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Road Traffic Noise Abatement: Integrating Engineering and Policy in Nairobi City, Kenya

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Abstract

This study aimed at proposing the integration of engineering framework guidelines and policy tool’s suggestion to in future assist in the evaluation and choosing of abatement options to quiet down Road Traffic Noise hotspots in Nairobi city. Class 1 Lutron SL 4033SD Sound Level Meters were used to collect the data in 42 locations along major streets forming the road network. Data collection took place between 6th July 2025 and 12th July 2025. ArcGIS Pro 3.4 software was deployed to generate noise maps and identify high-exposure road corridors (hotspots), which include the Central Business District, Eastleigh area, Thika Superhighway, Mombasa Road, Waiyaki Way, Uhuru Highway, Airport North Road, ICD Road, and Northern Bypass. Using Google Earth, street view images of each location were generated to project exposure targets to guide in the recommendation of mitigation strategy as per the developed engineering framework guidelines discussed. From the discussed engineering framework guidelines, noise barriers are the most feasible and practical solution. Tree belts are better suited where there is available land, and, as a complementary measure, while tunnels provide the greatest theoretical attenuation but can only be applicable to new or large-scale infrastructure projects due to their cost and complexity.

Keywords

Noise, Abatement, Policy

1. Introduction

Noise has increasingly been identified as a critical environmental pollutant, especially in developing nations, comparable in significance to water and air pollution [1]. Noise is an unwanted or harmful sound. Unlike music or speech, which carries meaning or some aesthetic value, noise lacks order and is often perceived as intrusive. The impact of noise extends beyond mere annoyance; it also has a measurable impact on human health, social well-being, and the overall quality of life. The World Health Organization (WHO) identifies environmental noise as the second largest environmental health risk in Europe after air pollution, and strongly links it to cardiovascular diseases, sleep disorders, reduced cognitive performance in children, and general annoyance among urban residents [2]. There are many different sources of noise in urban areas, including transportation systems, construction sites, entertainment venues, and industrial processes, whose combined influence contributes to the growing soundscape challenges.

Road Traffic Noise (RTN) has been identified as the most pervasive and intrusive form of environmental pollution in rapidly urbanizing cities worldwide [3]. With the exponential growth in vehicular traffic, expanding road networks, and increasing population density, city residents are experiencing unprecedented exposure to chronic noise levels. RTN normally exceeds both international and local regulatory thresholds, making it an urgent environmental and public health concern [4] [5].

Several studies have underscored the need for RTN measurement as a prerequisite for developing targeted and effective policies and mitigation measures. In the early 2000s, the European Union's Environmental Noise Directive (END) mandated large-scale noise mapping for major cities and transport corridors, showing how accurate measurement of RTN provides a baseline for noise mitigation and abatement strategies [6]. Similar efforts have been made in Paris by [7], by developing noise maps, showing how spatially explicit measurements identify hotspot areas and to guide the prioritization of countermeasures. In Antalya, Türkiye, [8] demonstrated that integrating measured traffic flow data into noise prediction models allowed city planners to design targeted interventions for reducing exposure to noise. As cities grow, there is a corresponding need to carefully design abatement strategies and policies to reduce the impact of RTN exposure on city residents, especially at major hotspot locations, thus improving residents' quality of life.

In Africa, efforts to measure and mitigate RTN are gaining steady recognition, although they remain severely understudied and less developed compared to those in Europe and America. In Nigeria, [9] emphasized the importance of systematic field measurements and urban design to address noise exposure. While in Accra, Ghana, [10] their study revealed that nearly the entire city's population is exposed to noise levels that exceed the WHO thresholds, underscoring the need for targeted interventions and policy action by city authorities.

A similar condition exists in Nairobi, Kenya, a rapidly developing urban area in Eastern Africa. It experiences chronic levels of noise exposure surpassing the recommended National Environment Management Authority (NEMA) and WHO limits. Unlike many areas where noise management has advanced through extensive mitigation infrastructure, Nairobi is still in the early stages of developing systematic approaches to measure and control RTN, with few empirical studies targeted towards it and most existing research focusing on isolated areas or specific transport corridors rather than providing comprehensive city-wide assessments, such as the study by [11]. As a result, there is a need for RTN measurement and evidence-based, targeted mitigation strategies to effectively manage noise exposure across the city, improving the soundscape and making habitation tolerable for city residents.

Mitigation of RTN requires a multi-faceted approach that combines regulatory frameworks, urban planning, and engineering interventions. While vehicle design improvements, road surface improvements, speed regulations, and land use planning play a crucial role in noise mitigation, they often take longer to implement, and they are limited by enforcement challenges. More effective and practical structural and environmental interventions, such as noise barriers, road tunnels, and tree belts, offer site-specific reductions in noise exposure levels [12] [13]. These methods, when carefully designed and applied, not only reduce RTN noise levels but also enhance the overall urban soundscape, contributing to the development of habitable cities.

This study, therefore, seeks to examine the potential of noise barriers, tunnels, and tree belts as targeted countermeasures for RTN hotspots in Nairobi City. By focusing on the engineering framework details and guidelines of each countermeasure, this study thus provides policy recommendations tailored to Nairobi's urban context, allowing for stakeholder engagement in abatement strategies for policy tool formulation. This paper is organized into six sections: the introduction, the literature review, the methodology, the results, the discussion, and the conclusion.

2. Literature Review

Sound is a form of mechanical energy that propagates through media: air, water, and solids. It travels as a wave, transferring energy from one particle to another. These waves propagate in all directions from the source, and are characterized by their frequency, amplitude, and wavelength [14]. When these waves reach a receiver, such as the human ear, they are perceived as audible sound. Understanding the propagation of sound is key in environmental studies as it forms the basis for measuring, analyzing, and mitigating noise pollution in urban areas.

As a physical phenomenon, sound becomes noise when it is unwanted or unpleasant to the receiver [14] [15]. While sound itself is just vibrations traveling through the ambient air in any environment, it turns into noise when it disrupts communication, interferes with daily activities, causes health-related issues, or causes annoyance or disturbance. Road Traffic Noise (RTN), in particular, is the unwanted and unpleasant sound produced by vehicles as they move along a roadway. It is a major source of urban noise pollution because it is persistent, difficult to avoid, and often exceeds recommended thresholds [2].

