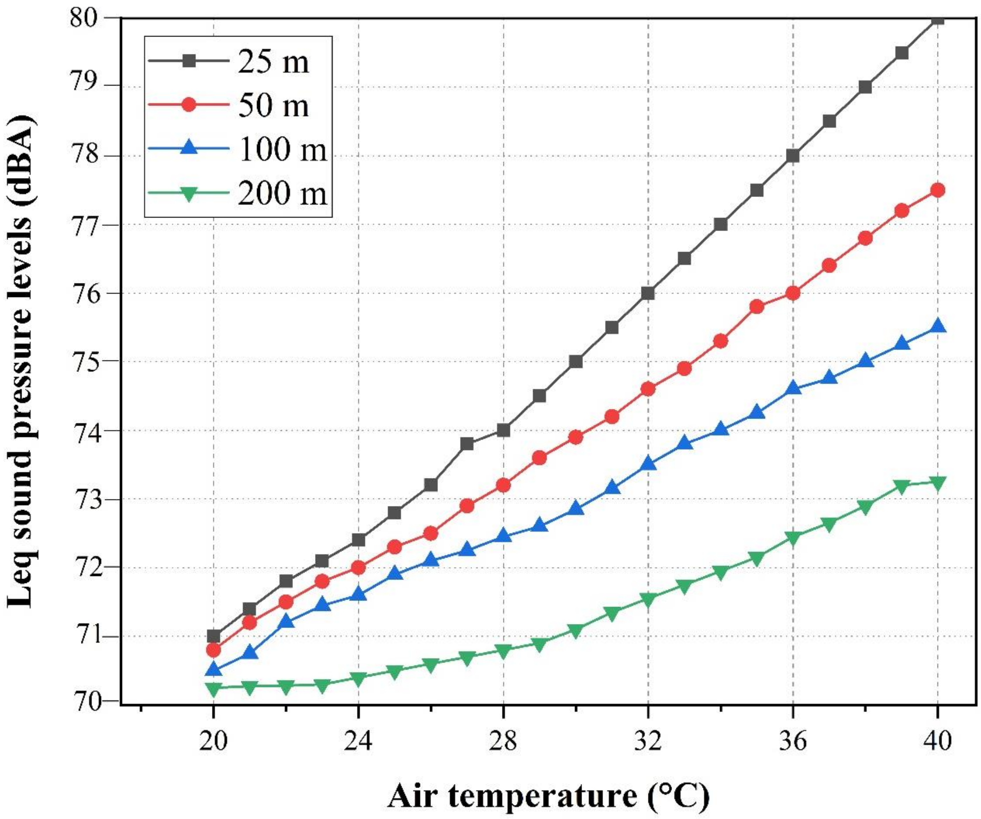


Figure 5.6 Sound level variation caused by air temperature at various measuring distances.

The combined effect of train speed and temperature on railway noise was evaluated to observe the impact of moving sources on sound variation. It was observed that there is no noticeable impact of train speed on the sound level variation induced by temperature differences, indicating that the effects of a moving source are insignificant in the case of sound variation caused by temperature change.

Measurements were carried out at 25, 50, 100, and 200 m to assess the dependency of sound levels on distance. At a particular air temperature of 20°C, the sound levels at 50, 100, and 200 m were 70.9, 70.6, and 70.3 dBA, respectively, whereas, at the air temperature of 40°C, the sound levels were 77.5, 75.4, and 73.1 dBA. The sound level difference at the same temperature increased with increasing measuring distance. It can be concluded that the measuring distance adds extra sound level difference in addition to temperature variation.

5.5 Influence of Humidity on Noise Propagation

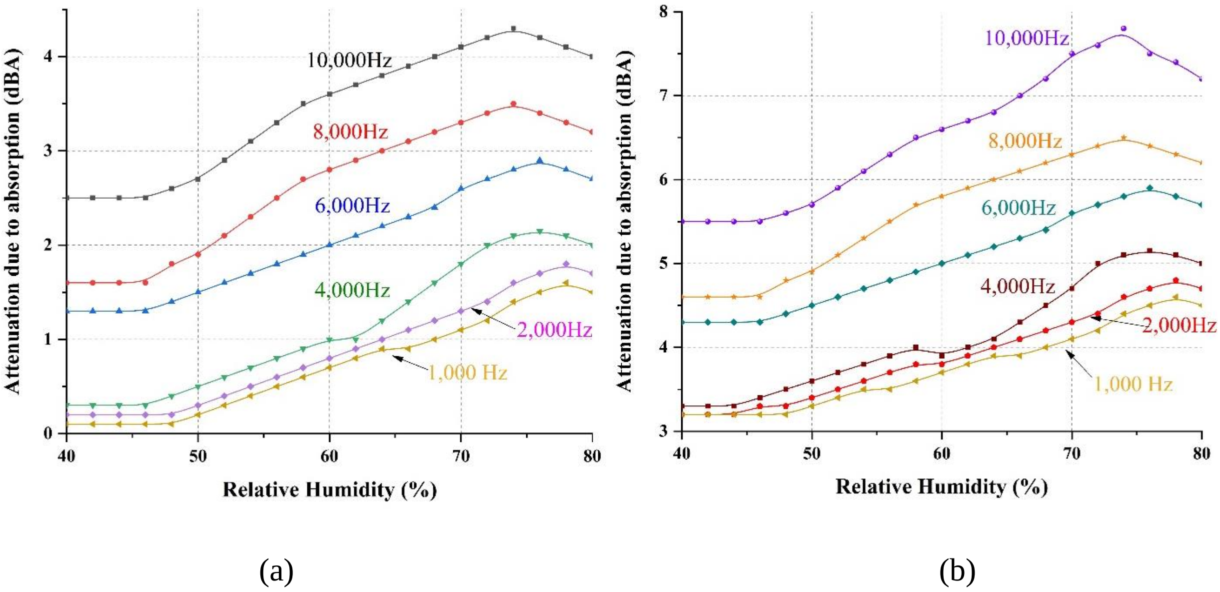


Figure 5.7 Atmospheric attenuation due to air absorption for different sound frequencies measured at (a) 100 m and (b) 200 m (Temperature = 20°C)

IS 9613-2 (1996) states that atmospheric attenuation is substantially influenced by sound frequency, ambient temperature, and relative humidity of the air but less moderately by ambient pressure. The atmospheric absorption (A_{atm}) during sound propagation through a distance '*d*' in meters is given by Equation (5.1).

$$A_{atm} = \frac{\alpha d}{1000} \tag{5.1}$$

Where α = atmospheric attenuation coefficient.

Equation (5.2) can be used to calculate the air absorption coefficient (α) using the measured parameters of noise frequency, relative humidity, and ambient temperature.

$$\alpha = f^2\left[\left(\frac{1.84*10^{-11}}{\left(\sqrt{\frac{T_0}{T}}\right)\frac{P_S}{P_o}}\right)\right] + \left(\frac{T_0}{T}\right)^{2.5}\left(\frac{0.1068e^{-3352/T} f_{r,N}}{f^2 + f_{r,N}^2} + \frac{0.01278e^{-2239.1/T} f_{r,O}}{f^2 + f_{r,O}^2}\right) \quad (5.2)$$

$$f_{r,N} = \frac{P_S}{P_o}\left(\sqrt{\frac{T_0}{T}}\right)\left(9 + 280He^{-4.17\left[\left(\frac{T_0}{T}\right)^{1/3}-1\right]}\right) \quad (5.3)$$

$$f_{r,O} = \frac{P_S}{P_o}\left(24.0 + 4.04 * 10^4 H\frac{0.02+H}{0.391+H}\right) \quad (5.4)$$

Where, $f_{r,N}$ and $f_{r,O}$ are the relaxation frequencies associated with the vibration of nitrogen and oxygen molecules are calculated using Equations (5.3) and (5.4) respectively, f is the frequency, T is the absolute atmospheric temperature in Kelvin, T_0 = 293.15 K (20°C, P_s is the local atmospheric pressure, and P_0 is the reference atmospheric pressure (1 atm = 1.01325×10^5 Pa), H is the relative humidity (%).

Equations (5.3) and (5.4) were used to calculate the attenuation coefficient of sound waves at various frequencies and humidity conditions using MATLAB programming language. The atmospheric attenuation produced by air absorption at 100 m and 200 m is shown in Figure 5.7 (a) and (b), respectively. A constant temperature of 20°C is considered for this analysis as the highest attenuation was observed at 20°C on noise fluctuation caused by temperature variation. The sound attenuation was found to be higher at higher frequencies and showed a similar trend at both the measuring distances (100 m and 200 m). The noise attenuation values increased with humidity and peaked between 70% and 80% relative humidity. As a result, sound attenuation attributed to humidity is quite minor at shorter distances (i.e., 25 and 50 m), but at a larger distance of 100 and 200 m, there is a considerable attenuation of 4.3 to 7.8 dBA. The maximum attenuation of 7.8 dBA at 200 m was observed, and humidity significantly influences sound propagation at larger distances. These results compare well with similar studies conducted by Harris (1969).

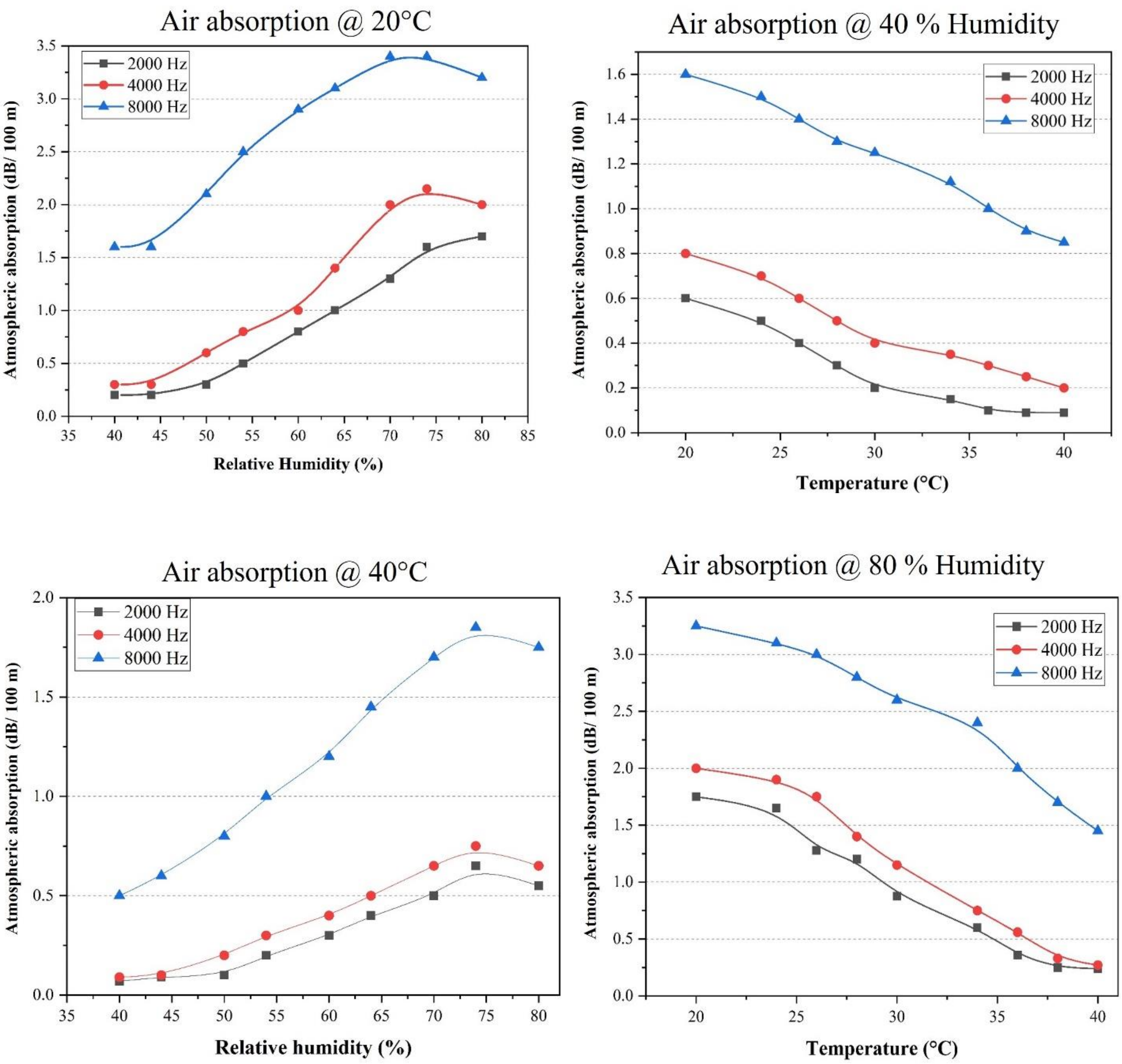


Figure 5.8 Atmospheric absorption as a function of relative humidity (%), temperature(°C), and frequency (Hz) according to ISO 9613-2:1996

Figure 5.8 depicts the atmospheric absorption values corresponding to different humidity and temperature conditions. The three-octave bands 2000, 4000, and 8000 Hz were chosen since they represent the overall frequency content of the sound signal. The results demonstrate the noise attenuation at minimum temperature and humidity conditions corresponding to 20°C and 40% humidity, while the 40°C and 80% humidity correspond to maximum temperature and humidity conditions. The atmospheric absorption values increase with increasing noise frequency, which means higher frequency waves are attenuated more efficiently than the lower frequency waves. The higher-frequency signals have shorter wavelengths and are more easily absorbed and scattered by the air molecules. The atmospheric absorption values increased with an increase in relative humidity. The air molecules in moist air are closely packed together, which makes the air denser. The increased humidity in the air can result in a greater degree of sound absorption, refraction, reflection, and scattering caused by the presence of water vapor molecules, thereby reducing the amount of sound energy that reaches the receiver. On the other hand, dry air is less dense and allows sound waves to travel longer distances. The study conducted by Wong and Embleton (1985) to investigate the influence of humidity on the speed of sound in air revealed a similar pattern as that in the current study, although the attenuation (in dBA) is different.

5.6 Statistical Analysis of the Transmission Path Parameters

The current study uses regression-based sensitivity analysis to investigate the relationship between railway noise levels and wind speed and direction, air temperature, and humidity to estimate the L_{eq} and L_{max} mean values. The degree of linear association between noise levels and meteorological conditions was measured using Pearson's correlation analysis before performing this analysis. The dependent and independent variables were treated symmetrically in this analysis, with no distinction made between them, and all the variables were considered random.

Table 5.2 provides the descriptive statistics of the noise levels (L_{eq} and L_{max}) and the influencing parameters. The mean noise levels of the L_{eq} (71.25 dBA) are lesser than the L_{max} (76.01) noise levels by 4.76 dBA since L_{eq} indicates the average sound energy over time and L_{max} is the maximum sound recorded during the observation period. The maximum noise level of 102.2 dBA was recorded when the train speed is 106 km/h, the wind speed is 5.3 m/s blowing towards the SLM, the temperature is 38°C, and the humidity is 45%. Most of the parameters are highly positively skewed and do not follow the normal distribution indicating that the data is not evenly distributed, except for L_{eq} and train speed, which exhibit considerable regional variability and follow a normal distribution with skewness near zero.

Table 5.2 Descriptive statistics of L_{eq} and L_{max} noise levels and influencing parameters.

Parameters	**Minimum**	**Maximum**	**Mean**	**Std. deviation**	**Skewness**
L_{eq} (dBA)	65.03	85.48	71.25	2.715	0.12
L_{max} (dBA)	73	102.2	76.01	4.69	2.35
Train speed (km/h)	26	106	70	10.5	0.42
Wind speed (m/s)	0.75	6.25	4.1	0.55	1.65
Temperature (°C)	20	40	31	3.63	2.87
Humidity (%)	40	80	55	11.15	3.12

A correlation matrix shows the amount of correlation between the dependent and independent variables in Table 5.3. The most prominent parameter showing a high correlation with railway noise is train speed, followed by wind speed, temperature, and humidity. The humidity shows a negative correlation, which infers that as the humidity of the air increases, the noise levels reduce. The correlation matrices also indicate the correlation among the independent variables. If a strong correlation exists between two independent variables, only one of the two variables can be used for modelling, while the other one is indirectly included by considering the variables that have a strong correlation.

