Traffic Noise Mitigation in High-Density Cities: Psychoacoustic Evaluation of Trees, Rooftop Gardens, Facades, and Water Features

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Abstract

Urban noise pollution poses critical health risks in high-density cities like Singapore, where traffic noise dominates residential environments. This study evaluates the effectiveness of four mitigation strategies. They are roadside trees, rooftop gardens, corrugated facades, and water features. Integrated acoustic (A/C/Z-weighted SPL) and psychoacoustic parameters (loudness, sharpness, roughness) are used in this evaluation.

Field recordings showed low frequencies below 100 Hz that are less audible to the human ear to be at a higher L_{eq} than mid and high frequencies. Heightened emphasis is placed to find methods to curb these low frequencies.

Comparisons of the 10 sites revealed that rooftop gardens were most effective in reducing A-weighted SPL (up to 14.5% reduction) and loudness (12.9–17.3 sone decrease). In particular, well-designed rooftop gardens were most useful, being the only site with significant decreases in LC_{eq} (11.13% reduction) and LZ_{eq} (10.26% reduction).

Trees reduced mid-frequency noise (7.47% LA_{eq} reduction) but were ineffective for low frequencies ($< 3.5\%$ LZ_{eq} reduction) and lost efficacy at higher elevations.

Similar to trees, facades offered moderate mid-frequency reduction (6.65% LA_{eq} decrease) but minimal reductions for low frequencies.

Water features significantly reduced psychoacoustic "roughness" (0.023 asper decrease), enhancing soundscape pleasantness despite high SPL.

Rooftop gardens emerged as the optimal solution for high-rise dwellings, while trees and facades remain viable ground-level options. Psychoacoustic analysis proved critical, revealing trade-offs between audibility reduction and low-frequency vibration control. These findings inform sustainable urban design in land-scarce cities, with an emphasis on urban noise mitigation.

1 Introduction

Housing in Singapore has been a pressing issue for the state since its independence. Though times have changed, the issue of land scarcity, connectivity and the environment still persists.

Tacking these issues, new estates have to reach a compromise. In this study, focus is placed on Build-to-Order (BTO) estates. These estates promise to improve housing in Singapore to one more modern than older flats.

To tackle connectivity, many new BTOs are built in prime locations, where flats are situated in central locations with excellent transport connectivity (Chew, 2023). However, issues arise as one of the drawbacks of living close to central locations include commercial and traffic noise, resulting in residents living in noisy environments. Most of these estates are built near expressways and major fork roads. Examples include; the Bayshore estate built just beside the East Coast Parkway (ECP), as seen in figure 1. The Mount Pleasant estate beside the Pan Island Expressway (PIE) as seen in figure 2. The Bidadari estate built near major road arteries as seen in figure 3.

This paper focuses fully on the Bidadari estate. As shown in figure 3, Bartley Road and Upper Serangoon Road provides excellent connectivity to work locations and the city via expressways. Thus, congestion occurs daily during peak hours, rendering these roads and the Bidadari Estate to be one of the most problematic traffic areas in Singapore (Urban Redevelopment Authority, 2025).

1.1 Traffic noise and its mitigation strategies and engineering

1.1.1 Analysis of traffic noise

Noise pollution are categorized as unwanted and harmful sound. As environmentalists focuses more on pollution, albeit the more tangible forms such as emissions and rising sea levels, attention is also placed on the "underestimated threat" of noise pollution (World Health Organization, 2011). As a result, environmental, public health and social impacts have surfaced in urban societies. Sufficient literature suggests a causal relationship between unwanted noise and human medical conditions such as chronic respiratory diseases (Zhang et al., 2023; Tian et al., 2025) and cognitive impairment (Glaubitz et al., 2022). Research has also been done on non-human species (Anzibar Fialho, Rocamora, & Ziegler, 2025), with sufficient evidence showing noise being a significant stressor on wildlife.

Noise pollution may originate from a wide range of sources, but this paper focuses on traffic. Thresholds are placed in multiple countries to protect urban environments. Examples include an equivalent continuous Sound Pressure Level (SPL) of 55dB(A) for 1 hour in Europe. This is denoted as 55dB $LA_{eq,\,1hr}$. This is set as adverse health effects begins to occur when exceeding 55dB(A) (European Environment Agency, 2020). The World Health Organization (2018) recommends SPL over an entire 24-hour day to not exceed 53dB, or $\mathrm{L}_{\mathrm{den}} < 53$dB.

$$L_{\mathrm{den}} = 10 \log \left(\frac{1}{24} \left(12 \cdot 10^{\frac{L_{\mathrm{day}}}{10}} + 4 \cdot 10^{\frac{L_{\mathrm{evening}}+5}{10}} + 8 \cdot 10^{\frac{L_{\mathrm{night}}+10}{10}} \right) \right)$$

SPL at night should also not exceed 45dB(A). Likewise, the National Environmental Agency (2023) of Singapore similarly specifies a maximum $LA_{eq,\,1hr}$ of 67dB(A) at the facade of all building.

However, estimations in 2013 showed more than 100 million individuals in the United States experiences annual L_{eq} levels higher than 70dB(A) in the United States alone, more elsewhere (Hammer, Swinburn, & Neitzel, 2013). In particular, traffic noise is the critical issue highlighted in urban environments, given its inescapable nature, intensity and continuity throughout the day. It's low frequency nature gives rise to the longer wavelengths.

$$v = f \cdot \lambda, \ \lambda = \text{wavelength of sound}$$

These sounds travel further (Gwee, 2025) and penetrate building structures easily. Thus, special materials and strategies are required to curb such low frequency noise (Ang, Koh, & Lee, 2019) within high density cities. This ensures negative effects of traffic noise on large populations of residents are reduced. Furthermore, particular attention has to be placed on children. Sufficient literature claims that chronic noise affects development in children (Basner et al., 2014). Similarly, the elderly population with existing health issues are at a higher risk too. Given this paper focuses on BTO estates, with many young families, this issue is highly pressing.

1.1.2 Strategies to tackle noise pollution

An abundance of engineering methods to mitigate noise pollution has emerged. With a focus on Singapore, classical strategies are implemented here in the form of roadside greenery. Rainforest trees and dense shrubbery are planted along the roadside. This effectively served as the primary noise mitigation method for the past century (Zhao et al., 2021).

Modern methods are now increasingly prevalent with an infrastructure-reliant population. Sound barriers are erected at areas with high noise provide some levels of refuge for residents. These are commonly used along overground MRT (metro) tracks and at temporary construction sites (Lim, 2017). Unfortunately, their unsightly nature, disruption to wildlife behavior and habitats are some concerns involved (Tran, 2025).

To meet greenery indicators in building-dense estates where trees with large canopies are not feasible, rooftop gardens similar to figure 15, are introduced. These rooftop gardens aim to bring greenery nearer to living spaces and offer areas of recreation for residents.

Furthermore, as Singapore advances in water technologies, water scarcity is no longer a pressing state issue. Water features such as fountains and waterfalls can commonly be found near private living spaces. They are no longer a luxury we cannot afford, and in this paper, a focus will be placed on its sound masking abilities.

1.2 Features selected for analysis

1.2.1 Trees

According to a similar project done by Gwee (2025), comparison of SPL was done between flats beside expressways without greenbelts, and flats with greenery near living quarters.

For flats with greenery, a significant decrease in SPL was seen. This aligns with theoretical literature. Vegetation reduces sounds due to its absorptive effects. Significant evidence also points towards the density of such greenbelts. The higher the density, the larger the reduction of SPL levels (Gwee, 2025). Furthermore, their reflective nature from surfaces also alters the phase of unwanted traffic noise. This provides destructive interference and lowers SPL even further (Dobson & Ryan, 2000)

1.2.2 Rooftop Gardens

Supported by field evidence, Gwee (2025) claims that a higher altitude sees a reduction in tree's effectiveness. SPL rose as one moves from the lower to higher stories of the same building. This may seem misleading as it is easy to hypothesize in the opposite direction. Many believe that being further from the sound source, its volume should decrease, especially when trees are still present to provide additional noise reductions. Given that data from Gwee (2025) suggests otherwise, it is thus clear that trees are more effective in shorter structures. Shorter architecture are more common in Europe, Malaysia and the Northern Americas. On the contrary, vertical architecture predominates Singapore's housing landscape due to land scarcity. Thus, for greenery to be effective sources of noise mitigation, they have to be elevated for the higher storied apartments. Current trees prove effective in reducing noise for lower storied flats. However, given that trees have a limited height, they need to be elevated to provide more noise protection for residents living at the higher levels. Thus, authorities in Singapore ensured that rooftop gardens are implemented in multiple newer estates to address this issue. Much literature focuses on the social (Yuen & Wong, 2005) and thermal (Wong, Cheong, et al., 2003; Wong, Chen, Ong, & Sia, 2003) aspects of such spaces. Regrettably, little acoustic studies on rooftop gardens were conducted.

1.2.3 Facades

In land scarce Singapore, trees with large canopies along roadsides hinders development. Areas by the roadside provide excellent connectivity to the rest of the estate. Such areas are best to be repurposed into social areas. However, noise mitigation effects on par with greenery are hard to come by, though still available. Research into facades (written often as façades) and walls are critical in this effort to improve noise insulation. Noise barriers are already tried, tested, and proven effective strategies. Development in their shapes and materials to maximize effectiveness continues. Unfortunately, designs provide neither the visual appeal nor the natural benefits trees provide. Still, some designs should be analyzed. Literature by Lee (2021) shows that a slated flat-tip structure provides maximum reductions in noise. This is compared against jagged-edge cantilevers, which already provides ample reductions. This paper attempts to analyze a corrugated facade with jagged edges, as shown in figure 4 to see how it fares against classical canopy trees.

1.2.4 Water Features

It is curious that refuge from loud traffic noise can be done by "adding more noise". In other words, sound masking. Sufficient literature proves that producing a soundscape using water features provides immense benefits. This includes reduced annoyance (Nang Li, Kwan Chau, Sze Tse, & Tang, 2011), especially when a green view is unavailable. Cognitive performances also saw an improvement, especially among tasks that require memory (Brocolini, Parizet, & Chevret, 2016). Furthermore, heightened "overall pleasantness" can be observed when water sounds of a similar SPL (Jeon, Lee, You, & Kang, 2010) are added to traffic noise (Rådsten-Ekman, Axelsson, & Nilsson, 2013). According to Jeon et al. (2010), water sounds should not be "less than 3 dB below the level of the urban noises". Furthermore, Rådsten-Ekman et al. (2013) compared sounds from seas, streams and waterfalls. Sufficient evidence lead to the conclusion that seas and streams produce heightened pleasantness. This is due to the lowered amounts of "splashing and hissing" of these water features. No added pleasantness is seen for waterfalls.

Unfortunately insufficient literature focuses on the psychoacoustic parameters of noise, as explained in subsequent paragraphs. This study attempts to analyze the sound masking effects of a waterfall. It is crucial to point out that this study neglects any psychological aspects due to the experimental constraints. It is also regretful that this paper fails to conduct findings at areas with streams and seas as they are not prevalent in Singapore.

2 Parameters and Environments

2.1 Analysis of Sound Parameters

This section focuses on salient points of the variables analyzed in the study. They are sound pressure level (SPL) loudness, sharpness and roughness.

2.1.1 Sound Pressure Level (SPL)

SPL is most commonly used academically and industrially for acoustic research. The measurement of sound pressure is done on the "sound intensity of the wave" (Svantek, 2025). This measurement is in the units of μPa. Dictated in industrial standards, the logarithmic scale is used on this sound pressure. This is due to ears having a non-linear sensitivity. SPL takes on the formula listed below.

$$L_p = 20\, log_{10} \left(\frac{p}{20 \cdot 10^{-6}} \right)$$

L_p has units dB while p takes on S.I. units of Pa.

It is easy to see how a difference in SPL can be derived as follows.

$$\frac{P_2}{P_1} = 10^{\frac{L_2 - L_1}{20}}$$

Furthermore, sound intensities can be calculated as follows.

$$\frac{I_2}{I_1} = \left(\frac{P_2}{P_1}\right)^2$$

This study omits analysis of intensity and pressure ratios as listed above. These parameters are overly complicated and do not do justice of the logarithmic scale that simplifies SPL analysis.

For this study, the A-weighted scale is used. This choice is made as the A weighting attenuates sounds with frequencies in the audible range of 250 Hz to 2000 Hz. This is according to Fletcher and Munson (1933), who specified that the mid-frequency range will be considered, while attenuating the lower and higher ends of the sound. The A-weighted SPL will thus serve as the primary indicator of traffic noise exposure in this study. A higher intensity sound from traffic noise will see a higher measured SPL. Hearing damage may also occur when certain limits are exceeded (Sun et al., 2025).

However, certain features of traffic noise may be incorrectly filtered out by the A-weighted scale. This is due to its emphasis on mid-range frequencies. Higher and lower frequency sounds may be neglected with this weighting. Certain road activities may reach frequencies above 11 kHz, such as that of ambulance sirens or tire screeches (Catchpole & Mckeown, 2007). Regretfully, the A-weighted filter neglects them. Similarly, low frequency drones tend to be less audible and noticeable in a soundscape. However, they give large detrimental effects to the human body if exposed in high intensities. This comes in the form of unwanted vibratory sensations and unease, disrupting our auto-nervous system. (Baliatsas, Kamp, Poll, & Yzermans, 2016). This is due to the "acoustic excitation" of cells in our body (Broner, 1978).

Given that traffic noise possesses these traits, decision to investigate the C-weighted and Z-weighted (unweighted/unfiltered/linear) SPL levels were also made. These scales do not attenuate any frequencies to a large extent to fit our ears. Thus, they are less popular on the industrial or academic level. However, they promote support to this study by providing a better understanding to sounds at all frequency levels (NoiseMeters Inc., 2025).

Certain aspects of noise fail to be fully highlighted by SPL levels. Thus, looking at SPL levels proves insufficient in showcasing the full effectiveness of a noise mitigation strategy. A study on psychoacoustic parameters are critical.

2.1.2 Loudness

The first psychoacoustic parameter is loudness, expressed in sone or soneGF. They are closely related to SPL levels. They analyze as the perceived intensity of sound by the human ear. This variable is particularly important in this study as sounds of similar SPL may be perceived very differently. This is due to differences in frequencies and perceived disturbances (Verrillo & Zwislocki, 2014). With it more closely related to human quantitative response, it provides a more human centric understanding to the sound. When paired against the more qualitative SPL, we can better deduce which feature provides the best noise insulation.

2.1.3 Sharpness

Sharpness, or pitch, characterizes the high frequency nature of the sound. The higher the frequency (above 3000 Hz), the sharper it becomes. Such frequencies are commonly described as "piercing and unbearable". It is inversely correlated to sensory pleasantness, where sharp sounds are immensely unpleasant for listeners (Fastl & Zwicker, 2007). Similar to SPL and loudness, this variable is critical in our analysis as two sounds with varying frequencies may have similar SPL but perceived very differently.

2.1.4 Roughness

Roughness measures the modulation of the sounds. It is also commonly referred to as fluctuations. These fluctuations are highly rapid and may cause immense annoyance to the human ear. These sounds are commonly referred to as "grating" and "aggressive" to the layman. This is particularly prominent at low frequencies (slow variations), where a change in amplitude or frequency is highly detectable (Head Acoustics, 2018). To quantify this modulation, the parameter roughness with units asper is introduced. According to Head Acoustics (2018), who provides the software, Artemis Suite (Head Acoustics, n.d.), used in this study, the calibration of 1 asper is made on a 60dB, 1kHz tone, with amplitude modulations at frequency of 70Hz and modulation depth of 1.