RTN comes from several sources, such as engines, tailpipes, tyre interaction with the road surface, and honking of horns [12] [16] [17]. Engines produce mechanical and combustion sounds, with heavy-duty vehicles like trucks and buses being particularly noisy, due to their large engines, and especially when they are accelerating. In particular, the old diesel-powered trucks are most implicated. Tailpipes add to this by releasing bursts of sound. Tyres interacting with the road surface produce friction, which creates a steady humming or roaring noise as the vehicles move at different speeds. This is also amplified by rough or poorly maintained road surfaces as well as worn-out tyres. The honking of horns introduces sharp and often unpredictable sounds in the environment. These different sounds mix and become continuous noise that spreads into the surrounding environment.

Different vehicle types also influence the RTN, with heavy trucks producing low-frequency rumbles, motorcycles generating sharp, high-frequency peaks, and saloon cars contributing a mid-range continuous hum. Traffic volume and flow influence the RTN as well, with congested conditions leading to constant noise and free-flowing traffic leading to more stable but often louder levels of noise due to the high speed of moving cars [16]. Road design is also an influencing factor on the levels and patterns of RTN. High-capacity roads, such as highways and expressways, that typically carry a large volume of fast-moving vehicles, result in higher noise levels as compared to local and residential roads, which are found lower in the hierarchy, producing relatively lower noise levels since they are designed for slower speeds and lower volumes of traffic [18]. Despite this, poor and unprecedented urban sprawl and lack of effective buffer zones expose city residents to elevated RTN levels.

Nairobi has experienced a rapid surge in population growth, accompanied by a corresponding increase in motorization [19]. The city's road networks serve as the backbone of transportation, with major roads such as the Thika Superhighway, Mombasa Road, Jogoo Road, Waiyaki Way, Uhuru Highway, Kiambu Road, Langata Road, and Outer Ring Road, carrying large volumes of vehicles daily. With Nairobi's motorization and population expected to continue rising, RTN levels are projected to worsen unless deliberate action is taken in an attempt to curb them. This situation highlights the urgent need for comprehensive mitigation strategies that can balance mobility needs with environmental and public health concerns. In response, mitigation strategies such as noise barriers, tunnels, and tree belts, which have been widely studied and implemented across different urban contexts to reduce RTN exposure, offer valuable lessons that can be adapted to Nairobi's case. Though these approaches differ in design principles, effectiveness, and suitability depending on the area in question, they provide a basis for tailoring interventions that can reduce noise exposure across Nairobi City's major hot spots.

2.1. Noise Barriers

Noise barriers are the most widely applied and studied forms of physical mitigation measures. Studies such as [20] along interstate highways in the Cincinnati area, [21] in Georgia, USA, [22] in Croatia, and [23] evaluated and even employed the use of noise barriers as RTN mitigation strategies. Noise barriers are solid structures placed at road edges that block the line of sight between the noise source and the receiver, constructed from materials such as concrete, metal, wood, earthen berm, transparent acrylic, or composite absorptive panels [24], see **Figure 1**. Their performance depends on several factors, such as the height, top-shape, length, material properties, and placement relative to both roadways and urban residents [12].

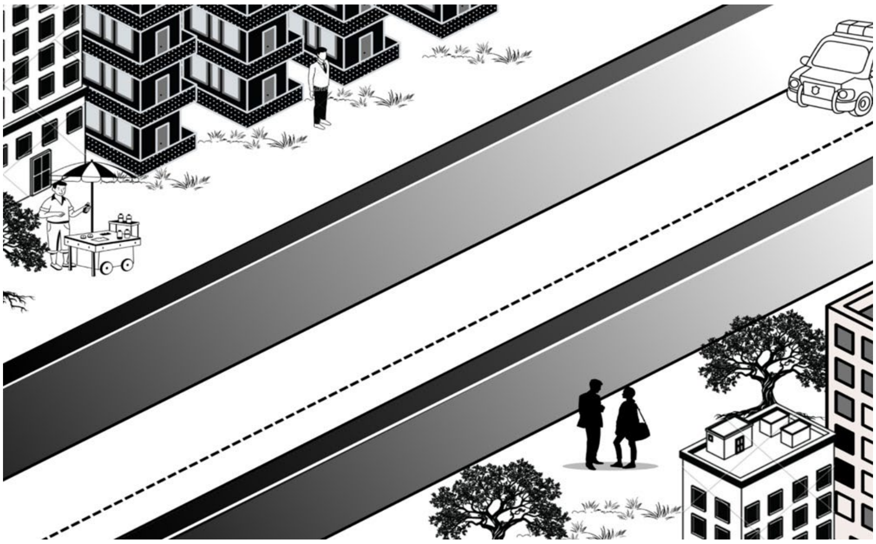


Figure 1. Noise barriers (Source: Author).

The shape of a barrier is defined in terms of its top geometry, which significantly influences its acoustic performance by altering the path of diffraction. There are different barrier shapes [25], see **Figure 2**.

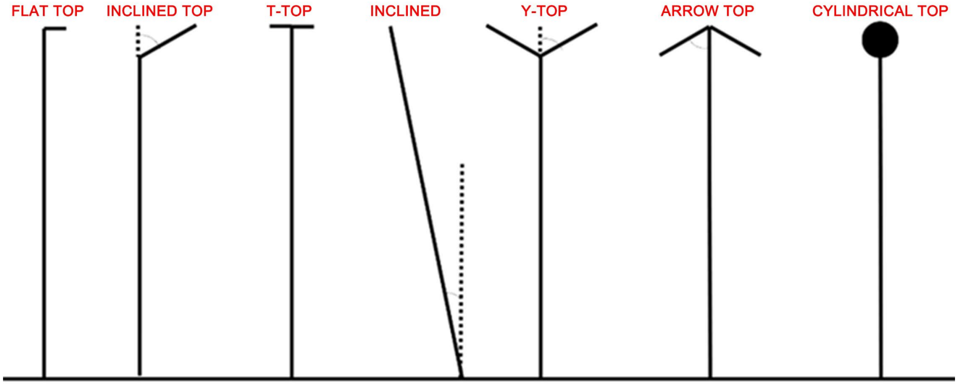


Figure 2. Different noise barrier shapes (Source: Author).

The simplest and most cost-effective is the flat-top barrier, though it provides only moderate attenuation. Angled-top barriers are tilted either towards the road or the receiver, improving their performance by redirecting sound energy and reducing diffraction paths. More advanced solutions, such as T-top, increase the path difference for diffracted waves. Some optimized designs also include cylindrical tops or multiple overhangs to further enhance effectiveness [26].

Noise barriers do not block sound waves coming from passing vehicles completely, but rather, they reduce RTN levels through reflection, diffraction, and absorption [12], see **Figure 3**.

