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Environmental Impact Of Noise Pollution In Urban Metro Systems: A Case Study Of Pune Metro

Mayur Pardeshi[1*], Shantini Bokil[2]
[1*]MTech Research Scholar, Department of Civil Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India.
[2]Professor, Department of Civil Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India.
*Corresponding Author: E-mail: mayurpardeshi2018@gmail.com

Abstract
In India, urban metro systems are being adopted more and more as effective solutions for the problems associated with urban mobility. However, further research is need to fully understand the environmental externalities connected to these systems, especially noise pollution. This study examines the effects of noise pollution on the environment in the Pune Metro, a recently opened urban transportation system, with an emphasis on finding effective mitigation techniques. The study determines the main sources of noise, such as wheel-rail interaction, braking systems, and station announcements, by conducting on-site noise level monitoring at a few stations and along track segments. Particularly at peak hours and in densely populated areas, noise levels at a number of locations were found to surpass the limits set by the World Health Organization (WHO) and the Central Pollution Control Board (CPCB). The study assesses both proposed and existing mitigation techniques in order to address these problems. To reduce noise, technical solutions including sound-absorbing tunnel linings, sturdy wheels, and track dampers have been explored. Additionally, there is potential for architectural interventions such as the construction of quieter public address systems and the placement of acoustic panels in stations. Regular noise monitoring, integration of noise control into metro planning guidelines, and launching public awareness campaigns to reduce behavioral noise are some policy-level options. The study comes to the conclusion that reducing the negative effects of metro-related noise pollution on the environment and human health requires an integrated strategy that combines engineering innovation, law enforcement, and community involvement. This case study of the Pune Metro contributes practical insights for other emerging metro systems across developing urban regions.
Keywords: *Environmental Impact, Noise Pollution, Pune Metro, Mitigation Strategies*

INTRODUCTION

One of the distinguishing characteristics of the twenty-first century has been urbanization, especially in emerging nations like India. Urban infrastructure, especially in the area of transportation, is under more strain as a result of rapid population expansion, migration to cities, and growing economic activity [1]. As part of a larger trend towards sustainable urban development, metro rail systems have been extensively implemented throughout Indian cities to address long-standing problems with air pollution, traffic congestion, and inefficient mobility [2]. Pune, one of the fastest-growing metropolises in India, launched its metro rail project with the vision of offering a reliable, eco-friendly, and efficient mode of public transportation [3].

It is anticipated that the Pune Metro will drastically cut down on both automobile emissions and reliance on private vehicles. Although metros and other mass rapid transit systems are known to have positive environmental effects, particularly in terms of lower greenhouse gas emissions and particulate pollution, their contribution to noise pollution is frequently disregarded [4]. One important but little-studied component of urban environmental health is noise pollution, which is defined as undesired or damaging sound that disturbs the natural environment [5] and has an impact on human well-being. In metro systems, noise is generated from multiple sources: the interaction between train wheels and rails, operation of braking systems, propulsion motors, station ventilation and announcement systems, and the general movement of commuters [6]. When metro infrastructure runs through densely populated urban areas—as is the case with Pune—such noise can have pronounced effects on surrounding communities. Excessive and prolonged exposure to transit-related noise has been linked to a range of negative outcomes, including hearing impairment, cardiovascular stress, sleep disturbances, reduced work productivity, and diminished quality of life [7]. Moreover, there are environmental consequences, such as the disruption of urban wildlife behavior and degradation of natural soundscapes [8].

The majority of study on metro-related noise pollution in Indian cities focuses on air quality, energy efficiency, and ridership trends, despite these ramifications [7], [9]. By carefully examining the environmental effects of noise pollution brought on by the Pune Metro, the current study aims to close a significant gap in this knowledge [10]. This study will not only measure the variations in noise levels at different locations along the metro corridor but also examine how much noise levels exceed the acceptable limits of noise levels as expressed by the World Health Organization (WHO) and Central Pollution Control Board (CPCB) [11]. This report has been completed but does identify the need for an additional analysis of mitigation strategies. Noise can be a relatively complex problem; dealing with it successfully involves a public awareness component, engineering design, land use planning, and a level of enforcement and regulations [12]. Given this complexity, the study considered many different types of noise mitigation strategies that ranged from policy measures (such as laws for noise monitoring, or recognizing community participation) to technological measures (such as changing the track, or working on noise barriers) [13]. The report seeks to be an effective and comprehensive framework for transportation officials, legislators, and urban planners in Pune and the future use of similar frameworks in other cities [14]. Ultimately, the goal of this study is not only to highlight a critical environmental issue but to contribute to the growing body of knowledge that seeks to make urban transit systems both efficient and environmentally sustainable [15] [16]. As cities continue to expand and invest in mass transit infrastructure, understanding and managing noise pollution will be crucial to maintaining the health, well-being, and livability of urban environments [17].

2. METHODOLOGY

In order to thoroughly examine the level of noise pollution brought on by the Pune Metro and investigate practical mitigation techniques, the methodology utilized in this study combines field-based quantitative data collecting with qualitative assessments. Study area selection, noise data collecting, benchmark comparisons, data analysis, and mitigation technique evaluation are the five main components of the three-month study, which was carried out between January and March 2025.