In summary, the 6 variables analyzed in this study are as follows.

- A-weighted Sound Pressure Level (SPL), denoted LA_{eq} with units dB(A)
- C-weighted Sound Pressure Level (SPL), denoted LC_{eq} with units dB(C)
- Z-weighted Sound Pressure Level (SPL), denoted LZ_{eq} with units dB(Z)
- Loudness with units sone
- Sharpness with units acum
- roughness with units asper

2.2 Selection of Primary Environments

As stated in section 1, The housing estate of Bidadari was selected for analysis due to its proximity to major road arteries like Upper Serangoon road and Bartley Road. This claim is clearly evident in figure 3. Furthermore, given that the estate is new, with projects still on going, many novel features to tackle traffic noise from listed road arteries can be found.

To select the best locations for study within the estate, a sound-walk of the estate by Lee (2025) was consulted (relevant data has been extracted into figure 5). It is clear that heavy traffic areas in figure 3 closely correlates to data from the sound-walk. The heavier the traffic, the higher the SPL readings at the location. This largely narrows down suitable locations for study. Additionally, a preliminary study was conducted to source for appropriate locations within the Bidadari estate. Its primary aim is to source for appropriate locations where noise mitigation features are available for analysis. Additionally, common traffic habits were observed. This preliminary study spanned a total of 1 day and a generic mobile application is installed on a mobile phone to obtain field data. This application was used to conduct preliminary recording of the LA_{eq} reading to promote the site selection process. 5 sites were initially selected. Traits of these sites are explained below.

2.2.1 Site 1: Control Environment

Level 5 corridor of Block 207A, facing Upper Serangoon Road serves as the first control of the experiment. This location is selected due to its proximity to the noise source, as seen in figure 6. Furthermore, it acts as a good control as there are few noise mitigation features nearby. As seen in figure 7 and 8, nearby trees are largely small, with few leaves on them. Preliminary collection of LA_{eq} readings on the mobile phone reads 72dB(A). Furthermore, the location has high moving traffic with most cruising at a speed of 30 km/h to 60 km/h. They are non-accelerating due to the presence of a merging lane and a downhill viaduct. This is annotated clearly in figure 8.

Drawbacks of this location include the two lanes having vehicles travelling in different states, as described above. The presence of trees, though at the minimum and at a smaller canopy, may still influence results, giving a lower volume than intended.

2.2.2 Site 2: Trees Environment

Level 3 corridor of Block 105A, facing Upper Serangoon Road serves as the location to analyze effects of trees in mitigating traffic noise. This location is excellent due to the presence of highly dense, thick rainforest trees situated directly (50 m) in front of the location recordings are made. As seen in figure 9, the trees described fully envelope the recording location. The decrease in volume between this environment and that of control (Site 1) is audible. Preliminary recordings on the mobile phone reads 68 dB, lower than recordings at Site 1. This location is also between 2 road junctions, both with heavy traffic. Cars have accelerated previously from the junction and are now cruising, preparing to come to a stop as they reach Site 2. Thus, cars will be travelling at a medium speed of 15 to 30 km/h, not accelerating. Drawbacks of this site are that cars may be accelerating out of the previous junction, influencing the soundscape. Furthermore, confirmation of traffic situations during recordings are not visual and purely auditory. This may lead to abnormalities.

2.2.3 Site 3: Rooftop Garden

This rooftop garden is located at level 3 of Block 201A, facing Upper Serangoon Road. This location serves to analyze the effects of modern rooftop gardens (vertical greenery) in mitigating traffic noise. It is regretful that greenery there are largely minimalistic and rather sparse, as seen in figure 10. However, a decrease in volume can still be heard as compared to Site 1 during preliminary analysis. A reading of $LA_{eq} = 61$dB was obtained, lower than recordings at both Site 1 and Site 2. Traffic conditions are also similar to Site 1 as it is situated only 1 block away from the latter.

Drawbacks of the locations exists as well and are as follows. There exist a bus stop not far away from the location, and exhaust sounds are clearly audible. This will lead to a higher SPL reading being obtained. Furthermore, grills are present for climbing plants to be wrapped on and these may provide some mitigation to noise, lowering SPL. Lastly, the location is largely indoors with a thick wall situated behind. A significant echo can be heard, and this may influence the soundscape.

2.2.4 Site 4: Facade environment

Areas behind the walkway and indoor shelter along Upper Serangoon Road serves to examine effectiveness of a facade in mitigating traffic noise. This facade analyzed features a jagged edge structure, as explained in section 1.2.3 and seen in figure 4 and 11. This walkway already proves effective in the realms of connectivity. Its effectiveness in mitigating noise will now be analyzed. Recordings are made behind the facade, directly in front of the living quarters of level 1 and 2 residents. Preliminary analysis of the facades proves that they are not highly effective. An LA_{eq} of 71 dB is obtained, close to the control environment at Site 1.

Unfortunately multiple drawbacks exist. There are greenery still present in the vicinity as shown in figure 11. This will lower SPL levels as compared to facades with no greenery. Furthermore, unlike past locations, the site is located on the ground level. As a result, characteristics of traffic noise may defer. Traffic is also slower moving as compared to the past 3 environments, resulting in differences in road conditions.

2.2.5 Site 5: Water features

The water features analyzed in this study is located in front of the side door of the condominium 8 @ Woodleigh. This serves as the location to analyze effects of waterfalls in the masking of traffic noise. Due to ethical constraints, entry into the condominium is forbidden. Thus, recordings are made by the roadside, directly in front (25 m) of the waterfall and 50 m from the road, as seen in figure 12. Thus, initial SPL readings are very high at LA_{eq} of 78 dB. However, as we are conducting analysis of psychoacoustics of waterfalls, a higher SPL is of no matter. Still, drawbacks of this location include it being on ground level, similar to that in Site 4. There also exist some shrubbery behind location where recordings are made. This may unfairly influence the SPL readings. Lastly, the traffic at this location is slow moving, and the control variable of traffic being of an equal speed is not satisfied at this location.

2.3 Selection of Secondary Environments

Recordings at secondary environments are also made. These sites aim to supplement the data acquired from the primary sites listed above. They either offer a fuller analysis of the noise reduction feature, or made in comparison to the primary analysis to observe any differences. The characteristics of such sites are as follows.

2.3.1 Site 6: Control Environment 2

The second control environment chosen for study is located at the level 3 stairwell of Block 214A, facing Bartley Road. This serves as the second control experiment, the first being Site 1 as described in section 2.2.1. Similar to Site 1, Site 6 has little greenery shielding the blocks from the road as trees are young, canopy sparse. This can be seen in figure 13. It is of equal proximity to the noise source as compared to Site 1, and has relatively high moving traffic with cruising speeds of 40 km/h. This secondary site is selected to test the following hypothesis: Traffic noise will decrease from Monday to Friday. As we progress through the week, road users are less agitated, display better driving habits and potentially lower traffic noises in totality. Furthermore, Site 6 is critical in ensuring that findings are generalizable and not site dependent. It also serves as a comparison between roads to ensure traffic of the days recordings were made are similar for both roads. This is due to Site 8 (explained in section 2.3.3) being compared to Site 3 in section 2.2.3. Yet, Site 3 is located at Upper Serangoon Road, while Site 8 is at Bartley Road. To make comparison fair, SPL levels should not be massively different between the two roads or at least scaled to match each other. Drawbacks include how the small number of trees at the site may still influence the sound, providing a slight barrier and lowering SPL levels. Still, preliminary analysis using the mobile phone application shows LA_{eq} levels of 73 dB, largely similar to that of Site 1.

2.3.2 Site 7: Trees Environment at a Higher Elevation

Level 8 of Block 105A, facing Upper Serangoon Road. This location is selected to compare against data in Site 2. It is situated right above Site 2, with its elevation from the ground approximately doubled, as seen in figure 14. This tests the hypothesis that a higher elevation will see a rise in SPL levels despite its larger proximity to the source of the noise. This is provided that there exists no rooftop gardens, where greenery is elevated like in Site 3. Furthermore, it will be used in comparison with Site 3 to determine the effectiveness in shielding traffic noise at a higher elevation using rooftop gardens. Preliminary analysis of SPL data at the site shows a reading of 66 dB.

2.3.3 Site 8: A Denser Rooftop Garden

This rooftop garden is located at level 4 of Block 214 multi-storey carpark. This location serves to analyze rooftop gardens that predominate those in BTO flats, where they are situated above multi-storey carparks, enclosed by flats, as seen in Figure 15 This site is used to supplement that of Site 3 as Site 3 is less common in Singapore, i.e. situated by the roadside, sparse vegetation. Site 8 on the other hand is denser and further away from the main road artery. This placement of rooftop gardens is more common in Singapore, more relevant to residents residing in the country, and worth investigating. Unfortunately, given that it is at a distance from the source of the traffic noise, it is expected to have a slightly lower SPL than the other sites. Furthermore, to ensure data collected at Site 8 is comparable to other environments, traffic conditions at Upper Serangoon Road must match those at Bartley Road to ensure a fair analysis. Still, Site 8 proves useful to investigate how rooftop gardens that predominates modern estates in Singapore provide insulation from noise. Preliminary data shows LA_{eq} levels of 59 dB, much lower than the data collected at Site 6. A significant decrease in volume can also be heard when travelling from Site 5 to 8 on foot, despite traffic noises still audibly prominent at Site 8.

2.3.4 Site 9: In Front of Facade Environment

Audio recordings at Site 9 takes place in front of that of Site 4, within the walkway and indoor shelter along Upper Serangoon Road. In other words, Site 9 is located in front of the facade, with no insulation between the road and the ears. This site is selected in direct comparison with that of Site 4. It provides deeper analysis of the effectiveness of the corrugated wall. The facade may exhibit porous characteristics, thus allowing high frequency sounds with shorter wavelengths to be absorbed. Furthermore, the uneven surfaces may diffract mid-range to high frequency sounds effectively. If true, a higher LA_{eq} will be seen as compared to Site 4. Higher frequencies above 3000 Hz will also have a higher L_{eq} for recordings at Site 9 than Site 4. Preliminary data collection at Site 9 shows a recorded LA_{eq} of 71 dB, similar to that of Site 1.

2.3.5 Site 10: Further Away from Water Features

Recordings at Site 10 are made approximately 50 m away from that of Site 5. This means that Site 10 is now further away from the waterfall than Site 5, with a distance of 75 m now, as compared to the 25 m as described in section 2.2.5. This also means that we are much nearer to the roads (10 m) as compared to Site 5. Figure 16 is provided to facilitate visualization. This location is selected to provide a better understanding of contributions to noise in recordings at Site 5 and analyze the psychoacoustics as well.

2.4 Methodology of Study

Recordings at Site 1 to 5 are done on 19 May 2025 (Monday), 21 May 2025 (Wednesday), and 23 May 2025 (Friday). Morning recordings of all 5 sites were done within the peak hours period of 08:15 to 08:45. Evening recordings were made during the peak hours of 18:10 to 18:40. The short recording window ensures recording of all 5 sites at each timing are completed without major changes in road conditions. Moments of abnormalities were avoided as well. This may include but not limited to fighter jet flybys, motorcycles and cars with modified exhausts, moments when no cars are on the roads for the entire duration of the recording, etc. Recording made that contains these abnormalities are avoided and not used in the dataset. Recordings are also limited to 2 minutes, with a minimum duration of 1 minute. This is to capture the full extent of a traffic light cycle. 2 recordings at each location and moment were obtained. This is to maximize precision of data collected, yet provide sufficient time to travel from one location to another within the 30 minutes recording window.

On 2 June 2025 (Monday), 4 June 2025 (Wednesday) and 6 June 2025 (Friday), recordings at Site 6 to 10 was conducted. It is important to note that the Singapore education holidays occur during the month of June. Thus, traffic could have been slightly different during these dates. However, analysis of traffic data on Google Maps on the day showed insignificant differences to those of the regular term. (It is regretful that Google Maps data on the days of recordings was not captured and cannot be retrieved for this report.)

The previous application used on the mobile phone is highly limited. Not only is the microphone not calibrated for recording, it fails to capture any psychoacoustic properties of the sounds. To ensure maximum accuracy, the equipment named SQobold, manufactured by HEAD acoustic, was used to capture recordings taken in this study. Analysis of these field recordings are conducted within the software Artemis SUITE. Despite the equipment having abilities to capture both the left and right channels, only the left channel will be analyzed. This is because the analysis of both channels is moot and will only inflate the already large dataset, which is undesirable.

3 Results and Analysis

This section will present the field results obtained. Detailed analysis will then be attempted to make sense of the results obtained.

3.1 Results

For each location, a maximum of 12 recordings are made. For each recording, they are labeled in the fashion explained in table 1.

<Date>	<Time of Day>	<Recording number>
MON	AM	1
WED	PM	2
FRI		

Table 1: Naming convention for each recording

For example, the second recordings done on Friday morning will be labeled **FRI-AM-2**. This labeling style ensures maximum precision and clarity.

Only raw data will be shown in this section. They will be tabulated succinctly for ease of reading. More statistical details and explanations for any abnormalities are provided in section A.

Site 1	LA_{eq}	LC_{eq}	LZ_{eq}	Site 6	LA_{eq}	LC_{eq}	LZ_{eq}
MON-AM-1	69.28	74.74	75.81	MON-AM-1	64.79	76.59	78.00
MON-AM-2	68.88	75.43	76.85	MON-AM-2	68.01	77.39	78.80
MON-PM-1	65.59	76.04	77.69	MON-PM-1	73.48	78.30	79.26
MON-PM-2	66.24	73.61	74.71	MON-PM-2	70.07	76.44	77.72
WED-AM-1	66.15	72.61	73.95	WED-AM-1	72.50	78.12	79.21
WED-AM-2	66.37	72.41	73.53	WED-AM-2	69.71	75.36	76.72
WED-PM-1	70.09	75.52	77.75	WED-PM-1	73.82	77.58	78.46
WED-PM-2	68.45	74.21	76.47	WED-PM-2	74.36	78.42	80.25
FRI-AM-1	68.10	75.50	77.22	FRI-AM-1	74.12	77.78	78.71
FRI-AM-2	70.43	77.40	79.20	FRI-AM-2	70.30	78.91	79.74
FRI-PM-1	70.74	76.88	77.80	FRI-PM-1	71.80	78.85	79.85
FRI-PM-2	71.63	76.68	78.00	FRI-PM-2	72.76	80.47	81.40
Average	68.50	75.09	76.58	Average	71.31	77.85	79.01

Table 2: SPL data of Site 1 and Site 6 presented beside each other. All units in dB.