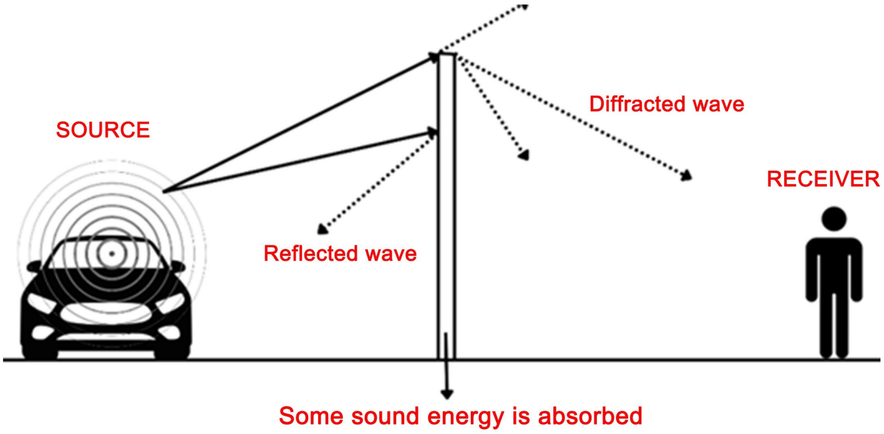


Figure 3. How sound is attenuated using a noise barrier (Source: Author).

There are engineering and mathematical principles of how noise barriers contain the propagation of RTN. These include: 1) reflection, 2) absorption, and 3) diffraction of noise waves.

2.1.1. Reflection

Noise barriers reflect part of the incident, sound waves either back towards the source or away from the receiver. The degree of reflection depends on the surface material; hard and very dense materials reflect more, while porous surfaces reflect less noise. The reflection loss is given by Equation (1):

$$L_R = -10\log_{10} R_E \tag{1}$$

where L_R is the loss due to reflection in decibels, R_E is the Reflection coefficient, which depends on the material used in the design of the noise barrier [27].

2.1.2. Absorption

Noise barriers made of absorptive or porous material also absorb some of the incident acoustic energy by converting the sound energy to heat. The absorption loss is given by Equation (2):

$$L_A = -10\log_{10} \alpha \tag{2}$$

where L_A is the loss due to absorption in decibels, α is the absorption coefficient defined as $\alpha = \left(1-\left|R_E\right|\right)$ and R_E is the reflection coefficient.

Absorptive surfaces are especially beneficial when barriers are placed on both sides of a roadway, as they reduce multiple reflections occurring between the parallel structures.

2.1.3. Diffraction

Diffraction is the bending or spreading of waves as they encounter an obstacle or an opening. This allows only part of the acoustic energy to reach the receiver, but with reduced intensity. Attenuation due to diffraction depends on the barrier height, the source-receiver geometry, and the wavelength of the noise. High-frequency sounds, which have shorter wavelengths, diffract less and are therefore more effectively blocked, while low-frequency sounds bend more easily, limiting the barrier performance. The diffraction loss is expressed through Maekawa's formula (1968), Equations (3) and Equation (4), as used by [28]:

$$L_D = 10\log_{10}\left(3+20N\right) \tag{3}$$

$$L_D = 10\log_{10}\left(2+5.5N\right) \tag{4}$$

where L_D is the loss due to diffraction in decibels. The Fresnel number N is defined as in Equation (5):

$$N = \frac{2\Delta}{\lambda} \tag{5}$$

and λ is the wavelength of the sound.

Δ is the path difference calculated as in Equation (6):

$$\Delta = d - r \tag{6}$$

And d as in Equation (7):

$$d = d1 + d2 \tag{7}$$

where $d1$ is the distance from the source to the top of the barrier, $d2$ is the distance from the top of the barrier to the receiver, and r is the straight-line distance from the source to the receiver, see **Figure 4**.

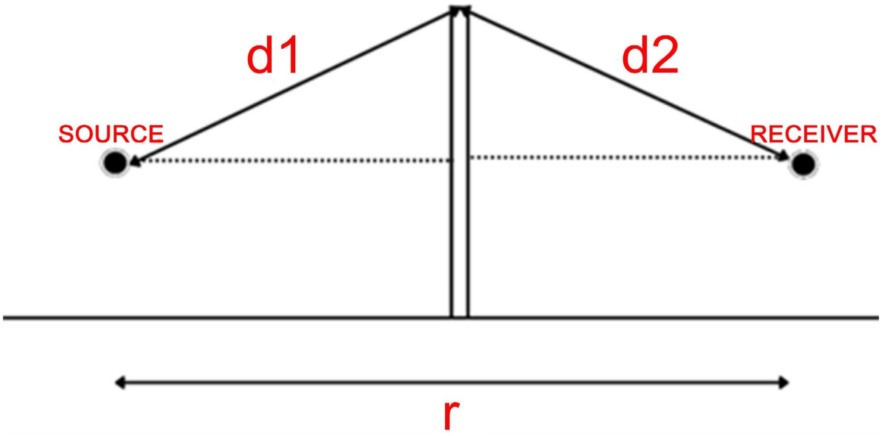


Figure 4. Geometry used to define diffraction over a noise barrier (Source: Author).

Equation (3) is valid in the case of point-like sources, while Equation (4) is valid for linear sources. Equation (4) is mainly used as RTN is viewed as a linear source

[28]. The overall barrier effectiveness is defined in terms of Insertion Loss (IL), which is the sound level perceived by the receiver before the noise barrier is placed and the sound level after the barrier, defined as in Equation (8):

$$\mathrm{IL} = \mathrm{SPL}_{\mathrm{before}} - \mathrm{SPL}_{\mathrm{after}} \tag{8}$$

where SPL refers to the sound pressure level.

A higher IL value corresponds to greater attenuation and thus improved barrier. Optimized barrier designs aim to maximize IL by combining diffraction control, through shape modification, with material absorption and reflective redirection [26]. The insertion loss can be estimated using Maekawa's formula (1968) as shown in Equation (4). The limitation of this is that it estimates the barrier insertion loss due to diffraction only, assumes a rigid, thin barrier, and neglects reflection and absorption. To improve Maekawa's formula, Kurze and Anderson [29] developed a more refined model that incorporates barrier thickness, absorptive properties, reflections, and atmospheric conditions as in Equation (9) and Equation (10):

$$\mathrm{IL} = \left(5\ \mathrm{dB} + 20\log\left(\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}\right)\right), N \le 12.5 \tag{9}$$

$$\mathrm{IL} = 20\ \mathrm{dB}, N > 12.5 \tag{10}$$

where N represents the Fresnel number calculated as in Equation (5).