A. Study Area and Site Selection

The study used a deliberately varied set of sites that represent the different physical and contextual elements of the metro network in order to provide a thorough and representative understanding of noise pollution throughout the Pune Metro system. To enable a comparative study of noise behavior in various structural contexts, both elevated and underground metro sections were included. A number of important considerations influenced the choice of study areas, including the most common land use types (residential, commercial, and mixed-use zones), population density, and the locations' closeness to sensitive receptors (such as schools, hospitals, and places of worship or culture) where exposure to noise may have more severe social and health effects. Five main categories of sites were chosen for field data collecting within this framework. Noise levels in above-ground infrastructure were revealed by elevated stations such as Vanaz, Ideal Colony, and Nal Stop. On the other hand, underground stations like Shivajinagar and Civil Court made it possible for the study to evaluate how noise travels and is perceived in enclosed underground spaces. In order to determine how much noise passengers were exposed to while in motion, onboard train compartments were observed during active transit between important stations. In order to measure the noise produced by train operations, servicing, and maintenance activities which frequently differ from those during routine transit—the metro depot area was included. Finally, a survey was conducted to assess the impact of metro-related noise on neighboring communities in residential areas situated within a 100- to 200-meter radius of metro routes. Two stations and - wherever possible- one residential location were identified from each of the Purple Line and Aqua Line respectively, Pune metro's two main operational lines to provide broad geographical situatedness and situational diversity. This thorough site selection procedure was intended to produce an accurate and holistic measure of noise pollution in different metro ecological settings.

B. Noise Level Data Collection

We used Class 1 precision Sound Level Meters (SLMs) that are recognized as highly objective and accurate and adhere to global standards, and specifically, the IEC 61672-1:2013 standards, to record noise level data for this research. In order to maintain objectivity and to secure accuracy of recorded results, all meters were carefully calibrated every day prior to use. Additionally, noise level collection was intentionally affected by factors such as weather. We ensured that we collected data during appropriately stable weather conditions to avoid any alterations to the noise due to external factors such as wind, rain, and unrelated, surrounding construction projects, that could interfere with the ambient noise associated with metro levels. Also, we documented diverse indicators in the acoustic characteristics we collected, and during analysis, used several of them to allow us to discuss only average and peak behaviors of sound. The average noise level for a given observation period was calculated using the Equivalent Continuous Sound Level (Leq) which provided us with an overall acoustic environment index. When we wanted to provide further detail on the peaks and troughs of noise exposure, we used Lmax and Lmin, which represent the maximum and minimum recorded sound levels we documented during the period. We also reported L10 and L90 values, meaning the noise values exceeded 10% and 90%, respectively, of the time. These factors were helpful in putting thresholds between background ambient sounds and dominant noise events. Finally, we also employed decibels A-weighted [dB(A)] which is mostly employed in environmental noise studies that takes into account environmental cues. To attain change over time in noise exposure, readings were carried out in a systematic manner using three important time units; the morning peak (7.30 am to 9.30 am), afternoon off-peak (12.30 pm- 2.00 pm), and the evening peak (5.30 pm- 7.30 pm). On various visits to different sites, each observation took 15-30 minutes, depending on the complexity and dynamics of place. To ensure such authenticity and representativeness of the data at each point, multiple measurements were taken.

C. Reference Standards and Benchmarking

The specified levels of the measured sounds were systematically correlated with two reference standards both national and international such that the level of the extent of the noise pollution in the Metro routes in Pune could be assessed. The research was followed by the limit of ambient noise indicated by the Central Pollution Control Board of India (CPCB) under the rules of 2000 that is, the Noise Pollution (Regulation and Control) Rules. The limits set maximum tolerable limits of noise in use of the following land-use categories; residential (55 dB(A) during the day and 45 dB(A) at night), commercial (65 dB(A) during the day and 55 dB(A) at night), and silent or sensitive zones (50 dB(A) during the day and 40 dB(A) at night in places of worship, hospitals, and schools). The study also included the World Health Organization community-noise guidelines for noise pollution, which do not call for outdoor living areas to remain below 55 dB(A) and for rail traffic noise to have a 24- hour average less than 70 dB(A) to avoid "significant annoyance or adverse health effects." The study was able to demonstrate deviations from acceptable regulatory limits and to identify the potential risks to the public's health and quality of life in.

D. Data Processing and Analysis

To produce a single database that identified each observation by location, date, and time period, all raw measurements were first entered into Microsoft Excel. The final spreadsheet was then entered into an input file for a more sophisticated statistical analysis using SPSS and R. Descriptive statistics (mean, median, standard deviation) were calculated at each monitoring point. Comparative tests detected trends between elevated and underground stations, and between platform settings along with train-based measurements. Time series plots were created using the same platform-based measurements to illustrate how noise levels fluctuated throughout the day. Results were geocoded (where geographic information was available) and displayed in GIS environments (i.e., Geographic Information Systems). The study also highlighted spatial "hotspots" by overlaying noise contours on land-use and urban density maps; it was also noted that all results were compared against national and international environmental-health thresholds. Special care was taken when reviewing the locations with the greatest likelihood of noise levels exceeding allowable limits in many cases, as these were locations that could present the greatest public-health threat.