Table 5.3 Pearson correlation matrix

"R" values	L_{eq}	L_{max}	**Train speed**	**Wind speed**	**Temperature**	**Humidity**
L_{eq}	1					
L_{max}	0.75	1				
Train speed	0.84	0.75	1			
Wind speed	0.55	0.52	0.6	1		
Temperature	0.21	0.23	0.18	0.62	1	
Humidity	-0.18	-0.17	-0.3	-0.35	-0.9	1

Green box: The values in the green box are positively correlated, i.e., values greater than 0.

Red box: The values in the red box are negatively correlated, i.e., values less than 0.

Yellow box: The values in the yellow box are perfectly positively correlated.

Analysis of variance (ANOVA) with a significance level of 95% (p = 0.05) was carried out to test whether there is a significant impact of the independent parameters on the variation of railway noise. A total of 106 observations were used for testing. As shown in Table 5.4, the regression values emphasize the substantial variance between the independent variables, while the residuals emphasize the significant variation within the independent variables.

The degree of freedom of regression is calculated by subtracting one from the number of independent variables (i.e., 4 -1 = 3), while the degree of freedom of residuals is calculated by subtracting the number of independent variables from the total number of observations, i.e., (106 - 4 = 102). The total degrees of freedom (105) equal the number of observations minus the number of constraints. This value influences the calculation of the test statistic and the critical value used to determine whether the result is statistically significant.

The sum of the square values and degree of freedom values are used to calculate the F-values. F-statistic is the test statistic used in the ANOVA test, and the F-calculated values are compared with the F-critical values. The calculated F-value is observed to be more than the F-critical value at a 5% level of significance, indicating that the effect of each independent variable is quite significant. The generated linear regression model for predicting L_{eq} has a coefficient of determination (R^2) of 0.73, implying that there is only a small difference between observed data and predicted data. For all the independent variables, the standard error (SE) values were found to be the lowest, indicating that there was very little deviation from the mean values. The t-values are the coefficients divided by the standard error, and all four parameters resulted in a p-value less than 0.05, indicating that all four variables significantly impact the predicted values. The intercept value 63.5 represents the background noise of the study area environment.

Table 5.4 Regression analysis for predicting L_{eq}.

ANOVA	Degree of freedom	Sum of squares	Mean of squares	F-calculated	F-critical
Regression	3	45.2	11.3	70.18	2.31715E-27
Residual	102	16.65	0.161		
Total	105	61.85			
		Coefficients	**SE**	***t*-stat**	***p*-value**
Intercept		63.5	1.24194	50.95	1.36771E-36
Train speed (*km/h*)		1.27	0.00758	25.61	0.006803
Wind speed (*m/s*)		0.61	0.00152	1.87	1.41115E-25
Air temperature (*℃*)		0.35	0.00012	0.56	2.41355E-23
Humidity (%)		-0.32	0.00024	-0.45	1.41115E-25

5.7 Noise Mapping

The noise maps prepared for railway noise propagation in the urban area serve as a communication tool between various stakeholders, including railway operators, local governments, and affected communities, to increase awareness about the railway noise impact and to develop solutions for reducing noise pollution. The use of GIS is not confined to the discipline of geography; it has also been applied to a variety of other domains, including the spatial distribution of noise levels. The current study uses ArcGIS desktop software to prepare noise maps for the selected study area. The Inverse Distance Weighting (IDW) interpolation technique was employed to interpolate the railway noise spatially. This method estimates the noise levels at a particular location based on the measured noise levels at the surrounding location. The step-by-step procedure to produce the noise maps using ArcGIS software is shown below:

1. **Data collection:** Acquire data on train speed, atmospheric temperature, wind speed and direction, and humidity levels to visualize the variations in railway noise.
2. **Import data into ArcGIS:** Import the data mentioned above to the ArcGIS software and organize the data in different layers.
3. **Prepare the base map:** Acquire GIS data regarding the location of railway lines, land use, topography, and proximity of residential zones to the railway lines. Utilize this data to generate a base map by incorporating the collected data layers into an ArcGIS project.
4. **Model noise propagation:** The ArcGIS Spatial Analyst extension is utilized to model the propagation of railway noise based on the input data. The current study uses the IDW method to predict unknown noise levels.
5. **Visualize and analyze the results:** The outcome of the noise propagation model is shown as noise contours on the base map. The results can be used to identify the areas with high and low noise levels, and the information gathered is utilized to suggest solutions for noise mitigation.

5.7.1 Inverse distance weighting method

This is a method of local interpolation that only uses sample points that are close to the point of estimation. The IDW method was employed in this study, and this technique assumes that there is an influence of the noise level measured at a particular location on the location at which the noise is not measured (Scabbia and Heggy 2018). The centered box with the question mark in Figure 5.9 represents the position of an unmeasured point that needs to be anticipated, while the surrounding points represent measured noise levels. The value shows the distance between the known and unknown locations around the arrow mark. In the current situation, Equation (5.5) is referred to as the weighing function (*w*).

$$50\ W_1 + 40\ W_2 + 55\ W_3 + 65\ W_4 + 60\ W_5 = \text{weighing function } (w). \tag{5.5}$$

Where, $W = \frac{1}{d}$, d = distance between the known and unknown noise values.

The unknown noise level is estimated from Equation (5.6). The flow chart in Figure 5.10 depicts the complete approach for noise mapping using the IDW technique.

$$Z = \frac{\sum_{i=1}^{n} z_i * w_i}{\sum_{i=1}^{n} w_i} \tag{5.6}$$

Where Z is the interpolated value for an unknown point,

w_i= weighting function, and

z_i= observed value at control point i.

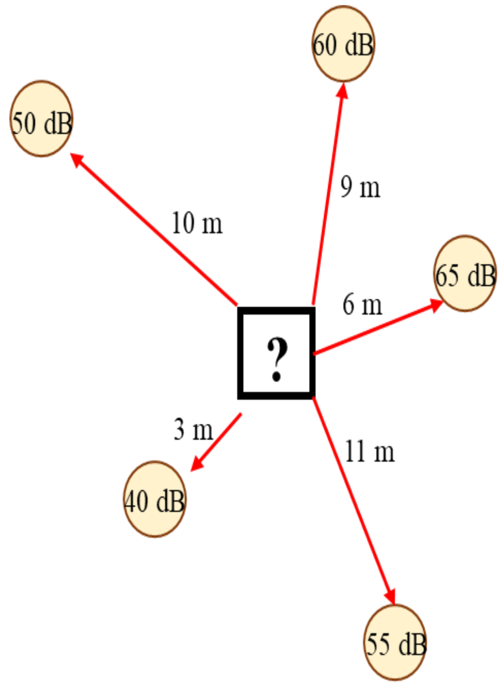


Figure 5.9 Surrounded measured noise values and distance between the measured and predicted point.

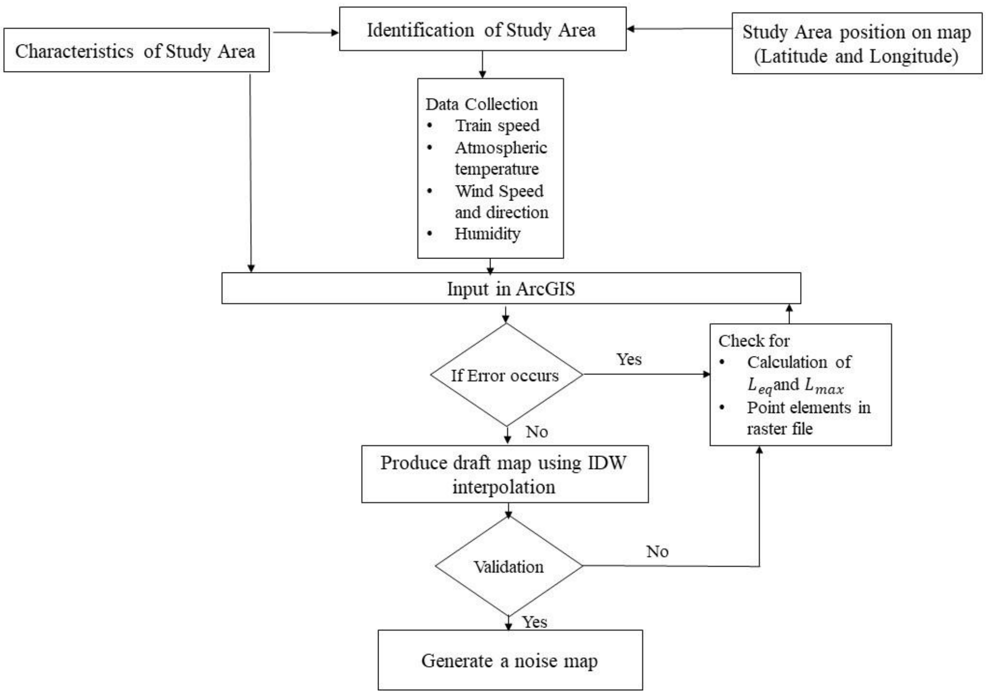


Figure 5.10 Flowchart for railway noise prediction map using IDW interpolation technique.

5.7.2 Noise mapping results

The noise maps are prepared by analyzing the emission of noise from trains at different speeds and the propagation of noise due to variations in meteorological conditions. The noise emission and propagation data were provided as input to the ArcGIS software, which provides graphical representations of the noise using a variety of colors to show the variation in noise levels. Figure 5.11 depicts the map used for noise contour mapping, with the length and width of the test site being 400 x 185 m. The x-axis indicates the distance along the length of the train, and the y-axis indicates the distance away from the railway line, while the noise levels are indicated by the colored sections on the map. The latitude and longitude of the test site, railway noise levels, atmospheric temperature, humidity, wind speed and direction, and train speed are the input parameters.

The train speed causes the most fluctuation in railway noise among all the identified parameters. As a result, noise maps were prepared for the test location corresponding to equivalent noise levels (L_{eq}), maximum noise levels (L_{max}), and minimum noise levels (L_{min}) when the trains were traveling at high and slower speeds. L_{min} represents the minimum threshold value, while L_{max} represents the maximum threshold value of noise levels measured during the single pass-by time of the train. The Central Pollution Control Board (CPCB) regulations of India state that the maximum permissible noise level in a residential zone is 45 dBA at night and 55 dBA during the day. Based on the current study, the L_{eq} noise level at 200 m from the railway line is 57 dBA. Hence, these noise maps recommend a minimum distance of 203 m, corresponding to 55 dBA, and 225 m corresponding to 45 dBA from the railway line in the absence of a noise barrier for the construction of residential buildings such that the trackside dwellers are exposed to noise levels well within the allowable limits.

The noise maps are intended to assist municipalities, environment and government agencies in visualizing the pattern of noise transmission in the atmosphere and formulate mitigation strategies. These maps can forecast noise based on the train speed and identify the noisiest regions, which terrain and impediments, including cuts, embankments, tunnels, and noise protection walls, may influence. The L_{eq}, L_{max}, and L_{min} noise maps predict the overall noise produced by the presence of the railway line within a residential zone and will assist urban planners when they are making plans for the development of a city or the construction of new railway lines.

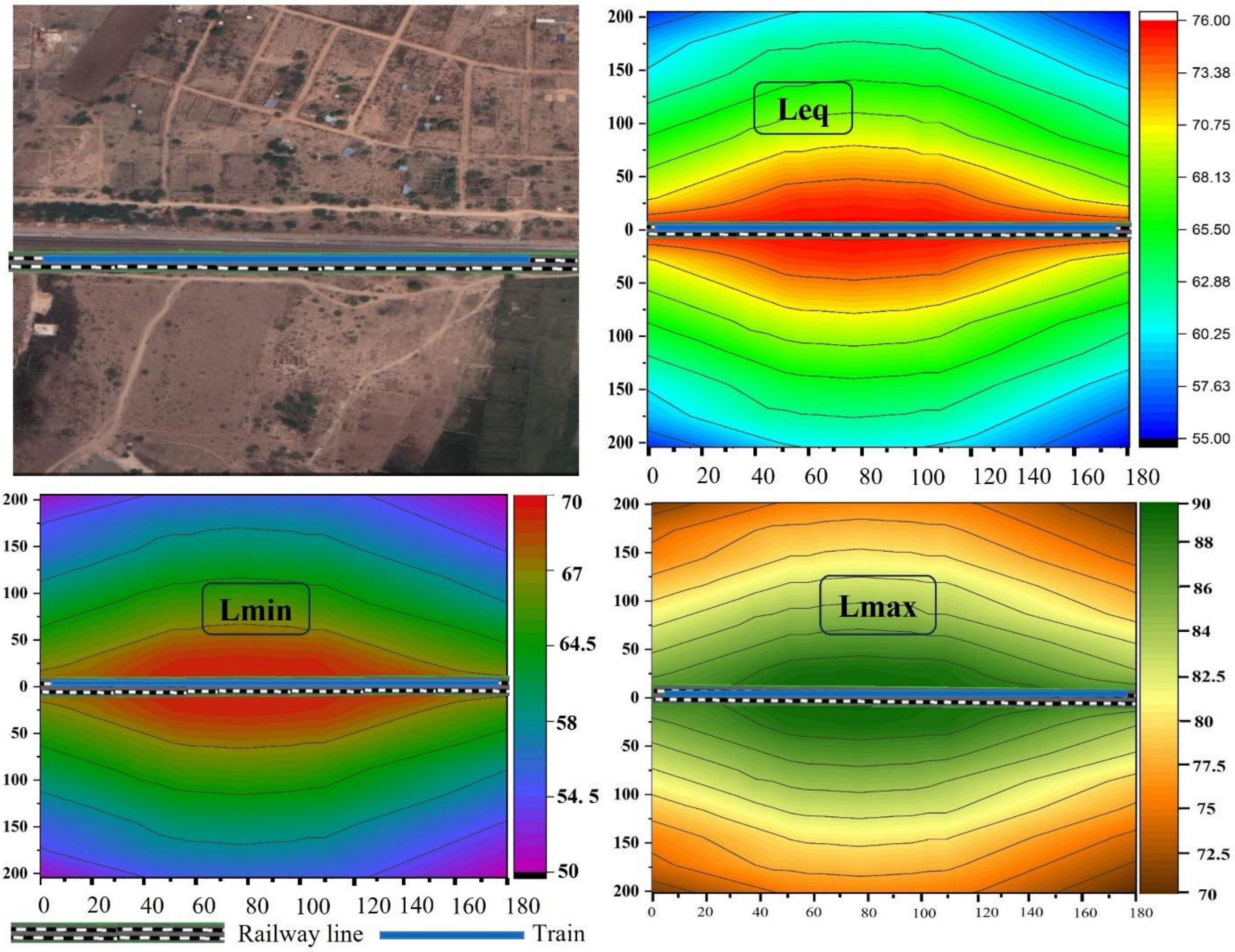


Figure 5.11 Map showing the test site considered for noise contour mapping and IDW interpolated noise maps for L_{max}, L_{eq}, and L_{min}

5.8 Variation of Noise due to the Presence of a Wall in Between the Source and Receiver

The presence of a wall between a noise source and a receiver can have a significant impact on the noise levels experienced by the receiver. These walls act like a barrier to trap the noise and prevent it from spreading to the surrounding areas. Few developed countries have implemented this concept of constructing noise barriers along high-traffic roads and railway lines despite the high cost of construction and land acquisition. In contrast, many middle and low-income countries constructed boundary walls along the tracks to protect railway lands from encroachments and to prevent people from trespassing the railway tracks. These walls are typically made of stone masonry with cement mortar or other durable materials and are designed to be tall enough to discourage people from climbing over them. However, the acoustic performance of these walls remains an area of potential development for middle and low-income countries. A series of recent accidents in India involving newly inducted semi-high-speed trains (Vande Bharat Express) with cattle damaged the trains' front end, resulting in significant delays in reviving the operations of such damaged trains. Consequently, the Ministry of Railways proposed constructing new boundary walls along the railway tracks to prevent trespassing. This study aims to assist in developing new boundary walls that can also function as noise barriers.

