Experimental Investigation of Living Architecture Design Tools to Attenuate Rooftop Noise

Jetvipa Kanjanakunchorn

A Thesis

in the

Building Science Graduate Program

Presented in Partial Fulfillment of the Requirements for the

Master of Applied Science in Building Engineering/ Building Science

at the

British Columbia Institute of Technology

Burnaby, British Columbia, Canada

Date (May, 2018)

BCIT

BRITISH COLUMBIA
INSTITUTE OF TECHNOLOGY
3700 Willingdon Avenue
Burnaby, British Columbia
Canada V5G 3H2
bcit.ca

Research Thesis

Student Name:	Jetvipa Kanjanakunchorn
Student Name:	

The above-named student has successfully completed the requirements for BSCI 9850 Research Thesis in the Master of Applied Science in Building Engineering/ Building Science degree

Supervisor:	Dr. Maureen Connelly
Signature:	[signature]
Date:	MAY 15, 2018.

Graduate Program Director:	Dr. Fitsum Tariku
Signature:	[signature]
Date:	May 17 / 2018

ABSTRACT

The aim of this research is to investigate the viability of designing urban rooftop soundscapes. The prerequisite is to reduce the sound propagation from road traffic by introducing living architectural rooftops with various components of sound attenuating technologies. The final goal is to turn unused rooftop space into a livable urban green space, where soundscape is balanced, and sound energy is reduced to the limits recommended by the World Health Organization (WHO).

The first part of this research is to identify the potential of living architectural technologies to attenuate noise from road traffic. More than 33 measurements are performed of living architecture design tools, such as green roofs, berms at edge, living wall barriers and overhangs, to investigate the behavior of sound attenuation in an anechoic chamber and in ODEON, a computer simulation software. The second part of this research is to use the findings on the proposed design tools for an architectural case study, a flat-roof five-storey building located on East Hastings Street. The use of a combination of green roof, berm, overhang, guard and living wall can reduced urban traffic noise from 70 dBA on the roof to 55 dBA, creating additional acoustically healthy habitable space in the urban environment.

ACKNOWLEDGEMENTS

I would like to express my deep appreciation to Dr. Maureen Rose Connelly, my supervisor, who spent her valuable time working close to me from the beginning of this programme. Thank you for bringing me into the world of the acoustic, preparing me to get through the difficult part of this research, and all the constructive suggestions you gave me in planning and carrying out this work. Without you, this research would not have been successfully completed. Not only am I grateful for the generous time you gave me, you also inspire me with the kindness of your attitude as a teacher and as a hard-working world developer making the world a better place to live. I really admire you and one day I will be as good as you.

I would also like to thank BCIT for the funding to do this research. Without this money, I wouldn't have survived in this expensive city while studying full-time as a student researcher. I would like to extend my special thanks to Ellen Scobie, Graduate Program Assistant, who assisted me with informative answers to my questions throughout the programme, and thanks to all my fellow classmates and lab mates for the way we helped each with understanding. Thank also extended to Kathleen Steward, my editor. I deeply appreciate your help in reviewing my book.

I also give special thanks to my families, my big family in Thailand and my host mom, Isabella Burtini in Vancouver. I am thankful to my dad and mom for the unconditional love, for the infinite amount of encouragement given to me through the years, and for always believing in me. You are the reason I have never given up. Moreover, I also extend my grateful thanks to my boyfriend in Thailand, who gives me 24/7 support, even though we live in different time zones. Lastly, I would like to congratulate myself, for my dedication to 5 years of hard work since I came to Canada. Thanks for all opportunities, experiences and challenges in life that made me become this person. I never thought I would have achieved this goal and learned to deal with these difficulties; it makes me a better person. Cheers for the sweet success.

CONTENTS

TABLE OF FIGURES

LIST OF TABLES

INTRODUCTION

This research investigates living architecture design tools as noise mitigation technologies for the acoustical design of rooftop spaces. Design tools — green roofs, berms, wall barriers and overhangs — are the selection of noise attenuation technologies which are studied in terms of shape, size and material as sound barriers effecting sound propagation on habitable roofs. Scaled physical measurements and prediction modelling of acoustic design tools in different configurations, as well as in combination, are performed. Then the findings of the investigation are applied to an urban rooftop. The goal for rooftop design is to attenuate noise to meet the World Health Organization's (WHO) recommendation of 55 dBA for an outdoor recreation area.

Noise pollution has been a major drawback in every urbanized region since the early modern age. Schafer (1993) writes about the noises around us through history to the modern era in his book, *The soundscape: Our sonic environment and the tuning of the world.* Post-industrial machinery which was developed to mass-produce goods to satisfy human needs has changed and turned the world of soundscape into a low fidelity (lo-fi) condition, where signals are overcrowded, ambient noise is high, and the sonic environment lacks clarity. Noise from automobiles has changed the world of soundscape into a flat-line-pitched sound, resulting in widely produced more continuous noise and lower frequency noise. These tragedies have been occurring in all big cities, including Vancouver.

In Vancouver, traffic road noise is considered the dominant noise source of the community (City of Vancouver, 1997). The road noise level in the downtown area of Vancouver (Figure 1) was mapped and illustrated on a 10-meter grid at 5-decibel intervals in Lday dB (A). A day-time period that describes only the noise of road traffic is illustrated by a range of colors representing the sound pressure levels (SPL) over the streets of the downtown Vancouver area (Connelly, M., 2011).

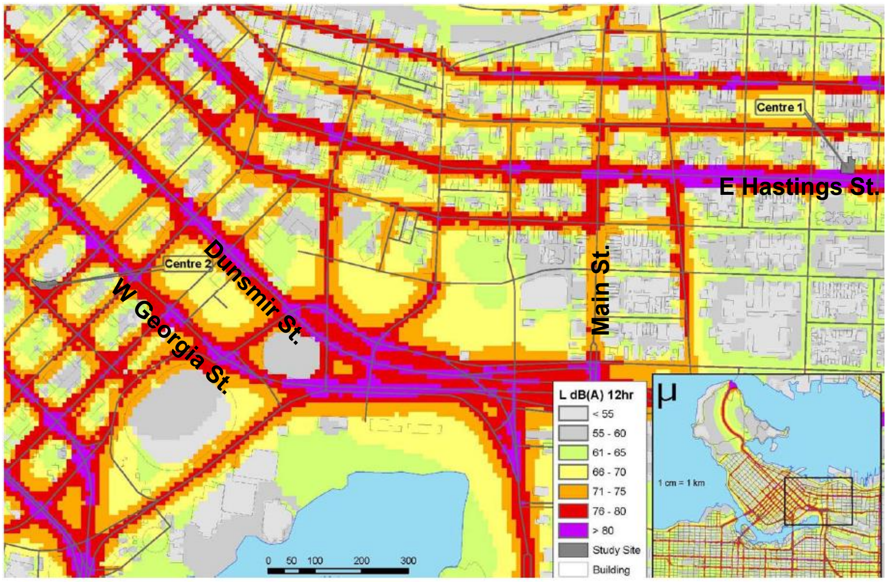


Figure 1: Road Traffic Noise Levels – Downtown Vancouver. (Connelly, M., 2011)

Many research studies show that roadway noise pollution affects the quality of life for humans in multiple ways. According to WHO, traffic noise causes millions of the world's inhabitants to suffer with several health-related problems. Annoyance, tinnitus, sleep disturbance, cognitive impairment, cardiovascular disease, and hearing loss, at the highest degree of suffering, are the health impacts of traffic noise exposure (Berglund et al., 2008). In the article, "Traffic noise health impacts second only to the air pollution," it states that "noise from rail and road transport is linked to 50,000 fatal heart attacks every year in Europe and 200,000 cases of cardio-vascular disease" (European Federation for Transport and Environment AISBL, 2016). The problems of traffic noise exposure in the city are considered a significant issue for the government to alleviate. The aspect of noise abatement often continues to be neglected in planning and architectural design, despite an increase in the negative impacts of transportation noise. WHO has recommended a maximum limit for noise exposure in a specific environment of a residential community at 55 dB(A) in an outdoor living area. Canada has adopted this criterion; however, rooftops are not often assigned the designation of outdoor living area, although they are often used as such.

City space has been taken over for dwelling and merchandising purposes. Lack of green space for breathing is a result of urban development. Residential buildings, mid-rise buildings, and high-rise office buildings are built, creating a dense block of structures. This state of city geography creates a canyon-like environment, which has an impact on environmental conditions, such as temperature, wind, shading, air quality, and the focus of this research, acoustics. Turning the empty rooftops into living green rooftops will significantly increase the overall green space for urban dwellers, promoting better physical health and greater mental health.

As much as a noise barrier could attenuate traffic noise propagated from the road, the presence of green space can attenuate the negative health impacts of noise as well. In the Netherlands, multi-level regression analysis was used to analyze the relationship between the number of health complaints by residents due to stressful life events and the amount of green space within three kilometers (Van den Berg, A. E. et al., 2010). The results showed that the closer the green space is to home, the healthier the life of the people influenced by it. This concept supports the idea of why we need to create and inhabit the green space in our city. The “home” is one of the smallest building mechanisms in the city, where an empty and non-used space such as a rooftop needs to be optimized as a green park with a healthy acoustical environment.

CHAPTER 1

LITURATURE REVIEW

The literature review for this research focuses on four areas of outdoor sound propagation. Urban road traffic noise is one of the main noise sources for this study. Investigating traffic sound propagation and the factors that affect sound propagation outdoors helps to clarify the sound paths of city activities and guide the way to adopt noise reduction practices for this project. The study of city soundscapes leads us to understand the physical acoustic keys behind the acoustical environment of a city. Defining the characteristics of sound absorbing materials is another important key to determining sound attenuation technologies. The variables of barrier material, shape, size and roof precedent were studied in order to apply them in a design application. The most challenging subject of study in this literature review was acoustic modelling and test parameters to achieve the highest performance of sound testing and give the most accurate test results.

1.1 Urban Noise Source

Urban noise source is one of the most harmful pollutions for the city environment, which affects city dwellers in many ways. An open space in the city next to a roadway could be directly affected by road noise pollution, since an indoor space usually has some acoustic protection from its structure or envelope. Traffic noise heavily impacts the soundscape of an empty space like a park or a rooftop, which has no cover. The main noise source in an urban area for rooftop space is, surprisingly, not direct noise from a plane, but road traffic. The function of sound travelling through space depends not only the sound power and distance from the sound source, but also on the time domain. The frequency that an airplane passes by a building is small compared to the number of vehicles passing by on the street. Consequently, the diffracted sound propagation from road traffic is shown as the most significant source that an acoustic designer needs to deal with when it comes to rooftop design.

Davies, H. W., et al. (2009) collected the data from 103 roadside sites for noise level in Metro Vancouver, British Columbia. Noise levels were measured with an SPL meter at 1.2 meters above the ground and at a 90° normal angle to the roadway. Twenty-four hours Leq measured every 5 minutes were averaged and the results ranged from 49.2 to 75.1 dBA; however, the values obtained depended on the traffic density and type of vehicle on the street. This indicated that the traffic noise pollution in Metro Vancouver shows a high exposure (dBA) at the pedestrian level, where a large proportion of that range exceeds 55 dBA, which is higher than the WHO recommendation for outdoor recreation space.

Traffic noise and highway noise, including noise generated by cars and trains, is considered a linear noise source. The referenced numerical study by Van Renterghem and Botteldooren (2012) modelled the traffic noise source using a coherent line source, as described in their methodology discussion. An incoherent line source would have been more appropriate because road traffic is generated by independent vehicles. Figure 2 is a graph of sound pressure levels for a car and a train, which was adopted from Jonasson and Storeheier (2001), Van Beek et al. (2002), and Jonasson et al. (2004) in *Urban Sound Environment* by Jian Kang (2006). It illustrates that the speed of a car affects the sound level differently in the 25 to 16 K frequency band sound spectrum range. For a fast-moving car at 110 km/h, a high frequency sound spectrum is dominant. At 1000 Hz, the sound pressure level reaches 107 dBA, which is considered twice as high as the limit recommended by WHO for outdoor living area noise exposure. Unlike a fast-moving car, a low-speed car at 30 km/h shows a very high sound pressure level in a low frequency range. It is above 90 dB(A) at the low frequency range of 25 Hz to 60 Hz.

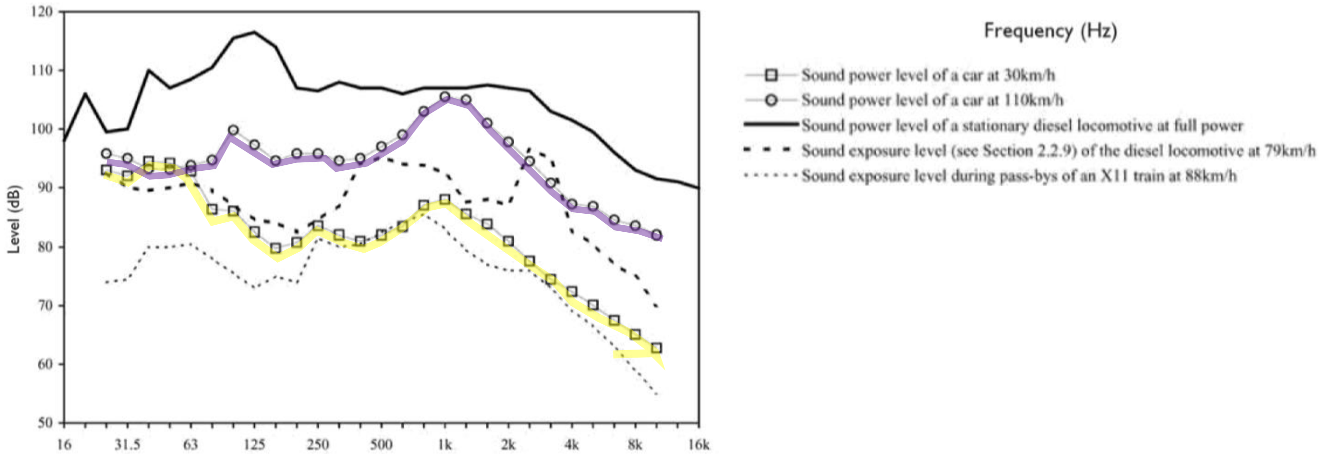


Figure 2: Typical spectra of car and train noise. (Kang, J., 2006)

1.1.1 City Soundscape

The soundscape is a field of interaction. Sound in nature illustrates in a wave form, and the wave is propagated by three parameters of interaction: intensity, frequency and time. Schafer (1993) described aural perception by those parameters of interaction: “(i)ntensity can influence time perception (a loud note will sound longer than a soft one), frequency will affect intensity perception (a high note will sound louder than a low one of the same strength) and time will affect intensity (a note of the same strength will appear to grow weaker over time).” In general, many studies present images of sound acoustics in 2-D (Figure 3). Amplitude (or intensity) is plotted against time, frequency against amplitude, or time against frequency. However, in the world of soundscapes, sound waves move in a 3-D plane, as shown in the Figure 4.