Site 2	LA_{eq}	LC_{eq}	LZ_{eq}	Site 7	LA_{eq}	LC_{eq}	LZ_{eq}
MON-AM-1	65.74	74.53	75.92	MON-AM-1	68.22	74.54	76.77
MON-AM-2	63.16	72.66	73.88	MON-AM-2	67.92	74.57	76.02
MON-PM-1	61.38	71.34	72.74	MON-PM-1	68.04	78.49	79.89
MON-PM-2	62.99	71.90	74.46	MON-PM-2	67.48	73.62	75.23
WED-AM-1	61.20	70.53	72.34	WED-AM-1	60.96	68.74	69.83
WED-AM-2	63.79	72.06	74.26	WED-AM-2	68.68	73.56	75.76
WED-PM-1	62.77	72.49	75.44	WED-PM-1	65.55	72.09	73.48
WED-PM-2	64.58	72.54	74.40	WED-PM-2	68.68	73.39	74.51
FRI-AM-1	65.03	72.15	73.90	FRI-AM-1	69.30	73.93	75.43
FRI-AM-2	66.33	73.94	75.08	FRI-AM-2	68.08	73.23	75.25
FRI-PM-1	66.07	72.63	74.79	FRI-PM-1	61.23	67.75	70.43
FRI-PM-2	59.84	68.45	70.21	FRI-PM-2	70.10	75.67	76.86
Average	63.57	72.10	73.95	Average	67.02	73.30	74.96

Table 3: SPL data of Site 2 and Site 7 presented beside each other. All units in dB.

Site 3	LA_{eq}	LC_{eq}	LZ_{eq}	Site 8	LA_{eq}	LC_{eq}	LZ_{eq}
MON-AM-1	58.18	73.40	78.28	MON-AM-1	58.12	70.09	72.65
MON-AM-2	59.11	71.39	76.22	MON-AM-2	58.31	70.28	72.36
MON-PM-1	57.91	70.80	74.96	MON-PM-1	60.96	70.60	71.90
MON-PM-2	58.12	71.02	75.43	MON-PM-2	61.02	68.46	70.09
WED-AM-1	58.97	72.33	76.26	WED-AM-1	58.21	68.00	69.53
WED-AM-2	59.25	72.27	76.86	WED-AM-2	60.48	69.90	71.06
WED-PM-1	60.20	73.42	77.62	WED-PM-1	62.68	70.96	72.81
WED-PM-2	59.91	72.05	76.18	WED-PM-2	62.23	69.58	70.99
FRI-AM-1	60.41	73.05	77.85	FRI-AM-1	62.72	69.40	70.79
FRI-AM-2	59.86	73.54	77.67	FRI-AM-2	60.93	70.33	72.18
FRI-PM-1	60.55	75.22	78.66	FRI-PM-1	59.08	67.74	69.69
FRI-PM-2	58.10	73.28	78.14	FRI-PM-2	63.00	70.38	71.58
Average	59.21	72.65	77.01	Average	60.65	69.64	71.30

Table 4: SPL data of Site 3 and Site 8 presented beside each other. All units in dB.

Site 4	LA_{eq}	LC_{eq}	LZ_{eq}	Site 9	LA_{eq}	LC_{eq}	LZ_{eq}
MON-AM-1	62.90	75.39	77.39	MON-AM-1	67.04	75.73	77.54
MON-AM-2	60.62	73.27	75.59	MON-AM-2	63.64	75.03	76.93
MON-PM-1	62.23	73.64	75.74	MON-PM-1	67.01	78.28	79.72
MON-PM-2	64.14	73.49	75.34	MON-PM-2	65.78	75.08	77.13
WED-AM-1	66.45	74.78	76.17	WED-AM-1	65.65	74.16	75.59
WED-AM-2	65.50	74.67	76.55	WED-AM-2	67.99	74.78	76.38
WED-PM-1	65.26	75.84	77.56	WED-PM-1	70.43	75.06	76.49
WED-PM-2	61.73	72.56	74.48	WED-PM-2	66.94	72.10	73.82
FRI-AM-1	64.70	74.71	76.68	FRI-AM-1	73.26	79.44	80.36
FRI-AM-2	65.19	74.40	75.94	FRI-AM-2	63.34	76.69	78.08
FRI-PM-1	67.16	74.85	76.36	FRI-PM-1	69.49	77.95	79.16
FRI-PM-2	63.21	72.39	74.25	FRI-PM-2	67.98	77.61	78.87
Average	64.09	74.17	76.00	Average	67.38	75.99	77.51

Table 5: SPL data of Site 4 and Site 9 presented beside each other. All units in dB.

Loudness/sone	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
MON-AM-1	26.9	25.1	15.4	20.3	28.5	25.0	27.7	14.1	29.2	40.0
MON-AM-2	29.2	22.1	15.8	19.6	48.8	28.4	27.5	14.4	23.6	39.2
MON-PM-1	24.0	19.0	14.2	22.0	35.1	36.3	26.8	16.4	29.3	35.3
MON-PM-2	24.9	20.7	14.3	24.5	44.3	33.3	26.2	16.4	27.3	29.5
WED-AM-1	25.2	18.2	16.2	26.3	43.2	34.1	22.2	15.2	23.0	36.9
WED-AM-2	22.4	21.5	15.4	26.6	39.0	32.4	26.3	15.6	29.3	25.1
WED-PM-1	28.2	21.0	16.2	24.9	45.3	36.7	23.3	18.7	32.6	27.3
WED-PM-2	28.0	21.6	16.0	20.8	47.7	37.0	29.1	18.0	28.5	33.5
FRI-AM-1	25.5	23.3	17.6	23.3	39.9	36.1	32.1	17.9	44.1	49.5
FRI-AM-2	35.4	26.4	16.5	25.5	38.5	35.0	23.7	16.0	26.0	0.0
FRI-PM-1	34.9	23.9	17.4	34.4	33.7	33.2	18.1	13.7	31.7	0.0
FRI-PM-2	39.5	17.3	14.8	24.7	35.7	39.4	31.0	23.1	33.7	0.0
Average	28.7	21.7	15.8	24.4	40.0	33.9	26.2	16.6	29.9	35.1
Decrease	0	7.0	12.9	4.3	-11.3	0	2.5	17.3	-1.2	-6.4

Table 6: Loudness data of Site (labeled S) 1 to 10

Sharpness/acum	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
MON-AM-1	2.00	1.78	1.65	1.85	2.72	2.02	2.16	1.48	2.23	2.54
MON-AM-2	2.11	1.57	1.81	1.83	2.65	1.97	2.15	1.44	2.16	2.56
MON-PM-1	2.01	1.66	1.61	1.84	2.60	2.38	1.88	1.71	2.23	2.53
MON-PM-2	1.93	1.71	1.66	1.93	2.78	2.15	2.13	1.70	2.01	2.56
WED-AM-1	2.08	1.63	1.68	1.98	2.73	2.31	1.82	1.71	2.02	2.66
WED-AM-2	2.04	1.61	1.71	1.93	2.73	2.06	2.14	1.75	2.21	2.75
WED-PM-1	2.17	1.71	1.70	2.02	2.91	2.76	2.00	2.09	3.11	2.61
WED-PM-2	2.09	1.71	1.72	1.90	2.71	2.72	2.73	2.06	2.46	2.58
FRI-AM-1	1.96	1.84	1.77	2.04	2.89	2.71	2.68	2.03	3.16	2.62
FRI-AM-2	1.97	2.20	1.76	1.99	2.73	2.02	2.07	1.72	1.92	0.00
FRI-PM-1	2.10	2.36	1.75	1.99	2.65	2.29	1.73	1.69	2.13	0.00
FRI-PM-2	2.12	2.09	1.85	1.82	2.64	2.27	2.09	1.79	2.07	0.00
Average	2.05	1.82	1.72	1.93	2.73	2.31	2.13	1.76	2.31	2.60
Difference	0	0.23	0.33	0.12	-0.68	0	-0.08	0.54	-0.26	-0.55

Table 7: Sharpness data of Site (labeled S) 1 to 10

Roughness/asper	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
MON-AM-1	.200	.192	.163	.205	.119	.178	.179	.192	.156	.239
MON-AM-2	.236	.202	.148	.160	.234	.214	.161	.209	.156	.209
MON-PM-1	.172	.191	.160	.166	.152	.201	.233	.176	.196	.175
MON-PM-2	.179	.186	.160	.179	.163	.182	.173	.170	.171	.160
WED-AM-1	.168	.193	.157	.189	.160	.203	.206	.157	.172	.153
WED-AM-2	.173	.205	.162	.184	.178	.202	.170	.160	.169	.117
WED-PM-1	.182	.190	.171	.169	.180	.147	.163	.139	.089	.127
WED-PM-2	.175	.197	.163	.165	.222	.140	.108	.128	.146	.160
FRI-AM-1	.187	.201	.189	.180	.155	.141	.117	.138	.163	.191
FRI-AM-2	.220	.209	.518	.186	.153	.166	.167	.169	.166	.000
FRI-PM-1	.203	.113	.165	.195	.131	.181	.155	.168	.200	.000
FRI-PM-2	.188	.110	.149	.171	.162	.437	.329	.194	.221	.000
Average	.190	.182	.192	.179	.167	.199	.180	.167	.167	.170
Difference	.000	.008	-.002	.011	.023	.000	.010	.033	.023	.020

Table 8: Roughness data of Site (labeled S) 1 to 10

3.2 Analysis of SPL Results

3.2.1 Analysis of Site 1 and 6 A-weighted SPL results

Site 1 and 6 are the control groups with no noise insulation measures present.

Thus, it is expected for LA_{eq} readings at these 2 sites to be higher than the other sites with noise mitigation strategies. This hypothesis is proven in this study and consolidated in table 9, where Site 1 and 6 have the highest average LA_{eq} readings (excludes waterfall).

Controls	Trees	RTGs	Facades
Site 1 68.50	Site 2 63.57	Site 3 59.21	Site 4 64.09
Site 6 71.31	Site 7 67.02	Site 8 60.65	Site 9 67.38

Table 9: Average LA_{eq}/dB of control, trees, rooftop gardens (RTGs) and facade environments

Thus, given that no noise insulation at Site 1 and 6 gives the worse LA_{eq} readings, it is worth claiming that "some insulation is better than nothing".

It is also worth noting that average and median LA_{eq} levels of these recordings at Site 1 and 6 exceeds benchmarks set by National Environmental Agency (2023) of 67 dB. However, studies of 1 to 2 minutes averaged are unrepresentative of a full 60 minute SPL reading. Furthermore, recordings made in this study takes place only when traffic is passing by. The full 60 minutes guideline by NEA also includes moments when vehicles are stationary or absent on the road, producing little to no sound. Thus, it is unfair to indicate a breach in regulations. Furthermore, as seen in table 2, 4 of the 12 recordings made at Site 1 shows readings of LA_{eq} are already below 67 dB, despite traffic being loud and fast. A similar situation of 1 instance occurs in Site 6.

Still, it is worth the effort to attempt to collect field data of 1 hour LA_{eq}. This is due to planning done in the past might not be representative of current traffic developments.

Another observation made at Site 1 is regarding the 2 different types of traffic at the location, merging traffic and downhill traffic. Recordings done on Monday mornings and evenings attempts to analyze the differences between these 2 situations. MON-AM-1 and MON-PM-1 are recordings of downhill traffic, while merging traffic is captured in MON-PM-2 and MON-AM-2. It is clear that the differences are insignificant to derive any major conclusions.

Furthermore, it is moot to derive any findings in terms of day. Hypothesis in section 2.3.1 which states that LA_{eq} levels will decrease throughout the week cannot be satisfied. This is due to data in table 2, where LA_{eq} readings fluctuate day to day. Still, it is worth noting that readings on Monday morning for Site 6 is significantly lower than the remaining days. Thus, it may seem that it contradicts the hypothesis. However, given that this happening is not seen at Site 1, it is unfair to judge the significance of these lowered readings. It could perhaps be only site and moment specific, thus unfair to come to any conclusions.

It is also worth pointing out that Site 1 and 6 are of different roads. Thus, the differences in average LA_{eq} is slightly large at 2.81 dB, with Site 1 at Upper Serangoon Road being lower than Site 6's Bartley Road. Despite the differences, analysis of features located at both roads can still be compared against each other as the upper bound of Site 1 falls above the lower bound of Site 6.

3.2.2 Analysis of Site 1 and 6 C and Z-weighted SPL results

Similar to that of LA_{eq}, control sites without insulation has the highest average LC_{eq} readings as compared to those with insulation. Similar conclusions can be made for the LZ_{eq} values.

However, unlike LA_{eq} readings, there is a large difference in average SPL values when comparing average LA_{eq} to LC_{eq}. For Site 1, the difference is 6.59 dB, while the difference is 6.54 dB for Site 2. The difference is even larger when comparing LA_{eq} to LZ_{eq}. For Site 1, the difference is 8.08 dB, while for Site 2, the difference is 7.7 dB. Given that LA_{eq} filters out the majority of lower and higher frequencies, (thus amplifying mid-frequencies), it is critical to analyze the reasons for the large differences.

Frequency analysis of control sites are conducted to explain this phenomenon. Depicted in figure 17, which displays data from **MON-PM-2**, the LA_{eq} against frequency graph can be seen in graph (b). There, SPL peaks at 300 Hz. However, for graph (f), which depicts LZ_{eq} against frequency, SPL peaks at 30 Hz. The issue is now clear. Traffic is a relatively low frequency. By using the A-weighted SPL levels, we mask this critical feature of traffic noise. It turns a blind eye to the higher amplitude low frequencies. Conclusions can also be made that humans may not just be affected by the low drone of the traffic noise, but also “feel the noise”. These are vibratory sensations from the traffic that at a very high amplitude, as derived from graph (f) of figure 17. According to Berlin and Adams (2017), the biomechanical vibrations of the skin lies within 2 to 20 Hz, but key areas such as the head eyeballs and chest resonate around 30-50 Hz, the peak amplitude of traffic noise. Thus, when at Site 1 and 6, we may feel the unwanted vibratory sensations due to constructive interference within their bodies.

Site 6	MON-AM-2	FRI-AM-1	Difference
LA_{eq}/dB	68.01	74.12	6.11
LZ_{eq}/dB	78.80	78.71	0.09
Difference/dB	10.79	4.59	

Table 10: Comparison between LA_{eq} and LZ_{eq} data

Further comparison between LA_{eq} and LZ_{eq} recordings can be made using the individual recordings of **MON-AM-2** and **FRI-AM-1**. It is clear that the difference between unweighted LZ_{eq} is minimal, yet a large difference of 6.11 dB can be seen from the readings. The difference when comparing unweighted LZ_{eq} and A-weighted LA_{eq} shows a more significant decrease on Monday’s recording than Friday’s. This indicates that prevalence of low frequencies on MON-AM-2 is higher than FRI-AM-1. When an A-weighting is applied, most of these high volume low frequencies are filtered out, resulting in a surprisingly low LA_{eq}.

With consultation of video recordings of the moment field data was collected, it is observed that on the mornings of Monday, there are a higher count of buses and trucks. Vehicles across the road are also largely stationary, resulting in low frequency noises being constantly present rather than fluctuating with passing vehicles.

Lastly, it is worth noting that when recordings are conducted, these vibratory sensations can indeed be felt by the human body, even for a short 10 minutes when at the location of the recording. However, once moved to the interiors, such as a stairwell or inside a lift, only the aftereffects can be felt, which involves an “unexplainable” fatigue. Furthermore, recordings at Site 1 and 6 directly faces the road. While such noise is undesirable at any location of residence, it is worth pointing out that living quarters are more nested within and shielded by windows. Thus, some refuge can still be provided. However, field data cannot be collected as it is unethical do so at these locations.