Despite numerous research works on noise barriers for different types of noise sources, there is a noticeable gap in the literature regarding the effectiveness of railway boundary walls to function as potential noise barriers. This is due to the fact that railway noise possesses unique characteristics that distinguish it from other types of noise. For instance, railway noise primarily comprises low-frequency components, which can propagate over longer distances and penetrate barriers more readily than high-frequency noise (Wang et al. 2018). Additionally, the noise generated by passing trains exhibits a steady, constant level, unlike other sources of noise that may fluctuate in intensity over time. Moreover, the noise from passing trains is highly directional, with greater intensity observed in the direction of the train's motion. Lastly, the Doppler effect can cause noticeable changes in the pitch of sound produced by a train's wheels and horn as it approaches and passes the receiver. Thus, due to the unique characteristics of railway noise, further studies are needed to evaluate the effectiveness of railway boundary walls to serve as potential noise barriers. In light of this, this study aims to evaluate an existing railway boundary wall in an urban area in terms of its ability to reduce noise and to propose an improved alternative using Computational Fluid Dynamics (CFD) simulations. The results of this study can be applied to other cities with similar characteristics and can assist urban planners and policymakers in designing an effective noise barrier in residential areas near railway lines.

Evaluating the effectiveness of noise barriers by modifying their geometry, shapes, and material composition experimentally can be challenging for researchers. Numerical simulation-based techniques offer an advantage in this regard, as they do not require the creation of a physical prototype and can quickly generate solutions. Complex engineering problems are generally solved using either analytical, numerical, or experimental approaches. Numerical simulation has become increasingly popular in recent years due to advancements in computational techniques. While analytical and experimental methods have been traditionally used, they can only address simple geometry problems. In the past, several numerical techniques have been used to determine the effectiveness of noise barriers, including the Finite Element Method (FEM) and Boundary Element

Method (BEM). A complex object has an infinite degree of freedom, which are challenging to solve, but FEM reduces into a finite degree of freedom with the help of meshing. To obtain the solution in a FEM, the complex geometry is precisely divided into a finite number of sub-domains known as elements and nodes. However, for vibroacoustic problems involving high frequency, CFD is a more suitable approach than FEM and BEM (Thompson 1993). The ANSYS software is used in this study to simulate the noise barrier and to produce various geometries and boundary conditions. A numerical model based on CFD is established to determine the insertion losses of an optimal boundary wall. This study provides a practical approach for future studies and a conceptual framework for developing noise barriers along railway lines.

5.8.1 Description of the CFD simulations and parameters investigated

Computational fluid dynamics is the computer simulation of fluid mechanics (liquids and gases) using numerical analysis and data structures. The basis for a CFD solver is the solution obtained through the continuity and momentum balance equations. CFD has become an essential tool for engineers, especially in designing and optimizing processes and equipment, owing to its cost and time reduction benefits for projects (Santana et al. 2020). Figure 5.12 shows the step-by-step methodology for modeling and simulating noise barriers using Ansys Software. The CFD model used in this study is based on Reynolds-averaged Navier-Stokes (RANS) equations. Because of its more preciseness and efficacy in terms of computation, RANS equations with the quantifiable k-ε turbulent model were preferred over Large Eddy Simulations. Equation (5.6) shows the RANS equation.

$$\rho\left(\frac{\partial \overline{U_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{U_i}}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\mu\frac{\partial \bar{U}_i}{\partial x_j} - \rho \bar{U}_i \bar{U}_j\right) - \frac{\partial \bar{P}}{\partial x_i} \tag{5.6}$$

The equation for turbulent kinetic energy k is shown in Equation (5.7).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{5.7}$$

The turbulent dissipation rate ε, in the k- ε model, is shown in Equation (5.8).

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{5.8}$$

Where, C_1= max $\left[0.43, \frac{\eta}{\eta+5}\right]$, $\eta = S\frac{\varepsilon}{k}$, $S = \sqrt{2S_{ij}}$, μ_t = turbulent velocity,

ρ = air density, U = wind speed, U_i = velocity component in *i* direction.

The adjustable constants C_1 , C_2, σ_k, σ_ε, are obtained by numerous iterations of data fitting for different ranges of flow values.

The L_{eq} noise levels were chosen as a standard for all railway noise emission levels. The material in the complete computational domain was regarded as a composite of air and sound waves. The flow of sound waves over the barrier was represented by a dimensionless quantity (χ) as in Equation (5.9).

$$\chi = C l_x l_y U_r / Q \tag{5.9}$$

Where, l_x and l_y are the length and width of the railway source, which is taken as 580 m (average length of all the trains) and 3.25 m, respectively. The average wind speed (U_r) is 3.5 m/s, which is taken in the direction of noise flow. Q is the volumetric flow rate within the domain. These mathematical equations were satisfactorily applied by Wang and Wang (2019). This study uses the semi-implicit pressure-linked equation algorithm (SIMPLE) technique to solve pressure-velocity coupling when an incompressible fluid is considered. The step-by-step procedure for solving CFD using ANSYS is shown in Figure 5.12.

This study categorizes various noise barriers according to their cross-sectional geometry. Height (H) is a crucial parameter for the rectangular barrier, and top length (TL) is a crucial parameter for the T-shaped barrier. The inclined top length (ITL) becomes the crucial parameter for Y-shaped barriers, while the top length $(TL)_i$ is the crucial parameter for inverted L-shaped barriers. The detailed full-scale geometry of all the barriers is shown in Table 5.5.

Table 5.5 Dimensions of the noise barriers considered for simulation

Simulated barrier shape	Crucial parameter	Dimensions
Rectangular	Height (H)	H = 3 to 6 m (interval of 0.5 m)
T-shaped	Top length (TL)	TL = 2 m
Y-shaped	Inclined top length (ITL)	ITL = 1.75 m
Inverted L-shaped	Top length $(TL)_i$	$(TL)_i$ = 1 m

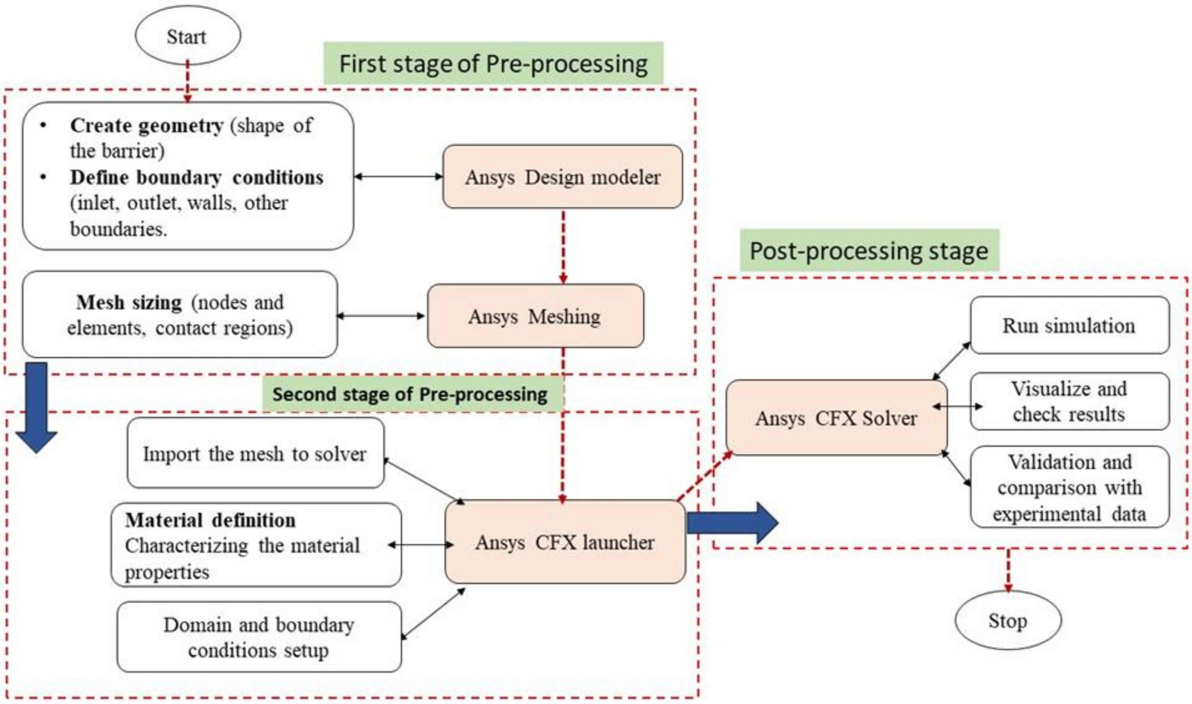


Figure 5.12 Flowchart of computational fluid dynamic analysis using Ansys software

In the current study, the computational domain was not at full scale, it is considered as 1:10 and had similar dimensions as the railway noise source and noise barrier. The x-axis is along the barrier length, i.e., parallel to the railway line. The y-axis is along the barrier's height, and the z-axis is along its thickness. The boundary wall at the test site is 110 m in length, height is 2.75 m, and thickness is 450 mm. The material used for construction is stone masonry with cement mortar. The computational domain is shown in Figure 5.13. The cross-sectional geometry is used to categorize various noise barrier shapes. Figure 5.14 shows the profiles of different noise barrier shapes considered for simulation. All the shapes are modelled to a scale of 1:10 to be compatible with the computational domain.

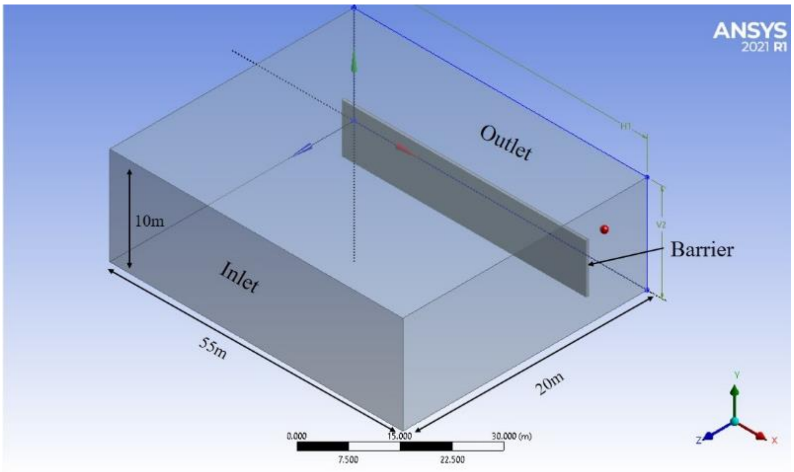


Figure 5.13 Computational domain of the noise transmission over the barrier.

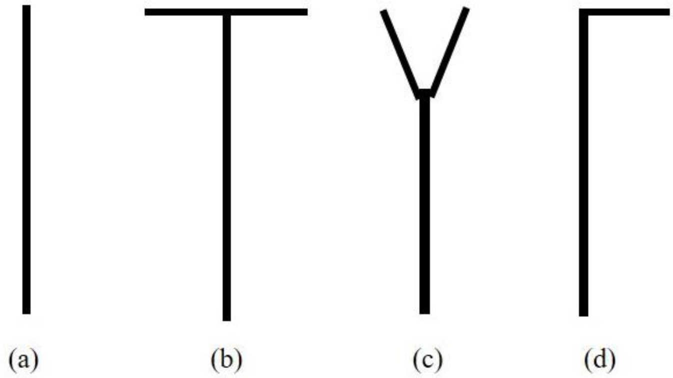
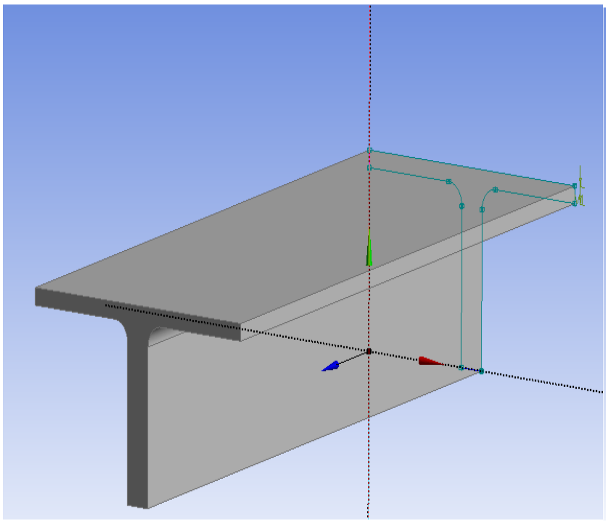
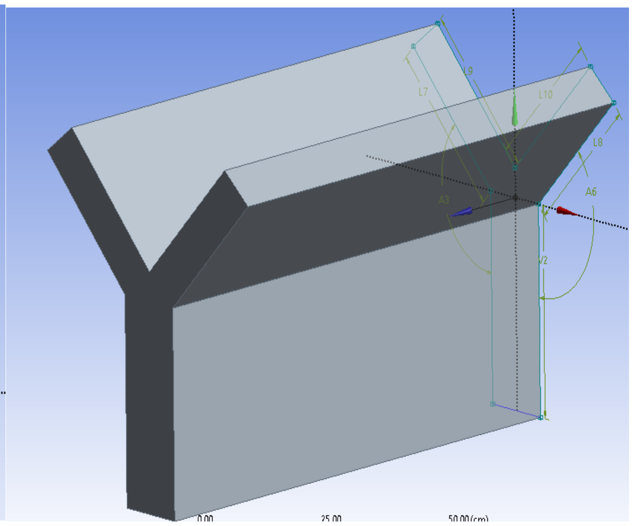


Figure 5.14 Different shapes of the barrier (cross-sectional view): (a) rectangular, (b) T-shape, (c) Y-shape, and (d) inverted-L shape.

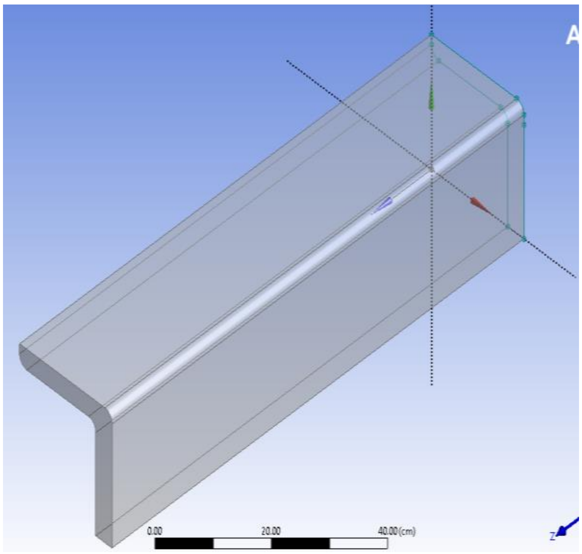
Figure 5.15 shows the different geometry shapes created for CFD simulation using ANSYS software. The sound from the train is characterized as a sound intensity flow input and is regarded as the moving line source. The computational domain's atmospheric parameters include 31°C air temperature, 55% humidity, and 3.5 m/s wind speed; these resemble the average climatic conditions at the test site during data collection. In order to conduct the simulation analysis, a segment in the study region with a length of 5 m was selected. The applied boundary conditions include an inlet defined as a velocity inlet that is a user-specified function and an outlet defined as the outflow of noise after passing over the barrier. The moving train with an average length of 580 m is considered as the emission source defined as a mass flow inlet. This methodology is similar to the studies conducted by Ashgriz and Mostaghimi (2002), and Issakhov et al. (2023). Mass flow rate is the product of volumetric flow rate and air density. The bottom surface of the domain is regarded as the ground and is assumed to be a stationary, rough surface. Surfaces on the top and the other sides are considered to have symmetric boundary conditions.