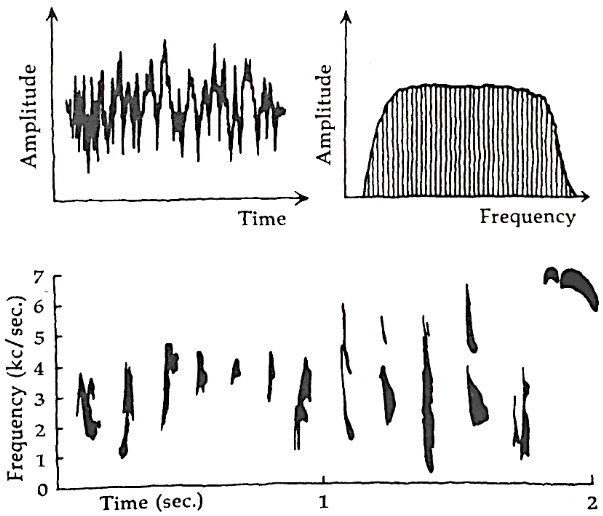


Figure 3: A two-dimensional representation of broad-band noise.

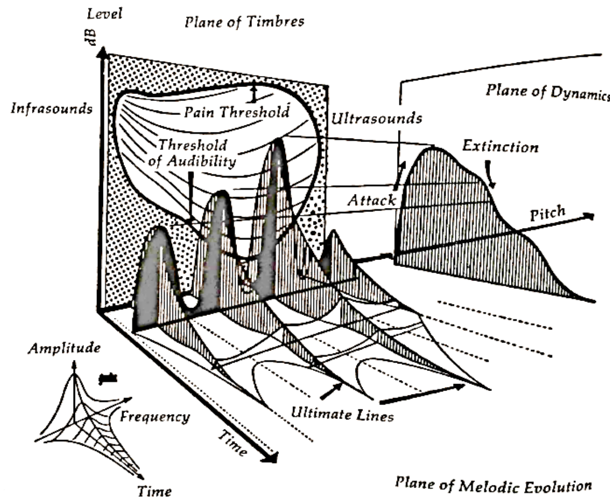


Figure 4: A three-dimensional of a simple sound object.

(Reprinted from Schafer, 1993)

For outdoor sound propagation, acoustical mechanisms effecting building surface reaction are absorption, diffraction and reflection. The factors effecting sound reflection and absorption are location and path distance from the source to the receiver; air attenuation due to absorption loss of the directed wave by atmospheric absorption; shape and type of reflecting or absorptive surface; spectral character such as smooth or rough surface; and lastly, the structural characteristic of the surface, which can be defined as rigid or porous.

Accurate Fresnel integral formulas for four building configurations, which defined the different number of sound diffractions over the building edge (Figure 5), have been illustrated and applied in numerical calculations to achieve the results of SPL at the receiving positions. Wei et al. (2015) highlighted the manner of traffic sound propagation in the city environment in “An efficient method to calculate sound diffraction over rigid obstacles.” The paper not only dealt with a single diffraction, but also presented double and multiple diffractions.

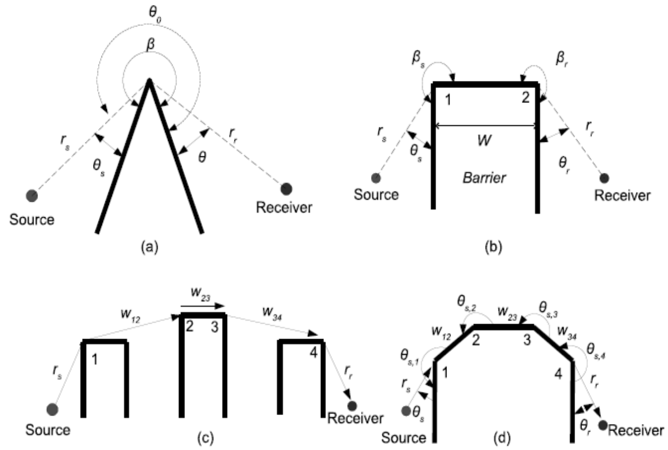


Figure 5: Four different building configurations that simplified a different diffraction function from source to receiver: (a) single, (b) double, (c) and (d) multiple. (Wei et al., 2015)

They pointed out that the factors for the diffraction function are diffraction path, diffraction angle and wedge of angle. Even though the insertion loss calculations from other engineering models existed, the accuracy was not satisfied. The main purpose of their research was, therefore, to validate the accuracy of the Fresnel integral calculations for the different diffraction functions. The result came out that their model was accurate and achieved less than 2 dB of prediction error. Figure 6 shows the Fresnel integral numerical equations for different sound propagation paths that were used in the calculations.

Single diffraction over a rigid barrier	Double diffraction of rigid barrier	Multiple diffraction over complex obstacles
$D_1 = \frac{e^{i\pi/4}}{\sqrt{2}} \left(\frac{0.37}{0.37 + X_+} + \frac{0.37}{0.37 + X_-} \right)$	$D = i \left(\frac{0.37}{0.37 + BX_{S+}} \frac{0.37}{0.37 + X_{R+}} \right)$	$D_l = \frac{e^{i\pi/4}}{\sqrt{2}} \left(\frac{0.37}{0.37 + B_l X_{l+}} + \frac{0.37}{0.37 + B_l X_{l-}} \right)$
$IL_1 = -10 \log_{10} \left[\frac{R^2}{L^2} \left(\frac{0.37}{0.37 + X_+} + \frac{0.37}{0.37 + X_-} \right)^2 \right]$	$IL_2 = -10 \log_{10} \left[\frac{R^2}{L^2} \left(\frac{0.37}{0.37 + BX_{S+}} \right)^2 \left(\frac{0.37}{0.37 + X_{R+}} \right)^2 \right]$	$IL_n = -10 \log_{10} \left[\frac{R^2}{L_{n-1}^2} \left(\frac{1}{2} \right)^{2C} \prod_{l=1}^{n-1} D_l^2 \right]$

Figure 6: Fresnel integral equation for different sound propagation paths. (Wei et al., 2015)

When traffic sound energy propagates over buildings or obstacles, high-frequency sound energy is commonly mitigated by the shielding capacity of its barrier. At the same time, low-frequency diffracted sound energy can still reach over the building rooftop—the reflection by roofing material plays a big role in this situation. Figure 7 shows the difference of the reflected sound wave outcome due to the difference in roofing materials. The left picture is a rigid roof and the right one is a sound absorbing green roof. In the case of a rigid roof, reflected sound energy shows constructive interference resulting from a highly reflective material hardscape, causing multiple sound energy waves with no phase change to reflect over the rooftop soundscape. On the other hand, in the green roof case, a good absorbing characteristic of material is presented. The high absorption coefficient of green roof material makes the roof absorb more sound energy compared to the rigid one. Phase change due to finite impedance creates a destructive interference. The meaning of this is that reflected sound energy was attenuated and became weaker over the path of the rooftop soundscape. Even near-glazing of incidence, phase change due to the finite impedance of reflected sound waves, changes the way sound energy propagates over the rooftop (Connelly and Hodgson, 2015).

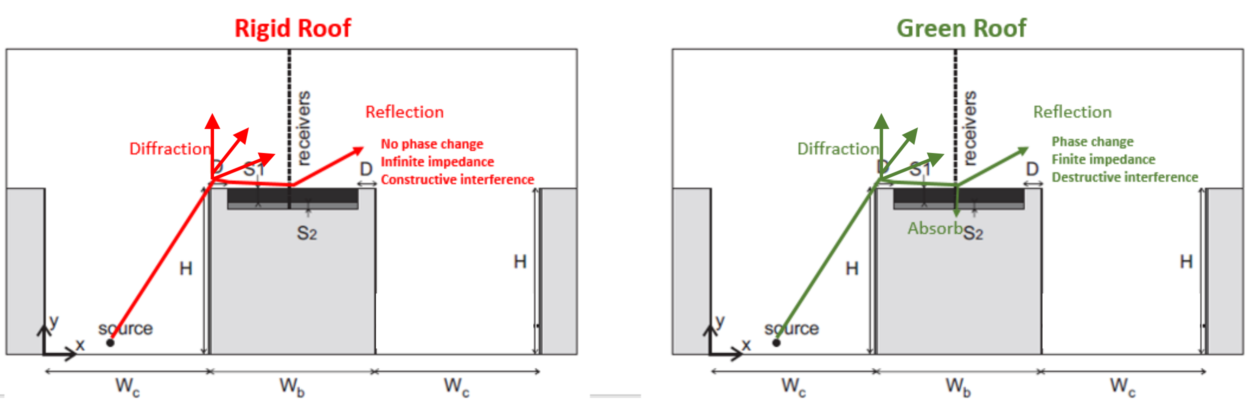


Figure 7: Sound propagation over the green roof in comparison to a rigid roof. (Adopted from Van Renterghem & Botteldooren, 2011)

Aside from the sound absorption property of the material, scattering is another acoustic mechanism of reflected sound energy once it hits the surface. According to the definition of a scattering coefficient provided by ISO 17497-1, the random-incidence scattering coefficients are related to the surface shape, size and characteristic dimension of the material surface. To study the amount of surface scattering, the characteristic length and depth of the surface, including the surface roughness, are parameters considered (Vorländer, M., 2007).

The random-incidence scattering coefficients are dependent on normalized frequency. Figure 8(a) shows the difference in reflective wave outcomes due to differences in material surface roughness. Specular reflection is presented in picture (a) and diffuse reflection is presented in picture (b). Figure 8(b) illustrates the size of the scattering waves as weight vectors of the surface reflection and the size of vectors. Table 4 in the Methodology chapter shows the suggested scattering coefficients at mid-frequency used for the ODEON computer simulation model.

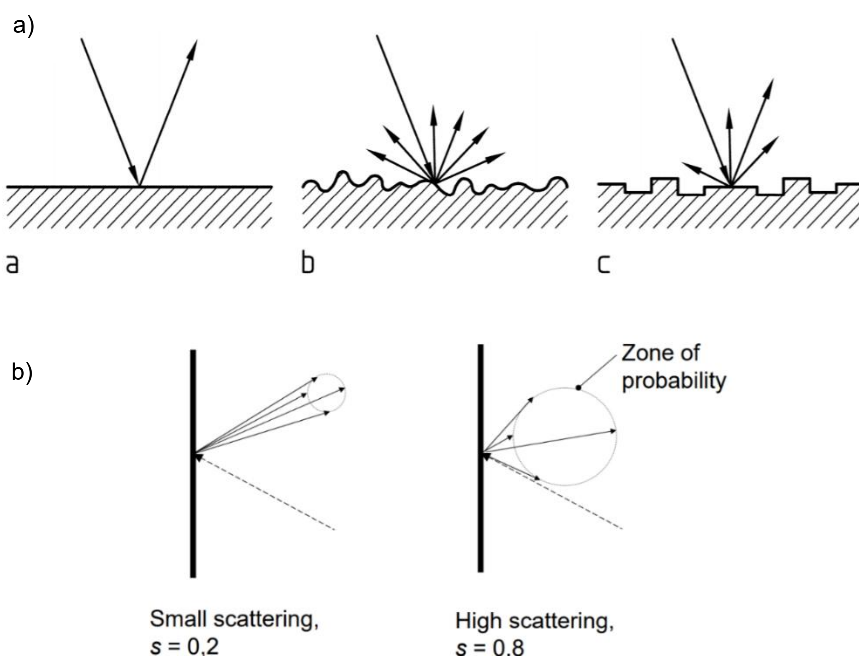


Figure 8: (a) Specular and diffuse reflection, (b) Scattering as weight vectors of surface reflection and the size of vectors. (Keranen et al., 2003)

1.2 Outdoor Sound Propagation and Factors Effecting Sound Propagation Outdoors

Outdoor sound propagation is unique and different from indoor sound propagation. Urban environmental sound propagates differently in a flat open area where sound energy moves like in a free field condition. In “The effect of buildings on acoustic pulse propagation in an urban environment,” Albert and Liu (2010) stated that the presence of the various buildings in the city, including trees and all kinds of structures, impacts sound propagation and induces multiple reflections on the building facades. The diffraction of sound waves over the building edge and scattering waves produce many millions of excessive sound energy waves, which influences the rooftop soundscape (Albert and Liu, 2010).

When considering outdoor sound propagation, the factors for its power reduction are various interactive effects at a distance from the source to the receiver, including source characteristic; ground and air attenuation; climate; relative humidity and temperature; wind speed and direction; attenuation by barrier; and surface reflection. In order to design a rooftop soundscape, the matter of sound propagation around barriers and over buildings needs to be studied in detail.

The considerations for designing a rooftop to prevent noise problems have been made in several research studies. The urban geometry and building shape impact traffic noise propagation in the outdoor environment. The distribution of reflected sound waves was considered in “The influence of urban canyon design on noise reduction for people living next to roads.” Echevarría et al. (2015) modelled different facade geometries and different types of street configuration

(Figure 10), according to the common street canyon set up (Figure 9), using a computer analysis of a full wave numerical study. The finite difference time-domain (FDTD) method was used for the study.

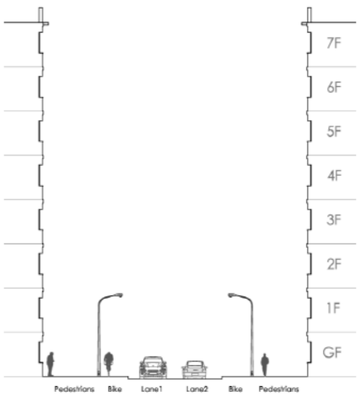


Figure 9: Street canyon setup in the model.

(Echevarría et al., 2015)

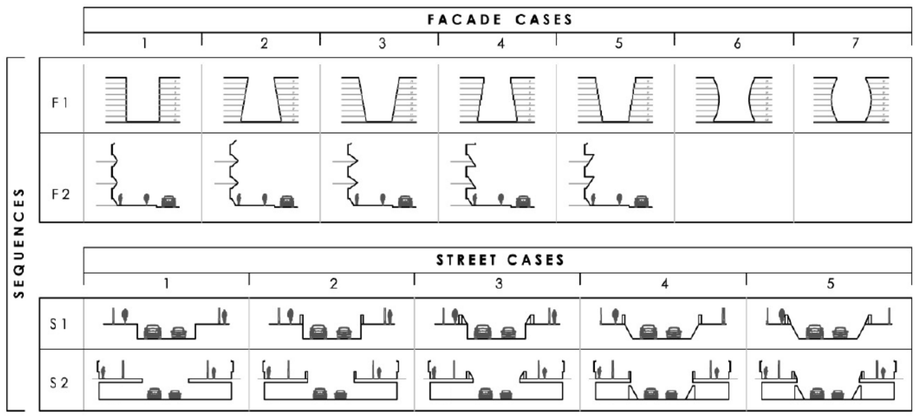


Figure 10: Facade sequences: F1_General shape of buildings. F2_Triangular shapes in facades. Street sequences: S1_Depressed roads at -1.7 m level. S2_Second level road + parking spaces.

(Echevarría et al., 2015)

The shape of the building facade influences reflected sound waves in the street canyon. The noise levels at the pedestrian level and near the window along the facade depend on the existing building shapes. Flat-inclining-upwardly facade, flat-vertical facade and concave facade are the shapes that showed the best noise mitigation. It has been proven that a reduction of noise in a canyon can lead to lower reflected sound energy reaching the rooftop. Thus, choosing a facade style that has the potential to mitigate noise is the most important thing to do at the design phase of a new building to obtain a quiet environment at the rooftop.