3.2.3 Analysis of Site 2 A-weighted SPL results

	Site 1	Site 2	Difference	Percentage difference
LA_{eq}/dB	68.50	63.57	-4.93	7.47%
LC_{eq}/dB	75.09	72.10	-2.99	4.06%
LZ_{eq}/dB	76.58	73.95	-2.63	3.49%

Table 11: Comparison between Site 1 and 2 data

A recap of Site 2: Site 2 involves the usage of trees to mitigate traffic noise. These trees have large canopies and can effectively curb some mid-frequency sounds. It is clear that trees are highly capable in reducing the LA_{eq} of levels of traffic noise. With a mean LA_{eq} of 63.57 dB, there exist a 4.93 dB drop in A-weighted SPL levels. This is in comparison to Site 1, which is also located at Upper Serangoon Road, and has LA_{eq} of 68.50 dB. The percentage decrease in LA_{eq} is 7.47%. Percentage difference is calculated using the formula below.

$$\text{percentage difference} = \frac{2|L_{eq,1} - L_{eq,2}|}{L_{eq,1} + L_{eq,2}} \times 100\%$$

The above details are summarized and displayed clearly in table 11.

This drop clearly aligns with past literature and classic practices of having trees planted by the roadside. Thus, it is wise to continue doing so as its absorptive (Gwee, 2025) and reflective (Dobson & Ryan, 2000) effects clearly aligns with field data collected in this study. Unfortunately, this study lacks in depth to analyze effects of density and relective-absorptive rates.

This drop is even more significant when comparing the maximum LA_{eq} of Site 1 (71.63 dB at FRI-PM-2) and minimum LA_{eq} of Site 2 (59.84 dB at FRI-PM-2). A drop of 11.79 dB can be seen with a percentage difference of 17.94%. Furthermore, the lower bound at Site 1 is 65.59 dB, very close to the upper bound of Site 2 66.33 dB. All data thus point towards trees being immensely effective in reducing LA_{eq} levels. Comparisons to the maximum and minimum of Site 6 is not done as the roads at Site 2 and 6 are different, making comparisons moot.

It is worth noting that the recording of FRI-PM-2 is the minimum of the entire Site 2 dataset. However, given that this data-point's LC_{eq} and LZ_{eq} levels are also an abnormality, this value of minimum might cloud judgement of the true effectiveness of trees.

3.2.4 Analysis of Site 2 C and Z-weighted SPL results

Trees are effective for low frequencies as well. As seen in table 11, LC_{eq} values saw a decrease of 2.99 dB, while LZ_{eq} values saw a decrease of 2.63 dB when compared to Site 1. This corresponds to a 4.06% and 3.49% decrease respectively. This drop for LZ_{eq} and LC_{eq}, where low-frequencies are prominent, clearly shows that the usage of trees to mitigate traffic noise is moderately useful. However, the drop is not very significant, as compared to that of LA_{eq}. This could have been because that the trees are not dense enough, as explained in section 1.2.1. Still, the conclusion that trees are not effective in mitigate low frequencies can be made. Given that traffic is largely comprised of low frequencies, it is not extremely useful to mitigate unwanted traffic noise pollution. Humans who are living in flats built behind a green belt can still feel large amounts of the vibratory sensations that comes with the low frequency nature of traffic noise. However, trees still provide the greatest decrease in LC_{eq} (-2.99 dB) as compared to rooftop gardens (-2.44 dB) and facades (0.92 dB). Thus, it cannot be replaced.

To summarize, trees are able to largely decrease audible noise from traffic, and provide some minor refuge in the vibratory sensations from the noise.

3.2.5 Analysis of Site 7 A-weighted SPL results

	Site 1	Site 7	Difference	Percentage difference
LA_{eq}/dB	68.50	67.02	-1.48	2.18%
LC_{eq}/dB	75.09	73.30	-1.79	2.41%
LZ_{eq}/dB	76.58	74.96	-1.62	2.13%

Table 12: Comparison between Site 1 and 7 data

	Site 1	Site 7	Difference	Percentage difference
LA_{eq}/dB	68.50	68.21	-0.29	0.42%
LC_{eq}/dB	75.09	73.76	-1.79	2.40%
LZ_{eq}/dB	76.58	75.48	-1.1	1.44%

Table 13: Comparison between Site 1 and 7 data, abnormalities removed

	Site 2	Site 7	Difference	Percentage difference
LA_{eq}/dB	63.57	67.02	+3.45	5.28%
LC_{eq}/dB	72.10	73.30	+1.20	1.65%
LZ_{eq}/dB	73.95	74.96	+1.01	1.36%

Table 14: Comparison between Site 2 and 7 data

To recap, Site 7 is located at a higher elevation than Site 2. The number of trees around, their type and their density is unchanged.

As we move to a higher altitude, the intensity of sound decreases, as seen in table 12, where LA_{eq} levels fell by 1.48 dB, 2.18%. This phenomenon is expected as more sound energies are dissipated away as distance increases.

Furthermore, as altitude increases, the distance from the trees also increases. At a further distance away, the decrease in LA_{eq} is less pronounced at 1.48 dB, 2.18% as compared to Site 2's 4.93 dB, 7.47% (shown in table 11). Thus, trees may be useful for lower storied flats, but not especially useful for higher floored ones. Effectiveness of trees decreases as elevation increases. This trait is even more pronounced when abnormalities are removed. According to table 13, the decrease in LA_{eq} is only 0.29 dB, at 0.42%. Comparing these numbers with Site 2's 7.47%, the above claim is clear.

Similar to Site 1, sounds at Site 7 exceeds National Environmental Agency (2023) ratings, but these 1 to 2 minute recordings are unrepresentative of the entire 1 hour dictated by the standards set.

3.2.6 Analysis of Site 7 C and Z-weighted SPL results

Similar to LA_{eq}, LC_{eq} for Site 7 are lower than Site 1. However, values are now higher than that of Site 2. This trait is also seen for LZ_{eq}. Comparing to Site 1, the decrease in LC_{eq} is 1.79 dB, 2.41%. The decrease in LZ_{eq} is 1.62 dB, 2.13%. Comparing these numbers to LA_{eq}, which saw a decrease of 2.18%, the decreases are somewhat similar. However, when abnormalities are removed, trends appear. Presented in table 13, the decrease in LA_{eq} is minimal, but for LC_{eq} and LZ_{eq}, decreases are much more pronounced. (Consult prof for an explanation why shorter wavelengths don't see much of amplitude decreases, but longer wavelengths the amplitude decreases more significantly.)

Significant findings can also be seen for comparisons to Site 2. According to table 14, as we increase in distance from trees, LC_{eq} increases by 1.20 dB, 1.65%. LZ_{eq} increases by 1.01 dB, 1.36%. These increases are minimal as compared to that of LA_{eq}, with an increase of 3.45 dB, 5.28%. Clearly, mid-range frequencies are louder at higher altitudes as compared to lower altitude with trees. These mid-range frequencies are mitigated by trees when at a lower altitude, but fail to be mighty effective for higher altitudes. They do not provide much blockade there, for we exceeded the height of trees. Moreover, for low frequencies, given that trees are of little use in the first place, their effectiveness when further away is not prominent as well.

3.2.7 Analysis of Site 3 A-weighted SPL results

	Site 1	Site 2	Site 3
LA_{eq}/dB	68.50	63.57 (-4.93)	59.21 (-9.29)
LC_{eq}/dB	75.09	72.10 (-2.99)	72.65 (-2.44)
LZ_{eq}/dB	76.58	73.95 (-2.63)	77.01 (+**0.43**)

Table 15: Site 1 to 3 SPL data. Bracketed values for Site 2 and 3 are comparisons to Site 1.

Site 3 features a rooftop garden located right beside Upper Serangoon Road, a major road artery. Data from trees and control are also listed below in table 15.

According to table 15, average LA_{eq} levels of 59.21 dB are much lower than both trees (63.57 dB) and control (68.50 dB). The decrease in LA_{eq} for rooftop garden is 9.29 dB at 14.5%, much better than that of trees of 4.93 dB, 7.47%. It is rather surprising for the effectiveness above trees as they seem to be perfect replacements. The performance of rooftop gardens clearly supersedes that of trees. The density of the rooftop garden is also not massively dense, as seen in figure 10. The heightened performance of rooftop gardens can even be seen when comparing the maximum of Site 3 (60.55 dB) to the minimum of Site 2 (59.84 dB), where the difference is minimal. The large difference in LA_{eq} for rooftop gardens as compared to trees may be attributed to a larger number of accelerating cars at Site 2, influencing trees' results. However, claim cannot be supported by evidence as the canopy is too dense at Site 2.

Results at Site 3 (59.21 dB) are also much lower than that at Site 7 (67.02 dB) as well. Site 7 features recordings at a heightened elevation, trees far away. It is deduced in section 3.2.5 that the trees at a distance provides little to no refuge from traffic noise (-1.48 dB, 2.18% when abnormalities are included. -0.29 dB, 0.42% when abnormalities are excluded.) These numbers are infinitesimal when compared to a 9.29 dB decrease at 14.5% for rooftop gardens. It is thus wise to build rooftop gardens like this at elevated floors of the apartment buildings to provide them with refuge from noise pollution. With the positive benefits of being far away coupled with the pros of a rooftop garden, LA_{eq} levels at these higher storied flats would likely be even lower than Site 3.

3.2.8 Analysis of Site 3 C and Z-weighted SPL results

LC_{eq} values for Site 3 rooftop gardens performed worse than that of Site 2's trees. The LC_{eq} values are 72.65 dB and 72.10 dB respectively. However, Site 3's values are still lower than Site 1 control. Rooftop gardens thus provide some refuge for C-weighted noises.

However, LZ_{eq} values are the most drastic for Site 3. When compared to LZ_{eq} of Site 1, a rise of 0.43 dB was seen. This increase is unprecedented, for it seems that implementing noise mitigation strategies only worsens the noise pollution. Reasons for this could be due to the heightened number of buses at the site. There exists a bus stop nearby, and the buses produce a large amount of low frequency sounds. Thus, data shows the LZ_{eq} readings are the worst of all features, yet its LA_{eq} readings are the best among all. This aligns with the theory of a larger number of buses, as the predominant low frequencies are attenuated, while largely absent mid-range frequencies are not attenuated. Thus, overall LA_{eq} readings are lowered.

LZ_{eq} values are also worse than trees. Multiple reasons could have surfaced. Firstly, trees are dense and provide slight amounts of refuge to low frequencies. However, the rooftop garden is sparse, so little to no refuge is available. Furthermore, the rooftop gardens selected has a concrete wall behind. This concrete wall is rather thick and impenetrable by sound. The low frequencies may have reflected off the walls and reach the ear again. Constructive interference could have occurred, amplifying the sound, resulting in readings even larger than the control Site 1.

In total, Rooftop gardens will audibly provide much traffic noise mitigation, much better than trees. However, residents can still feel the vibratory sensations within their bodies as they fail to provide refuge from the low frequency nature of traffic noise. Still, the added psychological effects of having greenery in living spaces outweighs the costs.

3.2.9 Analysis of Site 8 A-weighted SPL results

A recap of Site 8 features involve the rooftop garden to be located at a much enclosed space. It is located along Bartley Road, just a stone's throw away from Site 6.

Site 8 saw an LA_{eq} of 60.65 dB. Comparing that to Site 3 of 59.21 dB, Site 8's data seem to be slightly higher than that of Site 3. It's odd that Site 8 is more nested within blocks made of concrete, yet it's LA_{eq} levels are higher. However, when comparing the decrease in values from control Site 6, LA_{eq} values decreased very significantly. This is shown in table 16.

	Site 2 (against Site 1)	Site 3 (against Site 1)	Site 8 (Against Site 6)
$\triangle LA_{eq}$/dB	-4.93 (7.47%)	-9.29 (14.54%)	-10.66 (16.16%)
$\triangle LC_{eq}$/dB	-2.99 (4.06%)	-2.44 (3.30%)	-8.21 (11.13%)
$\triangle LZ_{eq}$/dB	-2.63 (3.49%)	+0.43 (-0.56%)	-7.71 (10.26%)

Table 16: Change in SPL in Site 2, 3 and 8 when compared against appropriate control sites.

Site 8's rooftop gardens that are more nested within blocks saw a 10.66 dB decrease in LA_{eq}, a 16.16% decrease. This is very significant as compared to -9.29 dB (-14.54%) of Site 3's rooftop gardens that are by the roadside and -4.93 dB (7.47%) in trees.

Indeed, raw data shows Site 8 being louder than Site 3. However, this is likely due to them being located adjacent to different roads. This means traffic conditions are also different, with Bartley Road being louder than Upper Serangoon Road. This is tabulated in table 9, where Bartley Road's Site 6 having a higher LA_{eq} than Upper Serangoon Road's Site 1. Thus, it is unfair to compare Site 3 and 8 individually.

Given the decrease is more prominent when rooftop gardens are nested like in Site 8, it is safe to conclude that the current rooftop garden designs are appropriate. However, Site 3 still provided much mitigation to traffic noise, so authorities may consider providing flats that are by facing the roads with rooftop gardens as well.

3.2.10 Analysis of Site 8 C and Z-weighted SPL results

Site 8 is the only site that saw effectiveness in reducing LC_{eq} and LZ_{eq} by over 10%. They performed even better than the classic trees, showcasing the superior performance in the modern rooftop garden designs in Singapore. It is clear that these designs can very effectively curb low frequency sounds, which is the prevailing issue throughout this study. Critics may point out that this could have been due to the larger distance from the roads, resulting in the significant decrease in LZ_{eq} values. However, Site 7 is also at a larger distance, yet the decrease is less significant as compared to Site 8.

3.2.11 Analysis of Site 9 A-weighted SPL results

Site 9 is located in front of a corrugated facade. When compared to that of control at Site 1, there's a decrease of 1.12 dB. This is only 1.65%, which is very minor, almost insignificant. This decrease can be attributed to porous characteristics of the facade. Given that it is porous, it is able to absorb some mid and high range frequency sounds. However, given that the recording location is in front of the facade, it is only expected for recordings to be equal, if not higher than control. This is due to sounds having a direct path to the ears, coupled with some unabsorbed sounds reflecting into the ears. However, this fall could be attributed to the presence of greenery nearby that already blocked some sounds before reaching the ears.

3.2.12 Analysis of Site 9 C and Z-weighted SPL results

Both LC_{eq} and LZ_{eq} are larger than control Site 1. This is likely due to the uneven surfaces of the facade being able diffracting the lower frequency sounds back to the listener. However, this claim cannot be fully confirmed as the difference in LC_{eq} is only 0.9 dB, and 0.92 dB for LZ_{eq}, which is too minimum, rendering any reasoning from this data moot.

3.2.13 Analysis of Site 4 A-weighted SPL results

Site 4 is located at behind a corrugated facade that attempts to block noise. Indeed, this feature proves useful, with a 4.41 dB decrease in LA_{eq} readings. This is a 6.65% decrease when compared to Site 1. This is likely due to some sounds being absorbed within the facade due to its porous design. They may be reflected away too and do not reach the listeners. These space-saving corrugated walls prove very effective in providing minimal "last mile" decreases in LA_{eq}.

These numbers are also approximately similar to that of trees at Site 2. They saw a 4.93 dB, 7.47 % decrease in LA_{eq} readings. Given that trees are only slightly better than facades, it is only logical that facades are appropriate replacements for them. Furthermore, given that Site 7 saw LA_{eq} levels that are almost similar to Site 1, it is also wise to propose installation of such facades at that location. All in all, these facades provide refuge from traffic noise for level 1 and 2 residents living near Site 4. Its effectiveness is almost similar to thick canopy trees, and perfect replacements when only LA_{eq} readings are analyzed.