(a)



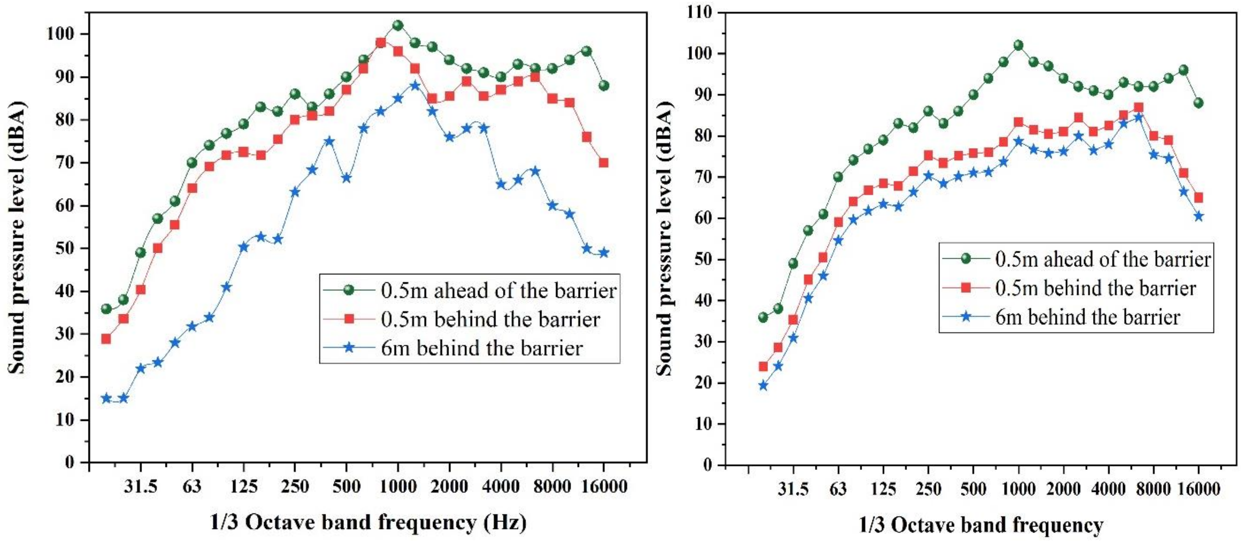
(b)



(c)

Figure 5.15 Noise barrier configurations in the computational domain (a) T-shaped (b) Y-shaped (c) Inverted L-shaped barrier.

5.8.2 Characteristics of railway noise spectra



(a) (b)

Figure 5.16 The variation of sound pressure levels in (a) free field condition and (b) in the presence of noise barrier at different measuring points.

To assess the performance of the existing noise barrier at the test site, sound level measurements were recorded at three designated points (categorized as A, B, and C) both in the absence and presence of the barrier. The A-weighted equivalent sound level for both scenarios is shown in Figure 5.16. The accuracy of the data was ensured by taking three measurements at different positions along the length of the barrier. The results were subsequently reported as the average value.

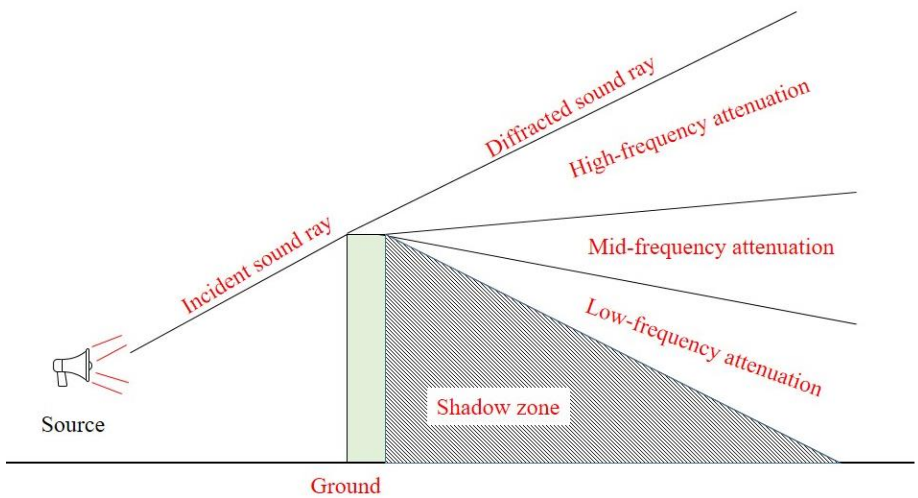


Figure 5.17 Several noise attenuation zones behind vertical noise barrier.

Figure 5.17 depicts the attenuation zones behind a noise barrier as a function of incoming sound frequency (Haron et al., 2019). The upper surface of the zone reduces high-frequency noise, while shadow zones are formed near the ground. Mid and low frequencies are attenuated in the intermediate region between the shadow and high-frequency zones. The height of the barrier is an essential parameter in reducing high-frequency railway noise. The current study recorded the noise spectrum at three locations in a free field condition with a 2.75 m high barrier. The results revealed that the frequency band spectrum peaked at 500-1000 Hz. Subsequently, after the installation of the barrier, the frequency spectrum shifted from mid-range to high-range frequencies. This shift occurred because of the diffraction of sound waves over the noise barrier, reducing the mid-range frequency spectrum. Consequently, the height of the barrier was restricted to only obstruct mid and low-range frequencies, not high-range frequencies. The current study employed ANSYS Fluent software to conduct simulations to assess the effectiveness of the increase in the height of the barrier in reducing high-frequency waves.

The barrier caused the SLM to record a higher noise level at point A because incident sound waves from the moving train contacted the barrier's surface and reflected to the same side. It was observed that the L_{eq} noise levels are higher by 2 dBA due to the presence of a barrier. In order to reduce the quantity of sound energy reflected by the barrier, absorbent surfaces must be provided. At point B, compared to no barrier condition due to the presence of a barrier, there is an average noise level reduction of 6.3 dBA. This reduction resulted due to the location of the measurement point in the shadow zone (a region through which sound waves fail to propagate). At point C, due to the presence of a noise barrier, there is an average reduction of 4 dBA. The noise attenuation observed at point C was lesser than at point B because the sound waves diffracted over the barrier's top surface, adding to the transmitted sound waves and emitting higher decibels. This is known as diffraction, and it occurs when sound waves encounter an obstruction such as a noise barrier (Song et al., 2022).

5.8.3 Evaluation of barrier's insertion loss

To replicate the noise experienced by residents living near the railway track, noise level measurements were conducted at point C in the presence and absence of a noise barrier, as illustrated in Figure 5.18. The noise spectrum of the railway noise displayed high sound pressure levels within the frequency range of 800 to 1500 Hz, with an average equivalent sound pressure level of 85.5 dBA. The overall equivalent sound pressure level in the presence of the barrier at point C was 80.3 dBA. According to the World Health Organization (WHO), noise levels in residential areas should not exceed 60 dBA during the daytime. However, the measured noise levels of 80 dBA in the current study exceeded the recommended limit by 20 dBA, indicating an unsafe environment that could potentially impair hearing with prolonged exposure. Consequently, the insertion loss of 5.5 dBA provided by the barrier is considered ineffective despite previous research works reporting insertion losses for barriers ranging from 3 to 25 dBA (Oldham and Egan, 2011; Jagniatinskis et al. 2017). Hence, the current study used numerical simulations to test the effectiveness of increasing the wall height and changing its shape to increase the noise attenuation.

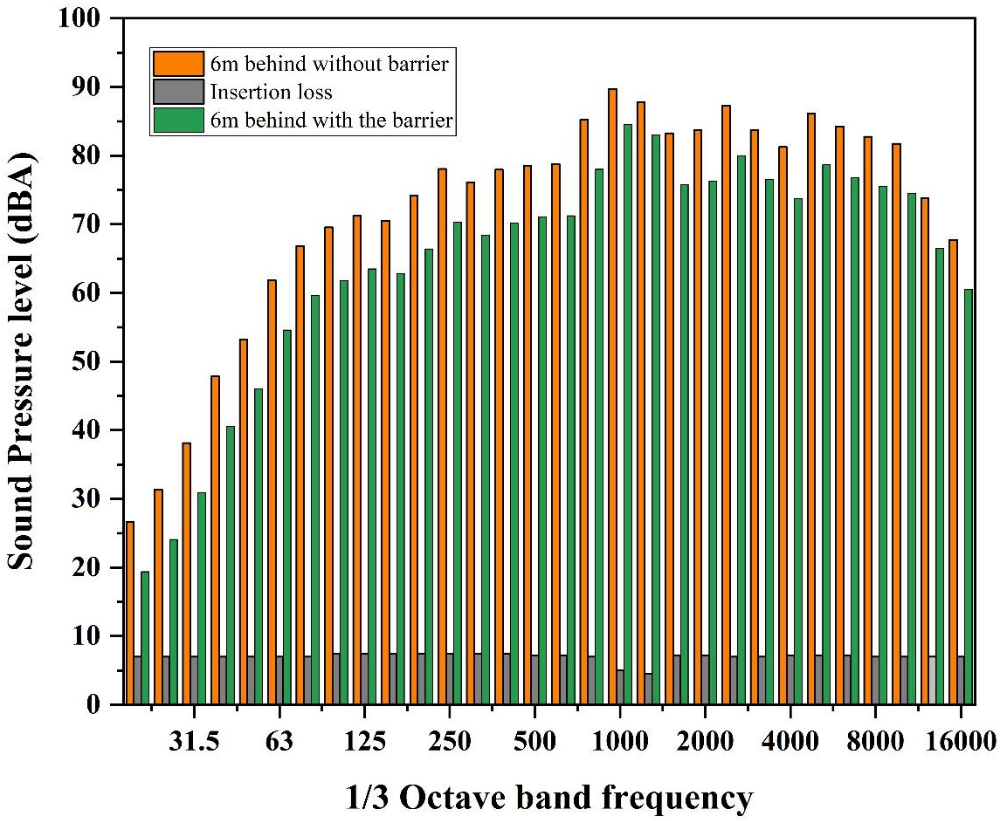


Figure 5.18 The variation of equivalent sound pressure levels at point C in the presence and absence of a barrier.

5.8.4 Variation of noise levels with change in barrier height

The height of a noise barrier is a crucial factor in reducing noise levels. The noise-reducing ability of the barrier increases with height. However, building a barrier of extensive height is impracticable due to safety concerns, structural stability, aesthetics, and economics. Therefore, a comprehensive analysis of noise levels at the specific site location for a particular type of noise source is necessary to determine the optimal height for a noise barrier.

The simulation run conducted over the 2.75 m barrier was validated using the experimental results in the current study. It was observed that the experimental result produced an insertion loss of 5.2 dBA, whereas the simulation resulted in a higher value of 6.4 dBA, which varies by 1.2 dBA. To account for this discrepancy, the simulation results for all barrier heights were adjusted by reducing them by 1.2 dBA. The modified results are presented in Figure 5.19.

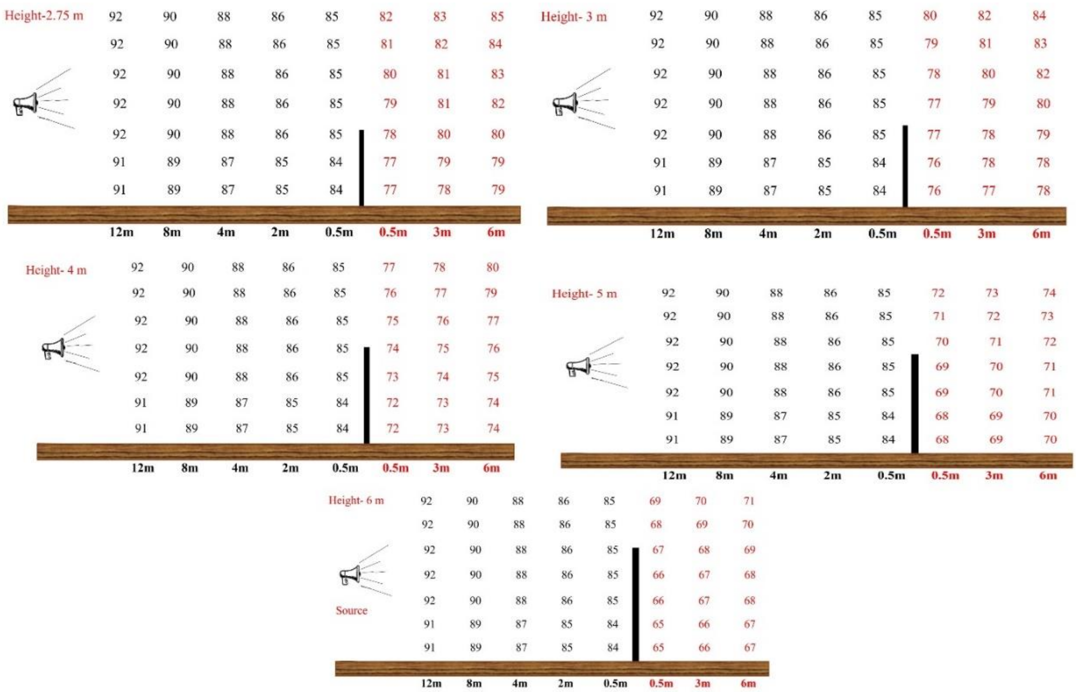


Figure 5.19 Variation of Insertion loss for the rectangular barrier with change in barrier height

The insertion loss had a positive correlation with barrier height. The noise attenuation was analyzed by incrementally increasing the barrier height from 2.75 m to 3 m and subsequently from 3 m to 6 m in 1 m intervals. The maximum insertion loss observed was 17 dBA when the barrier height was 6 m, a value 3.5 times greater than the 2.75 m barrier. At a measuring distance of 0.5 m behind the barrier (point B), every 1 m increase in barrier height resulted in a 3.6 dBA increase in insertion loss. Similarly, at a measuring distance of 6 m, the insertion loss increased at a slower rate of 1.91 dBA per meter than the former measuring distance.

At point B, sound levels were found to be trapped, particularly in the lower corner of the barrier. This is due to the presence of a shadow zone immediately behind the barrier, located at a distance of 0.5 m from the barrier, where all sound waves are diffracted by the top surface of the barrier, thus preventing the waves from reaching the sound level meter (SLM). However, the diffracted waves by the barrier converge back towards the receiver at point C, increasing the noise level.

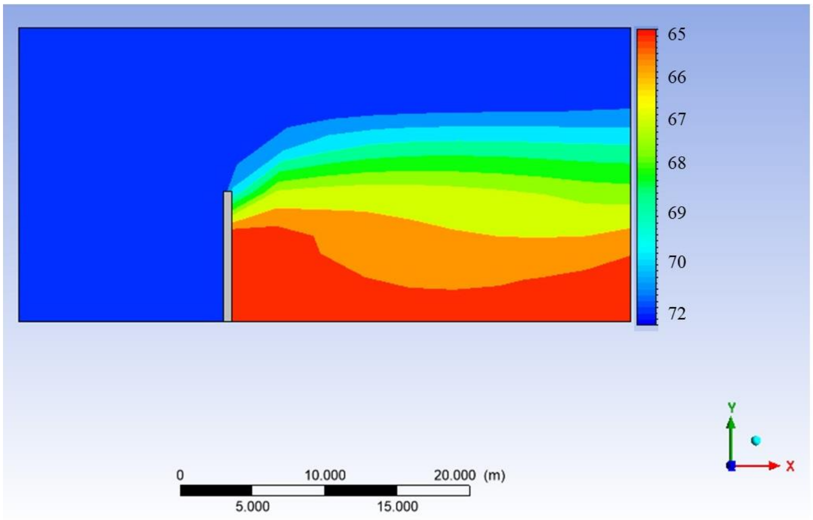


Figure 5.20 Contours of noise propagation over a rectangular noise barrier of height 6 m

The results depicted in Figure 5.20 demonstrate the dissipation of sound energy by a noise barrier modelled using the realizable *k*- *ε* model. The simulation findings reveal that a rectangular noise barrier with a height of 6 m can significantly reduce downstream noise levels, as shown in the various contour sections. The sound waves passing over the barrier create turbulence and vorticity behind the barrier, which impacts the dissipation of sound energy downstream. Additionally, the direction and intensity of the sound waves change abruptly at the top surface of the barrier. The incoming waves jump over the barrier and pass the vortex, significantly reducing noise levels at downstream. At point C, high and mid-frequency noise levels dominated. Therefore, the ideal strategy to minimize noise is not to raise the barrier's height; instead, it is necessary to design a barrier such that the receiver is in the shadow zone.