Building facades are essentially a series of barriers in a complex city configuration. In the parametric study of sound propagation between city canyons with a coupled FDTD-PE model, the presence of diffusely reflecting facades and balconies shows a significant increase in shielding capacity. A rigid facade has less shielding compared to a partly reflecting facade. Wind also affects the shielding capacity. Acoustic shielding due to the wind decreases significantly when downwind is the driving force for the street-to-roof configuration (Van Renterghem et al., 2006). One thing to be highlighted is that, in a real street canyon configuration, multiple reflections back and forth are shown along the facade. The more reflections of sound energy in the street canyon that build up, the higher chance of sound diffraction over the building edge presenting at the rooftop soundscape.

Another interesting paper on sound diffraction in the case of canyon-to-canyon propagation revealed the capabilities of noise barrier technologies for roofing. Van Renterghem et al. (2013) validated the sound propagation equations using a combination of two types of computer simulation software, a full-wave numerical model of finite-difference time-domain (FDTD)-2D application and a pseudospectral time-domain (PSTD)-3D calculation method. It is noted that in this model, wind and temperature gradients were not accounted in the test. An incoherent line source, representing an actual traffic stream, and a 6-storey building configuration, were used in the calculation. Figure 11 shows the diagram of building configuration over the street canyon set up for their model investigation.

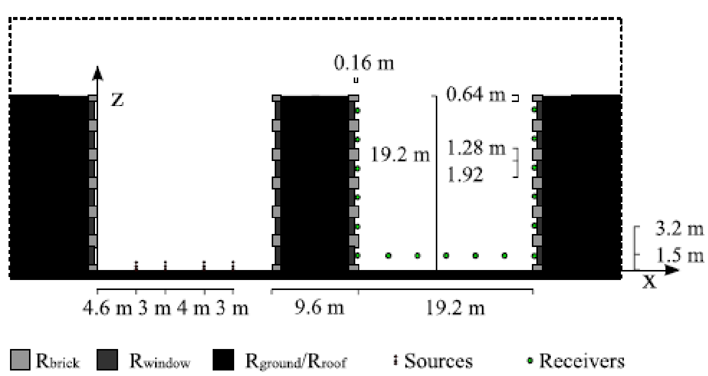


Figure 11: Diagram of 6-storey building over the street canyon set up in the model. (Van Renterghem et al., 2013)

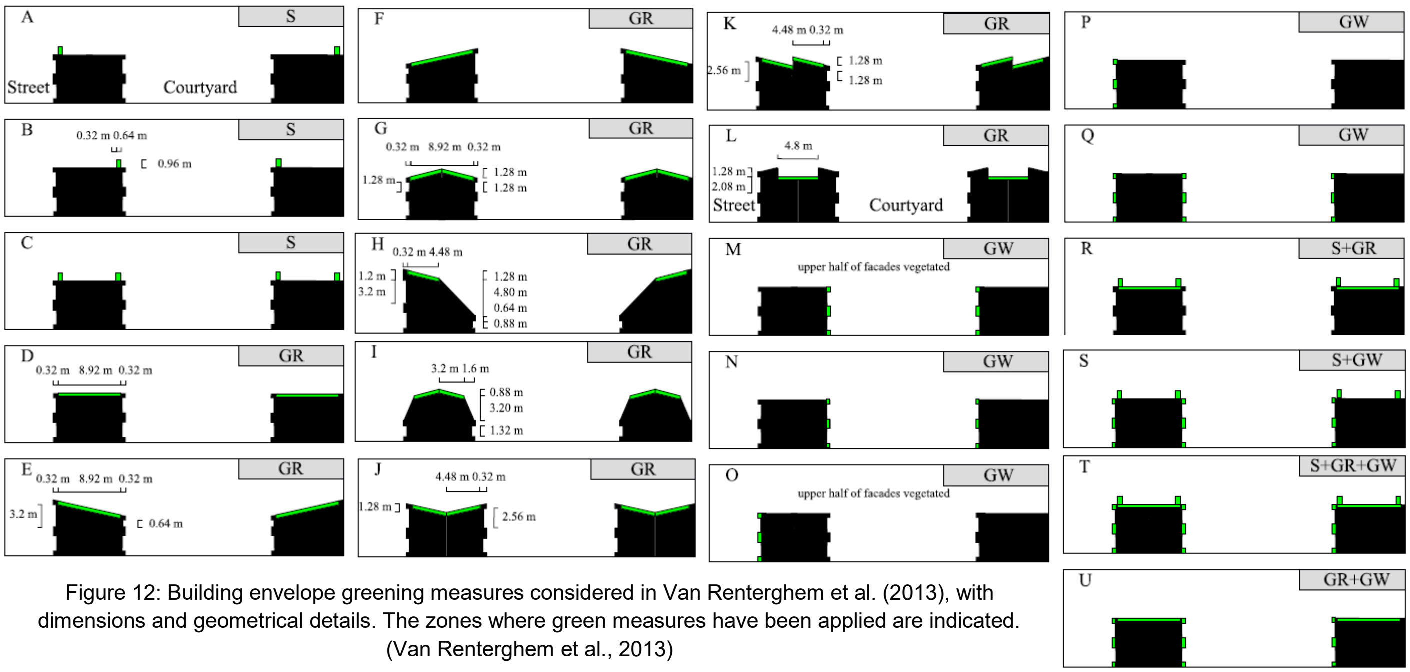


Figure 12: Building envelope greening measures considered in Van Renterghem et al. (2013), with dimensions and geometrical details. The zones where green measures have been applied are indicated. (Van Renterghem et al., 2013)

Twenty-one building envelope greening measures for potential traffic noise reduction were studied and categorized into four groups: vegetated low screens at roof edges (A-C), vegetated green roofs (D-L), green walls (M-Q), and the combination of those treatments (R-U). (See Figure 12.) The results show that the problem frequencies that pose the highest risk on the shielded zone area are low frequencies, because high frequencies are usually attenuated by the diffraction process over the building edge and barriers. A vegetated low screen at both roof edges, case (C), has the highest noise reduction compared to all the technologies. For the low-rigid screen, lower attenuation was shown. The efficiency of the green roof is strongly enhanced in the case of tilted roofs (E – I), where the single-value insertion losses in the courtyard are up to 7.5 dBA. With the depressed roofs, cases (J and L), a smaller insertion loss is presented, because the sound energy is not forced to interact with the green roof. Case (I) results in a maximum building envelope greening effect, with the soft diffraction edge at the center of the building. While the building facade materials effect sound propagation on the rooftop, a green wall facade makes the most traffic noise reduction compared with the non-vegetated green walls. Lastly, the combination treatments (R-U), with green roof or green wall with green roof edge screens (R and S, respectively) showed as the most efficient in reducing traffic sound propagation over the rooftop.

According to Van Renterghem, much of his research has been dedicated to numerical and modelling studies of traffic sound propagation over the rooftop. One of his studies of five cases of *in-situ* measurements of sound propagation over flat and extensive green roofs showed that the substrate of green roof has potential for sound absorbing properties (Van Renterghem and Botteldooren, 2011). “Growing mediums used in green roofs are highly-porous, and allow acoustic waves to enter the medium, which is a necessary property of a sound absorbing material.” His comment on the sound propagation relationship between the diffracting sound wave and the surface absorption of the green substrate demonstrates that attenuation occurs because of the large amount of interaction with the solid phase of the substrate. Therefore, this leads to the conclusion that a green roof has high potential to reduce diffracted noise compared to the rigid roof. Moreover, the difference in substrate depths is also important for a specific frequency spectrum sound attenuation. A shallow depth of substrate is positive for high frequency, while a greater depth is preferable for low frequency (Van Renterghem and Botteldooren, 2011). Another interesting research study by Van Renterghem et al. (2013) mentioned the angle of incidence of the diffracted sound wave. The high attenuation was owing to an incidence that was nearly parallel to the surface, resulting in an increase of substrate absorption coefficient compared to other incidences.

In “Reducing the acoustical facade load from road traffic with green roofs,” Van Renterghem and Botteldooren (2009) experimented with using a computerised FDTD method to evaluate the traffic noise attenuation with the presence of a green roof at building facades in two different configurations: acoustic shadow zone of the building and indirectly exposed facade of the adjacent canyon (Figure 13).

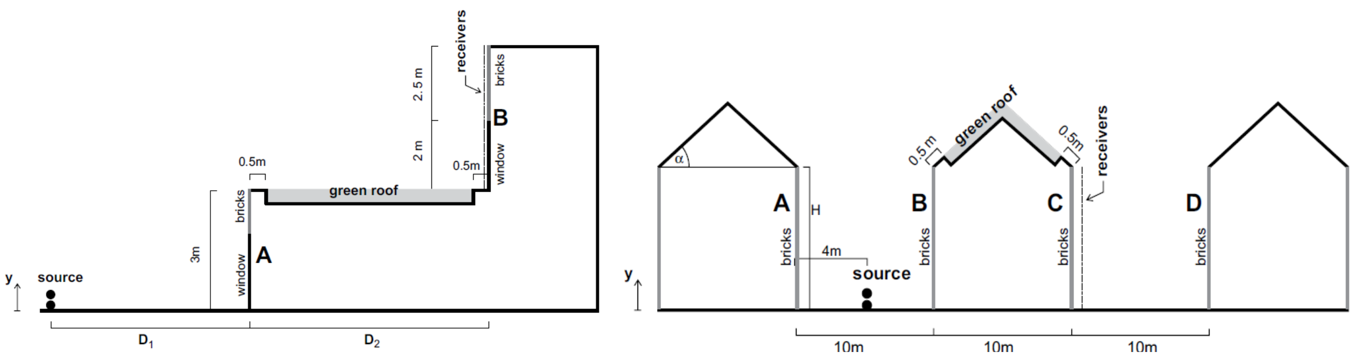


Figure 13: Configuration 1 (left): Green roof on building extension modelled with various substrate depths, Receivers are located along facade B. Configuration 2 (right), Green roof on saddleback roof in various slope angle, Receivers are located along facade C

(Van Renterghem & Botteldooren, 2009)

Different sound sources, light vehicles and heavy vehicles, were used for modelling. Receivers in the acoustic shadow zone (Configuration 1) were placed on the rooftop building facade to measure single-sound diffraction by a flat green roof. In the second configuration, receivers were placed on the building facade in an adjacent canyon to measure the double diffraction by a saddleback roof. The result leads to the conclusion that the important parameters for designing a house for acoustic shielding effect are roof type and roof coverage. For light traffic, the effect of a green roof increases. The more area of the green roof, the better noise reduction presents at the receivers. In terms of the roof slope, a flat roof is the best form for sound attenuation, but for the saddle back roof the authors stated that, “The negative effect of the saddleback form is completely compensated since the area over which sound waves interact with the green roof substrate during diffraction is larger” (Van Renterghem and Botteldooren, 2009). Therefore, the surface area of the roof over the sound wave interaction is an important parameter for yielding traffic sound propagation in the street canyon.

1.3 Rooftop Sound Attenuators

The previous section referenced the useful elements of roofs that significantly mitigate the sound propagation from road traffic. The roof types, details, roof technology and materials comprising for the roof are the important parameters to consider in reducing diffracted sound energy for rooftops, especially at the roof edge. This section reviews the roof technologies that are used in this research investigation.

1.3.1 Green Roof and Substrate

Intensive and extensive green roofs are two different types of green roof systems. The engineered ecosystem on the rooftop consists of a vegetation layer and substrate over a series of root barrier and waterproofing membranes (Oberndorfer et al., 2007). Intensive green roofs have deep growing medium (20 cm depth or more), and a more diverse plant community can be planted, as the deeper substrate depth allows the roots to penetrate deeper and wider. Unlike an intensive system, extensive green roofs have shallow growing mediums (usually much less than 15 cm) and are much lighter in load. MacIvor and Lundholm (2011) state, “Being less costly and material intensive, extensive green roofs are often the focus of most research studies because quantifying their benefits improves the likelihood of widespread retrofitting of existing buildings in cities.” Table 1 below illustrates the different aspects of extensive green roofs versus intensive green roofs.

Table 1: Comparison of extensive and intensive green roofs. (Table adopted from Oberndorfer et al., 2007)

Characteristic	**Extensive roof**	**Intensive roof**
Purpose	Functional; storm-water management, thermal insulation, fireproofing	Functional and aesthetic; increased living space
Structural requirements	Typically within standard roof weight-bearing parameters; additional 70 to 170 kg per m^2 (Dunnett and Kingsbury 2004)	Planning required in design phase or structural improvements necessary; additional 290 to 970 kg per m^2
Substrate type	Lightweight; high porosity, low organic matter	Lightweight to heavy; high porosity, low organic matter
Average substrate depth	2 to 20 cm	20 or more cm
Plant communities	Low-growing communities of plants and mosses selected for stress-tolerance qualities (e.g., *Sedum* spp., *Sempervivum* spp.)	No restrictions other than those imposed by substrate depth, climate, building height and exposure, and irrigation facilities
Irrigation	Most require little or no irrigation	Often require irrigation
Maintenance	Little or no maintenance required; some weeding or mowing as necessary	Same maintenance requirements as similar garden at ground level
Cost (above waterproofing membrane)	\$10 to \$30 per ft^2 (\$100 to \$300 per m^2)	\$20 or more per ft^2 (\$200 per m^2)
Accessibility	Generally functional rather than accessible; will need basic accessibility for maintenance	Typically accessible; bylaw considerations

The complexity of an extensive green roof is less in terms of plant communities, irrigation, and maintenance compared to an intensive green roof system. Only low-growing plant communities such as mosses and sedums can be planted on an extensive green roof. It requires little or no irrigation or maintenance. While an intensive green roof requires an irrigation system and maintenance, a variety of plant species can be planted. Therefore, both green roof systems have a positive impact on the ecosystem and its buildings. Reducing energy consumption by increasing the insulation layer, increasing sound absorption, and extending the longevity of the roofing membrane are the benefits of adding a vegetated layer on the roof of a building. Moreover, from an ecological point of view, creating a green space would improve the ecosystem, create habitat for wildlife, improve air quality and reduce of the urban heat-island effect for the city.

Connelly and Hodgson (2015), in “Experimental investigation of the sound absorption characteristics of vegetated roofs,” investigated the normal incidence absorption coefficient of six substrates, including sand, pumice and descriptive compost, in a laboratory to determine the significance of their sound absorption properties. A spherical-decoupling method using an impedance tube was used to measure the sound absorption of 25 *in-situ* vegetated test plots in three different plant communities. It was found that a physical characteristic parameter affecting the sound attenuation in the substrate test plot is moisture content (MC) and compaction or the percentage of organic matter. The investigation consequence leads to the conclusion that the absorption coefficient decreases with an increase in moisture content and increases with an increase in percentage of organic matter. The higher frequency spectrum range from 250-1000 Hz shows higher absorption coefficients. In terms of substrate porosity, high porosity in soil texture, which defines higher organic content, increases sound absorption. In comparison, sand has the least sound absorption property, while compost substrate mix ranks the highest, since it has a higher percentage of organic matter and higher pore volume (Connelly, M., 2011; Connelly and Hodgson, 2015).

Not only do green roofs have ability in absorbing sound from the outdoor soundscape, a potential for high mass and low stiffness through surface absorption could provide outstanding outdoor-to-indoor sound isolating (Connelly and Hodgson, 2015). The empirical findings on the sound transmission of green roofs in this study suggest that green roofs could significantly increase transmission loss from the exterior to the interior. This topic is not in the scope of this research. However, the proof from the field test of 33 m² of extensive green roof supports the finding that green roofs can absorb sound energy and increase transmission loss by 5–13 dB of environmental noise at the low and mid-frequency range, and 2–8 dB at the high-frequency range.