2.2. Tunnels

Another equally important but less frequently discussed measure is the use of tunnels as RTN mitigation tools. Through rerouting traffic underground, tunnels can serve as effective acoustic shields [30]. Tunnels, either circular in shape or rectangular, act like multimodal long enclosed waveguides. Unlike open roads, where sound radiates freely in the surrounding environment, the tunnel's structure confines the sound waves within a bounded space, thus reducing exposure to RTN [30]. The sound energy is trapped, reflected multiple times against the tunnel walls and roof, and gradually dissipated through wall absorption and modal cutoff effects [31] [32].

As a vehicle moves inside the tunnel, it generates noise as sound waves. These sound waves do not travel in a straight line but rather spread out spherically in a 3D region around a direct path [30]. Since they cannot expand spherically as in free space, they begin to behave like guided waves. The tunnel can be divided into two main regions, the near region and the far region, with a separator between the two regions known as the breakpoint [32], see **Figure 5**.

The near region is the region inside the tunnel and just at the portal entrance, and it is typically a few tunnel widths. In this region, the sound waves are not yet well organized; they spread in all directions as they would in open space, bouncing around inside, and reflecting from the roof, walls, and floor. Multiple modes exist at once, revealing a complex sound field, with spots of louder and quieter sound due to interference. After a certain distance known as the breakpoint, the near region transitions into the far region, calculated as in Equation (11):

$$Z_{NR} = \frac{2WH}{\lambda} \tag{11}$$

where Z_{NR} is the distance from the source to the breakpoint, W is the width of the tunnel, and H is the height of the tunnel, and λ is the wavelength of the sound.

In the far region, sound starts behaving like a guided wave, bouncing off in a structured way [32]. Parts of the sound propagate in certain allowed modes, while higher frequency components above the cutoff frequency are strongly attenuated. Mathematically, the cutoff frequency is given by Equation (12):

$$f_c = \frac{c}{2}\sqrt{\left(\frac{m}{W}\right)^2 + \left(\frac{n}{H}\right)^2} \tag{12}$$

where c is the speed of sound, W represents the tunnel width, H represents the tunnel height, and m and n are mode indices representing the lowest frequency mode that can propagate.

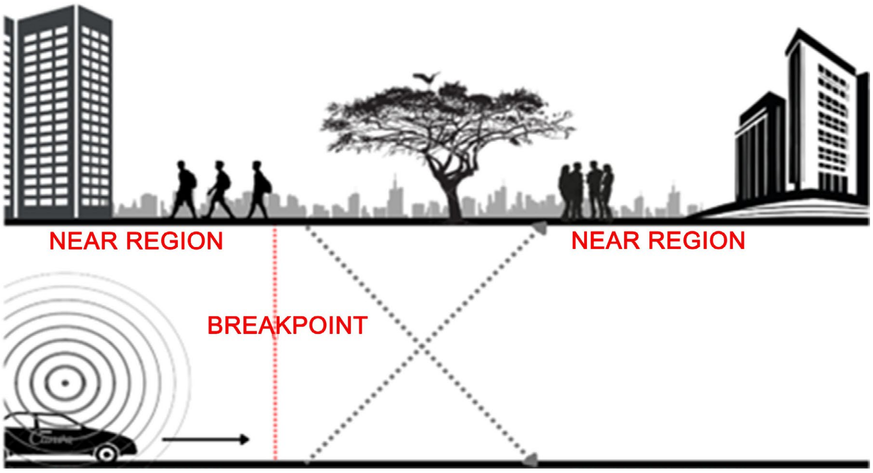


Figure 5. Use of tunnels (Source: Author).

Sound waves with frequencies above the cutoff frequency survive, propagating as guided modes. They are reflected along the walls at shallow angles and continue travelling efficiently with low loss. Waves with frequencies below the cutoff frequency become evanescent and decay rapidly. Additionally, higher frequency components die out quickly due to wall absorption and reflections, thus damping the overall sound spectrum that propagates [33].

Transition from the near region to the far region can be analyzed using the Fresnel zone theory. A Fresnel zone is a 3D region around a direct path between the source and a receiver. It is the volume around a path where the wave has constructive or destructive interference [33]. The first Fresnel zone represents the volume within which most of the sound energy contributes constructively to the direct path. In tunnels, noise containment happens by blocking the higher-order Fresnel zones, preventing the sound energy from escaping and causing signal loss and diffraction. This means that, beyond the near region, contributions from waves outside the first few Fresnel zones are suppressed, further damping noise transmission along the tunnel.

Sound attenuation inside a tunnel also depends on the multiple reflections and absorption of acoustic energy that occur. Every time a sound wave reflects off the tunnel wall or roof, part of its energy is absorbed, depending on the wall's absorption coefficient α, which is determined by the type of material used in the construction of the tunnel. The reflection loss in decibels is mathematically defined as in Equation (13):

$$L_R = -10\log_{10}\left(\left|R_E\right|\right) \tag{13}$$

where R_E is the reflection coefficient defined as in Equation (14):

$$R_E = \left(1-\alpha\right) \tag{14}$$

where α is the absorption coefficient.

After N reflections, the total cumulative loss can be approximated as in Equation (15):

$$L_{CUM} = N \cdot L_R \tag{15}$$

Engineers exploit this effect by designing tunnel linings with materials of moderate absorption [34], thus ensuring that the reverberation of sound does not become excessive while still limiting the transmitted noise. Altogether, tunnels mitigate RTN exposure through three main mechanisms: Trapping and containment, reflection and absorption, modal cutoff, and Fresnel suppression. In practical terms, the careful design of road tunnels explains why areas outside and above tunnels experience far less noise as compared to open road sections, thus they improve air and noise quality for city residents above.

2.3. Tree Belts

Tree belts represent another mitigation strategy, offering benefits in terms of both acoustic, ecological, and aesthetic aspects, see **Figure 6**.

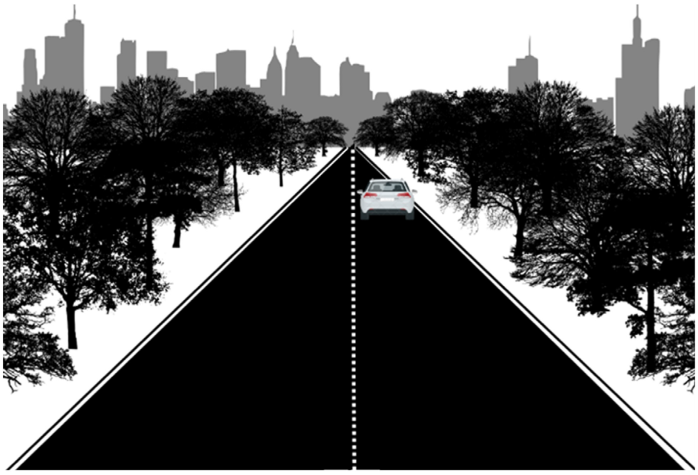


Figure 6. Use of tree belts (Source: Author).