3.2.14 Analysis of Site 4 C and Z-weighted SPL results

Facades saw similar characteristics like trees for LC_{eq} and LZ_{eq} readings. Values were largely unchanged as compared to the control. This is because the facade is too thin, thus unable to reflect away too much of the low frequencies. Still, some low frequencies are indeed reflected, as seen in an increase in values in front of the facade, as described in section 3.2.12.

3.2.15 Analysis of Loudness Results

Loudness results show a largely similar trend to LA_{eq} results. According to table 6, the clear superior method to mitigate traffic noise is rooftop gardens, with a 12.9 sone and 17.3 sone decrease in Site 3 and Site 8. This clearly shows that rooftop gardens are the superior option, more than trees of only 7.0 sone. For facades in Site 4, there is a 4.3 sone decrease in loudness, worse than trees. Although it is determined that for SPL, facades are suitable replacements, it is not mighty sure to be the case when analyzing loudness. However, they are still much better than Site 7's elevated location, which only saw a decrease in 2.5 sone.

Regarding sharpness data in table 7, Site 3 and 8 clearly has the greatest decrease in sharpness, 0.33 acum and 0.54 acum respectively. This shows rooftop gardens being incredible at reducing high range frequencies as well. It is also worth pointing out that Site 9, in front of the corrugated facade, there is an observed increase in sharpness by 0.26 acum. This is because of the corrugated facade's abilities to reflect and diffract high frequencies, resulting in an increase in high frequency noise when in front of the facades. This would result in lowered high frequency sharp sounds when behind the facade. It is proven in Site 4, where a decrease in 0.12 acum is seen. Lastly, it is worth pointing out that Site 5 and 10 have the highest sharpness. This is expected as the sound of water droplets colliding with a water reservoir is immensely sharp. They are at 0.68 acum and 0.55 acum higher than that of traffic noise.

Comparing roughness data (listed in table 8) for Site 1 to 5, Site 5's waterfall is the clear standout as it decreases roughness data by 0.023 asper, the most of the remaining sites. This is approximately doubled that of the next best option of Site 4's corrugated facades. It is nearly 3 times more effective than trees at Site 2. Clearly, water features reduce the "grating" and "aggressive" sounds of traffic. It is also easy to see how this provides a heightened "overall pleasantness" among road users.

However, Site 9 also sees an equal amount of decrease in roughness. This is expected as being in front of the corrugated facades, there is diffraction of sounds, resulting in less modulation of the sounds. Furthermore, given this data, it is easy to see how corrugated facades around living quarters can be beneficial in reducing roughness of sounds. This finding may be useful in the realms of interior design. However, given that this is only field data, dedicated lab experiments should be carried out to confirm its effectiveness.

Lastly, Site 8's rooftop gardens are the most effective of all strategies to reduce roughness, with a 0.33 asper decrease in roughness. This is expected, as Site 8 is already at a lowered volume, and this will lead to a smoother soundscape.

4 Conclusion

This study analyzes the effectiveness of trees, rooftop gardens, facades and waterfalls in mitigating traffic noise. A total of 6 acoustic and psychoacoustic parameters are analyzed. For acoustics, variables are Sound Pressure Levels of different weightings. The A, C and Z weightings are observed. For psychoacoustics, the loudness, sharpness and roughness parameters are observed. Clear evidence suggests that rooftop gardens are the best option. However, their designs need to be well considered as poorly designed rooftop gardens performed worse for C and Z-weighted SPL. Trees are moderately effective in reducing A-weighted SPL levels and loudness psychoacoustic parameters. However, they are not immensely useful in reducing low frequency sounds that are more felt than heard. Furthermore, effectiveness of trees decreases as elevation increases. Minimum refuge for higher storied flats are seen in this study. Hence, extra strategies such as rooftop gardens and facades have to be placed for these residents. Corrugated facades are similar to that of trees. Effects in the mitigation of low frequencies in traffic noise is minimal. However, they are generally effective in absorbing mid and high frequencies, as seen in a decrease in sharpness and A-weighted SPL. Given that its effectiveness is only slightly worse than trees, but saves a lot of space along roads, they are suitable replacement for trees when only noise pollution is considered. Lastly, waterfalls effectively decreased roughness of the traffic noise, producing a more pleasant soundscape. When all variables are considered, rooftop gardens are the most useful.

5 Acknowledgements

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List of Figures

Figure 1: Flats boxed in yellow directly faces the ECP expressway, highlighted in red

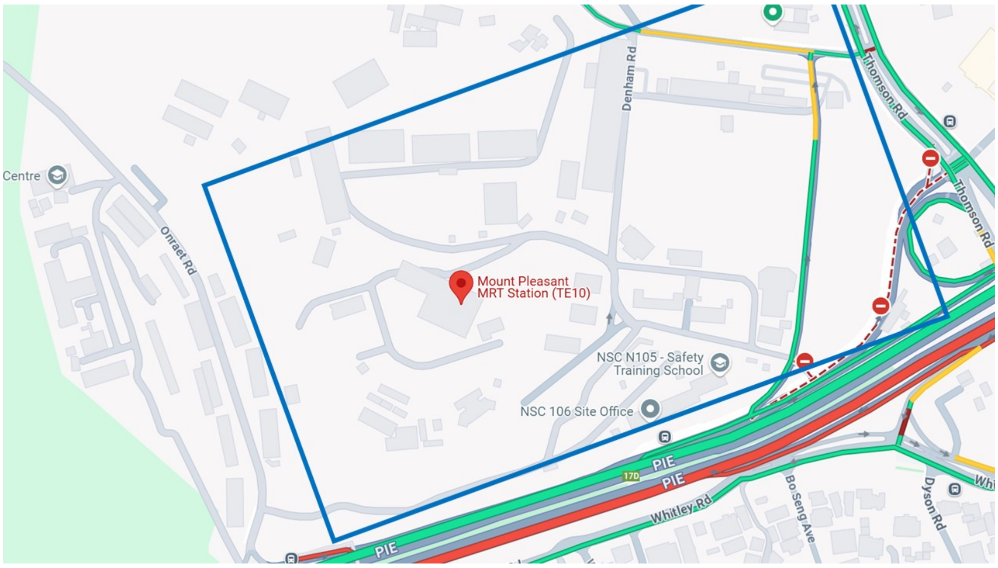

Figure 2: the Mount Pleasant estate, boxed in blue, built near a road artery on the PIE with daily heavy traffic

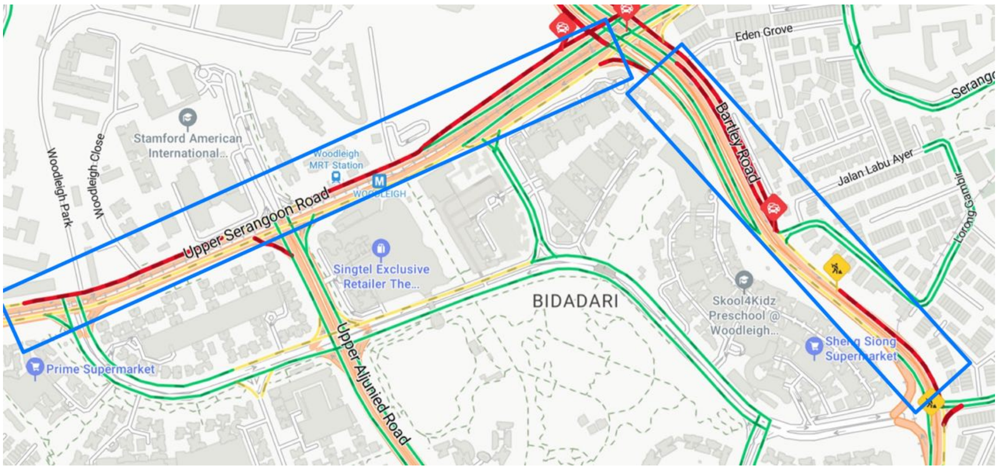

Figure 3: Map of Bidadari Estate. Heavy traffic areas boxed in blue.

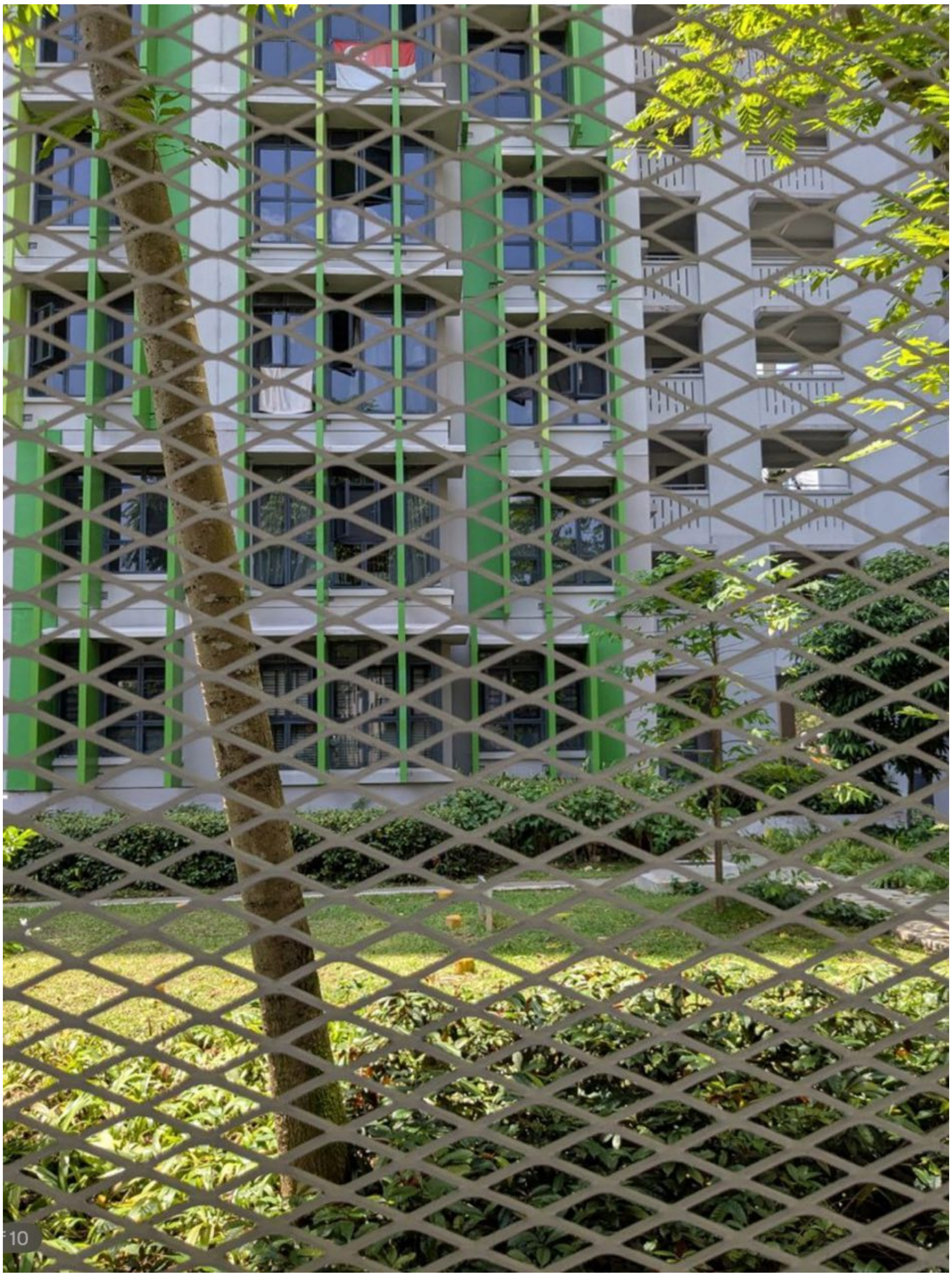

Figure 4: Corrugated facade used in this study.

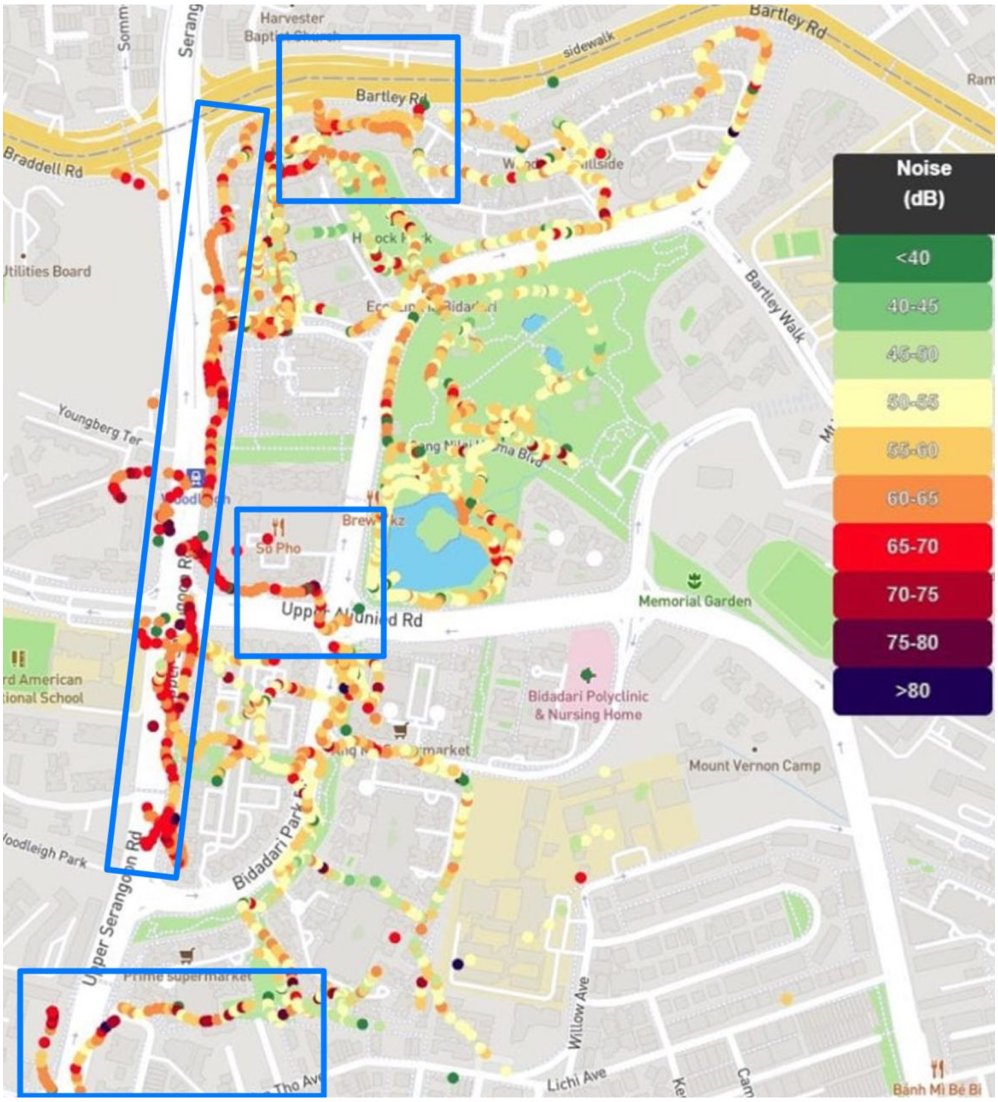

Figure 5: Soundwalk of Bidadari conducted by Lee (2025). Heavy traffic areas boxed in blue.