A sound-absorptive vegetated green roof dissipates sound energy by an absence of high impedance. The second part of Connelly and Hodgson's investigation of 25 roof plots shows that substrate depth and plant establishment also effect acoustic absorption. "The trend of increasing absorption with increasing depth was observed in the measurements of non-vegetated substrates" (Connelly and Hodgson, 2015). Overall, with the addition of vegetation on substrate, sound absorption of the substrate decreases. However, the absorption coefficient is optimum when the depth is up to 90 mm (9 cm). An extensive green roof with shallow depth can potentially dissipate sound energy as much as an intensive green roof, which requires more depth. The investigation of several rooftop plots confirmed that the functions of moisture content of the substrate, substrate depth, and plant community establishment are important parameters for sound attenuation on green roofs (Connelly, M., 2011; Connelly and Hodgson, 2015).

Attenuation due to ground cover on a green roof is another significant part of rooftop investigation. Different plant species and plant communities show different sound absorbing properties. Moreover, roof shape also influences sound propagation from road noise. In “Reducing the acoustical facade load from road traffic with green roofs” (Van Renterghem and Botteldooren, 2009), roof type and roof coverage are important parameters in designing a sound proof building envelope, besides walls and glazing units. “These aspects should be considered during building design and city planning, especially when road traffic is situated close to the building facades” (Van Renterghem and Botteldooren, 2009). A number of factors, such as roof surface area, height of the rooftop above the ground, substrate depth, temperature gradient, and organic content and water content of the plant species influence the equation of noise reduction. While these factors are interesting, the details of green roof assembly to mitigating sound in real construction practices have been missed. The findings from literature outline the selection of the model green roof used in this investigation, such as the type of rooftop substrate, substrate depth, and the species of plant that should be grown to suit the Pacific Northwest climate.

1.3.2 Earth Berm

An earth berm can attenuate a direct sound path. Only the diffracted sound energy can go around or go over this obstacle. Because of the solid body that has surface density of more than 10 kg/m², a bulk barrier of earth berm can manage to significantly reduce the sound energy (Peng and Lines, 1995). However, for green roof berms, the materials used for the berm structure needs to be lighter than the soil mass used at grade. Void form is an engineered non-biodegradable load bearing material which is used instead of soil to create the form of berm. Figure 14 shows a detailed cross-section of a typical berm consisted of an ideal substrate layers; void form, clay and topsoil.

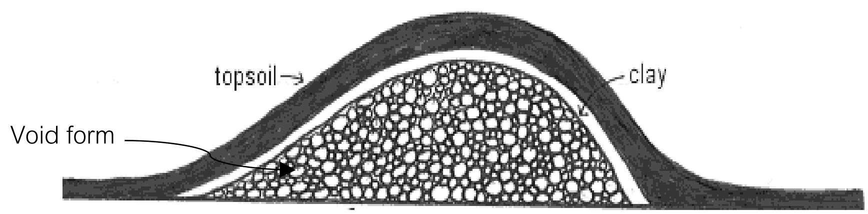


Figure 14: Ideal substrate layers for a berm.
(Adopted from “Building Soil Berms” by Bennett and Wilkins, 2017)

A barrier attenuation is calculated using an empirical relationship of Freshnel number (N) which N referred to the function of a barrier geometry and the wavelength.

$$N = \frac{2}{\lambda}(d_1 + d_2 - d).$$

The geometry of sound propagation over a barrier is defined as the images in Figure 15.

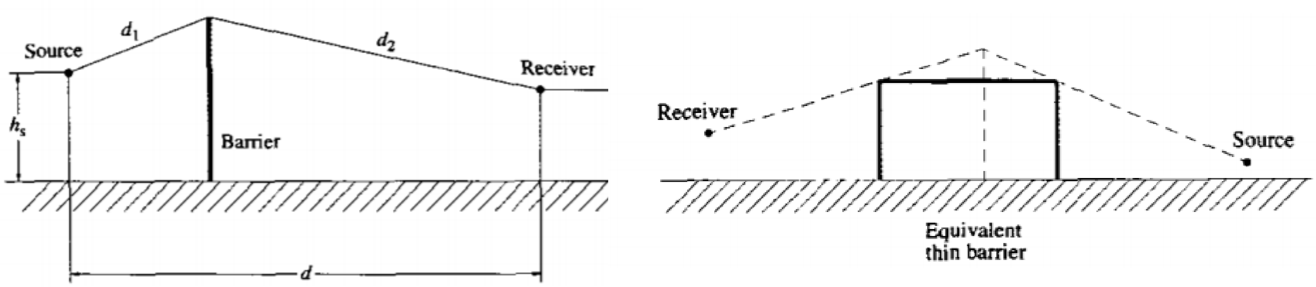


Figure 15: Geometry of sound propagation over a barrier. A thick barrier is equivalent to thin barrier. (Lines and Peng, 1995)

Therefore, the barrier attenuation can be calculated using this formula:

$$A_{\text{barrier}} = 10 \log (3 + 20N)$$

It is indicated that, an earth berm barrier in front of a building can possible attenuate the environmental noise as much as 6 dB(A). The combination of berm barrier and ground cover can potentially give a higher attenuation and significantly reduce environmental noise if it were well design in consideration of soundscape theory (Peng and Lines, 1995).

Van Renterghem et al. (2012) analyzed the matter of traffic noise shielding provided by earth berm and wall screen which has the same height in two atmospheres; with and without wind effect. The finding showed that with a strong downwind, 4 meters wall - screen lost almost its shielding capacity due to the refraction. With respect to berms, refraction by down wind could be reduced by decreasing a berm slope angle to 1:3 ratio (Berm 5 in Figure 16) or having a higher slope angle but with a flat top (Berm 4). In conclusion, selecting the berm size, shape and ratio that has the highest potential in noise reduction and, has the least effect by the worst-case scenario of down wind terrane would be the best solution for noise mitigation strategy. Therefore, the consideration of berm angle should response to drainage, aesthetic and low maintenance require (Bennet & Wilkins, 2017; Van Renterghem et al., 2012).

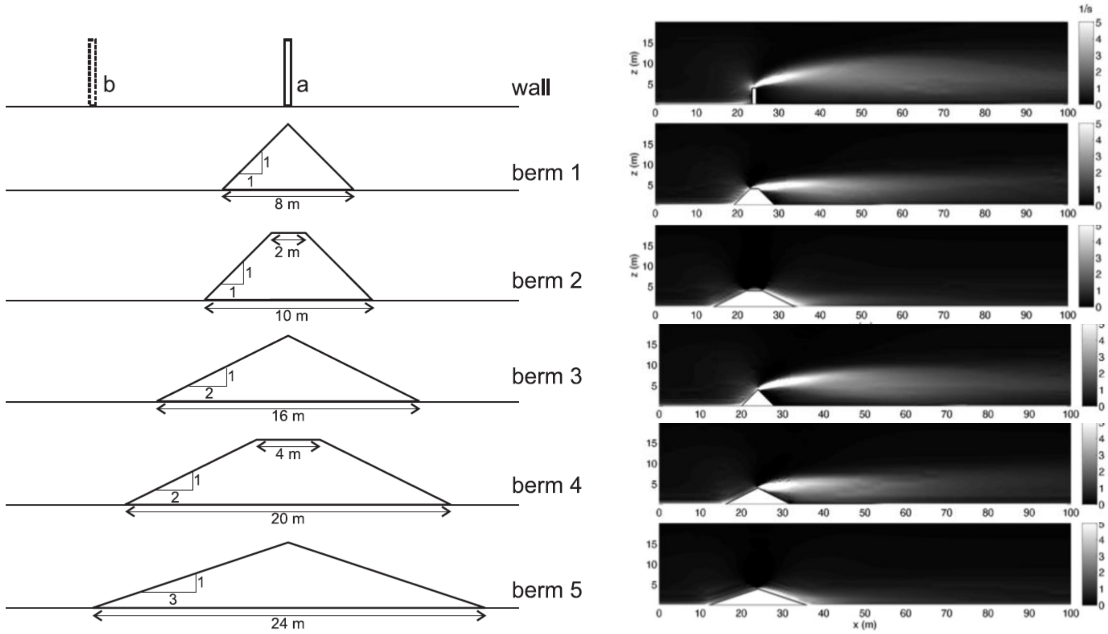


Figure 16: Noise barriers and berm that were numerically evaluated in this study, and the field plots of the vertical gradients in the horizontal component of the wind velocity near the wall and berms.
(Van Renterghem and Botteldooren, 2012)

1.3.3 Noise Barrier Wall and Living Wall

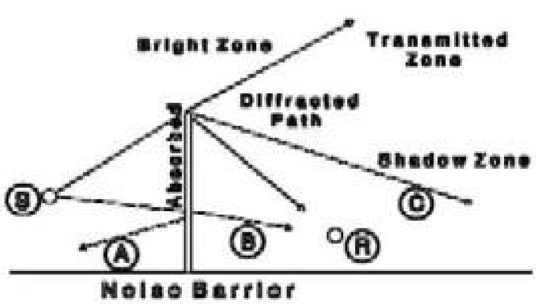


Figure 17: Various components of noise
(S) Source of Noise, (A)Reflected Noise,
(B) Transmitted Noise (R) the Receiver
(C) Diffracted Noise

(Noisesorb, n.d., Retrieved January 27, 2017)

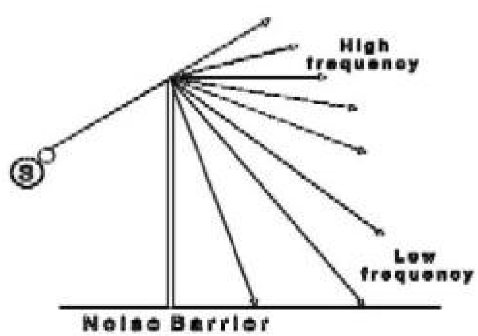


Figure 18: Low frequency sound diffracts more, therefore it bends around corners, whereas high frequency sound bends less.

(Noisesorb, n.d., Retrieved January 27, 2017)

Sound propagates around barrier in 3 ways; reflections, transmissions and diffractions. As it can be seen in Figure 17, the sound source (S) reflects when it hits the barrier at the same angle of incidence respecting to a normal angle (A). At this step, some of the energy will transmit (B) through and absorbed by barrier materials. Nevertheless, transmission loss by walls is not an area of interest in this research. However, wall materials are playing an important role when it comes to reflected sound energy which is attenuated by shielding capability of a barrier. Beyond that stage, if the direction of sound source goes over the building, sound energy will hit the edge of the building resulting in a diffraction of sound wave (C). Ray C illustrates different paths of sound propagation behind the obstacle such like buildings and sound barriers by the mechanism of diffraction.

Difraction is involved by the wavelength of the sound source. Low frequency spectrum is stronger and can be heard easier from the other side of a barrier in the shadow zone. High frequency is still present but tends to spread over the transmitted zone in more directional manner (Figure 18). In addition to the building edge diffraction, Echevarría et al. (2015), stated in their paper that wall top configuration affects diffraction. By having the flat-facade inclined upwardly or concave shape facade in the urban environment, it results in a lower reflected sound energy built up in the canyon which lead to a lower diffracted sound wave reached the rooftop (Echevarría et al., 2015). However, facade style and wall top configuration are not our scope of this research.

According to BC Building Code (2012), the minimum height of guards shall not be less than 1070 mm high for rooftop space or every exterior surface including balconies, porches, and mezzanines. The materials used for guard design is usually comprised of glass where it shall be a safety glass. Neither laminated or tempered type of glass is recommended by the code. The assembly details of glass and railing should have a very small opening between the joint such that a diameter is not over 200 mm to avoid the passage of spherical objects for the safety reason (BC Building code, 2012).

Adding a vegetated layer to the wall is a good example of combining nature and building together. While the city area has becoming so dense nowadays, vertical garden is the key to plant vegetation in an urban space. The consequences of having a greener city is not only reducing carbon dioxide produced by traffic, heating equipment (Perini, K. et al., 2011), but also absorbing the sound energy due to the absorption characteristic of the plants and substrates. In this study, the 1070 mm rigid guard made of glass panel is one of the design tool to be explore. A living guard covering with vegetation layer at the same height is another design tool in this investigation. It is more likely that vegetated guard will be potentially absorb more sound energy and minimize sound propagation to the other side of barrier than the rigid one. Rigid glass high wall, 3000 mm in height, and high vegetated wall are also investigated in the study.

Living wall is also called as "vertical garden" which refer to all forms of vegetated wall surfaces. The growing methods for planting on the wall are varied. Plants can be either rooted into the ground, in the wall material or in a modular panel which attached to the wall. Figure 19, shows 3 different methods to plant vegetation to the wall, a) a traditional way to plant vegetation onto the ground by the climbers attached themselves directly to the wall surface, b) indirect system, basically plant growing climbers the same way as in a previous method but they were supported by cables or trellis, c) another indirect system that plant vegetation in a planter boxes that attached to the wall and d), e), f) are different system of modular panels called as living wall system, which has the separated-growing mediums at each modular (Perini, K. et al., 2011).

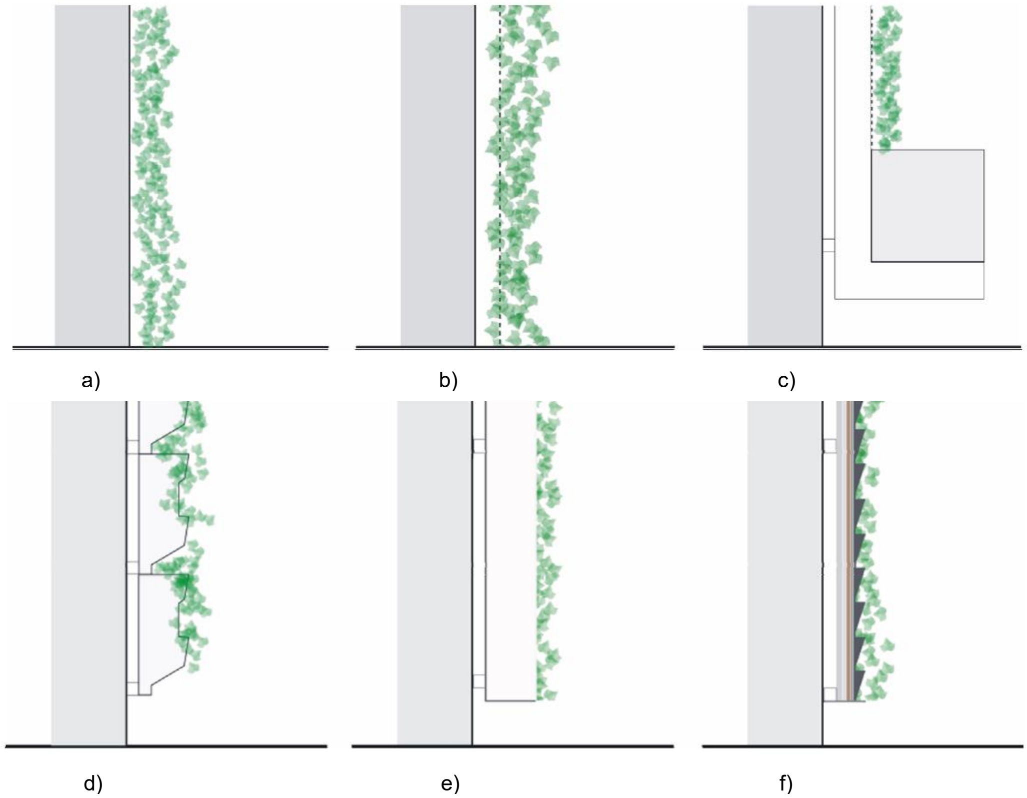


Figure 19: Methods to plant vegetation to the wall: (Perini, K. et al., 2011)
a) Direct greening system, b) Indirect greening system, c) Indirect greening system combined with planter boxes
d) LWS based planter boxes e) LWS based on foam substrate, f) LWS based on felt layers

1.3.4 Overhang

Even though an overhang is not considered to be living architecture, a layout where the overhang is part of the flat roof structure or extends from it can be made a part of the living green roof with a vegetated layer on top. An overhang, also called an *external horizontal shading device,* is the design solution to propose an optimum external shading for the building and occupants in building space. A number of research studies have investigated the effect of overhang geometry on the building energy consumption, which usually only point out the energy saving results for the interior occupying space. Incident solar radiation, transmitted solar heat gains, natural light penetration, and energy consumption were parameters focused in the past. Effective external shading blocks most of direct sunlight, although it admits indirect light from the sky, which could reduce solar heat input by 80% to 90% (Ossen, D. R. et al., 2005). But in addition, an exterior outdoor space on the rooftop could benefit acoustically when horizontal-overhang geometry is included as a part of building design strategy for the exterior facade.