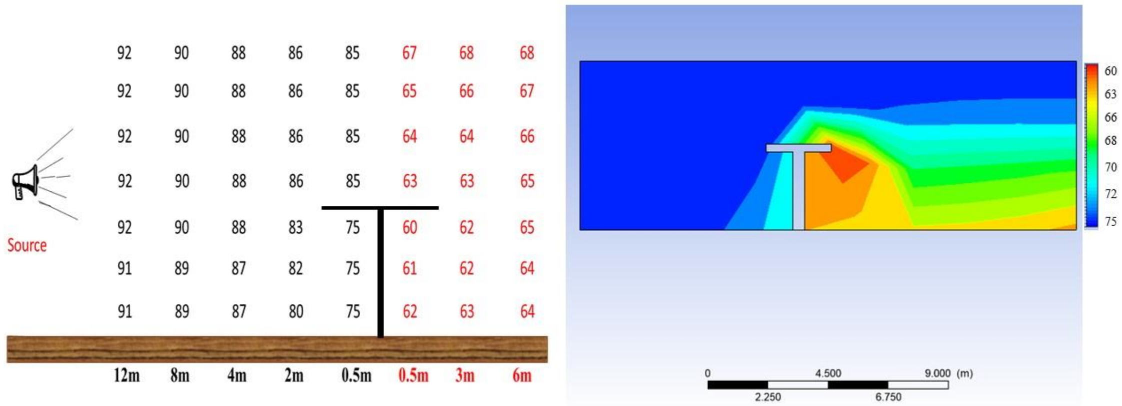
5.8.5 Variation of noise levels with change in barrier shape

The design of the top portion of a noise barrier has a significant impact on how sound waves are diffracted, scattered, and interfered by altering the path through which sound travels. This increases the number of areas where diffraction occurs and makes it more complex, ultimately reducing noise in the surrounding area. The best barrier shape will depend on the specific characteristics of the noise source and the environment in which the barrier will be used. The diffraction phenomenon is more complex when the top portion shape varies, leading to a higher number of diffraction occurrences and a reduction in noise transmission (Grubeša et al. 2012). This study investigates the insertion loss variation for different barrier shapes by altering the top portion.

Performance of T-shaped barrier

Due to limitations on the height of barriers, new designs and treatments for their top portions are needed to improve their performance and reduce noise in residential areas. The different shapes of noise barriers are used to optimize the effectiveness and match the surrounding area's aesthetics. Hence, the current study evaluates three different shapes (T-type, Y-type, and inverted L-shape) with a uniform height of 5 m while maintaining other parameters constant.

The present study conducted simulations to evaluate the acoustic performance of a T-shaped noise barrier with a projected top length of 2 m, and the results are shown in Figure 5.21. Gasparoni et al. (2011) suggested an optimal top length-to-height ratio between 0.2 and 0.4, which was satisfied by selecting a top length of 2 m after conducting several trials. The simulations showed that the T-shaped barrier provided more significant noise reduction than a rectangular barrier of equal height, with a maximum reduction of 20 dBA observed at point B. The T-shaped barrier created a shadow zone behind the vertical portion of the T-shape, which blocked a significant portion of sound waves from propagating to the other side of the barrier. Furthermore, the sound waves that climbed over the barrier caused turbulence and vorticity behind the wall. However, the T-shaped top length was found to cause the significant turbulence intensity to lose its energy, leading to higher noise attenuation. Additionally, wind shear in that region caused a pressure difference that further assisted in attenuation. Therefore, the higher attenuation observed with the T-shaped barrier was primarily attributed to its top-length projection.



(a) (b)

Figure 5.21 (a) Variation of Insertion loss for the T-shaped noise barrier, (b) contours of noise propagation over a T-shaped noise barrier.

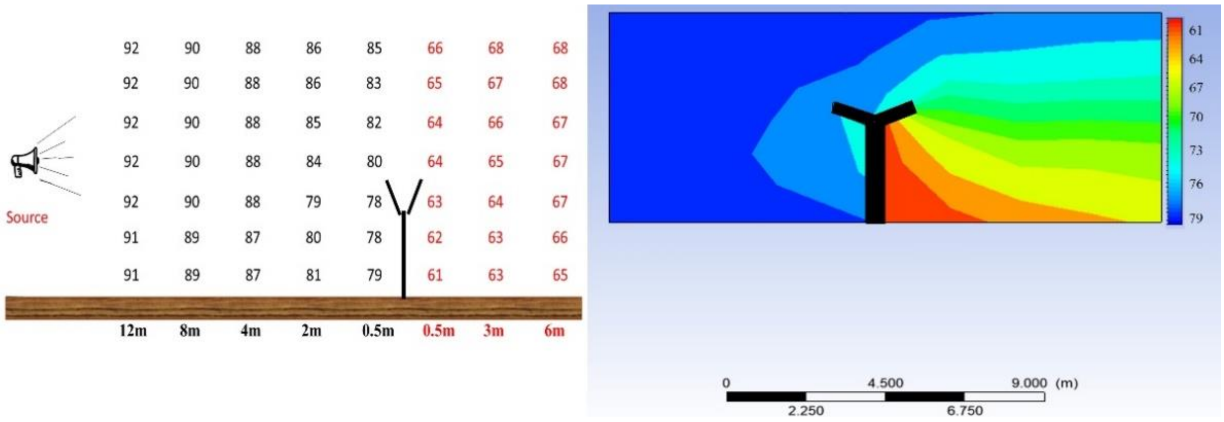
The top projection significantly reduced the noise levels at the front side of the T-shaped barrier by 8-10 dBA. The T-shaped barrier effectively reduced noise by creating a "*shadow zone*" on the upstream side of the barrier facing the noise source. This shadow zone blocks a significant portion of the sound waves from propagating to the other side of the barrier. Therefore, T-shaped barriers have the potential to be an effective solution for reducing noise in the zone near the noise source.

The noise levels at the facade of the residential zone were observed as 64 dBA, which is only 4 dBA higher than the permissible noise levels set by the Central Pollution Control Board (CPCB), India. The T-shaped barrier was found to be more effective than a rectangular barrier of the same height, as it provided an additional reduction of 3 dBA. The horizontal portion of the T-shape was found to scatter sound waves in multiple directions, thereby reducing the amount of sound that propagates to the other side of the barrier. Therefore, T-shaped barriers have the potential to provide an effective noise mitigation solution for residential areas near high-noise sources.

Performance of Y-shaped barrier

Y-shaped noise barriers are typically designed to be shorter and narrower than T-shaped barriers. They have a "Y" shape, with two legs extending outwards at an angle. The legs of the Y-shape are designed to reflect sound waves towards the noise source, reducing the amount of noise that reaches the other side of the barrier.

The current study examined a Y-shaped noise barrier that was 5 m tall, and the projection was inclined at a 45-degree angle. Results showed that the maximum noise reduction at the facade of the residential area was 18 decibels, which is 2 dBA less than a T-shaped barrier and 1 dBA more than a rectangular barrier. On the upstream side of the barrier facing the noise source, a noise reduction between 5 and 8 decibels was achieved due to the presence of the inclined projection. Compared to a T-shaped barrier, the Y-shaped barrier was found to be more effective in reducing noise levels on the upstream side. This was because the Y-shaped barrier created larger shadow zones on the upstream side of the barrier. The noise propagation and insertion loss through the Y-shaped barrier is shown in Figure 5.22.



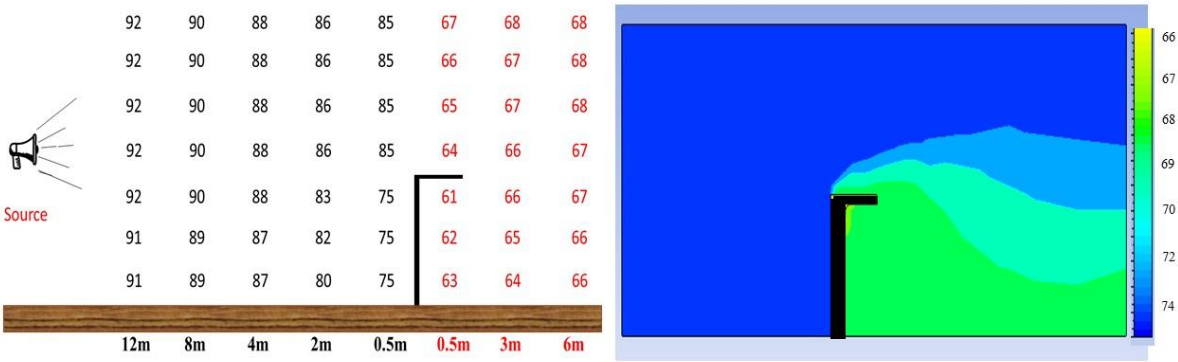
(a) (b)

Figure 5.22 (a) Variation of insertion loss for the Y-shaped noise barrier, (b) contours of noise propagation over a Y-shaped noise barrier.

Performance of Inverted L-shaped barrier

These types of barriers are designed in the shape of an inverted L, with one long vertical side facing the noise source and the other perpendicular to the receiver. This shape helps to reflect and redirect sound waves away from nearby residential or commercial areas, reducing the overall noise level. They are often used with other noise reduction strategies, such as vegetation barriers.

In the current study, the results of a numerical simulation study on an inverted L-shaped barrier with a height of 5 m and a projection length of 1 m revealed a noise reduction of 17 dBA at the facade of a residential area. This causes a lower level of noise reduction compared to T-shaped (3 dBA lesser) and Y-shaped (1 dBA lesser) barriers, but the same as that of a rectangular-shaped barrier. The insertion loss results and the noise propagation contour are shown in Figure 5.23. The barrier does not reduce noise on the upstream side, but there is a significant decrease on the downstream side due to the projection. These inverted L-shaped barriers are a suitable alternative when rectangular barriers of 6 m height cannot be implemented due to height restrictions, as they provide the same level of noise reduction.



(a) (b)

Figure 5.23 (a) Variation of insertion loss for the inverted L-shaped noise barrier, (b) contours of noise propagation over an inverted L-shaped noise barrier.

In conclusion, installing a T-shaped noise barrier with a top projected length of 2 m was found to be the most effective shape for noise reduction. The T-shape of the barrier offers increased effectiveness, as measured by insertion loss, due to the presence of two cantilever projections on either side of the barrier. These projections create a more significant path length difference, which is a key factor in determining the effectiveness of a noise barrier. To determine the most effective solution, it is important to note that a noise barrier's surface and material properties must be considered in conjunction with other factors, such as the barrier's height, shape, and location. Various materials and surface treatments may be considered to optimize the barrier performance.

5.8.6 Variation of insertion loss with change in barrier surface characteristics

The surface characteristics of a noise barrier can significantly impact its ability to reduce noise pollution. The reflectivity, texture, and surface porosity are key factors affecting the attenuated sound. Previous studies have classified barrier surfaces into three categories based on their acoustic properties: rigid, absorbing, and soft. The type of surface material used can impact the sound reflection and transmission, affecting the level of noise reduction achieved (Arenas et al. 2013). Therefore, careful consideration of the surface properties of a noise barrier is essential in designing an effective noise mitigation strategy.

The ANSYS software was utilized to create the 3D shapes of the noise barriers and place them in a fluid domain. Careful meshing was performed to ensure precision, and the wall was assigned specific material properties such as density, thermal conductivity, and heat capacity. Simulation parameters were established, including fluid characteristics and boundaries, and the ANSYS CFD solver was employed to compute the noise propagation over the wall. The simulation outcomes were assessed, and adjustments were made to the material properties, with the process repeated for various materials. The results of this investigation can be seen in Figure 5.24.

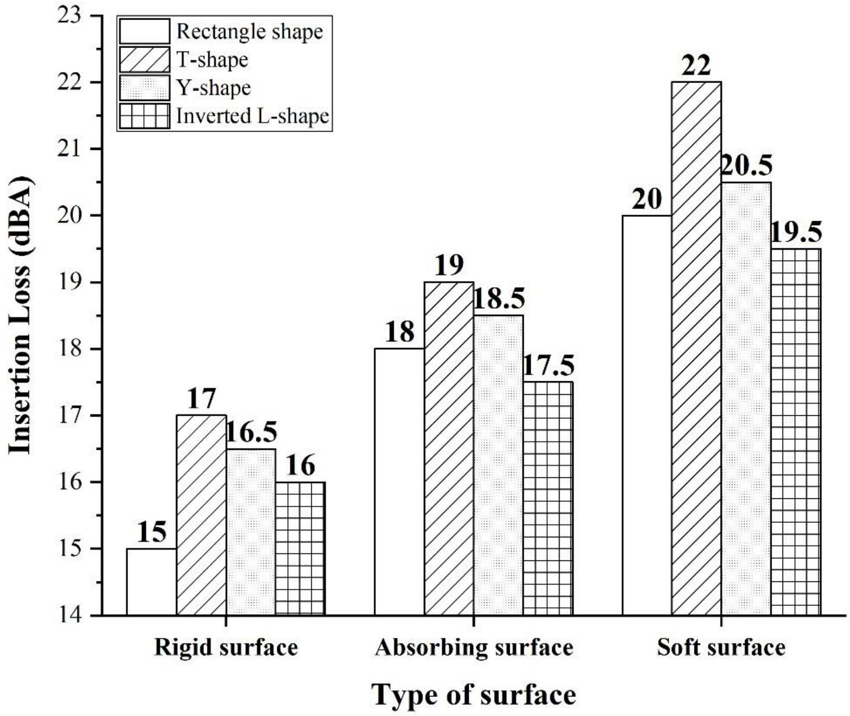


Figure 5.24 Insertion loss variation of noise barriers with change in surface material properties.

Rigid surface materials, such as concrete, metal, and wood, are designed to reflect sound waves away from the protected area. In this study, concrete was used as the rigid material, and it was observed that the T-shaped barrier surface covered with rigid material resulted in the maximum attenuation of the noise of 17 dBA followed by Y-shape, Inverted-L shape, and rectangular shape barriers.

Absorbing surface materials like fiberglass and rock wool are designed to absorb sound waves and decrease noise pollution. In the current study, fiberglass was used as the absorbing material, and it was found that the T-shaped noise barrier design again gave the maximum attenuation of 19 dBA, followed by Y-shape, rectangle shape, and inverted L-shaped barriers.

Soft surface materials, such as foam, plants, and vegetation, cover the barrier's surface. These barriers and noise reduction can also provide other benefits, such as visual aesthetics and wildlife habitats. These materials are designed to reflect and absorb sound waves. In this study, foam was used as the soft material, and it was observed that the T-shaped barrier design performed the best among all the tested shapes.

Based on the findings of this study, the most effective noise barrier for reducing railway noise is a T-shaped barrier with a height of 5 m and a projection length of 2 m. The barrier should be constructed using soft materials on its surface, reflecting and absorbing sound waves. This design resulted in the most significant noise reduction, with an attenuation of 22 dBA. It is worth noting that this study conducted a simulation test on the specific material and shapes, and the results are likely to vary depending on the type of material and its shape. Also, the optimal barrier design for one specific location may vary for other locations, as the noise source and the surrounding environment are expected to be different.

5.8.7 Correlation between insertion loss and noise barrier characteristics

The relationship between insertion loss and noise barrier characteristics, including height, shape, and surface material properties, is a complex phenomenon that requires careful investigation. One approach to explore such a relationship is to use a correlation matrix, which can detect multicollinearity among independent variables. Multicollinearity arises when two or more independent variables are highly correlated with each other, and it can complicate the identification of the individual effects of each variable on the dependent variable. By identifying and eliminating redundant variables, the dimensionality of the data can be reduced, and the efficiency and accuracy of the analysis can be improved (Hasmaden et al., 2022). Figure 5.25 shows the correlation results for the dependent and independent variables.

"R" values	Insertion loss	Barrier height	T-shaped	Y-shaped	Inverted L shape	Rigid surface	Absorbing surface	Soft surface
Insertion loss	1							
Barrier height	0.93	1						
T-shaped	0.85	0.82	1					
Y-shaped	0.81	0.78	0.75	1				
Inverted L shape	0.76	0.71	0.86	0.51	1			
Rigid surface	0.51	0.48	0.53	0.47	0.42	1		
Absorbing surface	0.58	0.52	0.56	0.5	0.45	0.53	1	
Soft surface	0.62	0.55	0.62	0.52	0.48	0.51	0.62	1

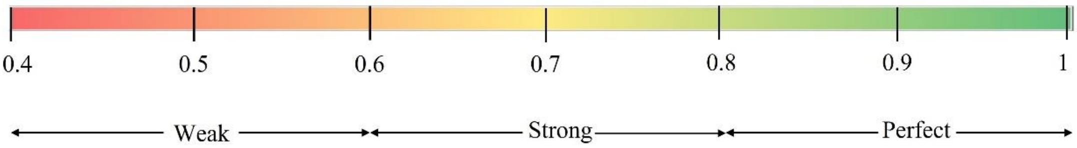


Figure 5.25 Correlation matrix for insertion loss and noise barrier characteristics

Chapter 6

IMPACT OF RAILWAY NOISE ON TRACKSIDE REISDENTS

This chapter quantifies the extent of railway noise within households located along these railway corridors and to explore the intricate relationship between noise levels and the resulting annoyance during routine daily activities through a comprehensive questionnaire survey. Structural Equation Model (SEM) was developed to analyze the complex relationships between annoyance, disturbance, and health effects and the results are presented.