E. Mitigation Strategy Evaluation

The study used a multi-pronged strategy that combined fieldwork, expert input, and global benchmarking to find and evaluate appropriate mitigation methods for noise pollution in the Pune Metro system. To record the type of noise reduction currently being undertaken on their metro corridors, a field study was conducted. Such installations were platform screen doors, rail dampers, ballast mats and noise barriers. Our site-level findings were supported by the reports of institutional sources that present the typical practices of mitigation used in other transit systems, e.g., the World Health Organization (WHO, 2018), or the International Association of Public Transport (UITP, 2018). Semi-structured interviews and expert consultations with key stakeholders, including Maha-Metro engineers, Pune Municipal Corporation (PMC) environmental officers, and more significantly, the urban planners who have experience of developing metro corridors elsewhere, complemented these findings. They were able to understand the expressibility of the proposed and existing interventions to a technical and contextual perspective through their observations. The study also used global best practices in order to widen the range of options. These comprised modifications to train tracks such as rail grinding, and strong fasteners, which accounted to most of the noise reduction measures in the US and Europe, according to Thompson (2009) and the FTA standards (2018). They also addressed improvements of the architecture of the station, following the example of the sound-absorbing ceilings and acoustic paneling that is used in the subterranean stations of the Singapore MRT and Delhi Metro (DMRC, 2011; WHO, 2018). More emphasis was paid to using strong wheels, smooth undercarriages, and the like of wheel skirts - these strategies have been quite successfully used in the European metro areas in the context of the efforts by the International Union of Railways (UIC, 2013). According to the Railway Technical Research Institute (RTRI), public address system improvement in Japan has demonstrated that enhanced clarity at lower volume levels can greatly reduce ambient station noise. In order to avoid noise intrusion into sensitive residential areas, the Ministry of Environment, Forests, and Climate Change (MoEFCC, 2010) of India recommended buffer zones and setback distances as urban design measures. The technical viability, cost-effectiveness, degree of noise reduction attained, and present or intended use inside the Pune Metro were the four main criteria used to evaluate each mitigation method. The study was able to uncover both promising ideas and current gaps for improved environmental noise management thanks to this integrated assessment.

Sources for Noise Mitigation Strategies in Metro Systems

1. Platform Screen Doors (PSDs)

In recent times, Metro transit systems have had PSDs (Platform Screen Doors) fitted in order to mitigate noise pollution in their stations and surrounding areas. According to a 2018 UITP report on Platform Screen Doors in Metro Systems: Benefits and Challenges, these doors serve two distinct functions. Firstly, as they separate passengers from the oncoming train, PSDs significantly reduce noise levels on platforms. The containment effect refers to the breaking of the direct path of wheel-rail interaction noise and sudden air pressure bursts from the fast-moving trains. Second, PSDs help to isolate and contain tunnel-aerial noise and limit the above-ground leakages of tunnel noise into public venues such as the station hall.

These doors are widely used in modern metro systems like the Singapore MRT and the Hong Kong MTR because of their historical ability to improve both safety and acoustic comfort. PSDs yield operational benefits like climate control and enhanced passenger safety by denying track access, noise reduction for passengers, and better passenger flow management. The inclusion of PSD indicates a larger commitment to environmentally clean, commuter-friendly urban transit infrastructure design.

2. Resilient Track Fastening and Ballast Mats

During resilient track fastenings, the elastomeric elements are installed between the rail and the supporting base, which involves sleepers or concrete slabs. Such elastic structures dampen a part of the vibrational energy created by the wheel-rail contact and decreases the ground noise as well as aerial noise. Ballast mats which are usually between the ballast layer or the slab track systems also observe the same pre-requisites. They minimize the volume of the vibration which passes to the neighboring buildings or delicate infrastructure by minimizing the connection between track structure and subgrade. They are durable composite or rubber.

In resilient track fastenings the elastomeric materials (concrete slab or sleeper) are inserted between the rail and the supporting surface. The versatile layers help to reduce the amount of noise in the ground and air since they partly absorb the vibrational energy produced in the process of wheel-rail interaction. Ballast mats are mats that are normally placed under the layer of the ballast and they are used just like the slab track systems. They also reduce the vibration being transferred to other structures or sensitive infrastructure since they decouple the track structure and the subgrade. They are composite or tough rubber made.

The use of these two technologies in combination by cutting mechanical wear and fatigue has the effect not only in making the metro system quieter but also having the effect of prolonging the life of track components. These techniques are also getting more application in urban localities that are overcrowded because structural noise reduction is crucial in terms of reducing the quality of life of the neighbors and minimizing complaints.

3. Rail Grinding and Track Maintenance

The combined effect of the use of these two technologies not only makes the metro system quiet but prolongs the life of the parts of the tracks with which mechanical effects collide and lead to wear and fatigues. In the heavily occupied urban space areas, such approaches are gaining popularity as reducing structural-borne noise in these areas is critical to preserving the living conditions of adjacent residents and decreasing complaints.