For high humidity region like Vancouver, the consideration of having roof overhang will increase durability of building and its materials. Overhangs protect walls from rain and offer durability and energy efficiency benefits. In wood-frame building, overhang provides protection against moisture and slows down the decay process of wood building materials. The findings from the study investigated by U.S. Department of Housing and Urban Development (1978) claimed that overhang could extend the life of the wall below and prevent the decay in buildings (HUD, 1978). Therefore, there are some drawbacks of installing overhang too, it increases an uplift load on roofing membrane which supported the overhangs. The design for overhang should consider the trade-off between wind load uplift and building durability. The protective overhang width recommended in the humid climate zones should be 12 to 24 inches or more if practicable (Residential Structural Design Guide, 2000).

1.3.5 Introducing Natural Sounds

Although the introduction of natural sounds is not in the scope of this thesis, a brief introduction reviews recommendation of future work. Nowadays, after the development of urbanism, outdoor ambient noise in the city became increasingly high resulting in a difficulty to perceive acoustic definition for city dwellers. One example that shown how loud is the urban ambient noise, is the rising sound power level of the police siren. Siren noise has been put up to

100 dB(A) or more, in order to alarm people beyond a very high background noise in an urban area. Not only the background noise from people activities, noise from the building such as mechanical system is also the critical noise source to be considered in an urban soundscape too.

Introducing natural sounds is a peaceful technique to balance a rooftop soundscape. Rehan, R. M. (2015) investigated the power of natural sound in “The phonic identity of the city urban soundscape for sustainable spaces.” He proved that sound of water in cities is soothing and therapeutic. The pleasure state can be reached by the powerful of moving water. While rushing water refers to an acoustic camouflage of traffic. Sound from water fountains can be used to mask the traffic noise and can be used to attract people attention. Even though natural sounds are crucial to reduce the annoyance of transportation noise from main roads, they actually bring up the SPL in the environment at the same time (Leventhall, H., 2004). Therefore, balancing rooftop soundscape with natural sound could affect in higher ambient noise level in over all. However, it would deliver more pleasant acoustic environment for the users.

The phenomenon of masking was confirmed by Schafer (1993), masking is the best way to exploit the environmental noise control. “Ventilating and air-conditioning noises, the noise created by uninterrupted traffic flow of highway, or the sound of water fountain are good masking noise sources.” (Schafer,1993). The most effective intrusive noise that can be masked should not be too loud (low to moderate intensity). In this case, natural sound masking on the rooftop would be able to balance the modified outdoor traffic noise that reached the rooftop soundscape and noise generated by mechanical system. Background noise level at rooftop would become much more acceptable, more pleasant to the user. Therefore, introducing sounds such as streaming water, singing birds, wind breeze etc., not only turn the urban spaces into much more pleasant soundscape, but also give an identity for the space too (Schafer,1993).

1.4 Modelling and Parameters

Before the barrier technologies can be tested to see the efficiency of sound attenuation on a rooftop, the experimental study of creating a sound source needs to be modelled in anechoic chamber to prove the accuracy of the source acoustic power that represented the real stream of traffic flow. One method that could be used to simulate the traffic source is, by using a point of line source to create a noise source of vehicles in the laneway. To achieve the source which is regarded as a line source of infinite length, the measurement of SPL at various receiving positions would show the attenuation by approximately 3 dB per doubling the distance from the source. The test is, ideally, followed an outdoor sound propagation theory where sounds are decreasing linearly (Koyasu and Yamashita,1973).

A line source experiment in 1973 by Masaru and Mitsuyasu, illustrates the idea how to acquire detail set up of the test in an anechoic chamber. C-shape stainless steel channel filled with small diameter steel balls (Figure 20), was connected with a motor that moved the channel back and forth to create a movement. “(t)he steel balls strike the walls of the channel and radiate broad band noise” (Koyasu and Yamashita,1973). Figure 21 shows the experimental set up of a source and a receiver microphone.

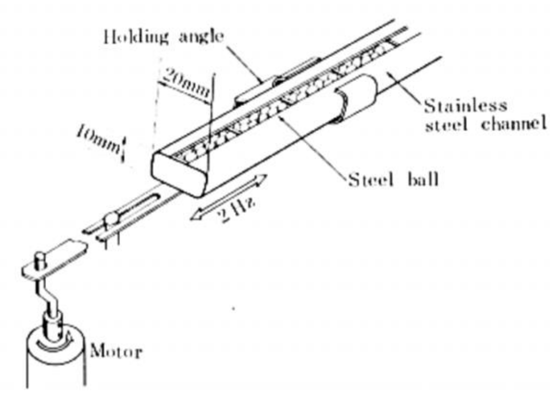


Figure 20: Details of line source set-up.
(Koyasu and Yamashita, 1973)

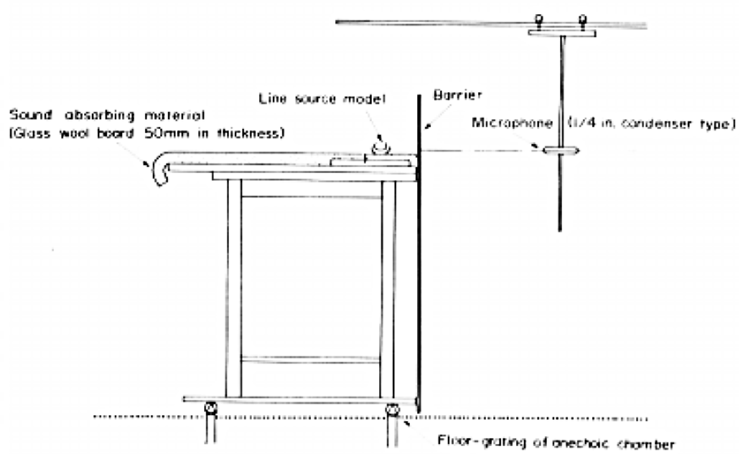


Figure 21: Experiment set-up in an anechoic chamber.
(Koyasu and Yamashita, 1973)

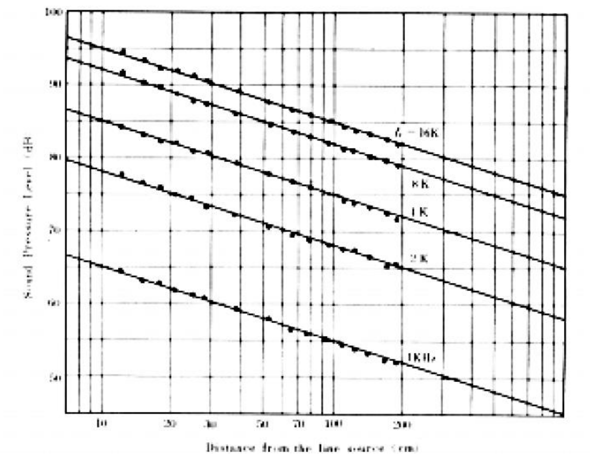


Figure 22: SPL as a function distance from the source. (Koyasu and Yamashita, 1973)

The various SPL measured at a direction normal to the source (Figure 22) shows an approx. 3dB attenuations at every twofold increase in distance at the centre frequencies of 1000, 2000, 4000, 8000 and 16,000 Hz. These confirms the accuracy of line source experimental model that mimic the traffic flow in a real street environment.

The “Scale model study of road traffic noise reduction by planting schemes” by Dragonetti et al. (2011) demonstrated the details construction of a traffic point source where materials being used were implied to a 1:20 model size to the real world in both dimension of traffic road to the environment, and physical of sound properties toward model materials. A 1:20 scaled model experiment of a point source on a specific height of the ground (0.3 m) was built and a tweeter was placed underneath a wooden floor as shown in Figure 23 to simulate a single vehicle noise source on the street model. Even though, in this research, a traffic line source was chosen for scale-model experiment in the next chapter, but the study on the detail assembly of a traffic point source could give some clues to adopt into a line source scale model experimental set up.

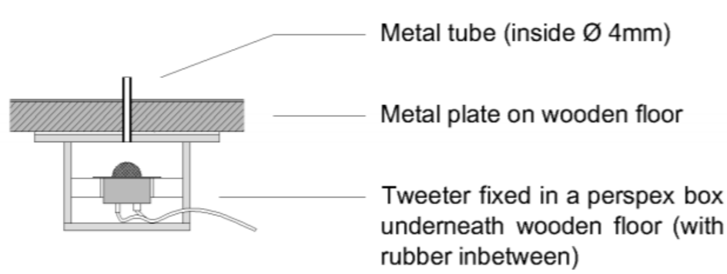


Figure 23: Point source detail set-up. (Dragonetti et al., 2011)

One of the methods to measure diffracted sound is scale modelling in an anechoic chamber. It is shown in “Laboratory study of the effects of green roof systems on noise reduction at street levels for diffracted sound” by Yang et al. (2010). A SPL measurement of 20 green roof tray models located at street level in a semi-anechoic chamber (Figure 24) was investigated to understand the factor parameters that impact on the diffraction noise reduction. The parameters such as roof structure, roofing area, position of green roof system and the type of vegetation were investigated. Two receiving microphones were placed at different locations which to ideally illustrate a single diffraction and double diffraction cases.

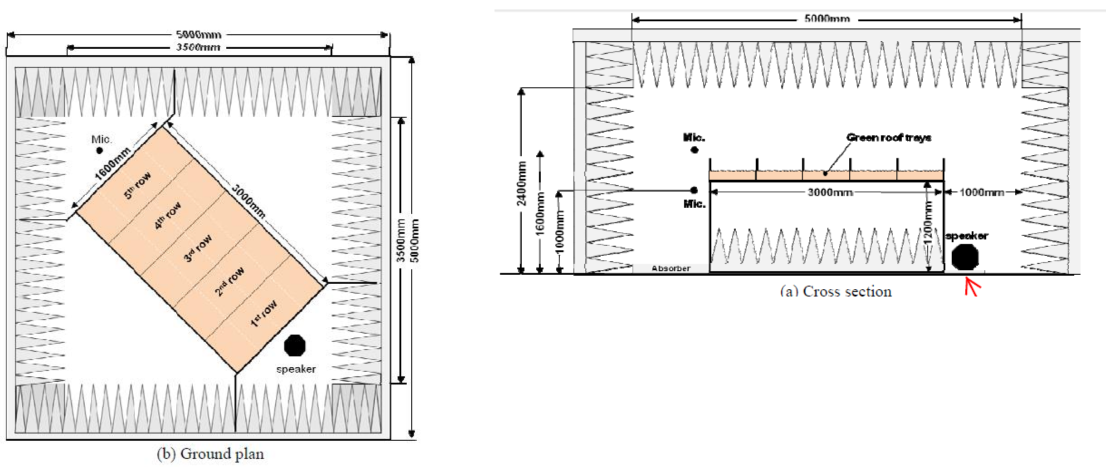


Figure 24: The cross-section and plan view of the scale model test in an anechoic chamber. (Yang et al., 2010)

Pruned fresh leaves and 100% Polyester cotton were used to represent the density condition of a leave in an anechoic chamber; maximum density of leave on green roof and extreme condition of sound absorbing by vegetation respectively. The test outcome showed that “With different areas of a green roof system, a noise reduction of over 10 dB was observed. The effect on noise reduction was gradually increased with increasing number of rows of the trays.” (Yang et al., 2010)

Another interesting scale model investigation on evaluating road traffic noise abatement by vegetation treatments was done by Jang et al. (2015). An urban scale model at 1:10 (Figure 25) was constructed in a semi-anechoic chamber to simulate a narrow street canyon of European urban area. The selected scale model materials with respect to real-scale materials and their structures were selected based on a 1:10 absorption coefficients of full scale materials. Table 1 illustrates a list of selected materials being used in their model and its absorption coefficients, as well as a comparable of an absorption coefficient of real-scale materials.

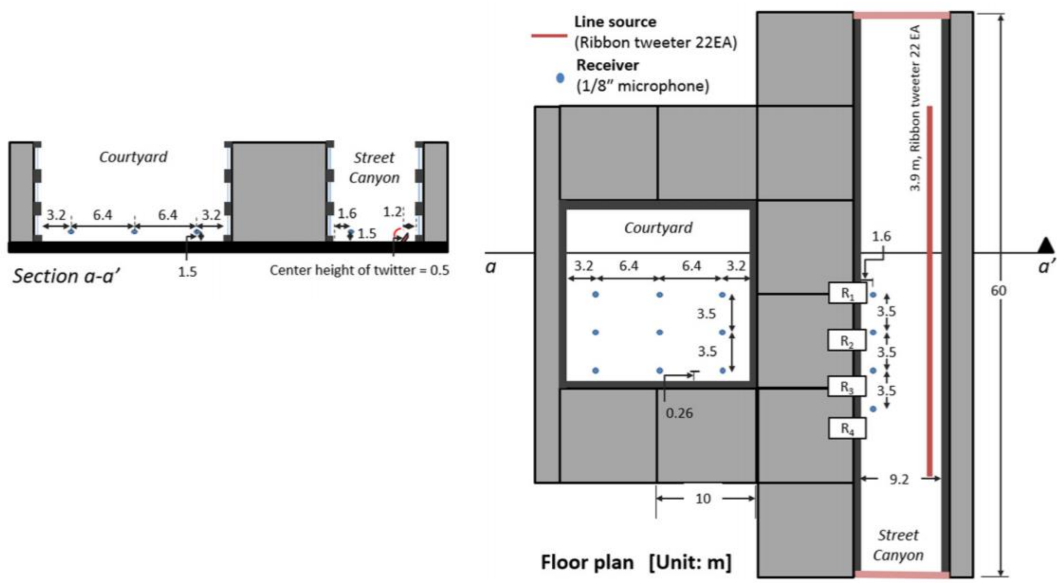


Figure 25: Reference configurations of an urban scale model, sources, and receiver positions. (Jang et al., 2015)

Table 2: Absorption coefficients of building and vegetation materials for both the real world and scale model. (Jang et al., 2015, adopted from Harris, 1991 and Yang et al., 2013a)

Material name (Scale model material is in bold, list of layers from top to bottom)	Absorption coefficients by frequency band [Hz]						
	125	250	500	1k	2k	4k	Avg.
Asphalt[a]	0.02	0.03	0.03	0.03	0.03	0.02	0.03
1.6-mm metal plate, 18-mm MDF, 20-mm air gap	**0.05**	**0.05**	**0.05**	**0.04**	**0.04**	**0.05**	**0.05**
Heavy glass (large panes)[a]	0.18	0.06	0.04	0.03	0.02	0.02	0.06
2-mm acrylic, 20-mm air gap	**0.21**	**0.09**	**0.05**	**0.04**	**0.06**	**0.04**	**0.08**
Brick, unglazed[a]	0.03	0.03	0.03	0.04	0.05	0.07	0.04
16-mm acrylic	**0.03**	**0.01**	**0.03**	**0.02**	**0.05**	**0.07**	**0.04**
Vegetated facade[b]	0.65	0.63	0.70	0.69	0.68	0.72	0.68
Felt (<1 mm), artificial grass, 10-mm polyurethane (PU)	**0.65**	**0.70**	**0.73**	**0.68**	**0.63**	**0.75**	**0.69**
Shrub[b]	0.34	0.60	0.78	0.91	0.91	0.71	0.71
PU (leaves), 30-mm of wood pick, hemp fabric, 20-mm expanded polystyrene	**0.33**	**0.65**	**0.87**	**0.88**	**0.85**	**0.80**	**0.73**

For the traffic source model, it was confirmed that a ribbon tweeters array could simulate a line source of traffic flow on a narrow street. By confirming this, a coverage angle of ribbon tweeter at all frequency ranges from 1–40K Hz was measured. A directivity of tweeter array was tested to find a coverage area at the facade and building configuration. Moreover, the measured noise spectra of the test signal by tweeter array source was compared with different noise spectra of the traffic noise by various studies to analyze a noise level of a model noise spectra within the frequency boundaries of traffic noise spectrum found in those studies. Twenty-two ribbon tweeters acted as a line source, generated test signal at 10s of steady-state pink noise. The measured signals were analyzed from 1K Hz to 40K Hz at a 1:10 scale model frequency level which represented the range of 100 Hz to 4K Hz (Jang et al., 2015).