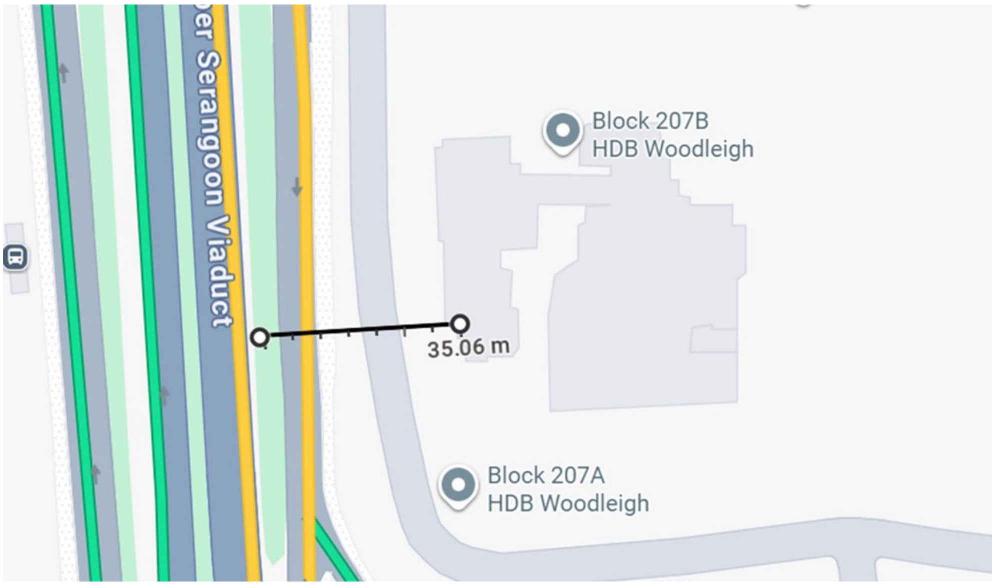

Figure 6: Distance from road to Site 1 from Google Maps.

Figure 7: Location of site 1.

Figure 8: Annotations of features at Site 1.

Figure 9: Location of site 2.

Figure 10: Location of site 3. Position recordings are made marked with red “x”.

Figure 11: Location of site 4.

Figure 12: Location of site 5. Position recordings are made marked with red “x”

Figure 13: Location of site 6.

Figure 14: Location of site 7. Position recordings are made marked with red “x”

Figure 15: Location of site 8.

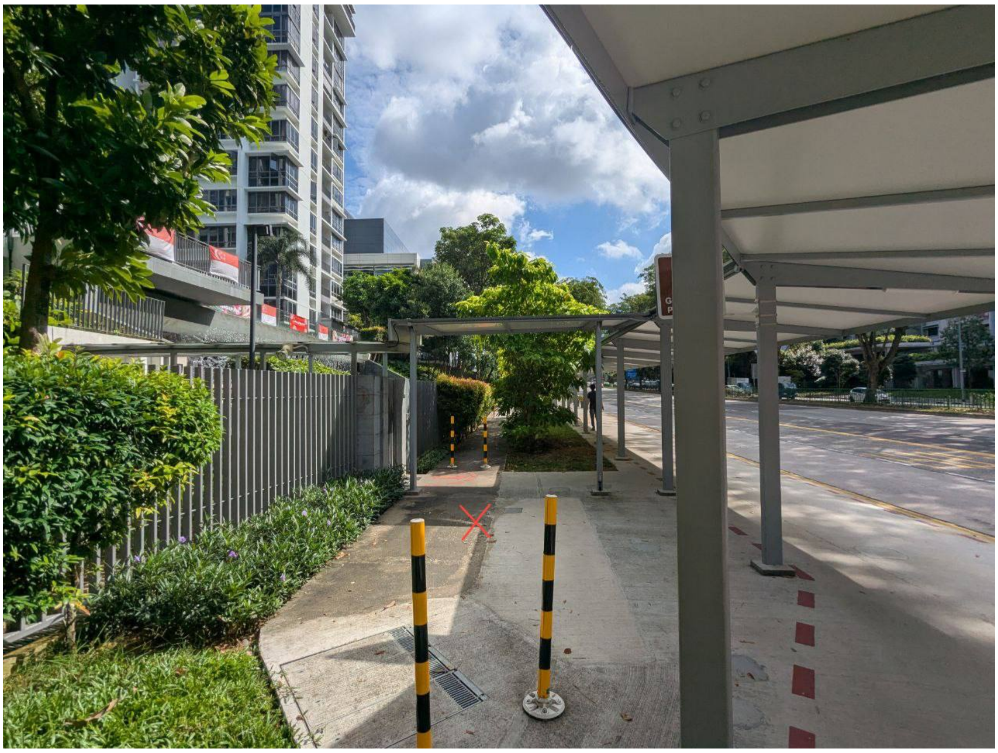

Figure 16: Location of site 10. Position recordings are made marked with red “x”

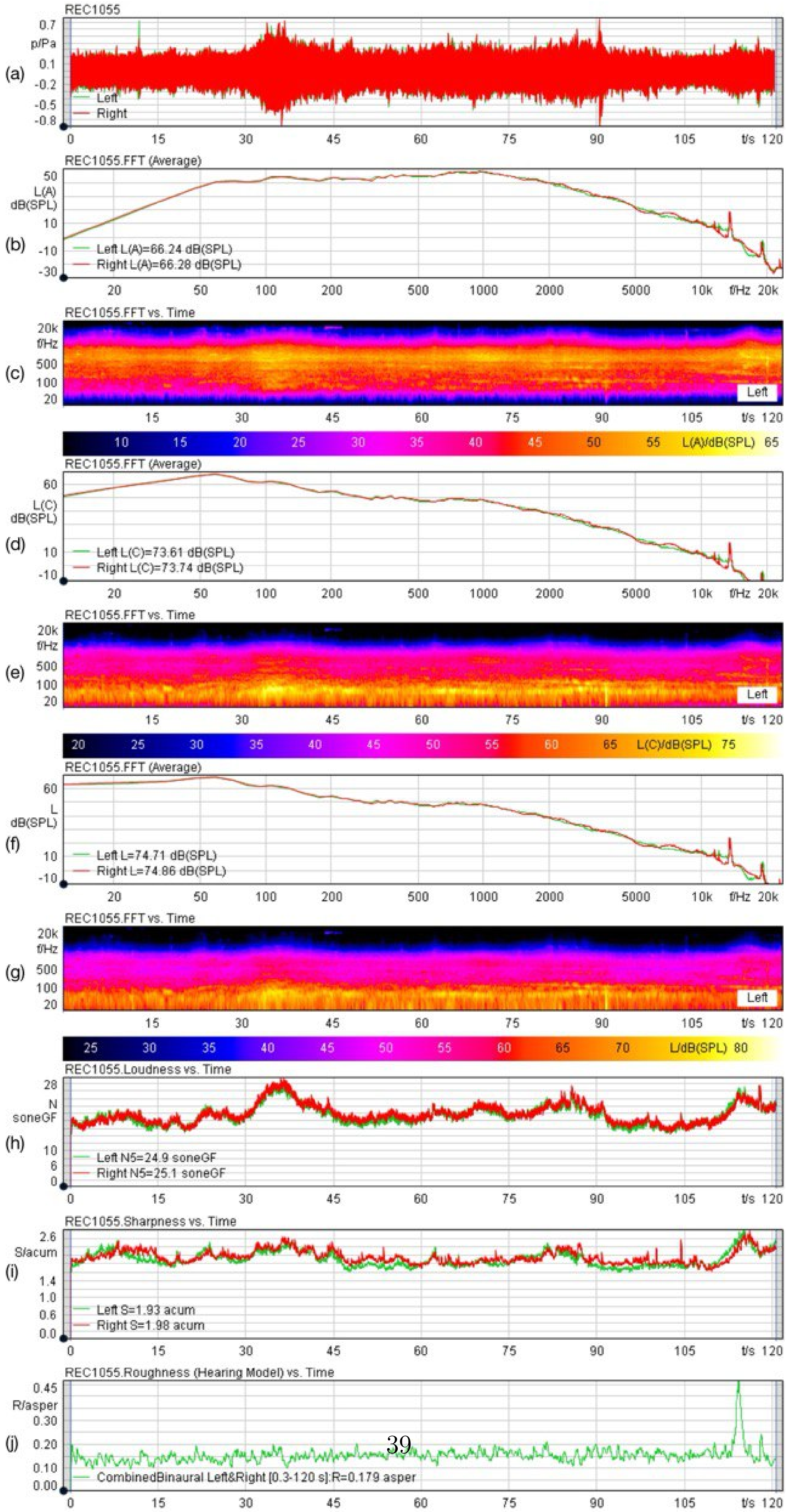

Figure 17: Recording MON-PM-2. For each recording, data is extracted from such charts.