The surface of the rails are worn down through constant train movement and this may cause corrugation or creating flat spots or a corrugated surface. The weaknesses become the places of impact or resonance of train wheels when it is passing by the object and produces loud sounds, which may influence the passengers and even the surrounding inhabitants. To eliminate these imperfections rail grinding is used with specialized machinery that grinds the rails by the use of rotating grinding stones to achieve the perfect rail profile once again.

Regular maintenance of the tracks is not only occurring through rail grinding; replaced worn parts, and verify fasteners, as well as level the rails to remove the deviation, are also part of the activities. These prevention efforts will limit noise and enhance the quality of the ride, safety, and energy efficiency by establishing a consistent train-to-track contact.

Through a strict grinding and maintenance program, officials of the metros will be in a position take noise pollution a notch lower, extend the life of the infrastructure and ensure the environmental standards are observed. Loudspeaker latting has been used greatly in domestic systems of transport within the US, in Europe and Asia as a cost-effective measure of noise management.

4. Acoustic Absorbers and Noise Barriers

Noise barriers and acoustic absorbers are important parts of the infrastructure aiming to keep and enforce noise ventilation during the metro system, particularly in heavily populated urban regions. These structures are intended to break and absorb the sound wave caused by passing trains and further extend to other nearby residential, business, or educational areas as indicated in the Technical Specifications for Interoperability - Noise TSI, with reference to the activities of the European Commission (2014). Noise barriers are constructed by the use of noise-absorbing granules like composite acoustic materials, acrylic panels, metal sheets having insulating cores or concrete specially treated. It is common to find them close in line to the elevated tracks or at ground level. Their length and height can differ according to the terrain around them, train velocity and the city population. Besides the physical impossibility of sound to travel in a line sight, the rough or perforated barriers enhance the sound-absorbing properties of many barriers as opposed to sound-reflective properties. Acoustic absorbers, on the other hand, have a tendency of being installed within architecture of stations or tunnel linings. This means the use of sound-dampening panels on walls, ceilings and track beds, baffles or foam-based treatment. They minimize reverberation and echo especially in an enclosed area such as in the tissue of a tunnel or underground station where echo bounces sound off the hard surface. Collectively, these passive mitigation measures are quite popular in the European metro networks, and are gaining popularity in the Asian and North American scenarios. They should be effectively placed, maintained and adapted to the local acoustics and environment. Through such actions, metro systems will be able to expose nearby places to minimal noise, making the city livable and ensuring that the noise control regulations are followed.

5. Rolling Stock Design (e.g., low-noise bogies, wheel skirts)

Rolling stock design is crucial for regulating and lowering noise emissions from metro systems, both outside and inside train compartments. According to the Railway Noise in Europe: State of the Art Report (UIC, 2013) published by the International Union of Railways, advancements in vehicle-level engineering have led to a significant reduction in operational noise levels. One of the main innovations is the use of low-noise bogies, which are the wheel and axle assembly underneath train cars. These bogies are equipped with vibration-dampening features, such as resilient wheels with elastomeric components, to absorb and distribute vibrational energy generated during movement. Both rolling noise and mechanical vibrations that are transmitted to the track and adjacent infrastructure are reduced by changing the design.

Additionally, among other streamlined undercarriage designs, wheel skirts and noise-dampening coverings help to contain and deflect noise from auxiliary equipment such as motors or brake systems as well as wheel-rail interaction. These covers not only enhance the train's aerodynamic profile but also act as acoustic barriers, lowering the volume of noise that reaches the surrounding area. Better suspension systems, quieter HVAC systems, and increased sound insulation in cabins are additional characteristics of contemporary rolling stock that improve passenger comfort while reducing noise emissions outside. Following their successful implementation in several European metro systems, these design improvements are gradually being incorporated into newer fleets across the globe, including in Asia and North America. These measures are particularly effective when combined with infrastructure-level interventions, making them a crucial component of an all-encompassing noise abatement strategy for urban rail transit.

6. Station Design Enhancements (e.g., acoustic panels, sound-absorbing ceilings)

Station design is a major aspect of noise minimization strategies, particularly in underground or enclosed metropolitan stations where noise annularity is a major concern. The Environmental Noise Guidelines for the European Region, the terminology document to be used by the WHO Regional Office for Europe in 2018, notes that a significant improvement in the acoustics of employees and passengers can be achieved by adding sound-absorbing materials to the design of the stations. Application of sound absorbing ceiling tiles and finishes, installation of acoustic panels in the walls and ceilings of the station are such notable interventions. These are materials used to reduce reverberance and echo within a confined space by reducing the amount of noise reflected on hard surfaces. This is more importantly important on an area whereby there is a large number of announcements to be made in the public, people walking up and down, and trains arriving or departing, which all increase background noises. These enhancements will raise the level of speech intelligibility as the reverberation time will be reduced, and lower volume level announcements will be easy to understand. As a consequence, there will be less need to use overly loud announcement sources and commuter acoustic fatigue as the noise exposure level will be reduced. Such elements are used effectively in places such as the metro systems of the Delhi Metro and Singapore MRT where aesthetic combinations of acoustic control solutions help balance the dictates of practical noise suppression control verses visual appeal. Summing up, the process of acoustic changes at the station level is an acceptable and useful option to increase the comfort of commuters and address environmental noise problems in subway networks.