They also do not block sound waves completely, but rather form a porous, lossy medium that attenuates sound energy through scattering, absorption, and the ground effect [35]-[37]. Wider and denser tree belts provide more attenuation. The trees help in noise management through 1) scattering and absorption, and 2) ground effect.

2.3.1. Scattering and Absorption

Scattering refers to the redirection of sound waves into multiple weaker waves traveling in different directions as they encounter obstacles like tree trunks, leaves, and branches. This effect is frequency dependent: higher frequencies are scattered more strongly, while low frequencies diffract around vegetation [35]. The leaves and bark, as well, absorb sound energy, converting it to heat energy. Absorption is dependent on the frequency of the sound wave, tree type, and density.

The main principle can be expressed as an exponential decay model similar to the Beer-Lambert law in Equation (16):

$$I(d) = I_0 \cdot \mathrm{e}^{-\rho\sigma s d} \tag{16}$$

where $I(d)$ is the sound intensity travelling through a distance d through the vegetation, I_0 is the initial sound intensity of the sound waves, ρ represents the number of scatterers or absorbers per square meter, and σs is the scattering-absorption cross section calculated as in Equation (17):

$$\sigma s = \frac{4\pi r^2}{\lambda^2} \tag{17}$$

And d represents the depth of vegetation.

The loss or attenuation due to scattering is expressed similarly as in [37] using Equation (18).

$$L_S = 20\log_{10}\left(k_{scatt}\right) \tag{18}$$

where L_S represents the loss due to scattering in decibels, and k_{scatt} is the effective scattering wavenumber representing the modification of sound propagation due to multiple scattering by trees along a path [37].

The loss due to absorption and scattering can also be estimated as in Equation (19):

$$L_S + L_A \approx 4.343\rho\sigma s d \tag{19}$$

This formula shows how both absorption and scattering combine to reduce sound levels with depth.

2.3.2. Ground Effect

Ground effect is described as how the ground interacts with sound waves. It causes either constructive or destructive interference, leading to either enhanced or reduced attenuation of RTN. Soft or porous ground surfaces, such as grass and soil, tend to absorb low-frequency sound, reducing the reflected energy and creating attenuation. Hard surfaces, such as concrete or pavement, tend to reflect sound waves, thereby amplifying sound at certain distances. The attenuation is expressed using the ISO 9613-2:1996 [38] standard as in Equation (20):

$$L_G = 4.8 - \frac{2H_m}{r}\left(17 + \frac{300}{r}\right) \tag{20}$$

where L_G is the ground effect attenuation, H_m is the mean height of the propagation path above the ground, and r is the distance from the source to the receiver. The total noise attenuation due to tree belts can be expressed as in Equation (21):

$$L_{CUM} = L_G + L_S + L_A$$

3. Materials and Methods

The study was conducted in Nairobi, the capital city of Kenya, see **Figure 7**.

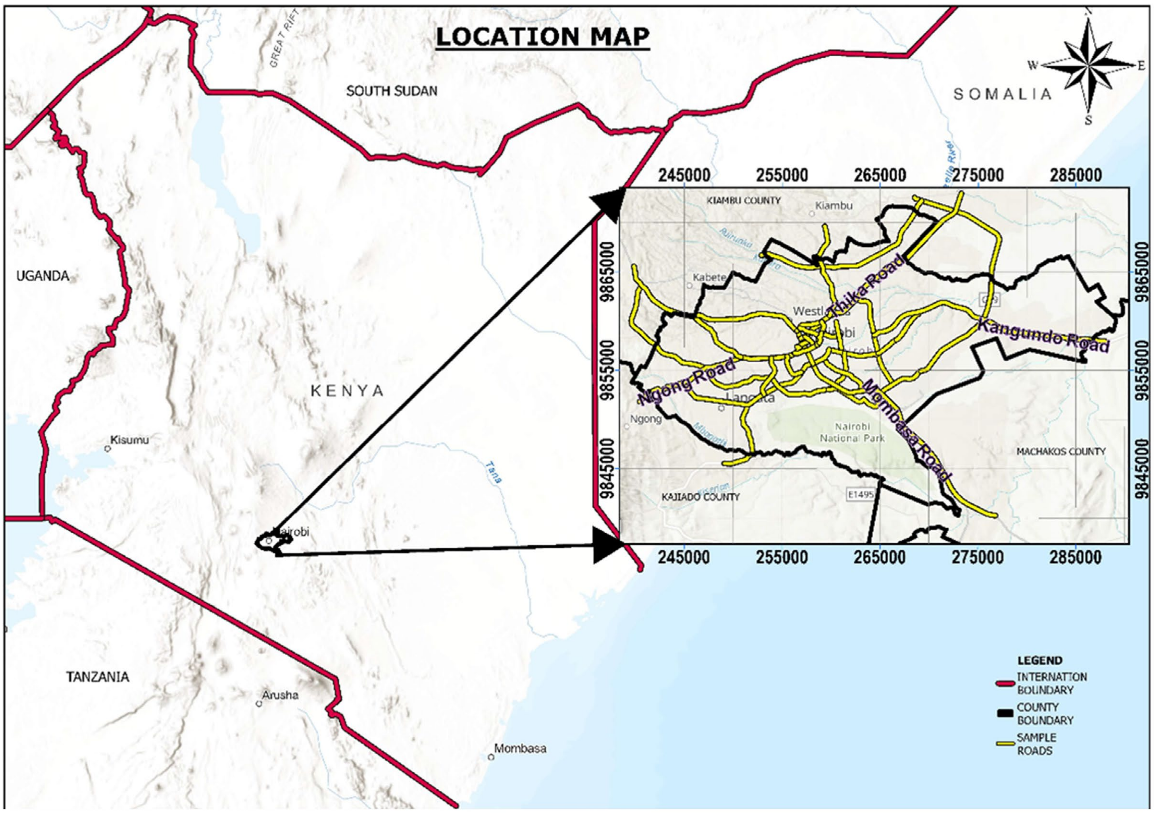


Figure 7. Nairobi City, Kenya (Source: Author).

This methodology applies a context-based evaluation of noise barriers, use of tunnels, and use of tree belts, by recognizing their strengths and limitations, to propose and recommend RTN mitigation strategies in Nairobi City hotspots.

3.1. Data Collection

The study was conducted in Nairobi, the capital city of Kenya. RTN levels were collected across 42 sampling points, see **Figure 8**, using a Class 1 Lutron SL 4033SD Sound Level Meter (SLM) for 7 days, which conforms to IEC 61672-1 standards.