6.1 General

Among several urban environment noise sources, railway noise has emerged as one of the significant contributors, especially in residential areas near railway lines. Recent statistics revealed that about 55% of the world's population (4.4 billion) live in urban areas, and by 2045, it is forecasted that the urban population will increase by 1.5 times (6 billion) (Navarrete-Hernandez and Laffan 2023). Unplanned urbanization has led to the settlement of migrants from rural areas in close proximity to railway lines, exposing them to continuous noise pollution and resulting in a range of adverse effects on their health and well-being. Studies show that residential properties exposed to 65 dBA or higher of railway noise experience a 14 to 18% decrease in land property value (Walker 2016). Prolonged exposure to railway noise can result in hearing damage, improper sleep, and even cardiovascular problems, with noise levels above 70 dBA posing a risk.

Annoyance is one of the most prevalent immediate consequences of rail transport-related noise exposure. Noise annoyance can be defined as a complex stress reaction consisting of several physiological, emotional, cognitive, and behavioural responses experienced by individuals when exposed to excessive or disturbing noise levels (Casado et al. 2023). As noise annoyance develops in less time than serious health issues, it could be an early warning sign for more severe health problems. Therefore, it is essential to consider the level of annoyance before setting the noise exposure limits. To develop these limits, it is essential to quantify the noise produced by the railways and its effects on residents' perception to implement noise mitigation strategies. Accordingly, a bibliographic analysis was conducted to investigate the keywords used in the literature from 2005 to 2022. This analysis aimed to gain insights into the various factors associated with the annoyance caused by railway noise. The results indicated that a substantial portion, approximately 85%, of the articles focused on urban regions in developed countries (Walls et al. 2004; Grubliauskas et al. 2014). Additionally, a keyword co-occurrence map was generated using VOSviewer software, as illustrated in Figure 6.1. The size of each node in Figure 6.1 corresponds to the frequency of its occurrence of a particular keyword used in the literature, with larger nodes indicating a higher likelihood of appearance. From Figure 6.1, it was observed that annoyance, railway noise, transportation noise, traffic noise, health, environmental noise, risk, long-term exposure, and quality of life have an inter-relationship that needs to be explored.

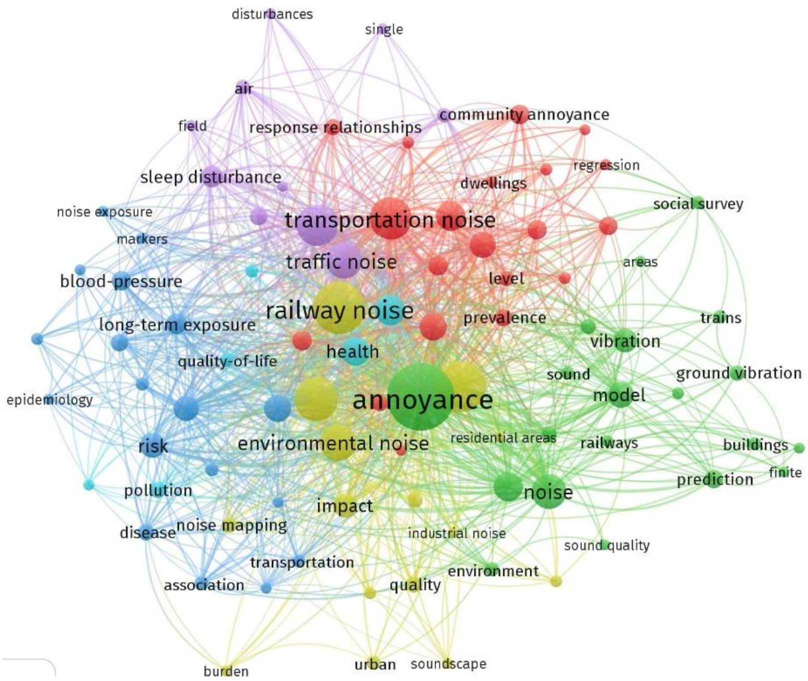


Figure 6.1 Keyword co-occurrence map on research related to railway noise annoyance

6.2 Noise Quantification and Human Response Studies

Several studies have been conducted to assess the impact of railway noise on human health (Lercher et al. 2008; Wrótny and Bohatkiewicz 2021). One approach frequently employed to quantify the impact is the measurement of sound levels generated by various noise sources in residential, silent, and commercial land zones. These studies have revealed significant findings concerning the equivalent (L_{eq}) and maximum (L_{max}) noise levels observed in that area, the sources of noise that contribute most significantly to overall noise levels, the temporal and spatial variability of noise levels, the effectiveness of existing noise control measures, and other relevant factors (Pennig and Schady 2014). Another approach evaluates human responses to railway noise to assess the level of annoyance created by this noise. These studies have provided valuable insights into the percentage of individuals sensitive to railway noise, the health effects of exposure to noise, attitudes, and behaviour towards the noise, and other factors (Welch et al. 2023). However, no studies have been conducted to assess the impact of railway noise on the trackside residents by considering both noise quantification and human response studies. Noise perception varies considerably from person to person and can be influenced by hearing ability, age, previous exposure, personal preferences, psychological factors, and cultural background (Brink et al. 2019). Combining noise measurement results and human response can facilitate a more accurate assessment of the impact of railway noise pollution on the surrounding community and for developing appropriate mitigation strategies. Conducting both noise quantification and human response studies has several advantages, including:

- **Comprehensive understanding:** Integrating noise quantification with human response surveys can offer a comprehensive understanding of the impact of noise on human beings. Objective noise measurements provide information on noise levels, whereas subjective human response surveys provide data on how people perceive and are affected by noise (Albert and Decato 2017).
- **Identifying correlations:** Identifying correlations between noise levels and human responses will identify the noise reduction strategies and policies.
- **Addressing limitations:** There are limitations in both the methods. Noise measurements may not consider factors such as the time of day or the specific context in which the noise occurs, while human response surveys may be affected by personal bias or memory. By combining these two methods, some of these limitations can be addressed, resulting in a more accurate and reliable evaluation of the impact of noise (Harrison et al. 2021).

Extensive research has revealed the adverse impacts of railway noise on the public’s well-being, with most research being done in developed nations. However, there is a noticeable lack of research in this area from developing countries like India. The significance of conducting this study in India is due to densely populated areas located close to railway tracks, an extensive railway network passing through urban and suburban regions, rapid urbanization in India, and infrastructure development leading to the expansion of cities and towns, which results in people often encroaching along the railway lines. Consequently, there is an increased likelihood that residents will be exposed to railway noise, thereby raising concerns regarding its impact on their quality of life and health. Furthermore, the issue of noise pollution seems to be receiving insufficient attention in India, as the general population remains unaware of its potentially harmful effects.

Accordingly, the present study aims to quantify railway noise by measuring the noise inside houses along the railway line. Additionally, a human perception survey was conducted to investigate the relationship between noise levels and annoyance during daily activities such as working, resting, conversing, eating, talking on the phone, and reading. As the current study involves questionnaire data, it is common to have complex relationships between variables. Structural Equation Model (SEM) helps to model and examine these complex relationships. In the context of railway noise perception, there are multiple variables, such as noise levels, distance from the railway track, individual characteristics, and psychological factors. SEM can handle these interrelated variables effectively. Hence the current study adopts the SEM approach to assess the questionnaire data as this is the most widely used in diverse studies (Roswall et al. 2015). In addition, this study examined the level of annoyance experienced by individuals as a function of rail traffic noise exposure, measured at different distances from the railway line.

6.3 Structural Equation Modelling

At the outset of this research, an Exploratory Factor Analysis (EFA) was conducted to investigate the underlying structure of the questionnaire data. The primary objective of this analysis is to identify the latent constructs that might explain the observed correlations among the questionnaire items. As there are many questions related to human perceptions of railway noise, there was initial uncertainty regarding the grouping of these items. EFA served the purpose of simplifying the data by revealing hidden factors and clarifying the connections between the items.

After identifying potential latent constructs through EFA, Confirmatory Factor Analysis (CFA) was performed to evaluate the goodness-of-fit between the observed data and the hypothesized factor structure. CFA was crucial in confirming the reliability and validating the model that was postulated based on the EFA results.

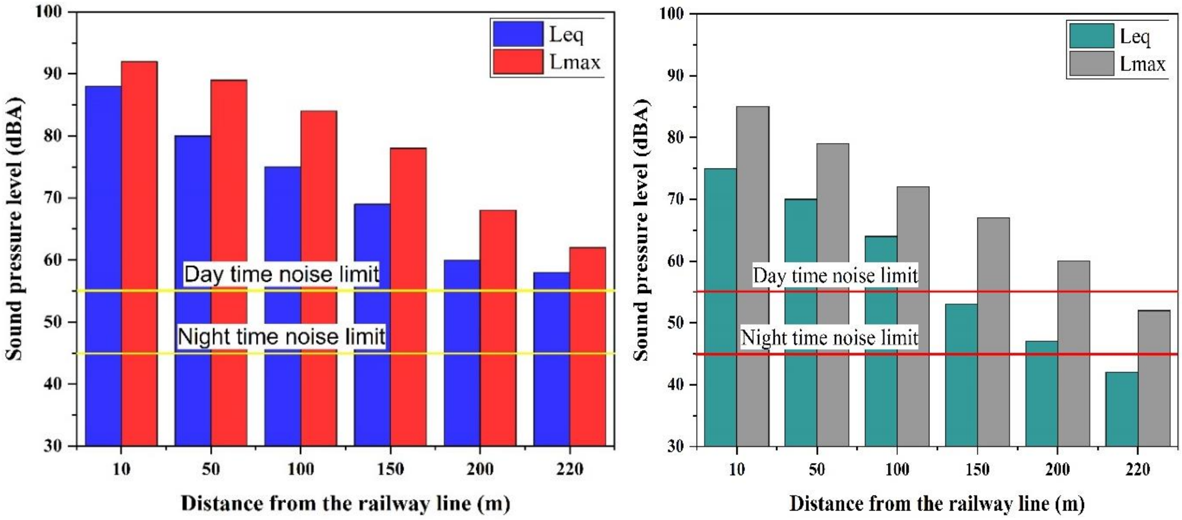
Development of Structural Equation Modelling (SEM) is the final step in this analysis and serves to test the structural relationships and hypotheses of the model. It is an advanced technique that combines both measurement models (CFA) and structural models (Song et al. 2016). SEM is a multivariate statistic that integrates the principles of factor analysis and path analysis. It finds application in research models encompassing multiple hidden variables referred to as latent constructs, each with numerous indicators. SEM facilitates the indirect measurement of these constructs and their interconnections through a series of observable variables derived from questionnaire responses. The primary objective is to examine the causal relationships between different categories within the conceptual framework, elucidating these relationships' direction and statistical significance.

SEM was chosen in the current study as it is the most powerful method for examining complex relationships between multiple latent variables and observed variables simultaneously. SEM identified how the factors interacted and influenced each other, providing a comprehensive understanding of the resident's perceptions of living near railway tracks. The software package SPSS 28 was employed to perform EFA, and AMOS 26 was used to conduct the CFA and SEM.

6.4 Noise Measurement Results in the Households

Equivalent continuous noise levels (L_{eq}), maximum noise levels (L_{max}), and minimum noise levels (L_{min}) were used to quantify the captured railway noise levels. L_{eq} represents the average noise levels generated by the passing train within a defined time interval. The noise was measured with the SLM, commencing when the train noise became audible during the railway noise measurement and concluding when the noise stopped. L_{max} indicates the peak noise level emitted by the moving train within the specified time frame, while L_{min} represents the lowest noise level produced by the moving train during the same duration. Throughout a significant portion of human history, individuals have relied on opening windows and doors in their dwellings to facilitate airflow and ventilation. Therefore, in the interest of analysis, particular emphasis was placed on measuring railway noise levels inside houses where doors and windows were left open. Figure 6.2 (a) and (b) depict the L_{eq} and L_{max} noise levels resulting from passenger and freight trains, respectively, as measured inside houses located between 10 and 220 m from the railway line. Notably, the noise levels from passenger trains exceeded those generated by freight trains. At a distance of 10 meters from the railway line, the maximum noise level emitted by passenger trains was 92 dBA, with a corresponding L_{eq} noise level of 87 dBA. Comparatively, the maximum noise level emitted by freight trains at the same distance was 85 dBA, with a corresponding L_{eq} noise level of 75 dBA. On average, passenger trains emitted 13 dBA and 9 dBA higher than freight trains in terms of L_{eq} and L_{max}, respectively.

As per noise guidelines by the Central Pollution Control Board, India (CPCB), as shown in Table 6.1, the noise levels from passenger trains exceeded the daytime noise limit by 36.8% and freight trains by 15%. During the night, passenger trains exceeded the noise limits by 75.15%, while freight trains surpassed them by 41.8%. These findings suggest that the noise levels generated by railway transportation, particularly passenger trains, have the potential to cause noise pollution that exceeds the recommended limits.



(a) (b)

Figure 6.2 (a) Noise level variation for passenger trains and (b) freight trains with the distance from the nearest railway line.

Table 6.1 Recommended L_{eq} noise levels in different land zones.

Type of land zone	**Daytime** (dBA)	**Night-time** (dBA)
Industrial	75	70
Commercial	65	55
Residential	55	45
Silence	50	40

A comprehensive study was conducted to evaluate the potential impact of railway noise on trackside residents. The study examined different locations within the premises, including the house's façade, interior with closed doors and windows, and interior with open doors and windows. Figure 6.3 illustrates the fluctuations in railway noise levels experienced by the household. The study findings revealed interesting patterns and significant differences between the three conditions. Notably, the noise levels measured at the house's façade were consistently higher than both the interior with open doors and windows and the interior with closed doors and windows. Specifically, the noise levels at the façade were found to be 5.5 dBA higher when measured inside the house with open doors and windows. Moreover, when measured inside the house with closed doors and windows, the noise levels at the façade were significantly increased by 10 dBA. The results suggest that the mere act of closing doors and windows can lead to a noticeable reduction in noise levels within the house. Furthermore, it highlights the importance of considering such factors in assessing the potential noise disturbance caused by railway activities on residential properties.

To validate the accuracy of the findings, a statistical analysis was conducted on households located within four distinct clusters. The households located at a particular distance from the railway line (i.e., 25 m, 50 m, 100 m, and 200 m) in each cluster are considered and analyzed. The null hypothesis (H_o) considered was: there is no significant difference in noise levels between the four clusters. Analysis of Variance (ANOVA) was performed at a significance level of 95% ($p = 0.05$) to ascertain whether the mean values of these clusters exhibited significant differences. The computed *p*-value of 0.56 suggests the rejection of the null hypothesis, and this concludes that there is a significant difference in noise levels between the four clusters. This implies that the distance from the railway line correlates with variations in observed noise levels. These findings suggest that residents in Zone I and Zone II experienced more significant health impacts attributable to railway noise compared to those in Zone III and Zone IV.