7. Case Study: Delhi Metro

The Delhi Metro is one of the famous cases of efficient noise control in the rail networks of big cities, particularly in crowded cities such as the capital city of India. The infrastructure and technology involved in the system have integrated advanced technology and infrastructure in a manner that minimizes noise pollution as indicated in the Environmental Impact Assessment (EIA) Reports prepared by the Delhi Metro Rail Corporation (DMRC) on various sites and released on various phases such as the Phase-III. One of the most notable interventions is the installation of track bed vibration isolators, and they help decouple the track and the supporting structure. This alleviates transmission of vibrations and structure-borne noise especially in higher and subterranean places where the above-mentioned effects are more evident. These isolators minimize the amount of noise in the metro and around the communities as they absorb and scatter the vibrational noise that is caused by train motion. Noise barriers have also been constructed by the Delhi Metro in the sensitive areas where there are schools, hospitals and residential areas, too, and also along the elevated railway lines. Such obstructions do not allow sound waves to pass directly between trains and immediately receive receptors. They are normally made of clear acrylic or other sound absorbent materials. This has been effective in maintaining the level of background noise to proper limits defined within the Central Pollution Control Board (CPCB) and other regulatory systems. Through such steps of anticipation, the Delhi Metro has set a regional benchmark in dealing with the issue of noise in mass rapid transport systems. Its multifold approach, encompassing the topics of compliance, technology, and infrastructure demonstrates the efficient and environmentally sustainable character of the metro systems. The lessons could be of great value to emerging systems such as the Pune Metro which are able to adopt and adjust similar methods according to the local setting and circumstances of operation.

8. Public Address System Optimization

To maintain the noise levels within the inside of a metro station to minimum manageable levels but ensure effective intelligibility of essential public service announcements, one will need to optimize a metro stations public address (PA) system. Improvement on producing low-noise PA systems which are both discrete and high-efficiency has been made significantly; at least, this was what research undertaken by Japan Railway technical research institute (RTRI) has found. Traditional public address systems are also on high-volume output, in enclosed environments, especially on underground metro stations, to ensure that the announcement can be heard over background noise caused by passing trains and people. It can however lead to listener fatigue and overall sound pollution. Conversely, the modern low-noise PA systems in RTRI do not require any manual adjustments to achieve or maintain appropriate sound level since directional loud speakers, advanced signal processing and real-time measurement of environmental noise is done. This interprets to mean that the announcements adjust automatically to the level of loudness that is dictated by the accompanying sound in the background but still remaining audible to the necessary levels of decibels. These systems are made more effective by positioning speakers strategically hence use clearer audio frequencies and less reverberation, thus eliminating distortion and echo resulting to that effect. This enhances the effectiveness of communication and acoustic comfort in stations as the commuters will be able to hear announcements at lower levels. By implementing such an optimized PA technology, metro systems can significantly reduce one of the frequently overlooked causes of noise pollution in a situation in which a lot of people use public transport. In the case of such systems as that of Pune Metro where a careful balance has to be drawn between the management of noise in environmental situations, and the need to communicate efficiently, the system applied by the Japanese trains is a valuable pattern to follow.

9. Urban Planning & Setback Regulations

Particularly in crowded urban areas, setback laws and urban planning are essential tactics for reducing the long-term acoustic impact of metro systems. Spatial planning is essential for preventing environmental noise at its source and along its path of propagation, according to the Environmental Noise Pollution Guidelines released by the Indian Ministry of Environment, Forests, and Climate Change (MoEFCC) in 2010. The rules stress how crucial it is to keep setback zones, or minimum distance buffers, between metro alignments and land uses that are sensitive to noise, like residential areas, schools, hospitals, and places of worship. The purpose of these setback measures is to lessen the direct transfer of train-related noise and vibrations onto nearby structures and public areas. Planners can naturally reduce exposure to excessive noise by placing new metro routes and infrastructure away from high-density or susceptible areas. This will lessen the need for retroactive noise mitigation. These rules are especially important when new metro lines or extensions are being designed and approved. The guidelines advise the use of alternate mitigation strategies, such as sound-insulating construction methods, green belts, or noise barriers, in locations where buffer zones are impractical because of space limitations. All things considered, the MoEFCC's strategy emphasizes how important it is to incorporate noise pollution control into the larger framework of land-use and urban planning. Following these setback guidelines can guarantee sustainable urban growth that complies with environmental health regulations and greatly improve the quality of life for locals in growing metro systems like Pune Metro.