ODEON acoustic simulation software is another method to model an outdoor sound propagation. Even though this software has been developed for mainly use to perform and measure interior acoustics of buildings. But it is also capable to investigate outdoor sound propagation. ODEON is an energy based acoustic software which the calculation is based on simple formulas (Sabine, Eyring, Arau – Puchades). Acoustic simulation tools and measuring system in ODEON could be used to acquire SPL, SPL(A), T30 and STI from performing simulation. The simulations of an open-air sound propagation of a theater using the ODEON software has illustrated in “Predicting the acoustics of ancient open-air theatres: the importance of calculation methods and geometrical details,” Lisa et al. (2004) modelled two different levels of detailed theater configurations to study the importance of geometrical details for acoustics. Figure 25, on the left side, showed a simple computer model and on the right side showed a detailed model. In conclusion, the importance of the details when creating models has a strong influence to get an accurate outcome. Using the image-source method at low-order reflections and then using the secondary source ray-tracing calculation method give the best results from the simulation. Therefore, some acoustic mechanism for outdoor sound propagation are limited in ODEON. With appropriate material inputs for scattering coefficient, transparent coefficient and the type of surface-based calculation for scattering method, outdoor situation can be possible to study and can be able to achieve a good predicting result as well (ODEON, 2017).

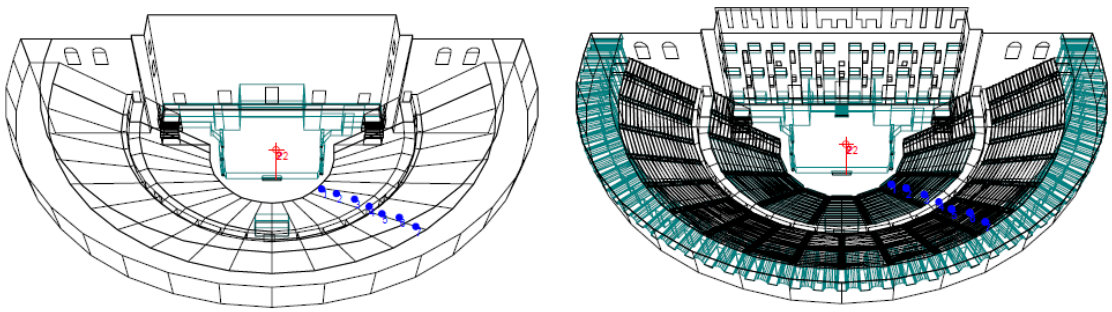


Figure 26: The Aspendos Roman theatre with a performance stage. a. Simple computer model. b. Detailed computer model. The dot on the stage is the source and the dots on the seating area are 7 receiver positions.

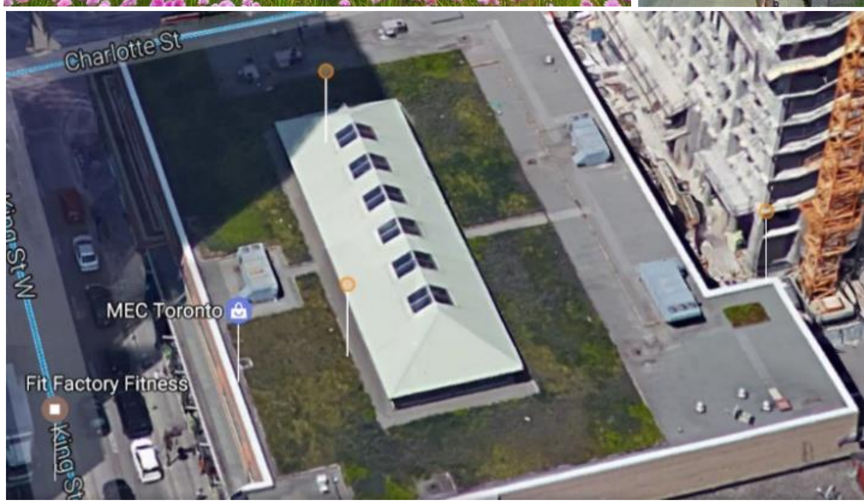
Reprinted from “Predicting the acoustics of ancient open-air theatres: the importance of calculation methods and geometrical details” by M. Lisa, J. H. Rindel, & C. L. Christensen, 2004.

1.5 Green Roof Precedent

Green roof technologies have become an ultimately sustainable building practice in North America. There are several benefits of installing green vegetation on the rooftop in variable and extreme Canadian climates, such as reducing storm water runoff, energy consumption, urban heat-island effect and improving air quality. City of Toronto applies the City’s Green Roof Bylaw to standardize new commercial, institutional, and residential development applications. More than 300 new green roofs have been built in Toronto since 2010 and approximately 500 green roofs provide over 250,000 square meters of green space to the City (Green roofs, n.d.). Some examples of existing green roof precedent that show the technologies of green roof practices, especially at edge details, are illustrated.

Mountain Equipment Co-op: Downtown Toronto, Extensive green roof, 6,500 ft²

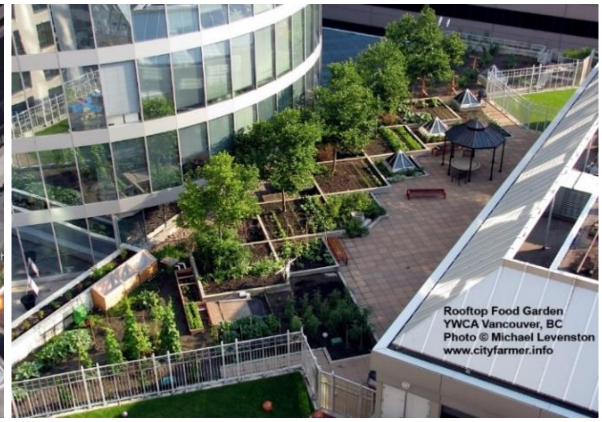




Figures 27-28: MEC rooftop, Toronto. (Reprinted from "List of green roofs," Retrieved January 27, 2017)

From this green roof case study, it is noticed that mechanical system boxes were placed on the rooftop. The roof edges were made from thick, solid concrete having some height to act as a fencing or barrier. Green roof soft-scape area was placed almost cover 80% of the rooftop area and off-set from the building edges about 2 m away.

<u>Rooftop Food Garden, YWCA</u>: Downtown Vancouver, Extensive green roof, 650 ft²



Figures 29-30: Rooftop Food Garden, YWCA, Vancouver. (Reprinted from “Vancouver’s YWCA Rooftop Food Garden,” Retrieved January 27, 2017)

The YWCA Vancouver has developed a Rooftop Food Garden which completely run by volunteers to offer their food product to the low-income families who live in the downtown East side area. One of the top project goals is not only to produce fresh, locally grown food, but also to create the local birds and insect habitat in the space where community members can get gathering in a clean environmental garden at the heart of downtown Vancouver.

From the top view of the rooftop, half of the rooftop space was dedicated to a food garden project. The extensive green roof with the depth of 150 – 250 mm is the green roof system being used to plant those vegetables, herbs, fruit, nut trees, berry bushes etc. The outdoor pavement and the gazebo area next to the garden beds are used as a living space where people can get together having an activity or get relaxed by a healing garden.

<u>Olympic and Paralympic Village</u>: Vancouver, Extensive and Intensive green roof, 287,000 ft²

Figure 31-34: Olympic and Paralympic Village rooftop, Vancouver. (Reprinted from "Olympic & Paralympic Village rooftop," Retrieved January 27, 2017)

One of the biggest green roofs in Vancouver is the Olympic Village rooftop comprising a vegetated-roof area of over 50% of the total area. The rooftop space was designed to make the use of the space to be an outdoor living area for residents. The small step waterfalls were brought in to the space. Stainless-steel fences were used at the edge. The shrubs were plant behind the fence to reduce noise annoyance and to increase an acoustic privacy while still allowed people to see through for the urban view. Apart from the benefit of the space being used for recreation, a number of potential social, economic and environmentally sustainability benefits are the outcomes of creating a green space on rooftop. However, choosing the right type of green roof system can be another advantage by helping to ensure that the plants require less maintenance and will maintain their appearance. That was the reason why this green roof was combined with both systems.

<u>100 Years of Chulalongkorn University park and recreation center</u>: Bangkok, Thailand, Extensive and Intensive green roof, 482,200 ft²

Figures 35-38: 100 years of Chulalongkorn University park and recreation center.

A new green space in the heart of Bangkok, Thailand, was designed based on the idea of bringing the sense of happiness into the city space. The architectural concept design is to combine a garden and a roof into one where the park space can be extending infinitely to the roof. The garden area is sloping up to a roof level, allowing rainwater to flow down and kept in a retention pond where the water can be reused, and creating a place for the bird's habitat. The "cell block" underground of green roof serves as a water retardation and the green roof substrate protects the building by absorbing and dissipating heat which make the building cool.

CHAPTER 2
RESEARCH METHODOLOGY

A model of a line source on a 1:10 scale was first constructed for testing in an anechoic chamber. The prerequisite for this test was to develop a model of the real-world geometry boundary-box line source that could generate sound energy which represented a traffic line noise source. After construction, the 1:10 scale line source model performed in alignment with sound propagation theory. The same real-world scale geometry boundary box was also modelled for acoustic computer simulation. The array line source in the computer model generated the same sound pressure level as the constructed scale model, and thus the computer line source was normalized to the source at the reference receiver model in the anechoic chamber (AC) 2.75 m away from the source. It was critical for the computer simulation to cross-validate the line source, before starting the next investigation of design tools. A baseline model (street-to-roof configuration) was constructed and prepared for the design tools investigation. The detailed construction of both models are discussed in this chapter.

A library of design tools was adopted from literature on studies of different types of design tools to reduce road traffic sound propagation on and over the roof. An overhang (OH), green roof (GR), earth berm (B), guard barrier (G), and walls (W), where the walls are solid or have a living wall on one or both sides of the rigid wall surface, are the design tools for investigation in the first part of this research. The second part of this research is to employ the design tool technologies from the first investigation to create sonic subzones on a rooftop that meets the noise criterion recommended by WHO for outdoor recreation space. The noise criterion is less than or equal to 55 dBA. The best performing design tools were selected to apply on a rooftop site. The selected site for this design program investigation is on East Hastings Street, where the highest traffic noise exposure occurs in Vancouver. Details on site selection are shown in the appendices. The outcome of developing acoustic design tool applications on a city rooftop site can be used as a guide for rooftop landscape designers, acoustic designers and architects in designing rooftop space, with consideration to using living architectures to mitigate noise.

2.1 Modelling

A 1:10 scale model was constructed in an anechoic chamber which approximates a quasi-free field condition for outdoor sound propagation. The volume of the anechoic chamber is (W x D x H): 950 x 1500 x 1200 mm. Sound waves and building dimensions were reduced to a 1:10 scale. In a 1:10 scale model, the frequency of sound will be 10 times higher; for example, 250 Hz is represented by 2500 Hz and 2000 Hz is represented by 20,000 Hz. The limit of the sound analyzer used in the laboratory test was 20K Hz. The material selection and associated absorption coefficient for the baseline model were obtained from material measurements in a reverberation chamber that followed an ISO 354 standard (Jang et al., 2015). Table 2 (p. 43 in LR) lists the selected model materials used to construct a 1:10 scale model of a street-to-roof configuration in an anechoic chamber.

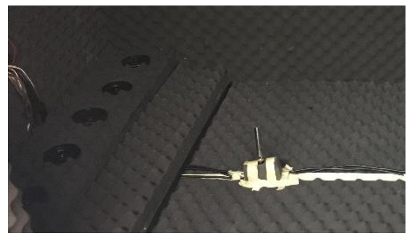
The selection of vegetation for the 1:10 scale model in the anechoic chamber test represents the absorption coefficient of a vegetated roof. The similar absorption properties of the scale model and real-scale materials were matched within 0.09 in all frequency bands from 125–4K Hz (Jang et al., 2015). The scattering coefficient for the scale model vegetation could not be evaluated because its absorption coefficient was greater than 0.5.

2.1.1 Construction of a Line Source Scale Model for Source Validation Test

The goal for constructing the line source for this research was to simulate the acoustic property of traffic flow close to a real traffic source on the street. An incoherent line source is an ideal source to use for scale modelling and numerical modelling of traffic noise exposure, and the sum of the total uncorrelated point sources is similar to a real stream of traffic flow (Van Renterghem and Botteldooren, 2012). For this research, five different line source models were constructed and evaluated. Table 3 shows the different detailed construction of each line source model built for anechoic chamber evaluation. Each is different in terms of materials, source speakers and model geometries. The line source model should show the sound pressure levels that have 3 dB attenuation per doubling of the distance at all frequencies for the architectural acoustic wide-band, plus the low range which represents engine noise (63–2000 Hz).

Table 3: 1:10 scale model of line source operations.