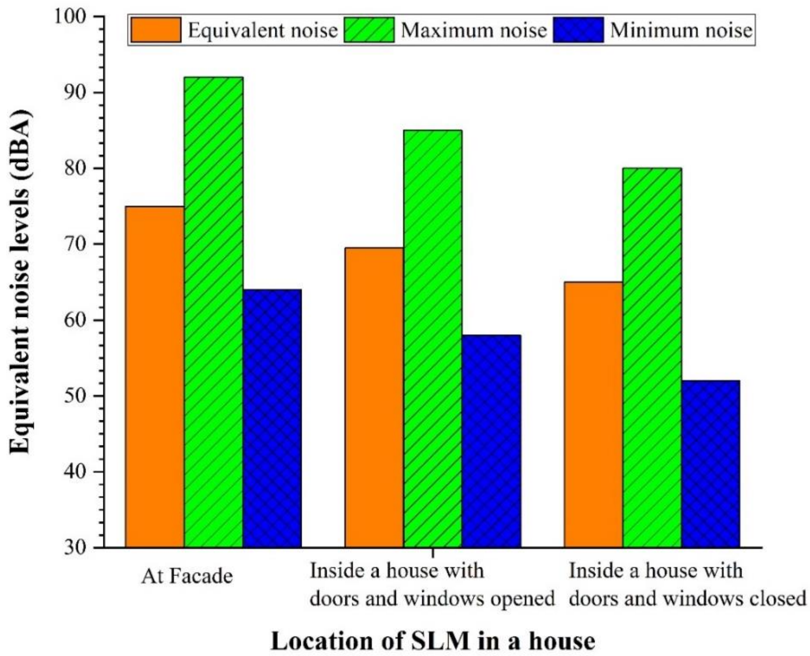


Figure 6.3 Noise levels measured at different locations of a house

6.5 Conceptual Model Framework for Railway Noise Perception

6.5.1 Exploratory factor analysis

Exploratory factor analysis (EFA) was first conducted to extract the dominant factors causing railway noise annoyance based on the household survey data. Principal component analysis and varimax rotation were employed to determine the orthogonal factors and the factors with an eigenvalue greater than one. As shown in Table 6.2, four factors related to annoyance and two factors related to health impacts were derived from EFA representing approximately 63.4% of the total variance with factor loadings ranging from 0.40 to 0.95. Additionally, some variables with factor loading values below 0.4 were excluded from further analysis due to their weak correlation.

Table 6.2 Summary of EFA on the noise perceived by trackside dwellers.

Questioner related to railway noise perception		**Factor Loading**	**Variance (%)**
Factor 1: Annoyance in general			**25.23**
A1	Does the railway noise annoy you?	0.95	
A2	Do you think railway noise causes higher annoyance than the vibrations caused due to train movements?	0.58	
A3	What do your guests think about the railway noise? Do they complain about it when they stay at your house for a few days?	0.85	
A4	In your opinion, will the upcoming new railway line cause a greater annoyance than before?	0.72	
Factor 2: Annoyance based on variation in source			**7.35**
S1	In your opinion, do passenger trains cause more annoyance than freight trains?	0.48	
S2	Do you find diesel locomotives more annoying than electric locomotives?	0.62	
S3	Should there be mitigation measures taken against the noise coming from existing railways?	0.81	
Factor 3: Annoyance based on location of stay			**11.25**
L1	Do you think that railway noise affects the property's value?	0.58	
L2	Does this railway noise get used to a person more quickly than other noises?	0.63	
L3	Do you consider that your street, compared to the rest of the city, is nosier?	0.64	
Factor 4: Annoyance based on time of exposure			**5.65**
T1	The railway noise annoyed you to a greater extent when you first moved near the railway line?	0.47	
T2	Over time, do you feel that you have adapted to the railway noise and it does not annoy you as much as before?	0.45	
T3	While relaxing at night, do you feel more annoyance than when working in the morning?	0.59	
Factor 5: Disturbance to daily activities			**10.52**
D1	Reading / studying	0.75	
D2	While relaxing	0.82	
D3	Sleeping	0.91	

D4	Religious activities	0.46	
D5	Talking over phone	0.62	
Factor 6: Health effects			**7.31**
H1	Cardio-vascular problems	0.45	
H2	Head ache	0.55	
H3	Improper sleep structure	0.63	
H4	Hearing problem	0.65	

Factor 1 represents the general annoyance caused by the railway noise, accounting for the highest proportion of variance at 25.23%. Factor 2 corresponds to the annoyance caused due to variations of source within railway such as change in train type (freight or passenger), or locomotive type (diesel or electric), explaining 7.35% of the variance. Factor 3 explained the annoyance related to the location of stay, while Factor 4 described annoyance related to time of exposure. Factors 3 and 4 account for 11.25% and 5.65% of the variance, respectively. Factors 5 and 6 are related to the disturbances and health impacts caused by the railway noise, and explain the variance of 10.52% and 7.31% respectively. These primary factors, in terms of annoyance due to railway noise, align with findings from prior research (Das et al. 2021). This confirmed that the perception of railway noise can indeed lead to annoyance, disturbances, and health effects.

The Kaiser-Meyer-Olkin (KMO), which measures the sampling adequacy of the data for factor analysis, resulted in a value of 0.735 as shown in Table 6.3. As the KMO value exceeds 0.70 suggests that the sampling adequacy criteria have been satisfied (Alpu 2015). Bartlett's test of Sphericity is used to test the correlation within the variables. The correlation was assessed at a 95% significance level. If the significance value (p-value) of Bartlett's test of Sphericity is less than 0.05 the variables are perfectly correlated to each other. This infers that the questions used for the human perception study are related to each other and are considered as useful variables. The scree plot shown in Figure 6.4 determines the optimal number of factors to be retained in the final solution. In the current study, six factors are retained as their eigenvalues are greater than 1.

Table 6.3 KMO and Bartlett's test results.

KMO and Bartlett's test		
Kaiser-Meyer-Olkin measure of sampling adequacy		**0.735**
Bartlett's test of Sphericity	Approx. chi-square	251.85
	Degree of freedom	300
	Sig. (*p*-value)	.000

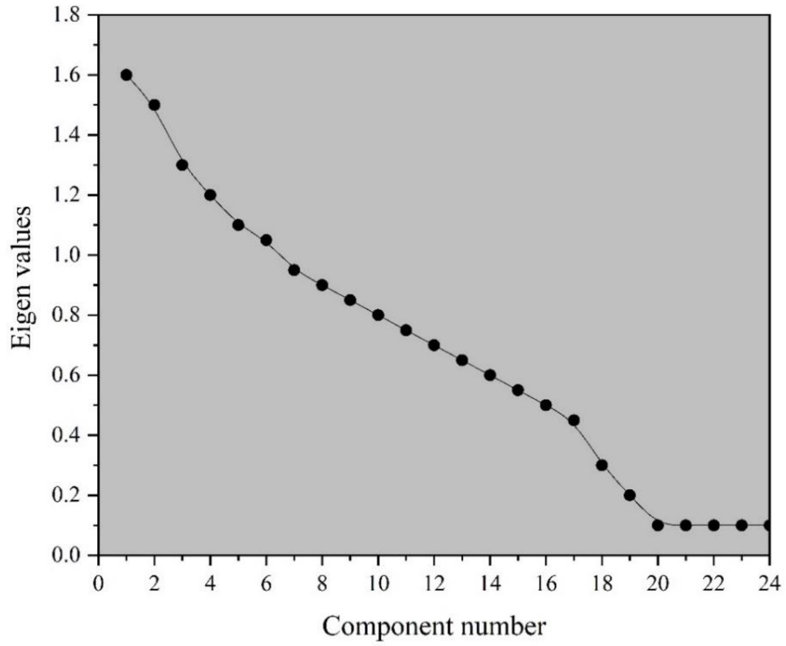


Figure 6.4 Scree plot showing the eigenvalues of the variables.

The descriptive statistics of the variables considered in the formulated factor can be seen in the Table 6.4. The mean and standard deviation values represent the level of annoyance as per the 5-point categorical scale.

Table 6.4 Descriptive statistics of the variables considered in the formulated factors

Question		**Mean**	**Standard Deviation (±)**
A1	Does the railway noise annoy you?	4.75	1.5
A2	Do you think railway noise causes higher annoyance than the vibrations caused due to train movements?	2.9	1.2
A3	What do your guests think about the railway noise? Do they complain about it when they stay at your house for a few days?	4.25	1.3
A4	In your opinion, will the upcoming new railway line cause a greater annoyance than before?	3.6	1.1
S1	In your opinion, do passenger trains cause more annoyance than freight trains?	2.4	1.6

S2	Do you find diesel locomotives more annoying than electric locomotives?	3.1	1.7
S3	Should there be mitigation measures taken against the noise coming from existing railways?	4.05	1.2
L1	Do you think that railway noise affects the property's value?	2.9	1.1
L2	Does this railway noise get used to a person more quickly than other noises?	3.15	1.0
L3	Do you consider that your street, compared to the rest of the city, is nosier?	3.2	0.9
T1	The railway noise annoyed you to a greater extent when you first moved near the railway line?	2.35	1.3
T2	Over time, do you feel that you have adapted to the railway noise and it does not annoy you as much as before?	2.25	1.5
T3	While relaxing at night, do you feel more annoyance than when working in the morning?	2.95	1.4
D1	Reading / studying	3.75	1.2
D2	While relaxing	4.1	1.3
D3	Sleeping	4.55	0.8
D4	Religious activities	2.3	1.7
D5	Talking over phone	3.1	1.1
H1	Cardio-vascular problems	2.25	1.2
H2	Head ache	2.75	1.1
H3	Improper sleep structure	3.15	1.3
H4	Hearing problem	3.25	1.5

6.5.2 Confirmatory factor analysis

A Confirmatory Factor Analysis (CFA) was conducted to assess the reliability and validity of both observed and latent variables within the study. To assess reliability, Cronbach's alpha coefficients were computed for all variables. The results indicated strong reliability, as all latent variables exhibited Cronbach's alpha values exceeding 0.7. The construct validity was evaluated through the examination of convergent and discriminant validity. Convergent validity refers to the extent to which the measured variables accurately represent the underlying latent construct. On the other hand, discriminant validity assesses the degree to which a latent variable is distinct from others. Several indicators, such as Standardized Factor Loadings (SFL), Cronbach Alpha (CA), Average Variance Extracted (AVE), Construct Reliability (CR), and Maximum Shared Variance (MSV) were employed to estimate convergent validity.

To ensure strong convergent validity, the SFLs of the observed variables must be at least 0.5 or higher. Moreover, for adequate convergence, both the AVE and CR should surpass the thresholds of 0.5 and 0.7, respectively. The Discriminant Validity is well-established as the MSV values for the constructs were lower than the AVE values, indicating clear distinctions between them. The results from the CFA indicate the best model fit, as evidenced by Chi-square/Degree of freedom ($\chi2/df$) at 1.36, which is well below the acceptable threshold of 3. Other fit indices, including a Root Mean Square Error of Approximation (RMSEA) of 0.074, Root Mean Residual (RMR) of 0.034, and Comparative Fit Index (CFI) of 0.904, further support the model's goodness of fit. These findings align with the recommended thresholds established by Zarei et al. (2021), where values of RMSEA should be below 0.08, RMR below 0.05, and CFI above 0.90. Additionally, a preliminary assessment of univariate normality was conducted as part of the initial analysis. As listed in Table 6.5, all the observed variables showed reasonably good convergent validity.

Table 6.5 CFA results for the convergent and discriminant validity

Latent variables		**SFL**	**CA**	**CR**	**AVE**	**MSV**
Factor 1: Annoyance in general	A1	0.642	0.835	0.911	0.632	0.168
	A2	0.865				
	A3	0.771				
	A4	0.768				
Factor 2: Annoyance based on variation in source	S1	0.729	0.722	0.774	0.534	0.128
	S2	0.781				
	S3	0.678				
Factor 3: Annoyance based on location of stay	L1	0.712	0.653	0.947	0.693	0.356
	L2	0.844				
	L3	0.887				
Factor 4: Annoyance based on time of exposure	T1	0.485	0.716	0.917	0.615	0.326
	T2	0.499				

	T3	0.893				
Factor 5: Disturbance to daily activities	D1	0.740	0.852	0.938	0.683	0.168
	D2	0.860				
	D3	0.829				
	D4	0.859				
	D5	0.823				
Factor 6: Health effects	H1	0.575	0.752	0.865	0.598	0.154
	H2	0.735				
	H3	0.689				
	H4	0.674				

6.5.3 Structural equation model

To investigate the correlation between annoyance, disturbance caused to daily activities and health effects, a Structural Equation Model (SEM) was developed. This SEM was built within AMOS, using path analysis, and it involved incorporating factor scores derived from CFA conducted in AMOS. In the process of hypothesis testing, the present study employs disturbance to daily activities as a mediator and distance of the dwelling unit from the railway line as a moderator. A mediator serves as an intermediate variable explaining how the independent variable impacts the dependent variable. The mediators are often integrated into the model to assess the indirect impacts of independent variables on dependent variables during hypothesis testing. On the other hand, a moderator is an additional variable that influences the strength of the relation between an independent variable and a dependent variable. It allows researchers to identify the circumstances under which the relationship between the independent and dependent variables is stronger or weaker. The conceptual framework of the SEM outlines the relationship between the latent constructs, as depicted in Figure 6.5.

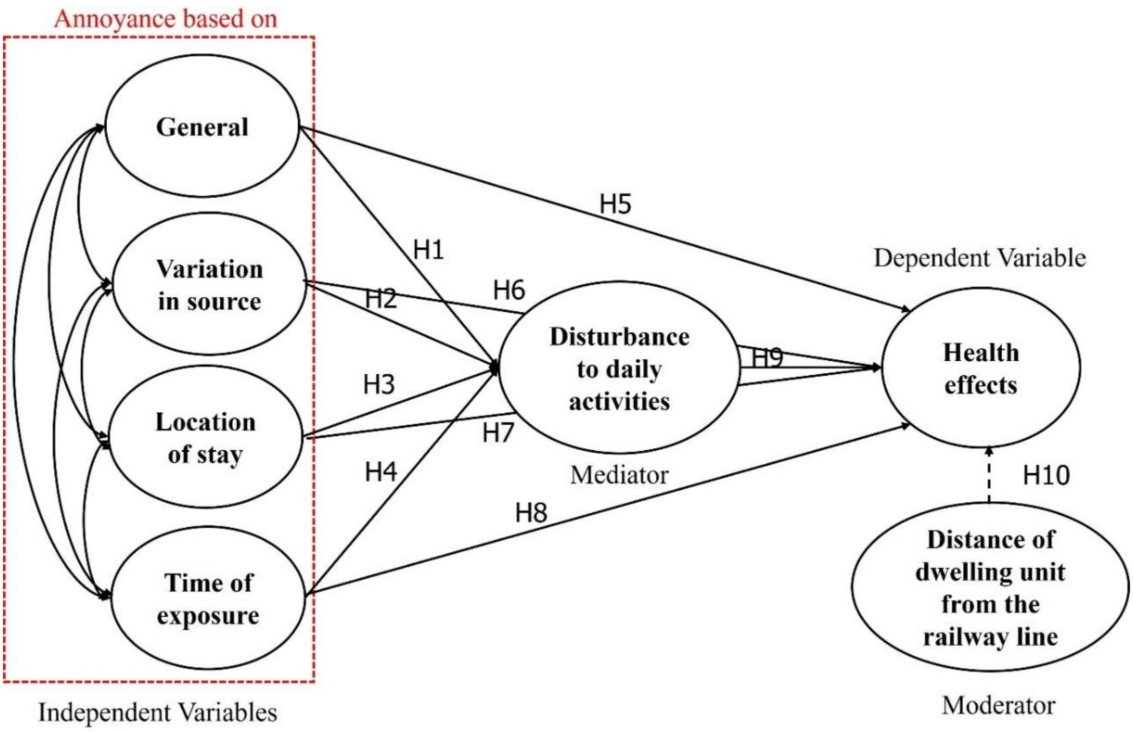


Figure 6.5 A conceptual SEM of the railway noise annoyance perceived by track-side dwellers.

The hypotheses are formulated to test the relationships between independent and dependent variables, as well as the potential mediating and moderating effects of other variables. In total ten hypothesis were formulated as follows:

H1: Annoyance in general can cause disturbance to daily activities.

H2: Annoyance based on variation in the source can cause disturbance to daily activities.

H3: Annoyance based on location of stay can cause disturbance to daily activities.

H4: Annoyance based on time of exposure can cause disturbance to daily activities.

H5: Annoyance in general can cause health effects.

H6: Annoyance based on variation in source can cause health effects.

H7: Annoyance based on location of stay can cause health effects.

H8: Annoyance based on time of exposure can cause health effects.

H9: Disturbances to daily activities can cause health effects indirectly.

H10: Distance of dwelling unit from the railway line moderates the health effects.

The assessment of hypotheses involves the use of global and local tests to evaluate various aspects. Global tests aim to determine if the developed model adequately represents the observed data as a whole. Common global tests include tests for goodness of fit, including the chi-square test, the CFI, and the RMSEA. On the other hand, local tests evaluate specific aspects of the model, such as the relationships between individual variables or particular coefficients. The local test employed in the current study is the *p*-value for individual relationships. To accept the hypothesis, both global and local tests must be consistent and indicate a strong fit for the overall model.