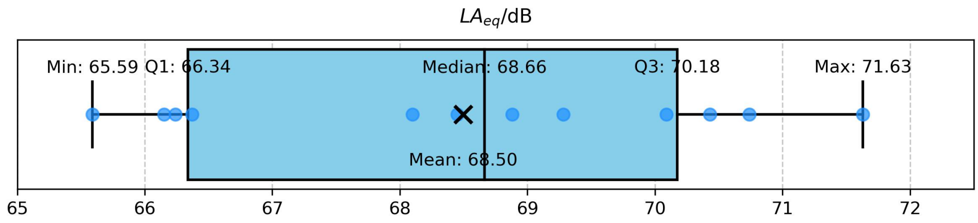

Figure 18: Box plot for Site 1 LA_{eq} values

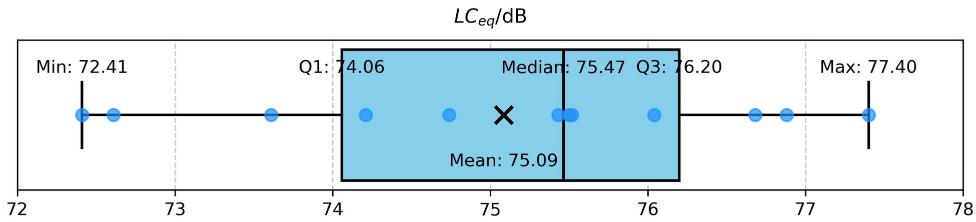

Figure 19: Box plot for Site 1 LC_{eq} values

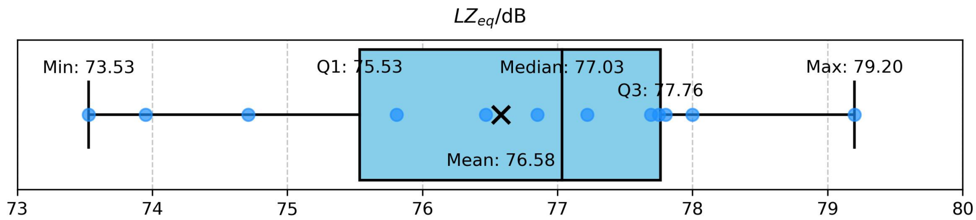

Figure 20: Box plot for Site 1 LZ_{eq} values

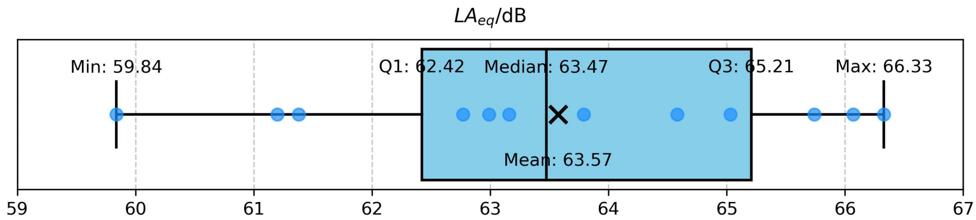

Figure 21: Box plot for Site 2 LA_{eq} values

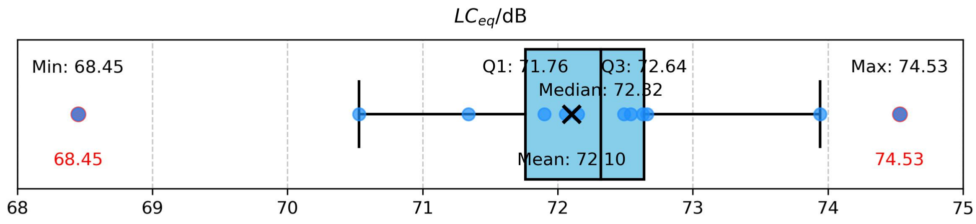

Figure 22: Box plot for Site 2 LC_{eq} values

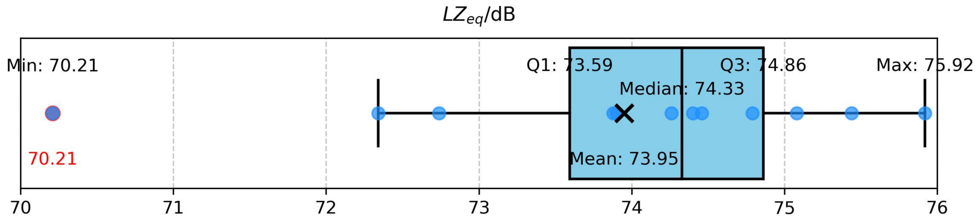

Figure 23: Box plot for Site 2 LZ_{eq} values

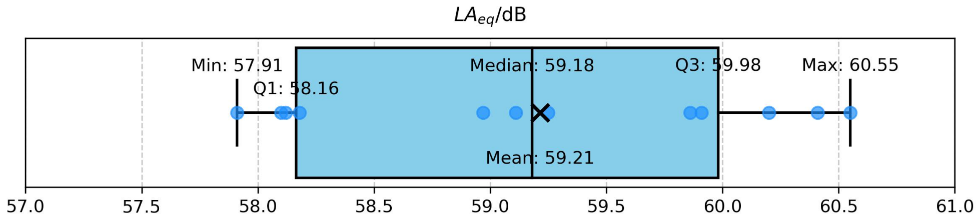

Figure 24: Box plot for Site 3 LA_{eq} values

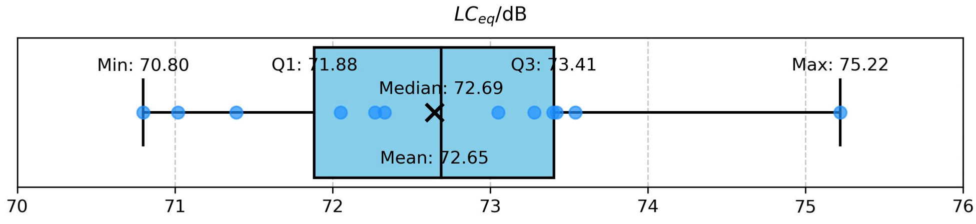

Figure 25: Box plot for Site 3 LC_{eq} values

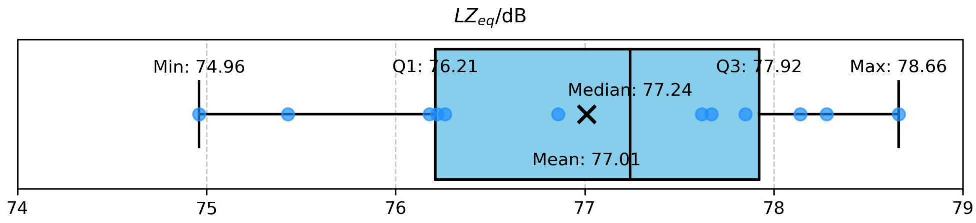

Figure 26: Box plot for Site 3 LZ_{eq} values

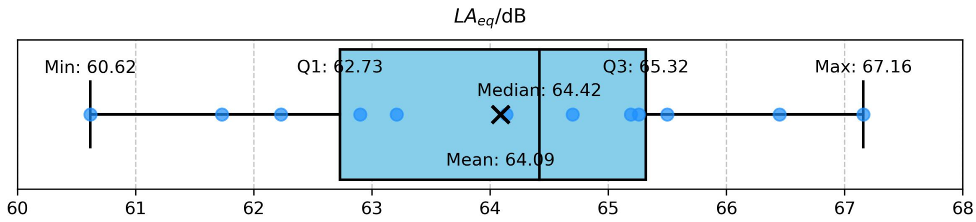

Figure 27: Box plot for Site 4 LA_{eq} values

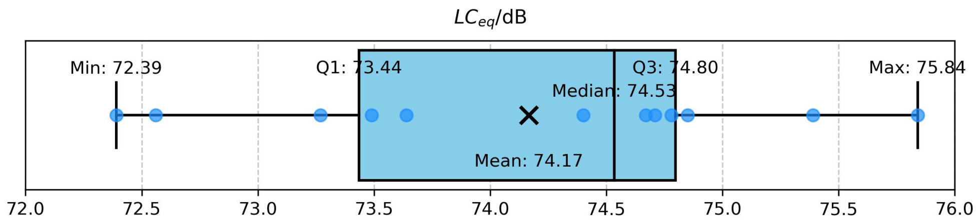

Figure 28: Box plot for Site 4 LC_{eq} values

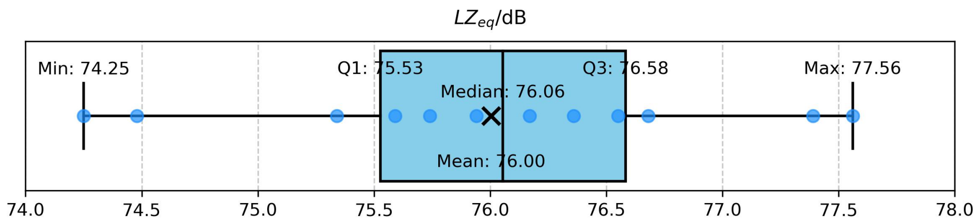

Figure 29: Box plot for Site 4 LZ_{eq} values

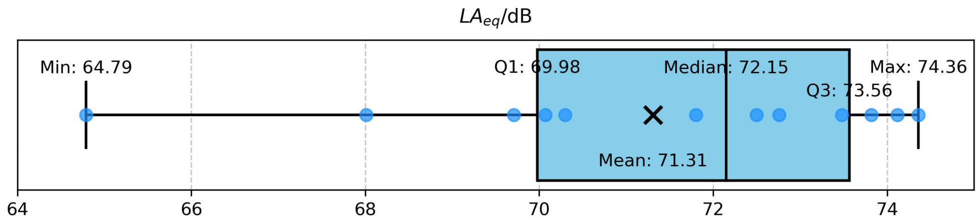

Figure 30: Box plot for Site 6 LA_{eq} values

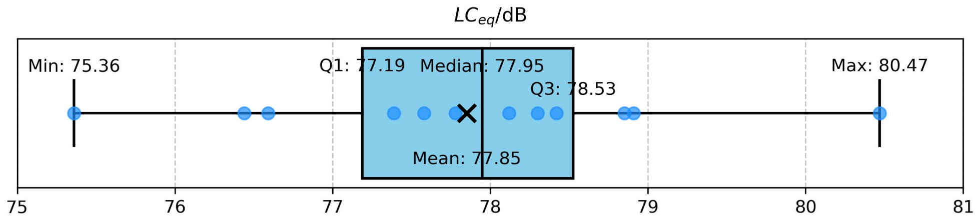

Figure 31: Box plot for Site 6 LC_{eq} values

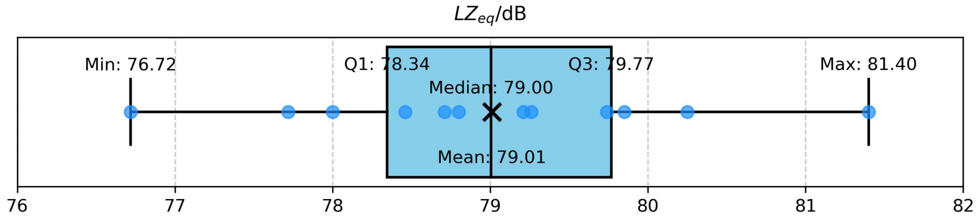

Figure 32: Box plot for Site 6 LZ_{eq} values

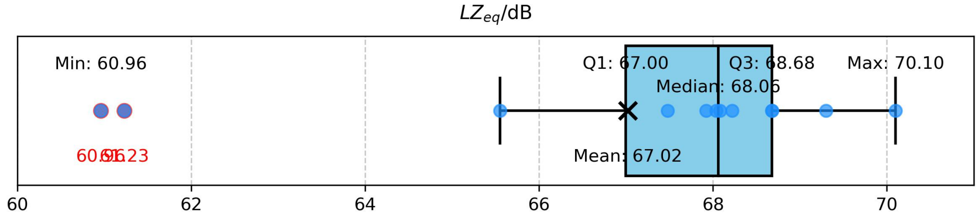

Figure 33: Box plot for Site 7 LA_{eq} values

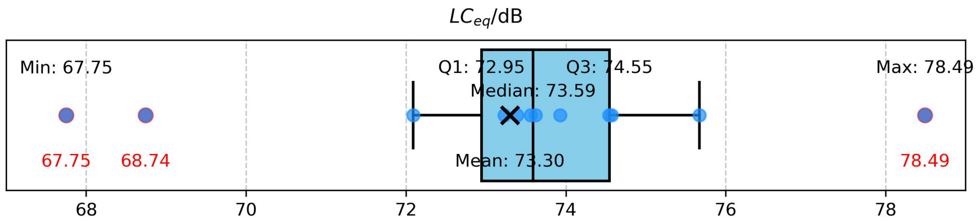

Figure 34: Box plot for Site 7 LC_{eq} values

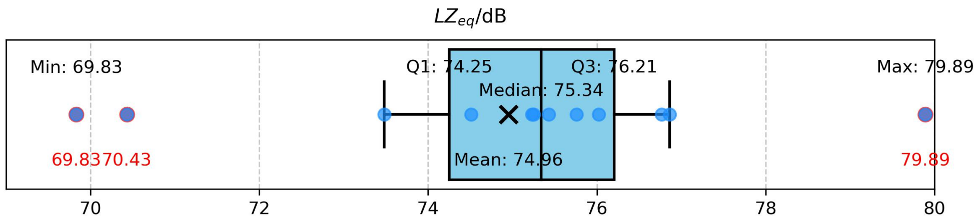

Figure 35: Box plot for Site 7 LZ_{eq} values

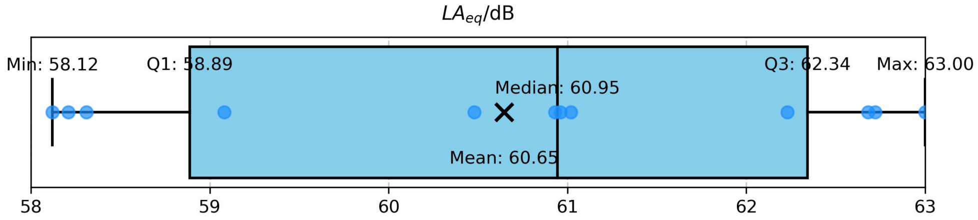

Figure 36: Box plot for Site 8 LA_{eq} values

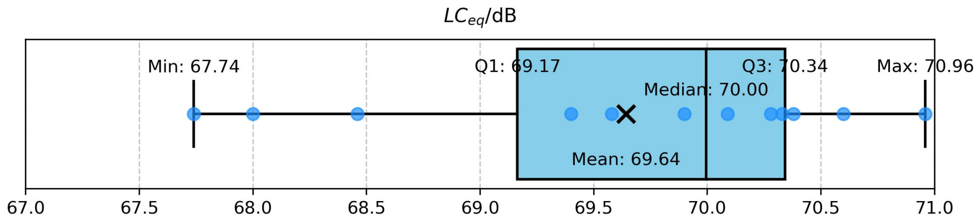

Figure 37: Box plot for Site 8 LC_{eq} values

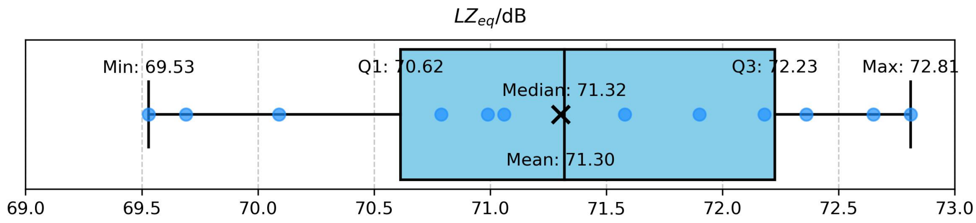

Figure 38: Box plot for Site 8 LZ_{eq} values

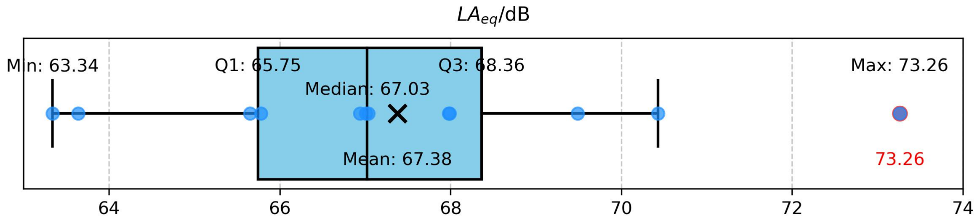

Figure 39: Box plot for Site 9 LA_{eq} values

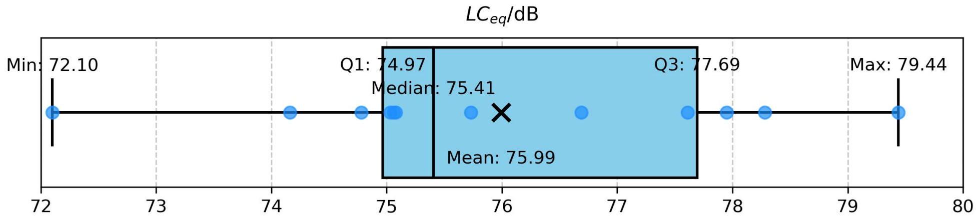

Figure 40: Box plot for Site 9 LC_{eq} values

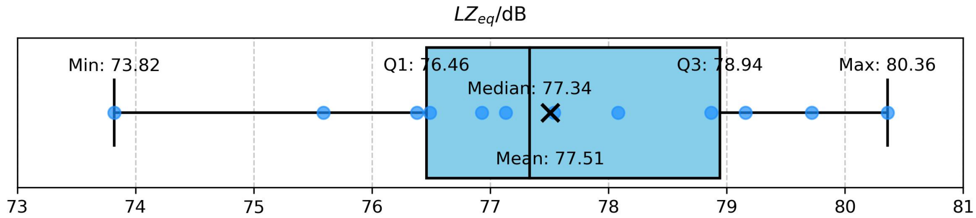

Figure 41: Box plot for Site 9 LZ_{eq} values

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A Appendix

A.1 SPL Results from Site 1: Control Environment 1 and Site 6: Control Environment 2

Site 1 and 6 SPL values are relatively high. According to table 2, the minimum LA_{eq} level at Site 1 is 65.59 dB, while it can reach a maximum of 71.63 dB. The LA_{eq} level at Site 6 ranges from 64.79 dB to 74.36 dB. It is observed that LA_{eq} of Site 1 to have a smaller range than $LA_{e}q$ of Site 6, 6.04 dB as compared to 9.57 dB. This is likely due to the unusually low LA_{eq} readings on Monday mornings. Reading of 64.79 dB for **MON-AM-1** and 68.01 dB for **MON-AM-2** much lower than the third lowest LA_{eq} of 69.71 dB. These values, especially the first recording on Monday mornings resulted in a larger deviation of the median from the mean, as seen in the box-plot in figure 30 The box-plot of Site 1 can also be seen in figure 18 Despite the large deviations, recordings are not counted as statistical outliers as they still fall above the lower bound, i.e. $\text{Q1} - 1.5 \cdot (\text{Q3} - \text{Q1})$. They also provide valuable findings for the study.

The median of the recording for Site 1 is 68.66 dB, which is lower than that of Site 6, 72.15 dB. For Site 6, the median is more significantly different than Site 1. This is also due to the extreme value of Monday morning recordings.

Arithmetic means are used in table 2, figure 18 and figure 30. These means are calculated with the formula below to produce the average LA_{eq} levels.

$$LA_{eq} = \frac{\sum_{i=1}^{n} LA_{eq,\,i}}{n}, \text{ where } x_i \text{ represents individual } LA_{eq} \text{ readings.}$$

However, given the logarithmic nature of SPL readings, all L_{eq} readings are also derived logarithmically to ensure the reliability of the arithmetic mean. The formula is listed below.

$$LA_{eq\,\text{logarithmic}} = 10\,log_{10}(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{LA_{eq,\,i}}{10}})$$

	Site 1			Site 6		
	LA_{eq}	LC_{eq}	LZ_{eq}	LA_{eq}	LC_{eq}	LZ_{eq}
Arithmetic Mean	68.50	75.09	76.58	71.31	77.85	79.01
Logarithmic mean	68.92	75.35	76.88	72.02	78.04	79.17
Difference	0.43	0.26	0.30	0.71	0.19	0.16

Table 17: Comparison of Arithmetic and Logarithmic Means at Sites 1 and 6

Table 17 clearly shows the minor differences in average LA_{eq} readings that are negligible. Thus, analysis of data using arithmetic mean is acceptable.

For LC_{eq}, the range of values for Site 1 exists from 72.41 dB to 77.40 dB. The arithmetic mean is 75.09 dB, which exists very close to the logarithmic mean of 75.35 dB. Thus, with a difference of 0.26 dB, this average LC_eq is acceptable for usage in analysis. The median LC_{eq} value for Site 1 is 75.47 dB. The data is left skewed as seen in figure 19, with a difference of 0.38 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.55 dB and range of 4.99 dB. There are no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 70.85 dB and 79.41 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalities.

The LC_{eq} for Site 6 ranges from 75.36 dB to 80.47 dB. The arithmetic mean is 77.85 dB, which exists very close to the logarithmic mean of 78.04 dB. Thus, with a difference of 0.19 dB, this average LC_eq is acceptable for usage in analysis. The median LC_{eq} value for Site 6 is 77.95 dB. The data is left skewed as seen in figure 31, with a difference of 0.1 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.28 dB and range of 5.11 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 75.18 dB and 80.53 dB. However, the value of 80.47 dB lies very close to the upper bound. This value exists on the second recording of Friday evenings. It is worth noting that this recording is made just shortly after an aircraft flyby. Although no sounds for the aircraft could be heard before recording was begun, it could have been the reason for the large difference from the next loudest value.