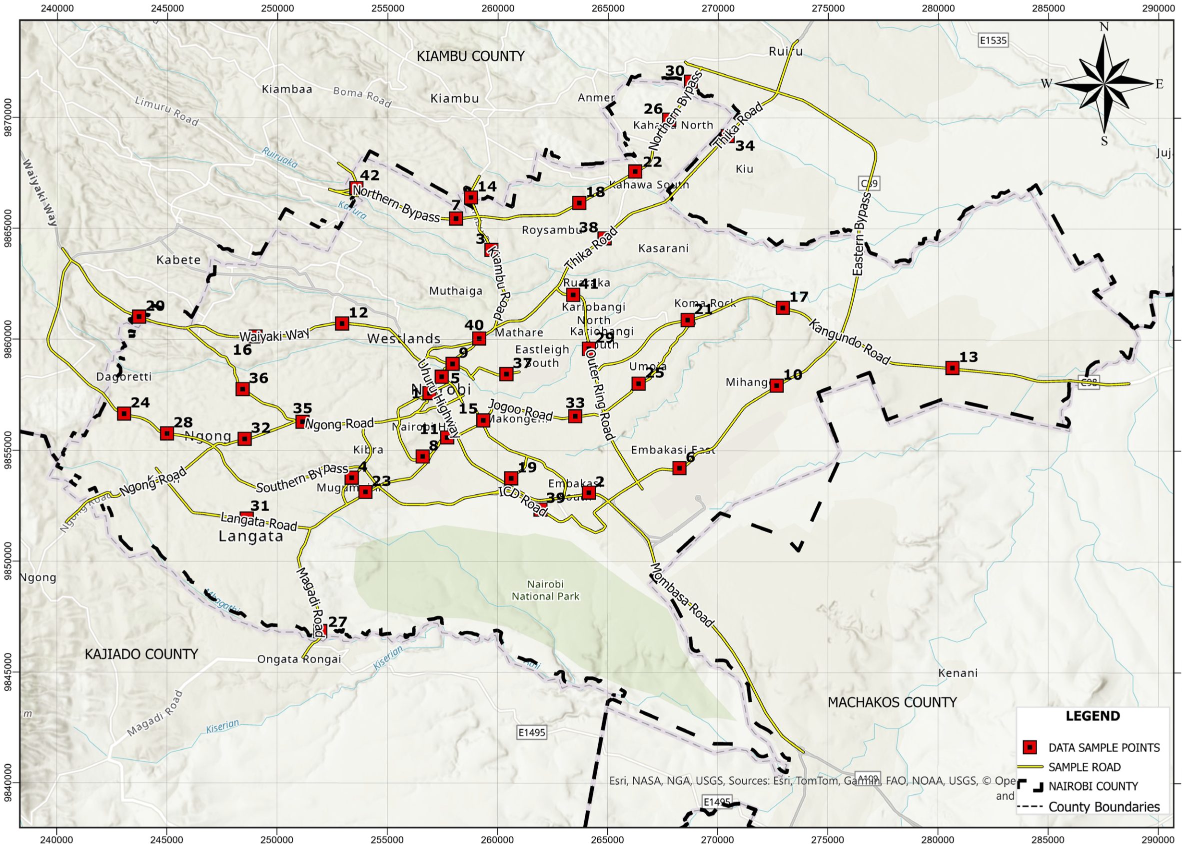


Figure 8. 42 Sampling Points across Nairobi (Source: Author).

The SLM was calibrated before the measurement campaign to ensure data accuracy and reliability; no recalibration was required between individual measurement sessions. During measurement, the SLM was positioned at an approximate height of 1.2 meters, maintaining a horizontal distance of about 1.5 meters from the road edge to minimize reflections and direct influence from passing vehicles. The fast response mode, which is perfect for capturing the varying nature of RTN, was chosen on the SLM, and an A-weighting filter setting was used to account for how the human ear responds to sound. In order to guarantee high resolution for the computation of crucial acoustic metrics, including Leq(dBA), data were logged at 2-second intervals throughout each sampling session. The measurements yielded A-weighted continuous sound levels (Leq), which served as the basis for evaluating RTN exposure across Nairobi. From 6:00 A.M. to 6:00 P.M., noise levels were recorded at each of the 42 sampling points, at 15-minute intervals throughout the day. This led to 13 records every day for each site. These values were averaged to get the daily average Leq.

The RTN levels were averaged across the 7 days and spatially visualized using ArcGIS Pro 3.4 Software, allowing for the identification of major noise hotspots. The 42 sampling points were interpolated using Inverse Distance Weighting (IDW) to create continuous noise surfaces. The chosen interpolation values preserved the observed spatial variability while highlighting proximity effects. In order to verify that the sampling density was sufficient to satisfy corridor-scale hotspot identification, a straightforward hold-out validation was carried out by eliminating a portion of measurement locations and comparing expected and observed values.

Using spatial visualization from Google Earth Street views, the physical context of each noise hotspot was assessed, similar to the approach of [38], and a mitigation strategy was proposed as a suitable intervention.

3.2. Strengths and Limitations of the RTN Countermeasures

3.2.1. Noise Barriers

Properly designed Noise barriers present a wide range of advantages, with their performance depending on barrier height, length, and the relative positioning of the road and receptors. Their main advantage is the predictable noise reduction, which can be estimated using established models such as Maekawa (1968) or the Kurze-Anderson model (1971). They also provide immediate effectiveness, are relatively cost-effective, offering measurable benefits without the need for major changes to road alignment or traffic patterns, improve health and residents' well-being, and are applicable in dense urban areas [12] [39]-[41]. Their limitations lie in their aesthetically unappealing nature and limited low-frequency attenuation [40].

3.2.2. Tunnels

These structures provide significant noise attenuation outside their structure, as all the noise is contained and trapped inside. It offers the highest potential ambient noise reduction strategy that can be easily integrated with urban planning. Tunnels free up surface land for alternative uses and reduce visual intrusion. Its limitations lie in very high capital and maintenance costs, and it requires complex engineering work. They also require ventilation systems to manage exhaust gases, which adds to their operational costs [42] [43].

3.2.3. Tree Belts

Tree belts offer modest attenuation, though wider and denser vegetation can yield more noticeable reductions. Besides their effect on the soundscape, tree belts also provide ecological benefits as they improve the air quality and carbon sequestration. They are also aesthetically pleasing to the environment [44] [45]. Their limitations lie in less noise reduction predictability as compared to noise barriers, require significant land and time to mature, and their performance depends on vegetation density and the tree species.