Table 1: Priority Action Plan for Pune Metro

Mitigation Measure	Global Example	Action Plan for Pune Metro	Timeline
Wheel and Rail Maintenance	Tokyo Metro	Regularly grind rails, install rail dampers, and use profiled wheels to reduce friction noise.	Short-Term (0-6 months)
Noise Barrier Installation	Singapore MRT	Install transparent acoustic barriers and angled reflectors near residential areas.	Short-Term (0-6 months)
Speed Control in Sensitive Zones	London Underground	Introduce automated speed control, especially in residential zones like Swargate.	Mid-Term (6-12 months)
Silent Brake Systems	Hong Kong MTR	Retrofit older trains with composite brake blocks and electromagnetic braking systems.	Mid-Term (6-12 months)
Station Design Improvements	Dubai Metro	Install acoustic panels, rubberized flooring, and anti-vibration mounts in high-traffic stations like Shivajinagar.	Mid-Term (6-12 months)
Real-Time Noise Monitoring	Seoul Metro	Deploy IoT-based noise sensors and develop a Noise Control Dashboard for real-time analysis.	Short-Term (0-6 months)
Vegetative Buffers	Munich U-Bahn	Plant dense green belts and climbing plants along elevated tracks to absorb noise.	Long-Term (1+ year)
Community Engagement & Awareness	Copenhagen Metro	Launch a Metro Noise Helpline, conduct monthly meetings with residents, and gather feedback.	Long-Term (1+ year)

3. RESULTS & DISCUSSIONS

The measured environmental noise levels at several Pune Metro stations, divided into elevated/at-grade and underground categories, are shown and analyzed in this section. Bar charts have been used to compare the lowest and highest noise levels for various station types. The findings shed important light on the extent and spatial variation of noise pollution brought on by subway operations.

Noise Levels at Elevated and At-Grade Metro Stations

Fig 1: Noise Levels measured at Vanaz Metro Station

Fig 2: Noise Levels measured at Anand Nagar

The above noise levels are measured using Lutron SL-4023SD Sound Level Meter

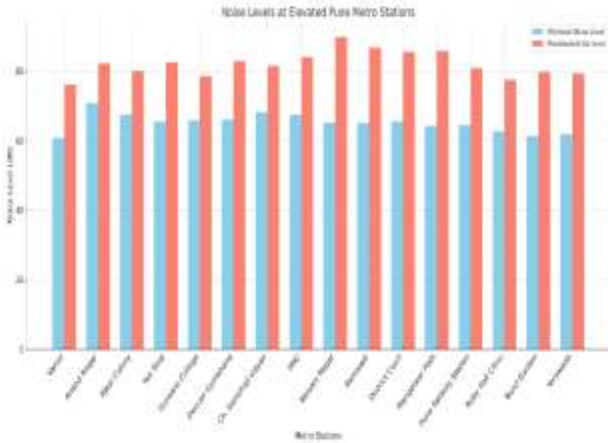

Fig.3: Noise Levels at Elevated Pune Metro Stations

The first bar graph shows the lowest and highest noise levels (measured in decibels) that were observed at 16 elevated metro stations in Pune. Locations along important transit routes, such as the Aqua Line and portions of the Purple Line, were used to gather the data.

Key Observations:

Maximum Noise Peaks: Kalyani Nagar had the highest recorded noise level, at 89.8dB. Ramwadi and Mangalwar Peth were next in line, at 86.7 dB and 85.7 dB, respectively. These stations are located in areas with high traffic or commercial activity, where city noise and metro activity combine to increase overall sound exposure.

Moderate to High Minimums: There was a consistent baseline of operating and ambient noise, as evidenced by the fact that even the minimum noise levels at several stations were between 65 and 70dB. Anand Nagar, for example, reported a minimum of 70.7 dB, which reflected the platform's background ambient, mechanical, and human activity.

Low Noise Zones: Yerawada (61.9–79.2 dB) and Vanaz (60.7–76.0 dB) are relatively quiet stations that are situated in more residential areas or on the outskirts of the city. Both the minimum and maximum dB levels were lower for them. A dynamic and fluctuating acoustic environment, frequently reliant on train arrival, announcements, or passing traffic, is suggested by the noise fluctuation range of 15–25 dB between minimum and maximum measurements seen in the majority of stations.

Implications:

According to the graph, noise levels at higher metro stations routinely above the 70 dB threshold that the WHO recommends for safe, extended exposure. High maximum values are important because they get close to or exceed occupational hazard thresholds, especially those exceeding 85dB. The information emphasizes the necessity of:

- Better acoustic insulation in busy urban stations
- Quieter rolling stock technology
- Noise mitigation techniques including sound-absorbing barriers.

Noise Levels at Underground Metro Stations

Fig 4: Noise Levels measured at Civil Court Metro Station

The above noise levels are measured using Lutron SL-4023SD Sound Level Meter

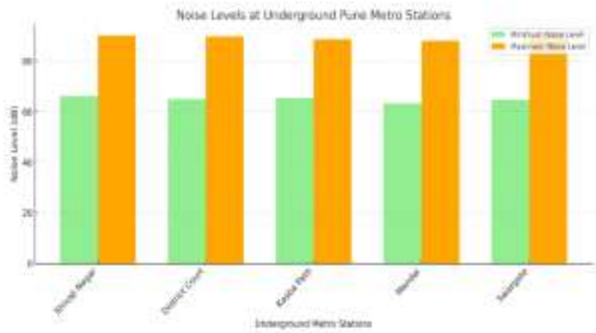

Fig.5: Noise Levels at Underground Pune Metro Station

The study also evaluated the noise levels at Shivaji Nagar, District Court, Kasba Peth, Mandai, and Swargate, five important Purple Line subterranean stations. For both lowest and maximum noise levels, these subterranean stations showed smaller but consistently high ranges compared to higher stations. Mandai had the lowest noise levels at 63.3 dB, while Shivaji Nagar had the lowest at 66.2 dB. The highest recorded noise levels ranged from 88.1 dB to 90.2 dB, with Swargate and Shivaji Nagar at the top of the range. This pattern is a result of underground infrastructure's acoustic limitations. Because enclosed tunnel conditions reduce the amount of sound that may escape, noise is amplified and reverberated from:

PA system announcements
Train acceleration and deceleration
Mechanical vibrations transmitted through concrete tunnel walls
HVAC (heating, ventilation, and air conditioning) equipment

Underground stations constantly expose people to high-intensity noise because they trap and amplify internally generated sounds, in contrast to elevated stations where noise is influenced by the surrounding environment. The following issues are of great concern:

Metro employees' occupational exposure
Passenger comfort and hearing health
Noise fatigue and stress-related effects in confined areas

The following must be included in station design to address these:

Real-time noise monitoring in stations
Quieter train technology (brake pads, smooth tracks)
Acoustic linings and sound-absorbing materials
Controlled PA volume levels

Equivalent Continuous Sound Level (Leq) Analysis

The Equivalent Continuous Sound Level (Leq) was computed in order to assess the total exposure to noise pollution from the Pune Metro System. The steady sound level that, over a certain time period, has the same acoustic energy as the fluctuating sound levels recorded during field observation is represented by this metric.

The mathematical expression for Leq is:

$$L_{eq} = 10 \times log \sum_{i=1}^{n} f_i \left(10^{\frac{Li}{10}}\right)$$

where,

L_{eq} = Equivalent continuous sound level (in dB),

L_i = Individual maximum sound pressure level readings (in dB),

f_i = Relative frequency of each noise level (assumed to be equal),

n = Total number of readings.

Calculation:
Assuming equal weighting for each of the 21 maximum sound level data obtained from elevated (16 stations) and underground (5 stations) metro stations, the calculated result is:

$$\boxed{L_{eq} = 85.84\,\mathrm{dB(A)}}$$

Interpretation:
According to the results, the average noise exposure from the Pune Metro system is roughly 85.84 dB(A), which is significantly higher than the CPCB's 55 dB(A) daytime residential noise limit and the World Health Organization's recommended threshold of 70 dB(A) for continuous environmental noise. For commuters and employees, such exposure can cause hearing fatigue, elevated stress levels, and long-term auditory damage, especially if it lasts for extended periods of time (during peak commuting hours, for example). The Leq value also confirms previous results from this study, which showed that at peak hours, the majority of underground stations exceeded 88–90 dB while central elevated stations above 85dB.

Comparative Insights & Implications
The two groups can be compared as follows:
Underground stations retain constant high noise levels due to internal metro system acoustics and structure. Elevated stations show greater noise variability due to influences from external sources and urban form.
This differentiation calls for certain noise reduction techniques. Supported by data-driven environmental monitoring, future planning should incorporate noise-sensitive design into both elevated viaducts and subterranean systems.

Location-Specific Noise Readings Around Pune Metro
Four carefully chosen sites connected to the Pune Metro system were used for field measurements in order to have a better understanding of the variance in noise exposure brought on by metro operations:
On Empty Platform
Beneath the Metro Station (Ground Level)
Inside the Metro While Traveling
On Roadways Beneath Elevated Metro Structures
Every site records a distinct acoustic profile that adds to exposure to commuter and ambient noise. The observed minimum and maximum noise levels in each of these four situations are compiled in the table below:

Table 2: Noise Level Readings at Key Metro-Related Locations:

Location	**Min Noise Level (dB)**	**Max Noise Level (dB)**
On Empty Platform	60.0	70.0
Beneath the Metro Station (Ground Level)	62.0	78.0
Inside the Metro While Traveling	66.8	81.2
On Road Beneath Elevated Metro Structures	71.0	95.0

I. On Empty Platform
An empty platform retains a moderate background sound level, according to noise measurements made without people or train activity. The platform environment, which has readings between 60 and 70 dB, is influenced by continuous low-level noises like:
- HVAC systems or passive ventilation
- Electrical equipment (lighting, PA systems in standby mode)
- Ambient echoes from surrounding traffic (for open elevated stations).

The acoustic reflectivity of structural materials provides modest amplification even if it is quieter than operational phases, suggesting a baseline that leads to long-term noise exposure, particularly for on-duty staff.

II. Beneath the Metro Station (Ground Level)
Sound levels were between 62 and 78 dB at ground level, right underneath elevated metro stations. The following factors are combined to produce these readings:
Urban street noise (engines, horns), structure-borne vibrations from above subway activities, and echo effects from overhanging concrete platforms. This area serves as a transitional acoustic environment, subject to both street-level urban noise and metro-generated noise, which frequently impacts surrounding homes, businesses, and people.

III. Inside the Metro While Traveling
Noise levels inside a moving metro train varied from 66.8 dB (the lowest) to 81.2 dB (the highest). Numerous internal and external sources are captured by these levels:

- PA announcements and ventilation systems
- Tunnel-induced reverberations and friction during acceleration and deceleration
- Mechanical noise from rolling stock and motors.