No	Materials and Model Specification	Photos	Aperture
1.	**Wooden box with top sheet (450 mm depth)** - (W x D x H) = 900 x 450 x 180 mm - 3 wall speakers ϕ 210 mm placed 280 mm on center - White noise spectrum		150 mm gap on top of the wooden box
2.	**Wooden box with top sheet (300 mm depth)** - (W x D x H) = 900 x 300 x 180 mm - 3 wall speakers ϕ 210 mm placed 280 mm on center - White noise spectrum		150 mm gap on top of the wooden box

No	Materials and Model Specification	Photos	Aperture
3.	**3 tweeters on acoustic foam panel** - (W x D x H) = 950 x 100 x 350 mm - 3 tweeters ϕ 80 mm placed perpendicular to the receivers, 240 mm on center - White noise spectrum		No enclosure
4.	**6 tweeters on acoustic foam panel** - (W x D x H) = 950 x 450 x 120 mm - 6 tweeters ϕ 80 mm placed 120 mm on center - Pink noise spectrum		No enclosure
5.	**6 tweeters in PVC pipe** - 4" diameter pipe x 950 mm long - 6 tweeters ϕ 80 mm placed inside, 120 mm on center - Pink noise spectrum		7 mm ϕ, 16 holes on pipe

The method to evaluate all five set-ups was the same. Following is the detail of the 5th set-up (shown in Figures 39 to 42). The source model consists of a set of 6 tweeters (80 mm in diameter) which was placed in a 4" (100 mm) diameter PVC pipe with 16 x ϕ 40 mm holes (holes skipped at speaker positions). The length of the PVC pipe had been cut to a tight fit of the width of an anechoic chamber, which is 950 mm. The source tweeters were wired in parallel and connected to the sound generator/sound amplifier (Figure 94(a), in the appendices), which generates both pink and white noise spectrums. The pink noise was selected to be the emitting noise spectrum, because it includes noise from the entire spectrum but emphasizes the specific lower frequencies, which could represent the traffic noise.

A Soundbooks with three channel outputs was used as a measurement tool and connected to the three, 1/2" microphones (G.R.A.S. 26CA) (see Figure 94(b), in the appendices). Six receiver microphone positions were fixed to measure attenuation over the distance from the traffic noise source model. While testing inside the anechoic chamber, it was assumed that the sound propagated in a homogeneous, non-moving atmosphere and there were no wind effects and temperature gradients.

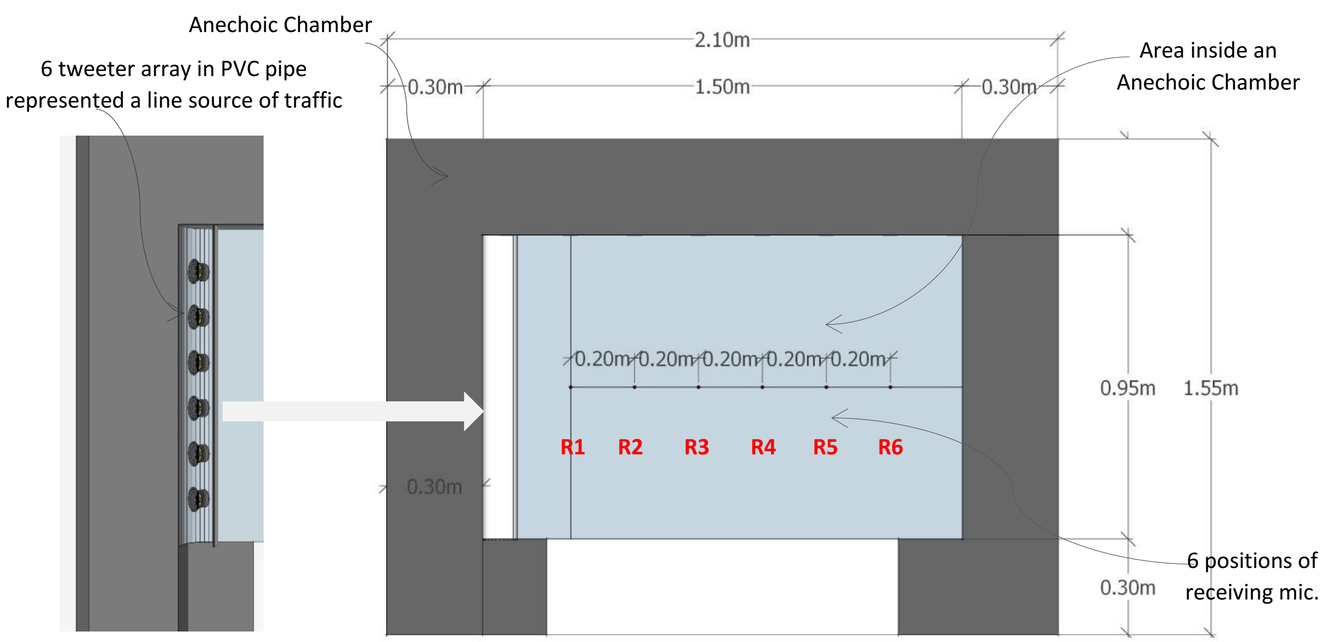
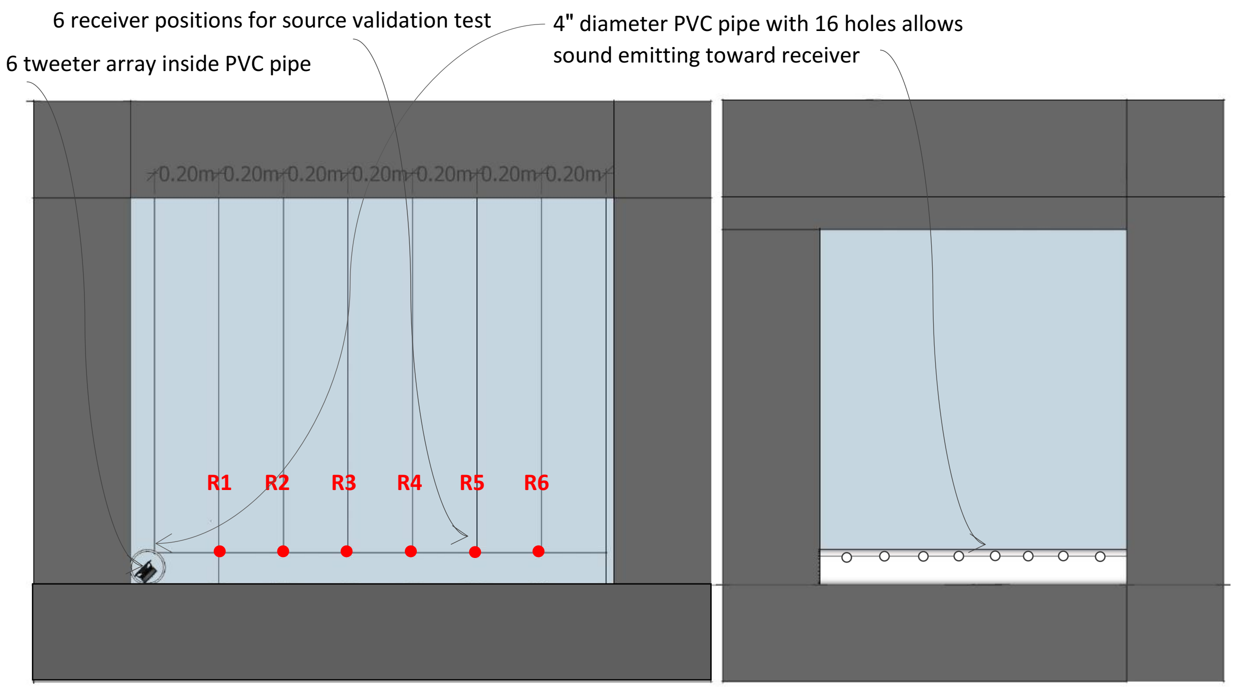


Figure 39: Top view of source modelling experiment set-up in the anechoic chamber.



Figures 40-41: Cross-section views of source modelling experiment set-up in the anechoic chamber.

Figure 42: (a) The tweeters angle set-up inside PCV pipe, (b) Image of cross-section of PVC pipe source, (c) Image of line source experiment set-up in anechoic chamber.

2.1.2 Scale Model Street-to-Roof Configuration Set-up in Anechoic Chamber

A baseline street-to-roof building configuration model on a 1:10 scale was built from the selected materials (Table 2) and yields the same absorption coefficient of real-scale materials. An 18 mm medium-density fibre board and 16 mm acrylic represent the building facade. The street and sidewalk consist of a 1.6 mm metal plate, 20 mm air gap and 18 mm MDF structures, which, in layers, represent asphalt and concrete. A 2 mm acrylic plate was used for wall and guard technologies in the scale model test. It was designed to be placed and removed from the baseline model. The overhang is made of 16 mm acrylic. Finally, the vegetated facade, as well as berm materials, are made of artificial grass, 10 mm polyurethane and 1 mm felt (listed from top to bottom). The construction of a 1:10 scale model is shown in Figures 43 and Figure 44.

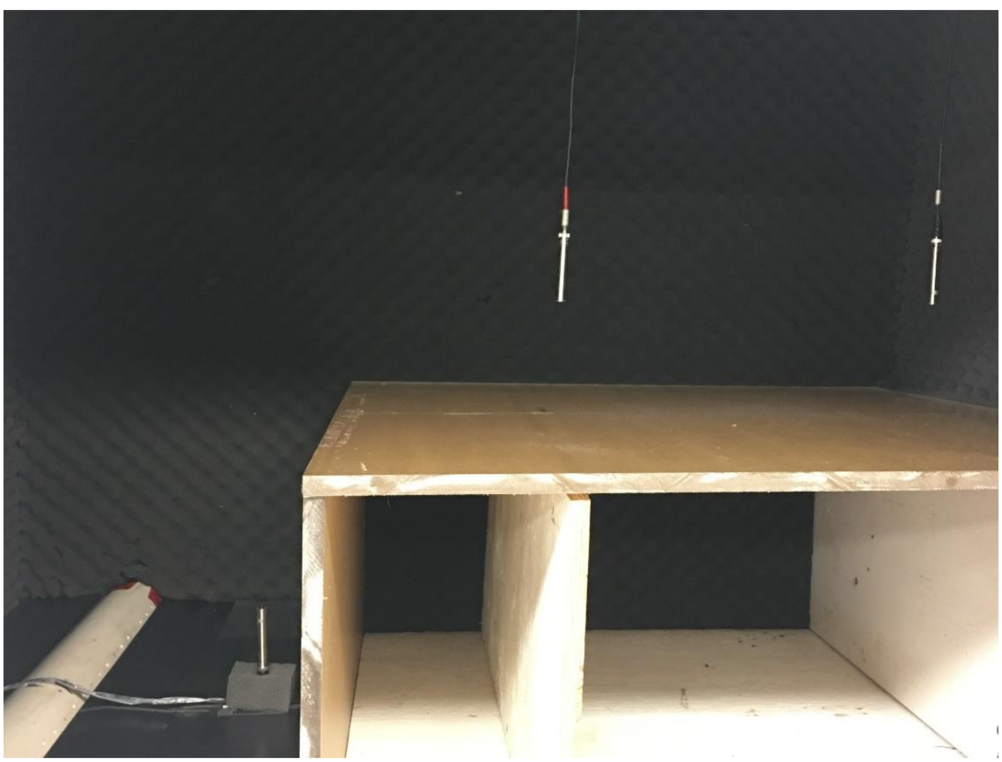


Figure 43: The picture illustrates a 1:10 scale model street-to-roof configuration (Baseline ROOF) and source receiver positions.

To evaluate a 1:10 scale model, three 1/2" precision high-frequency microphones (G.R.A.S. 26CA) were used for the measurement, which represented three receiver positions (one on street level, two on rooftop level). Note that the dimensions given in this section refer to the real scale. The microphone height was set at 1.5 meters above the street, which is considered the height of the basic location of human ears in a standing position, and also set at roof level. The line source simulating a continuous one-lane traffic flow of heavy traffic was at 0.5 m above the street level, considered the best possible representative of the average height of the car and truck engines. In a 1:10 physical scale model, the detailed set-up of a line source is explained in the previous section.

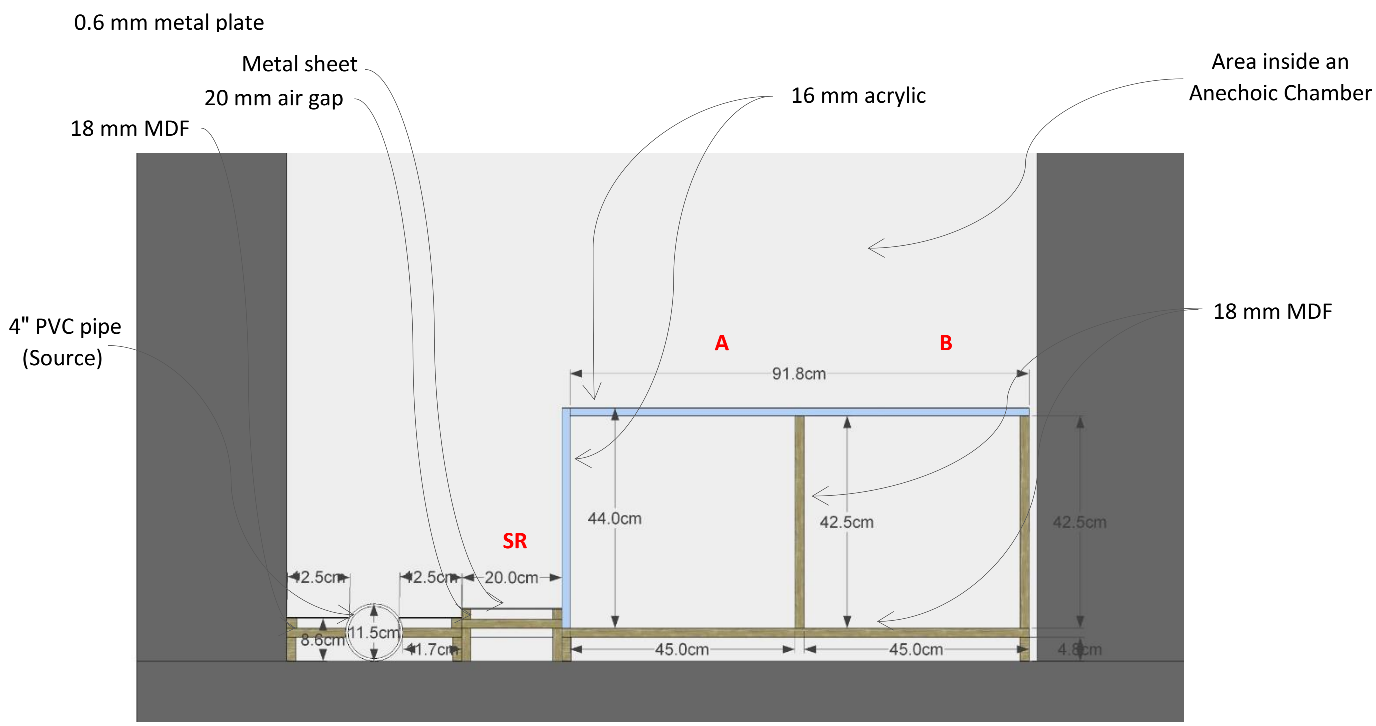


Figure 44: Construction of a 1:10 scale model street-to-roof configuration and Source receiver positions (front elevation).