3.3. Guidelines for the Selection of Road Traffic Noise Mitigation Strategy

Selecting an appropriate RTN mitigation strategy requires considering technical feasibility, cost-effectiveness, community preferences, and environmental impacts [12] [46]. A structured decision framework was used to ensure consistency and transparency across all identified hotspot corridors. The framework considered: sensitivity of nearby receptors such as residential areas, schools, and hospitals, constructability within the existing urban fabric, and an indicative cost band.

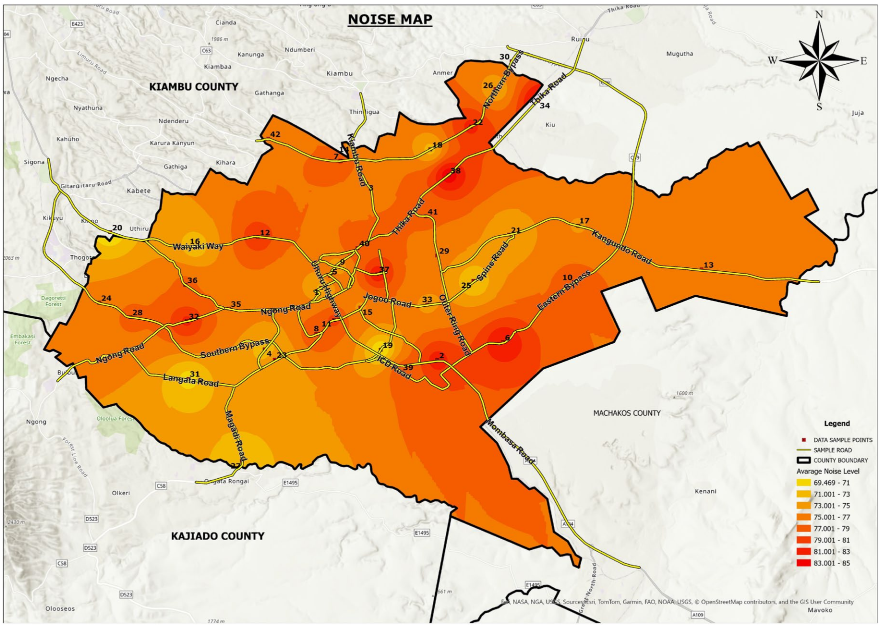
For Dense urban corridors, Noise barriers are the most common choice due to limited land space available and immediate effectiveness. Typical barrier designs assume heights of approximately 3 - 5 m with sufficient length to prevent end diffraction effects. When properly designed, roadside noise barriers are expected to achieve insertion losses in the range of 5 - 15 dB(A), depending on geometry, materials, and source-receiver configuration. Tunnels also offer the most effective solution because they trap noise with expected surface-level noise attenuation exceeding 20 dB(A), but they can only be applied where there is adequate expenditure and space for construction, as well as proper ventilation systems. Tree belts are less effective physically in dense corridors because they require significant width to achieve even modest attenuation, which is often unavailable in highly populated areas. Effective tree belts require a minimum vegetation width of approximately 15 - 30 m with high vegetation density, combining trees and shrubs. Under such conditions, expected noise attenuation ranges between 2 - 6 dB(A), with greater effectiveness achieved as vegetation matures.

Along Suburban corridors, noise barriers are still very effective and can be designed with more flexibility to suit the selected area. Tree belts are more feasible in such areas than in densely populated areas, because there is more roadside space, thus offering more than just acoustic value. Tunnels are not applicable in suburbs mainly due to the lack of available land for construction. In peri-urban and rural settings, tree belts are more sustainable and highly effective, since land availability allows for planting of wide belts, providing multiple co-benefits at lower cost. For Industrial Corridors, noise barriers are effective for shielding industrial noise sources or heavy freight corridors from nearby settlements. In highly sensitive areas such as schools and hospitals, Tunnels are justified where budgets allow, offering the most effective long-term solution, though Noise barriers are often used because they provide immediate shielding and offer predictability in the insertion loss [47] [48].

Measured noise levels were evaluated against both national and international guideline limits. According to the National Environment Management Authority (NEMA) of Kenya, the permissible daytime environmental noise limit for mixed residential and commercial areas is 60 dBA (Leq, day) [49]. The World Health Organization (WHO) recommends an outdoor daytime environmental noise limit of 53 dBA (Leq, day) to minimize adverse health effects [2]. All measured RTN values in this study were directly compared against these limits to assess exceedance levels.

4. Results

The RTN levels were measured, see **Appendix**, and spatially visualized using ArcGIS Pro 3.4 software, see **Figure 9**.



Esri, NASA, NGA, USGS, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 9. Noise map showing average RTN values.

From the noise map, areas such as the Central Business District and Eastleigh, roads such as Thika Road, Ngong Road, Mombasa Road, ICD Road, Uhuru Highway, Waiyaki Way, Airport North Road, and Northern Bypass were identified as major noise hotspots in Nairobi City. In comparison, some residential areas like Karen and Runda were identified to have low RTN levels recorded, although they are still above the recommended NEMA and WHO limits. Overally, all the measured sampling points in this study exceeded both limits, indicating significant noise pollution. The Nairobi Central Business District is a dense urban area, filled with high-rise buildings, narrow streets, different commercial activities, and high vehicular traffic, spanning buses, Public Service Vehicles (PSVs), and private cars, see **Figure 10**. Due to limited space, tunnels and tree belts are impractical. Noise barriers offer a more efficient solution, providing acoustic relief in a constrained built environment.

Figure 10. Street view of the Central Business District.

In Eastleigh, an area with mixed commercial and residential activities, persistent traffic congestion is experienced, which contributes to the high levels of RTN, with the narrow road corridors and high pedestrian density making it a challenging hotspot, see **Figure 11**.

Figure 11. Street view of Eastleigh area.

Noise barriers are recommended to shield residential areas and pedestrian zones from RTN. Tunnels are unlikely to be feasible in this context, given the high density of vehicles and people. Tree belts, as well, are unlikely due to the limited space available.

Ngong Road functions as an arterial road that links the Central Business District with the southwestern suburbs, see **Figure 12**.

Figure 12. Street view of Ngong Road.

With a few trees already in place, the use of noise barriers will provide incremental noise attenuation, improving the RTN exposure levels in the area. Tunnel construction could be considered for future expansions, particularly at intersections where grade separation is required.

The Thika Superhighway is a major high-capacity roadway characterized by high vehicular traffic accompanied by high speeds, see **Figure 13**. Elevated RTN levels have been consistently documented along their length.

Figure 13. Street view of Thika Superhighway.