The LZ_{eq} for Site 1 ranges from 73.53 dB to 79.20 dB. The arithmetic mean is 76.58 dB, which exists very close to the logarithmic mean of 76.88 dB. Thus, with a difference of 0.30 dB, this average LZ_eq is acceptable for usage in analysis. The median LZ_{eq} value for Site 1 is 77.03 dB. The data is left skewed as seen in figure 20, with a difference of 0.45 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.68 dB and range of 5.67 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 72.19 dB and 81.10 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalities.

The LZ_{eq} for Site 6 ranges from 76.72 dB to 81.40 dB. The arithmetic mean is 79.01 dB, which exists very close to the logarithmic mean of 79.17 dB. Thus, with a difference of 0.16 dB, this average LZ_eq is acceptable for usage in analysis. The median LZ_{eq} value for Site 6 is 79.01 dB. The data is not skewed in any direction as seen in figure 32, with a difference of 0.01 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.19 dB and range of 4.68 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 76.21 dB and 81.90 dB. However, the value of 81.40 dB lies very close to the upper bound. This value exists on the second recording of Friday evenings, similar to the maximum value of LC_{eq} for Site 6. Explanation of the aircraft flyby above still holds for LZ_{eq}.

A.2 SPL Results from Site 2: Trees Environment and Site 7: Trees Environment at a Higher Elevation

According to table 3, the LA_{eq} for Site 2 ranges from 59.84 dB to 66.33 dB. The arithmetic mean is 63.57 dB, which exists very close to the logarithmic mean of 64.00 dB. Thus, with a difference of 0.43 dB, this average LA_eq is acceptable for usage in analysis. The median LZ_{eq} value for Site 2 is 63.47 dB. The data is right skewed as seen in figure 21, with a difference of 0.1 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.98 dB and range of 6.49 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 58.25 dB and 69.38 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LA_{eq} for Site 7 ranges from 60.96 dB to 70.10 dB. The arithmetic mean is 67.02 dB, which exists very close to the logarithmic mean of 67.71 dB. Thus, with a difference of 0.69 dB, this average LA_eq is acceptable for usage in analysis. The median LA_{eq} value for Site 7 is 68.06 dB. The data is left skewed as seen in figure 33, with a difference of 1.04 dB between arithmetic mean and median. This large difference and left skew is due to the presence of abnormalities in the dataset. The standard deviation is at 2.84 dB. This is rather large and generally unacceptable. This large standard deviation is also due to the presence of abnormalities in the dataset. With a range of 9.14 dB, it is rather large, but still acceptable. There exist 2 outliers in the dataset. The interquartile bounds calculated to be 64.47 dB and 71.20 dB. However, the LA_{eq} of **FRI-PM-1** reads 61.23 dB, while that of **WED-AM-1** reads 60.96 dB. These readings have exceeded the lower bound by 3.24 dB and 3.51 dB respectively. Given that the elevated position, it is rather hard to observe traffic situations at the Site. Thus, the starting and stopping timings are completely based on auditory means. It is regretful that a better explanation can be derived for these lowered LA_{eq} readings. When the two outliers are removed, the mean would increase by 1.19 dB to 68.21 dB.

The LC_{eq} for Site 2 ranges from 68.45 dB to 74.53 dB. The arithmetic mean is 72.10 dB, which exists very close to the logarithmic mean of 72.34 dB. Thus, with a difference of 0.24 dB, this average LC_eq is acceptable for usage in analysis. The median LA_{eq} value for Site 2 is 72.32 dB. The data is left skewed as seen in figure 22, with a difference of 0.22 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.49 dB and range of 6.08 dB. There exist 2 outliers in the dataset. The interquartile bounds calculated to be 70.44 dB and 73.95 dB. However, the LA_{eq} of **FRI-PM-2** reads 68.45 dB which exceeded the lower bound by 1.99 dB. **MON-AM-1** reads 74.53 dB, which exceeded the upper bound by 0.58 dB. Given that the Site exists behind thick tree canopies, it is difficult to observe traffic situations at the site. Similar to explanation given for site 7, the starting and stopping timings are completely based on auditory means. It is regretful that a better explanation cannot be derived for these lowered LA_{eq} readings on **FRI-PM-2**. However, it is worth pointing out that skies on that day seem to be mildly overcast, and perhaps road users are driving more cautiously, resulting in this lowered reading. The abnormality on **MON-AM-1** will still be used in the dataset as it exceeded the upper bound by only a minor amount.

The LC_{eq} for Site 7 ranges from 67.75 dB to 78.49 dB. The arithmetic mean is 73.30 dB, which exists very close to the logarithmic mean of 74.09 dB. Thus, with a difference of 0.79 dB, this average LC_eq is acceptable for usage in analysis. The median LC_{eq} value for Site 7 is 73.59 dB. The data is left skewed as seen in figure 34, with a difference of 0.29 dB between arithmetic mean and median. The standard deviation is at 2.73 dB. This is rather large and generally unacceptable. This large standard deviation is due to the presence of abnormalities in the dataset. With a range of 10.74 dB, it is rather large. There exist 3 outliers in the dataset. The interquartile bounds calculated to be 70.54 dB and 76.95 dB. However, the LC_{eq} of **FRI-PM-1** reads 67.75 dB, while that of **WED-AM-1** reads 68.74 dB. These readings have exceeded the lower bound by 2.79 dB and 1.8 dB respectively. These 2 outliers are completely similar to that of Site 7's LA_{eq} outliers. Similarly, no good reason can be conceived for these outliers. Furthermore, the LC_{eq} of **MON-PM-1** reads 78.49 dB which has exceeded the upper bound by 1.54 dB. When the 3 outliers are removed, the mean would increase by 0.46 dB to 73.76 dB.

The LZ_{eq} for Site 2 ranges from 70.21 dB to 75.92 dB. The arithmetic mean is 73.95 dB, which exists very close to the logarithmic mean of 74.18 dB. Thus, with a difference of 0.23 dB, this average LZ_eq is acceptable for usage in analysis. The median LZ_{eq} value for Site 2 is 74.33 dB. The data is left skewed as seen in figure 23, with a difference of 0.38 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.49 dB and range of 5.71 dB. There exist 1 outlier in the dataset. The interquartile bounds are calculated to be 71.69 dB and 76.76 dB. However, the LZ_{eq} of **FRI-PM-2** reads 70.21 dB, exceeding the lower bound by 1.48 dB. This outlier is completely similar to that of Site 2's LC_{eq} outlier. Similarly, no good reason can be conceived apart from the weather. When the outlier is removed, the mean would increase by 0.34 dB to 74.29 dB.

The LZ_{eq} for Site 7 ranges from 69.83 dB to 79.89 dB. The arithmetic mean is 74.96 dB, which exists very close to the logarithmic mean of 75.68 dB. Thus, with a difference of 0.72 dB, this average LZ_eq is acceptable for usage in analysis. The median LZ_{eq} value for Site 7 is 75.34 dB. The data is left skewed as seen in figure 35, with a difference of 0.38 dB between arithmetic mean and median. The standard deviation is at 2.62 dB. This is rather large and generally unacceptable. This large standard deviation is due to the presence of abnormalities in the dataset. With a range of 10.06 dB, it is rather large. There exist 3 outliers in the dataset. The interquartile bounds calculated to be 71.32 dB and 79.14 dB. However, the LZ_{eq} of **FRI-PM-1** reads 70.43 dB, while that of **WED-AM-1** reads 69.83 dB. These readings have exceeded the lower bound by 0.89 dB and 1.49 dB respectively. These 2 outliers are completely similar to that of Site 7's LA_{eq} and LC_{eq} outliers. Similarly, no good reason can be conceived for these outliers. Furthermore, the LZ_{eq} of **MON-PM-1** reads 79.89 dB which has exceeded the upper bound by 0.75 dB. When the 3 outliers are removed, the mean would increase by 0.52 dB to 75.48 dB.

A.3 SPL Results from Site 3: Rooftop Garden and Site 8: Denser Rooftop Garden

The LA_{eq} for Site 3 ranges from 57.91 dB to 60.55 dB. The arithmetic mean is 59.21 dB, which exists very close to the logarithmic mean of 59.31 dB. Thus, with a difference of 0.10 dB, this average LA_eq is acceptable for usage in analysis. The median LA_{eq} value for Site 3 is 59.18 dB. The data is right skewed as seen in figure 24, with a difference of 0.03 dB between arithmetic mean and median. It has an acceptable standard deviation of 0.930 dB and range of 2.64 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 55.44 dB and 62.71 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LC_{eq} for Site 3 ranges from 70.80 dB to 75.22 dB. The arithmetic mean is 72.65 dB, which exists very close to the logarithmic mean of 72.82 dB. Thus, with a difference of 0.17 dB, this average LC_{eq} is acceptable for usage in analysis. The median LC_{eq} value for Site 3 is 72.69 dB. The data is left skewed as seen in figure 25, with a difference of 0.04 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.20 dB and range of 4.42 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 70.80 dB and 75.22 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LZ_{eq} for Site 3 ranges from 74.96 dB to 78.66 dB. The arithmetic mean is 77.01 dB, which exists very close to the logarithmic mean of 77.16 dB. Thus, with a difference of 0.15 dB, this average LZ_{eq} is acceptable for usage in analysis. The median LZ_{eq} value for Site 3 is 77.24 dB. The data is left skewed as seen in figure 26, with a difference of 0.23 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.14 dB and range of 3.7 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 73.64 dB and 80.49 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LA_{eq} for Site 8 ranges from 58.12 dB to 63.00 dB. The arithmetic mean is 60.65 dB, which exists very close to the logarithmic mean of 60.99 dB. Thus, with a difference of 0.34 dB, this average LA_{eq} is acceptable for usage in analysis. The median LA_{eq} value for Site 8 is 60.95 dB. The data is left skewed as seen in figure 36, with a difference of 0.3 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.75 dB and range of 4.88 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 53.71 dB and 67.53 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LC_{eq} for Site 8 ranges from 67.74 dB to 70.96 dB. The arithmetic mean is 69.64 dB, which exists very close to the logarithmic mean of 69.75 dB. Thus, with a difference of 0.11 dB, this average LC_{eq} is acceptable for usage in analysis. The median LC_{eq} value for Site

8 is 70.00 dB. The data is left skewed as seen in figure 37, with a difference of 0.36 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.01 dB and range of 3.22 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 67.40 dB and 72.11 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LZ_{eq} for Site 8 ranges from 69.53 dB to 72.81 dB. The arithmetic mean is 71.30 dB, which exists very close to the logarithmic mean of 71.43 dB. Thus, with a difference of 0.13 dB, this average LZ_{eq} is acceptable for usage in analysis. The median LZ_{eq} value for Site 8 is 71.32 dB. The data is left skewed as seen in figure 38, with a difference of 0.02 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.08 dB and range of 3.28 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 68.20 dB and 74.64 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

A.4 SPL Results from Site 4: Facade Environment and Site 9: In Front of Facade Environment

The LA_{eq} for Site 4 ranges from 60.62 dB to 67.16 dB. The arithmetic mean is 64.09 dB, which exists very close to the logarithmic mean of 64.49 dB. Thus, with a difference of 0.4 dB, this average LA_{eq} is acceptable for usage in analysis. The median LA_{eq} value for Site 4 is 64.42 dB. The data is left skewed as seen in figure 27, with a difference of 0.33 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.90 dB and range of 6.54 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 58.85 dB and 69.20 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LC_{eq} for Site 4 ranges from 72.39 dB to 75.84 dB. The arithmetic mean is 74.17 dB, which exists very close to the logarithmic mean of 74.29 dB. Thus, with a difference of 0.12 dB, this average LC_{eq} is acceptable for usage in analysis. The median LC_{eq} value for Site 4 is 74.53 dB. The data is left skewed as seen in figure 28, with a difference of 0.36 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.04 dB and range of 3.45 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 71.39 dB and 76.84 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalies.

The LZ_{eq} for Site 4 ranges from 74.25 dB to 77.56 dB. The arithmetic mean is 76.00 dB, which exists very close to the logarithmic mean of 76.11 dB. Thus, with a difference of 0.11 dB, this average LZ_{eq} is acceptable for usage in analysis. The median LZ_{eq} value for Site 4 is 76.06 dB. The data is left skewed as seen in figure 29, with a difference of 0.06 dB between arithmetic mean and median. It has an acceptable standard deviation of 0.97 dB and range of 3.31 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 73.95 dB and 78.16 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalities.

The LA_{eq} for Site 9 ranges from 63.34 dB to 73.26 dB. The arithmetic mean is 67.38 dB, which exists very close to the logarithmic mean of 68.27 dB. Thus, with a difference of 0.89 dB, this average LA_{eq} is acceptable for usage in analysis. The median LA_{eq} value for Site 9 is 67.03 dB. The data is right skewed as seen in figure 39, with a difference of 0.35 dB between arithmetic mean and median. It has an acceptable standard deviation of 2.67 dB and range of 9.92 dB. These large values are unacceptable, largely due to the presence of 1 outlier. The outlier exists on FRI-AM-1, where readings of 73.26 dB exceeded the upper bound set at 72.29 dB. It is unfortunate that no good reason can be provided for this abnormality.

The LC_{eq} for Site 9 ranges from 72.10 dB to 79.44 dB. The arithmetic mean is 75.99 dB, which exists very close to the logarithmic mean of 76.43 dB. Thus, with a difference of 0.44 dB, this average LC_{eq} is acceptable for usage in analysis. The median LC_{eq} value for Site 9 is 75.41 dB. The data is right skewed as seen in figure 40, with a difference of 0.58 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.97 dB and range of 7.34 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 70.88 dB and 81.79 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalities.

The LZ_{eq} for Site 9 ranges from 73.82 dB to 80.36 dB. The arithmetic mean is 77.51 dB, which exists very close to the logarithmic mean of 77.85 dB. Thus, with a difference of 0.34 dB, this average LZ_{eq} is acceptable for usage in analysis. The median LZ_{eq} value for Site 9 is 77.34 dB. The data is right skewed as seen in figure 41, with a difference of 0.17 dB between arithmetic mean and median. It has an acceptable standard deviation of 1.78 dB and range of 6.54 dB. There are also no outliers as all the 12 values in the dataset exists within the acceptable lower and upper bounds of 72.74 dB and 82.66 dB. The minimum and maximum value of this dataset is also sufficiently far from the bounds for considerations of experimental abnormalities.

A.5 SPL Results from Site 5: Water Features and Site 10: Further Away from Water Features

Statistical analysis for SPL raw data for Site 5 and 10, water features are neglected as they are moot to this study. SPL values of waterfalls at these sites are not analyzed here. Rather, the psychoacoustics of waterfalls are of greater interest and will be analyzed clearly. It is also critical to point out that FRI-AM-2, FRI-PM-1 and FRI-PM-2 recordings were unavailable. This is due to the condominium turning off the waterfall, thus no readings can be made.

A.6 Psychoacoustic Results

The tables 6, 7 and 8 lists the individual psychoacoustic data, followed by the mean of each psychoacoustic variable at each Site. Unlike SPL data, statistical analysis is not conducted. This is because there exist no possible methods to source for abnormalities within psychoacoustics.