Despite its brief length, this type of exposure is recurrent and has a direct impact on commuter comfort. The measured values approach upper thresholds for safe auditory exposure, particularly during long rides, but remain within predicted bounds for enclosed transport systems.

IV. On Road Beneath Elevated Metro Structures

The noise intensity here peaked at 95 dB and did not drop below 71 dB, making it the noisiest place in the research. The readings here show:

- Heavy traffic below and simultaneous metro movement above
- Engines, honking, and ground-level human activity
- Noise reflection and channelling between underpasses and structural columns.

Urban noise pollution is most likely to occur in these acoustic convergence zones, particularly for everyday commuters, autorickshaw drivers, and street sellers that use the same roadways. Hearing fatigue, stress, and long-term auditory health problems can arise with prolonged or recurrent exposure to noise levels above 85dB.

The data unequivocally shows that different metro-related places present differing levels of noise exposure, with on-road and in-transit scenarios frequently surpassing acceptable criteria. These results highlight the necessity of specific noise reduction measures, including: Quieter rolling stock technologies, barriers or absorbent panels along roadways beneath elevated lines, noise-insulating materials at stations, and intelligent urban planning to lessen acoustic load in high-exposure areas.

Ethical Considerations

Since there were no direct human participants engaged and all data was gathered in public spaces, the study was free from formal ethical approval. Onboard and station measurements, however, required authorization from Pune Metro authorities. Throughout the research process, no identifiable or personal information was documented.

4. CONCLUSION

It was such a study which investigated the effect of the noise pollution caused by Pune Metro on the stations and trains, as well as, other neighbouring cities. Metros cause the lessening of air defilement and gridlock; however, they can cause noise in delicate and thick city settings. There was frequent encroachment of CPCB and WHO noise limits in elevated and underground stations, trains and residential places. Most noise was provided by rush-hour trains, elevated platforms and stations located close to residential areas. According to the report, metro networks implement the technologies of damping, noise walls, and alterations of structure either unevenly or ineffectively. It would involve engineering and policy in noise management. The careful research conducted at the study can reveal some of the most important environmental effects of noise pollution in Pune Metro. To begin with, noise pollution is a very damaging environmental factor that has been neglected in a sensitive area such as the house and the business premises around the metro infrastructure. The surrounding neighbourhoods are disrupted by passing trains and station activities particularly the elevated lines and the vicinities of the stations. At various locations of observation, empirical readings of Equivalent Continuous Sound Level (Leq) exceeded the daytime and night time ambient noise limits by Central Pollution Control Board. Prolonged exposure to noise is dangerous to both the people living in the area and the employees of the metro. These scenarios can lead to stress, sleeping disorders and impaired hearing in children and the aged.

The underground construction reduced noise, but altered interior sound. Much of interior noise was devised by braking systems, mechanical ventilation as well as announcements to be made in these small settings. The sound should be absorbed by the wall panels, ceilings, and PA systems in case they help the staff and passengers to hear better. According to the measurements, there were times when Metro trains could reach a peak of 75 85 dB(A). Contact noise due to wheels and rails can be reduced by grounding of rails, and use of heavy-duty wheels or dampers. The inquiry ascertained that no monitoring of noise or environmental performance of the metro in Pune could be observed. The lack of transparency and regulatory enforcement requires quality institutions, noise auditing, and the involvement of communities. The integration of technologies in planning and the democratic administration can green and quieten the Pune metro.

5. RECOMMENDATIONS

This paper suggests several mitigating approaches that would minimize noise and promote environmental sustainability of Pune Metro. The noise barriers and the sound absorbing materials must be constructed and utilized initially in the upper metro sections and the vicinities of residential locations and sensitive receptors, such as schools and hospitals. The intensity of noise pollution in neighbourhoods can be significantly abridged through the practices. Pre-emptive maintenance and regular rolling material and track maintenance will minimize mechanical sound because of damaged tires, deteriorating elements, and rough rails. Heavy fasteners and rail grinding prevent noise and smooths track surface in a long-term period to improve wheel-rail contact. Acoustically optimised public address (PA) systems, platform screen doors to dampen the noise between the platforms and the tunnels and the walls and ceilings using acoustic linings should be used in underground stations. This will curb noise in the small areas and enhance comfort to the commuters. There should be an institutionalized noise monitoring program in the city involving Maha-Metro or Pune Municipal Corporation. This program is to incorporate transparency of the data, constant monitoring and reporting to the people. This would ultimately lead to regulation compliance and confidence in the population. Lastly, noise should be dealt with in urban planning. Buffer areas and the length of setback were to be developed in the future development of metro by keeping in mind the recommendation of the MoEFCC guidelines about the gap needed between the metro infrastructure and residential or integrated complexes. Pune can become a role model in the development of environment friendly transport by incorporating noise mitigation into planning and policies. In general, this study concludes with the importance of noise pollution control in sustainable urban vehicles transportation. Through Pune Metro case study, Indian cities are equipped on how to expand its metro system as well as the advantages and the disadvantages. Besides defending the health and the quality of life of the population, noise management adds to the environmental standing of mass transit as one of the possible future elements of the urban transportation environment.

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