Noise barriers will serve as an effective and practical countermeasure. Additionally, tree belts where there is available land can be implemented as a complementary buffer. For future planning, more tunnels, such as the Pangani interchange tunnel, could be considered to contain noise.

Mombasa Road serves as a critical freight and passenger corridor linking the Central Business District with residential, airport, and industrial areas, see **Figure 14**, with heavy truck traffic contributing to the majority of the elevated RTN levels.

Figure 14. Street view of Mombasa Road.

The most effective strategy is the installation of noise barriers, particularly adjacent to residential and institutional zones. Tunnel construction may be applicable in new expansion projects as a long-term solution. Tree belts may not be feasible due to the limited land space available.

The ICD Road is dominated by heavy-duty freight vehicles, generating both high-intensity and low-frequency noise, see **Figure 15**. Also, due to less traffic congestion, vehicles move at very high speeds, contributing to the growing RTN levels.

Figure 15. Street view of ICD Road.

Noise barriers with sufficient height and mass are recommended to attenuate truck-generated RTN. As a complementary measure, tree belts can be implemented on available land to provide long-term attenuation, particularly for high-frequency components. While tunnels may be beneficial in new design phases, the existing corridor does not readily allow for their implementation.

The Northern Bypass is a peri-urban corridor with increasing traffic volumes, including heavy trucks, see **Figure 16**.

Figure 16. Street view of Northern Bypass.

Due to minimal development in the area, land is available for the deployment of tree belts, reducing noise propagation to adjacent residential and commercial zones. Strategic noise barriers can be installed near sensitive areas such as schools or hospitals. In the future, tunnel options at major intersections or interchange redesigns could be considered as part of integrated RTN management.

Waiyaki Way is a multilane highway with heavy traffic volumes and dense built-up surroundings, see **Figure 17**.

The most suitable abatement measure is the installation of roadside noise barriers to shield adjacent residential estates and institutions from high traffic noise due to limited land space; the construction of tunnels and the use of tree belts are not feasible in this area.

Figure 17. Street view of Waiyaki Way.

Uhuru Highway is characterized by very high traffic volumes as it forms part of the Nairobi CBD corridor and a major roundabout that channels multiple arterial routes, see **Figure 18**.

Figure 18. Street view of Uhuru Highway.

Since land availability in this area is highly constrained, the deployment of noise barriers would serve as an effective measure. Tunnels are not feasible because of prohibitive costs in such a built-up area, and tree belts cannot be implemented effectively due to the lack of space.

Airport North Road connects the Jomo Kenyatta International Airport with the Eastern Bypass and the Industrial Area, serving as a major freight and passenger corridor, see **Figure 19**.

It carries a high proportion of heavy trucks, alongside airport shuttle buses, PSVs, and private vehicles, resulting in persistently elevated Road Traffic Noise levels. Due to limited roadside space, the most effective abatement measure is the installation of noise barriers. Tree belts may also be deployed in areas where land is available, as a complementary measure. Tunnels are not feasible in this case due to prohibitive costs and the existing road design constraints.

Figure 19. Street view of Airport North Road.

Karen is a suburban residential area characterized by low population, low vehicular traffic, and green spaces, see **Figure 20**.

Figure 20. Street view of the Karen area.

Though RTN levels here are lower than those along the main arterial roads, they still exceed the recommended thresholds. To preserve the acoustic environment, tree belts should be maintained and expanded. Localized noise barriers around schools or health facilities can be implemented as an additional abatement measure. Tunnels here are unnecessary given the relatively low traffic density and available green space.

Runda, like the Karen area, is a low-population, low-vehicular-traffic, high-income residential area with significant greenery, see **Figure 21**.

Figure 21. Street view of the Runda area.

RTN levels are lower but remain above the recommended limits. Maintenance and expansion of tree belts is the most suitable abatement measure, ensuring long-term livability and improving the aesthetic value. As in the Karen area, noise barriers can also be selectively deployed around sensitive land uses such as schools or hospitals. Tunnel interventions are not applicable in this context.

By applying different strategies according to local context, the study ensures that the proposed measures are both technically feasible and cost-effective.

5. Discussion

The assessment highlights that while tunnels offer the greatest theoretical reduction by fully enclosing traffic and trapping noise, they are only feasible in select road expansion or new construction projects. Noise barriers emerge as the most practical intervention for most road corridors. Tree belts, though offering modest attenuation, play a critical role in residential areas and also as complementary measures, where they improve both the acoustic and environmental quality in terms of urban greening effects. A combination of these measures, tailored to the land-use and spatial context of each hotspot, offers a balanced strategy for managing Nairobi's RTN exposure. Consequently, as has happened in economies such as Germany, the Nairobi city management needs to begin the debate on new RTN policy instruments. The illumination of RTN hotspots highlighted in this paper is only a sounding pointing us to the need for policy problem discussion. The output of which will inform the solution framing as well as the implementation vision.

6. Conclusion

This study concludes that Nairobi city, just like its counterpart cities elsewhere in developing nations with rapidly rising motorization of their roadways, requires an urgent mitigation policy. The RTN hotspots identified will continue to negatively impact the well-being of city residents due to prolonged high noise exposures. The German noise policy instrument [50] can act as a benchmark foundation for Nairobi city. Finally, this study recommends that Nairobi City should adopt a comprehensive noise abatement policy that prioritizes noise mitigation measures, particularly in high noise corridors and sensitive areas, while integrating noise considerations into urban planning and traffic management. Furthermore, public awareness campaigns and enforcement of regulatory noise limits aligned with NEMA and WHO standards are essential to ensure compliance and to protect community well-being, thus creating a sustainable urban environment.

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Author Declarations

This work was carried out in collaboration among all authors. Author OAE designed the study, performed all the analysis, and wrote the first draft of the manuscript. Authors OSN and GJF proofread the draft. All authors read and approved the final manuscript.

Disclaimer (Artificial Intelligence)

The authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Conflicts of Interest

The authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1. The computed Leqs for each sampling point.

Sampling Pont	Leq dB(A) from SLM
1	72.57
2	81.88167
3	75.08167
4	72.03333
5	75.775
6	82.745
7	79.21833
8	78.63333
9	74.045
10	77.64833
11	76.685
12	79.64833
13	80.02833
14	75.05833
15	74.19167
16	74.69
17	71.90667
18	74.89
19	72.44667
20	69.45167
21	70.00167
22	73.055
23	81.46
24	73.61667
25	75.17917
26	71.06167
27	73.4
28	71.97667
29	77.54833
30	75.12
31	75.965
32	70.41333
33	81.36417
34	74.6125
35	83.64667

Continued

36	76.83167
37	77.38833
38	82.365
39	84.1
40	78.19167
41	78.735
42	77.545