The Chi-square/Degree of freedom (χ^2/df) serves as an indicator of how well the developed model aligns with the observed data. A lower χ^2/df signifies the best fit, although it is sensitive to sample size. GFI, which measures the accuracy of the model-implied covariance matrix to the observed covariance matrix, is deemed acceptable when it exceeds 0.90. CFI evaluates the enhancement in model fit compared to a reference model. RMSEA measures the disagreement between the model-implied covariance matrix and the observed covariance matrix, while also considering model complexity. A lower RMSEA value indicates a better fit. Table 6.6 shows the results of global tests conducted on the model to assess its fitness. The results in the current study produced favourable values while evaluating the validity of the structural model.

Table 6.6 Goodness-of-fit indices of the proposed model and the recommended values (N = 316).

Model fit index	**χ^2/df**	**GFI**	**CFI**	**RMSEA**
Observed values	3.25	0.93	0.92	0.05
Recommended values	2.0 to 5.0	> 0.90	> 0.90	< 0.08

In this study, the maximum likelihood approach was employed to calculate the regression coefficients of the paths in the model. Table 6.7 presents the standardized path loadings (β) along with their corresponding statistical significance (*p*-values). Notably, six out of the eight specific hypotheses formulated in accordance with our research objectives exhibited statistical significance, with the exceptions being H4 and H8.

Table 6.7 Hypothesis testing results and standardized path loading values

Research Hypothesis	**Estimate (*β*)**	**Standard Error**	**Critical ratio**	***p*-value**
H1: Annoyance in general: disturbance	0.81	0.035	10.35	0.003

H2: Annoyance based on variation in source: disturbance	0.62	0.024	2.63	0.002
H3: Annoyance based on location of stay: disturbance	0.73	0.021	5.24	0.001
H4: Annoyance based on time of exposure: disturbance	- 0.56	0.036	-6.35	0.005
H5: Annoyance in general: health effects	0.75	0.055	1.02	0.000
H6: Annoyance based on variation in source: health effects	0.58	0.026	2.45	0.004
H7: Annoyance based on location of stay: health effects	0.63	0.039	10.57	0.003
H8: Annoyance based on time of exposure: health effects	-0.51	0.052	-3.25	0.002

In terms of the Hypothesis formed to investigate annoyance-induced disturbance (H1 to H4), it was observed that disturbance associated with the time of exposure showed a strong negative relationship (β = - 0.56, $p < 0.05$), while other disturbances associated with variation in the source and location of residence exhibited a substantial positive relationship. This implies that residents living in certain locations along the railway line and when there is a variation in railway noise source, residents are more likely to experience higher levels of disturbance due to annoyance.

Concerning the hypotheses related to annoyance-induced health effects (H5 to H8), a strong negative relationship (β = - 0.51, $p < 0.05$) was observed between the duration of exposure and health effects. Conversely, health effects associated with the variations in the source and location of residence exhibited a substantial positive association. These findings imply that residents in particular geographic locations near the railway line and those exposed to diverse railway noise sources are at a heightened risk of encountering more pronounced health effects due to annoyance.

These results were somewhat contradicting with Ledesma et al. (2021) and the difference was due to the difference in railway infrastructure and noise levels produced by it, cultural and socioeconomic factors, population density, and living conditions, socioeconomic status of residents.

6.5.4 Mediation and moderation testing

The dependent variable in the mediation analysis is health effects, with the independent variables being railway noise annoyance and daily activity disturbance. Assessing the indirect effects of disturbances on health and determining their statistical significance are the main goals of the mediation analysis. The results of the mediation analysis are presented in Table 6.8, revealing that the indirect effects of disturbances on health are statistically significant ($\beta = 0.111$, $p < 0.05$), thereby confirming the acceptance of hypothesis H9.

Table 6.8 Mediation testing results

Hypothesis No.	**Total effects**	**Direct effects**	**Indirect effects**	**Remarks**
H9	β = 0.157 P = 0.001	β = 0.046 P = 0.001	β = 0.111 P = 0.000	The hypothesis is accepted since indirect effects are statistically significant.

The moderation analysis is conducted by treating the distance of dwelling units as a moderator variable that influences the strength of the relation between health effects and annoyance caused by railway noise. The results indicate that the distance of dwelling units exerts a positive and significant influence ($\beta = 0.024$, $p < 0.05$) on health effects, hence H10 is accepted. The results of the moderation analysis are presented in Table 6.9.

Table 6.9 Moderation testing results

Hypothesis No.	**Estimate (β)**	**Standard error**	**C.R.**	***p*-value**	**Remarks**
H10	0.024	0.054	5.450	0.043	The hypothesis is accepted since indirect effects are statistically significant.

Chapter 7

SUMMARY AND CONCLUSIONS OF THE STUDY

This chapter includes a summary of current research work, along with conclusions and limitations. Further, the scope for future work is also presented.

7.1 Summary

Noise control strategies can be employed at various stages, including the source, transmission pathway, and receiver. Among these methods, the most effective approach for managing potentially harmful noise in any setting is to minimize it right at the source. The literature review has revealed that less research has been done on eliminating railway noise at the source. Hence, the current study aims to mitigate noise emanating from the sources based on a thorough study of train specifications to identify problems leading to high and unwanted noise generation. The influence of several parameters such as train type, train speed, train length, and measuring distance on the train noise was analyzed. In addition to these source-related factors, the current study investigates noise levels at railway level crossings, where several activities related to transportation noise were involved. Hence, the current study measured train honking noise levels at a level crossing for various train speeds, train lengths, and climatic conditions to assess train horns' impact on trackside residents. The study evaluated four distinct scenarios at the level crossing, with noise measurements conducted for each scenario, which are as follows: (i) level crossing in the open condition where there is a smooth flow of vehicular and pedestrian traffic, (ii) closed condition where there is an accumulation of vehicular and pedestrian traffic, (iii) passage of train with and without honking, and (iv) gate opened after the passage of the train where the drivers tend to accelerate the vehicles. In addition to impact assessment, the current research uses the ANN technique to model train honk noise levels. The study involved collecting and analyzing a total of 194 train horn recordings.

Next, the study focuses on investigating the transmission of the noise produced by the railway line to find the safest distance from the railway track in the absence of a noise barrier for housing construction so that the people residing in those houses will be subjected to sound levels less than the prescribed sound levels. Transmission path characteristics are crucial in elevating or abating the noise levels. Most of the research has been conducted on noise emitted from a stationary point source; meteorological effects on more realistic time-varying line sources, such as railway noise, have received little attention in the literature. As a result, the current study uses railway noise as a realistic time-varying moving line source to investigate the effects of wind speed, wind direction, air temperature, and humidity on railway noise propagation. Furthermore, this research generated noise contour maps for spatial visualization and presentation of the current noise pollution due to trains in an urban area. A total of 106 train observations were collected for analysis. In addition, the variation of railway noise due to the presence of a wall between the source and receiver is analysed to evaluate the acoustic performance of railway boundary walls to serve as noise barriers through a simulation-based approach. The study aims to determine the boundary walls' optimal geometry, shape, and surface material by varying these factors and evaluating their impact on noise reduction. To achieve this, a numerical model based on CFD is used to predict the insertion losses of an optimal boundary wall. In addition to the numerical model, field tests were conducted for the railway boundary walls constructed with stone masonry on either side of the railway line. The efficiency of the barrier was evaluated by measuring the noise spectra in front of the barrier and at behind the barrier at several points along the length of the barrier.

Finally, the study evaluates the impact of railway noise on the residents by measuring noise levels inside the houses along the railway tracks. A human perception survey was also conducted to explore the correlation between noise levels and annoyance experienced during daily activities. A population size of 316 respondents was selected based on statistical considerations to represent the diverse residents living along the railway line. Factors such as age, gender, proximity to the railway line, duration of stay, education, and occupation of the respondents were considered for developing the exposure-response relationship. Integrating the findings from noise measurements with human responses can lead to a more precise evaluation of the impact of railway noise pollution. Since the current study employs a questionnaire-based approach for quantifying human response, a Structural Equation Model was employed to examine the intricate relationships among the variables.

7.2 Conclusions

The following are the significant conclusions drawn from the current study:

i. The analysis of the variation of railway noise with change in train type indicated that passenger trains, specifically LHB trains, exhibited elevated noise levels. In the case of freight trains, it was observed that loaded open wagons produced increased noise levels. Train length was found to be a significant parameter in railway noise generation in the case of freight trains rather than passenger trains. Train speed has the strongest correlation with railway noise, and an increase of 2.8 to 3 dBA was observed by increasing the train speed by 10 km/h. The variation of railway noise with changes in wind direction detected an average sound level difference of 7.8 dBA for the same wind speed. A 1°C increase in air temperature resulted in a 0.51 dBA increase in sound level. The influence of humidity is relatively minor at shorter distances (i.e., 25 and 50 m), but at larger distances of 100 and 200 m, there is a significant attenuation of 4.3 to 7.8 dBA. The noise maps suggest a minimum distance of 203 m, corresponding to 55 dBA, and 225 m corresponding to 45 dBA, from the railway line for the construction of residential buildings when there is no noise barrier.

ii. Among all the four scenarios analyzed at the level crossing, the highest noise levels were emitted when the railway gate was closed, permitting train passage and honking; the maximum noise recorded was 104 dBA. When the roadway vehicle's engine was not turned off during the waiting period, an additional 10 dBA of noise emanated and an additional 2 to 3 dBA of noise due to the presence of pedestrians at the railway gate. When the railway gate was opened to the roadway traffic, an additional 5 dBA of noise emanated due to the sudden acceleration of two-wheelers and cars.

iii. The analysis conducted on the railway boundary wall at 0.5 m ahead of the barrier recorded a higher noise level because the sound waves from the moving train hit the barrier and reflected back to the same side. When noise levels were measured at 0.5 m behind the barrier, there was a decrease in noise by 6.3 dBA, and also, the noise levels at the façade of the residential area were found to be 4 dBA lesser. As the height of the barrier increased, the insertion loss also increased, and the highest insertion loss was 17 dBA when the barrier height was 6 m. The T-shaped noise barrier with a vertical wall height of 5 m and a projected top length of 2 m obtained the most significant noise reduction of 20 dBA. The Y-shaped noise barrier is less effective than a T-shaped barrier but more effective in reducing noise on the upstream side. The noise barriers with different surface materials were tested, and it was found that the T-shaped barrier covered with a soft material resulted in the highest noise reduction of 22 dBA.

iv. The noise measurements taken at residential units located several distances from the railway line indicated that both passenger and freight trains exceeded the noise guidelines set by the CPCB of India. Noise levels at the façade were consistently higher than the interior, with a significant increase of 10 dBA when doors and windows were closed. Annoyance caused based on general criteria, variation in source, and location of stay positively affected the disturbances to daily activities and health effects. The annoyance based on time of exposure showed a negative impact on the disturbances to daily activities and health effects. This indicates that residents living along the railway line have become more accustomed to the noise over time, and this phenomenon is known as habituation or adaptation. The distance of the dwelling unit from the railway line enhances the relation between annoyance and health effects. The disturbances to daily activities caused by annoyance from railway noise can indirectly affect health due to the complex relationship between environmental stressors like noise and human well-being.

v. Several noise prediction modes were developed by considering the noise source, transmission path, and receiver parameters. The MLR model developed in this study could be used to estimate train noise in cities similar to that of Warangal in Telangana state, India. The developed ANN model accurately predicts railway noise and can be a valuable substitute for analytical models in forecasting railway noise at level crossings.

7.3 Research Contributions and their Practical Implications

The current study makes significant contributions to both theoretical knowledge and practical applications in the field of noise control. Here are the highlighted research contributions and their practical implications:

1. **Identification of Source-related Factors:** The study fills a gap in existing literature by focusing on mitigating railway noise at its source. By thoroughly analysing train specifications and identifying factors contributing to high noise generation, such as train type, speed, and length, the research provides valuable insights for implementing noise control strategies directly at the source. This contributes to the development of more targeted and effective noise mitigation measures.
2. **Assessment of Level Crossing Noise:** By measuring noise levels at railway level crossings under various scenarios, including train passage with and without honking, the study offers practical insights into the impact of train horns on trackside residents. This information is crucial for optimizing railway operations and minimizing noise disturbances in surrounding communities.
3. **Investigation of Transmission Path Characteristics:** The research examines the transmission of railway noise to determine safe distances for housing construction in the

absence of noise barriers. By considering factors such as wind speed, direction, temperature, and humidity, the study provides valuable data for urban planning and infrastructure development, ensuring that residential areas are located at safe distances from railway tracks to mitigate noise exposure.

4. **Evaluation of Noise Barrier Effectiveness:** Through simulation-based approaches and field tests, the study evaluates the acoustic performance of railway boundary walls as noise barriers. By identifying optimal barrier geometries, shapes, and surface materials, the research offers practical guidance for designing and implementing effective noise mitigation measures along railway corridors, enhancing the quality of life for nearby residents.
5. **Assessment of Human Perception and Response:** By integrating noise measurements with human perception surveys, the research provides insights into the impact of railway noise on residents' daily activities and well-being. The development of a Structural Equation Model facilitates a deeper understanding of the complex relationship between environmental stressors like noise and human health, informing policy decisions aimed at minimizing adverse effects on community health and quality of life.

7.4 Limitations of the Study

The limitations of the current study are presented below:

1) The variation in railway noise is influenced by factors such as wind turbulence, air pressure, ground characteristics, and the existence of any obstructions between the source and receiver. However, due to the complex nature of the analysis, these variables were not considered in this study.
2) While performing a simulation study on noise barriers, the noise levels emitted by the line source were constant as the distance from the source increased. This assumption was made to simplify the calculations and avoid the need to develop another model to account for the variation of noise levels with distance. Additionally, the study kept the source and receiver distances from the barrier constant, even though this would significantly impact the noise propagation over the barrier when the source is close to it.
3) The effects of atmospheric temperature, humidity, and wind speed variations on noise propagation were not considered as such effects would increase the complexity of the present analysis. These conditions can have a significant impact on the effectiveness of the barrier

in reducing noise pollution. However, it can be challenging to accurately simulate these conditions and their effect on the barrier using computational fluid dynamics (CFD) due to the complexity of the environment. It is acknowledged that excluding these parameters may lead to an underestimation of the insertion loss values, but the overall process of noise propagation for different noise barriers remains the same, and trends are expected to remain consistent.

4) While the current study develops multiple linear regression models to predict L_{eq} and L_{max}, the model is capable of predicting railway noise based on factors like train speed, type, and length. The model consistently outputs noise levels higher than established guidelines. This tendency towards overestimation is particularly higher during night times characterized by minimal background noise. As a result, the model's predicted base noise values may not accurately reflect the actual ambient noise conditions during such periods.

7.5 Scope for Future Work

This study can be extended further by taking into account the following points:

1. While evaluating the influence of source components on railway noise, it was assumed that track parameters such as surface roughness, profile, joint spacing, ballast type, and condition remained constant. This study can be extended by considering the above source parameters and evaluating the impact of these on railway noise variation.
2. More studies must be conducted on the directivity of the sound waves from the horn placed on top of the locomotive. The variation of noise levels and its propagation pattern at various wheel and rail roughness has to be studied.
3. Rolling noise modelling is well established, but aerodynamic noise modelling is still in the developing stage. The contribution of other sources like equipment noise, engine noise, cooling fan/ ventilation, etc. has to be modelled to develop a comprehensive noise control measure.
4. In transmission path characteristics, the impact of wind turbulence, air pressure, ground characteristics, and any obstructions between the source and receiver must be considered to develop more accurate noise maps.
5. Implementing a methodology to separately record background noise levels at the study sites would facilitate a more comprehensive analysis of the impact of trains compared to

background sound levels. This approach would offer valuable insights into the relative contributions of trains and background noise to overall noise levels, thus understanding the overall perception of annoyance and the health impacts associated with railway noise.

6. Studies should focus on monitoring and evaluating railway honking during nighttime to comprehensively assess noise impacts on public health and well-being and effective noise management policies.

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BOOK CHAPTER

1. **Kumar, B.S.**, and V. Chowdary. 2023. "Railway noise pollution in urban environments: sources, effects, and control strategies." *Handbook of Vibroacoustics, Noise and Harshness*. https://doi.org/10.1007/978-981-99-4638-9_2-1