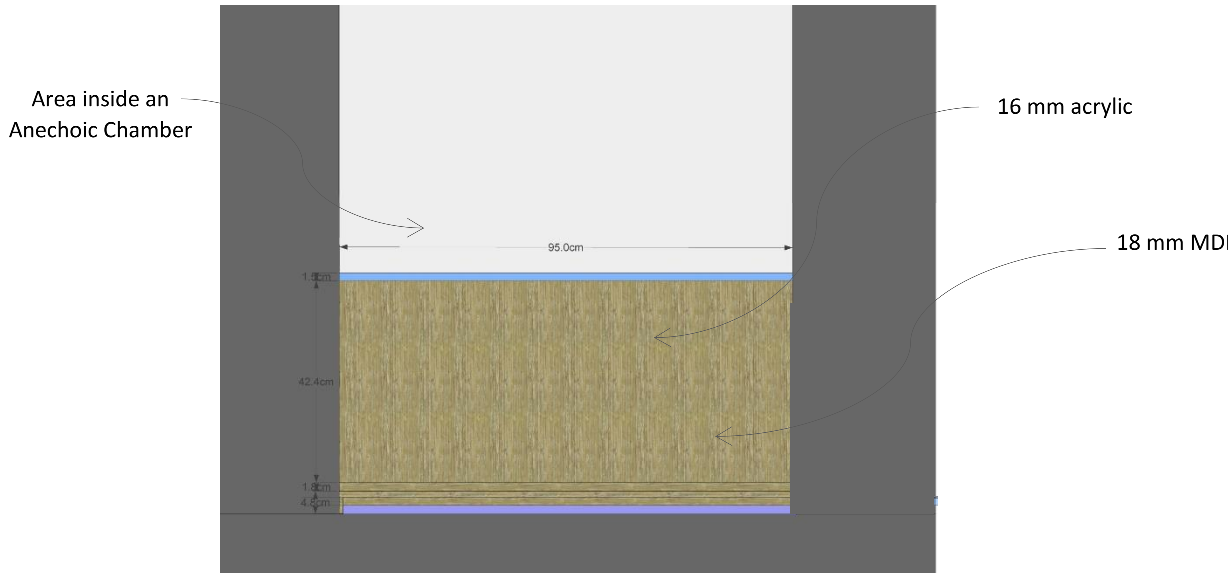


Figure 45: Construction of a 1:10 scale model street-to-roof configuration and Source receiver positions (side elevation).

2.1.3 ODEON Acoustic Simulation Model

ODEON acoustic simulation software provides a good prediction of sound propagation within a context. The building model and its surrounding were built in SketchUp 3D modelling software, and then exported for acoustic simulation in ODEON using a plug-in “SU2Odeon” to export the geometry. An incoherent line source, a set of points source array, was used in ODEON. Noise source and receiver positions were placed in the same positions as in the scale model. The street-to-roof configurations with noise abatement technologies were then modelled to find out the performance of noise mitigation by the design tools on a rooftop in the ODEON acoustic simulation model.

The measured absorption coefficients of the scale model materials were used as the input values of absorption coefficient in ODEON (see Table 2). The scattering coefficient of the model in the simulation was set to 0.05 (default) for all baseline building materials. However, the scattering coefficient of the design tools were varied from 0.05–1.00, considering the shape and the roughness of material of the scale model surface (see suggested scattering coefficients in Table 4, from the ODEON manual). The transparency coefficient of the baseline model materials was set to 0.00, which was the default for the material for a solid wall. However, for the design tool materials, various values of transparency coefficient from 0.00–0.60 were applied with regard to the acoustics of its material transparency. Finally, the type of material setting was mostly set to 'Ext.' (Exterior), providing less diffraction at the lowest frequencies suitable for outdoor sound propagation.

Table 4: Suggested scattering coefficients in the ODEON simulation model (ODEON manual).

Material	Scattering coefficient at mid-frequency
Audience area	0.6–0.7
Rough building structures, 0.3–0.5 m deep	0.4–0.5
Bookshelf, with some books	0.3
Brickwork with open joints	0.1–0.2
Brickwork, filled joints but not plastered	0.05–0.1
Smooth surfaces, general	0.02–0.05
Smooth painted concrete	0.005–0.02

2.1.4 Baseline Roof Configuration and Source Set-up for the ODEON Simulation Model

The measurements were taken in an anechoic chamber using the 1:10 scale model; each measurement was crossed-checked with the ODEON computer model simulation. The attenuation over the distance to all receiver locations from the line source model was determined. The baseline configuration of the scale model and the ODEON simulation model were compared to each other for calibration of ODEON. Twenty-five omni-directional speakers were arrayed as the line source in the ODEON model (see ODEON source set-up model in Figure 47) with an +EQ level adjustment at the array source editor window (see Figure 48). The source model was calibrated to the average SPL of the scaled model at each receiver location, by adjusting the level adjustment of the SPL in the speaker array source.

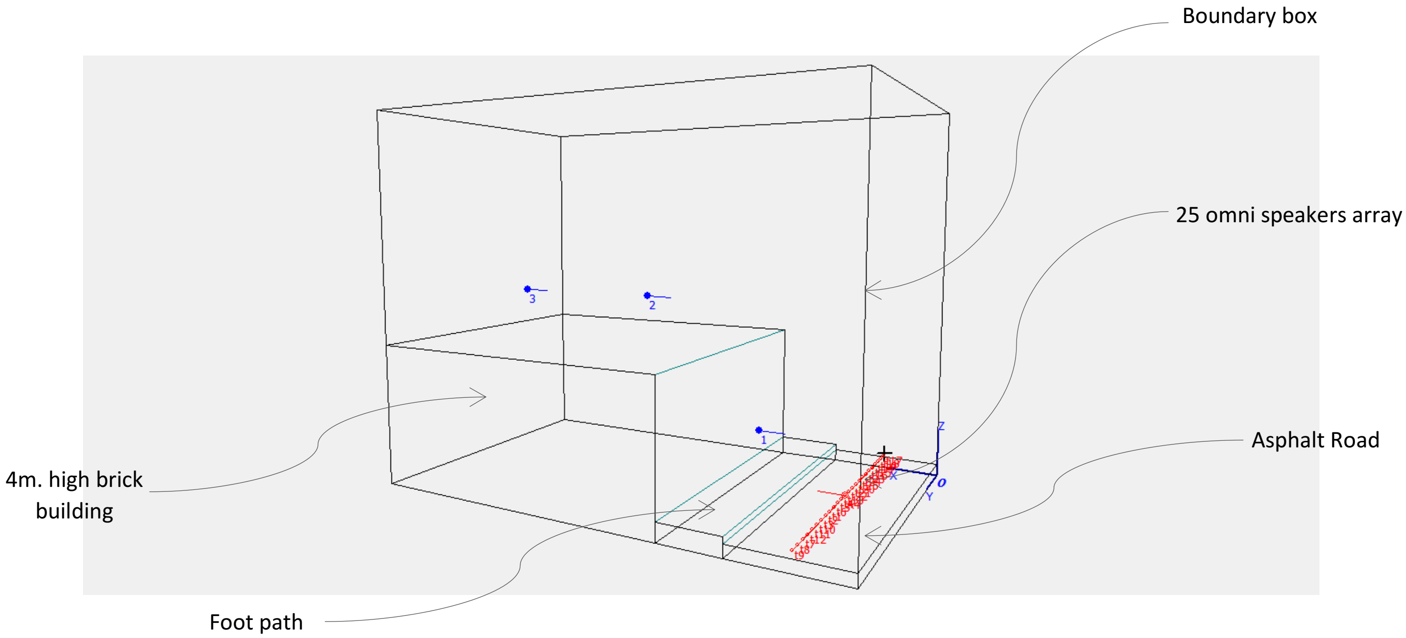
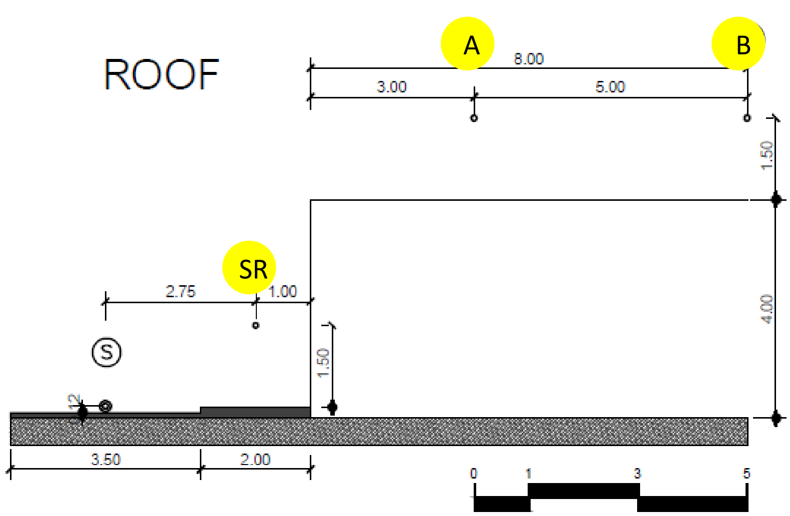


Figure 46: The perspective of the 25 omni-directional speakers array set-up of the baseline ROOF configuration model in ODEON.

(a)



(b)

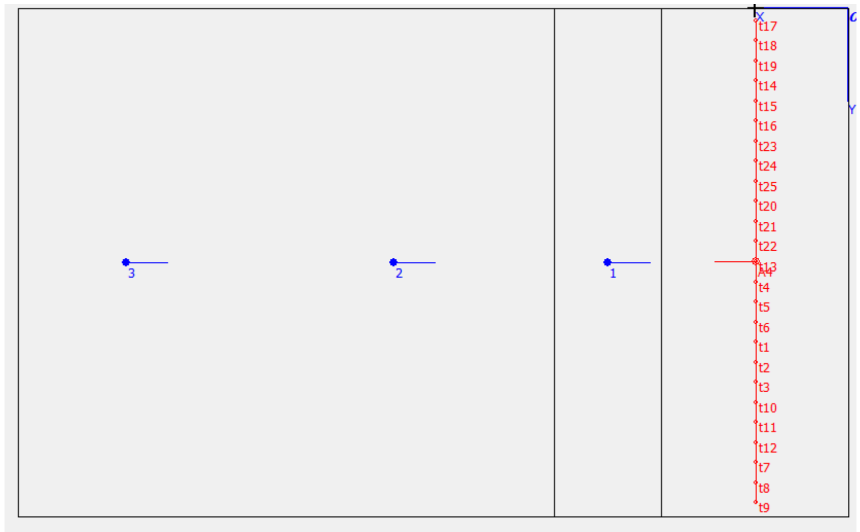


Figure 47: (a) elevation view, (b) plan view of the 25 omni-directional speakers array of the baseline ROOF configuration model in ODEON.

Table 5: Scattering coefficient material lists for the ODEON model baseline ROOF.

NO.	Materials	Scattering Co. (SC)
#91	Boundary box	0.05 (default)
#109	Asphalt (Jang et al, 2014)	0.05 (default)
#1012	Brick facade, unglazed (Jang et al, 2014)	0.05 (default)

Table 6: Material absorption coefficient lists for the ODEON model baseline ROOF.

NO.	Materials	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
#91	Boundary box								
#101	Overhang, Guard, Wall - smooth unpainted concrete (Bobran,1973)	0.01000	0.01000	0.01000	0.02000	0.02000	0.02000	0.05000	0.05000
#109	Asphalt (Jang et al, 2014)	0.05000	0.05000	0.05000	0.05000	0.04000	0.04000	0.05000	0.05000
#1012	Brick facade, unglazed (Jang et al, 2014)	0.03000	0.03000	0.01000	0.03000	0.02000	0.05000	0.07000	0.07000
#15101	Vegetated layer, Berm (Jang et al,2014)								

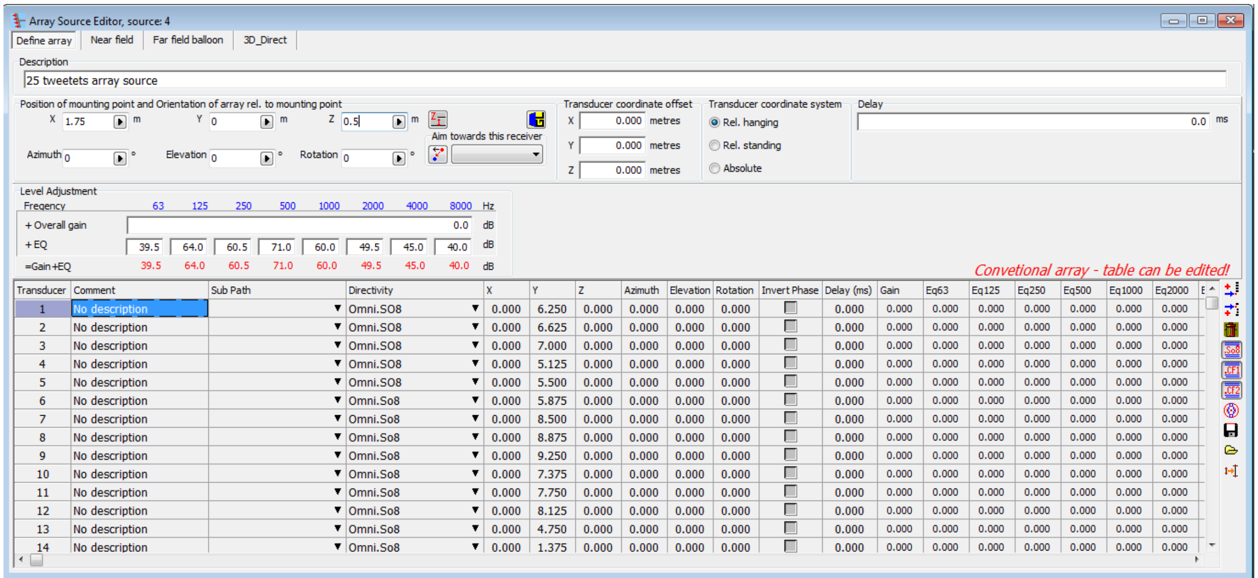


Figure 48: Level adjustment inputs of the line array source in ODEON.

Figures 46 and 47 illustrate an array source set-up and three receiver positions at full scale of the baseline ROOF configuration in the ODEON model. The simulated traffic line source consists of 25 arrayed Omni speakers laid on the center of the asphalt road parallel to the street and the building facade. There were three receiver locations. SR (Source Receiver) was placed 2.75 m away from the source and 1.5 m above the sidewalk level, A (Receiver A) was on the rooftop level 3 m away from the building edge and 1.5 m above the roof, and B (Receiver B) was 8 m away from the building edge and 1.5 m above the roof. The three receiver locations represented the height of human ears in the human standing position. The one-lane street configuration in this test was 3.5 m wide and the sidewalk was 2 m wide. In the test simulation, it is assumed that the street length and building area are an infinite length. The boundary box covered the whole building configuration and the absorption coefficient was set to almost 100% absorption, representing outdoor sound propagation in the real atmosphere (see Table 6, Material absorption coefficient lists for the ODEON model baseline ROOF).

2.2 Design Tool Investigations

The design tool technologies selected for the research investigation are an overhang (OH), green roof (GR), earth berm (B), guard barriers (G) and walls (W), where the guards and walls are solid or have a living wall on one or both sides of the rigid surface. Thirty-three configuration design tools were investigated and evaluated in a simple street-to-roof configuration (ROOF) as shown in Figure 49, for both the scale model and ODEON model. Two receivers (Receivers A and B) were placed at the roof level and one receiver (SR) was on the street level. The traffic noise attenuation from the Source Receiver (SR) to Receivers A and B in the ROOF configuration that is associated with those design tools was compared to the attenuation of a baseline rooftop (ROOF) case to determine the design tool performance.

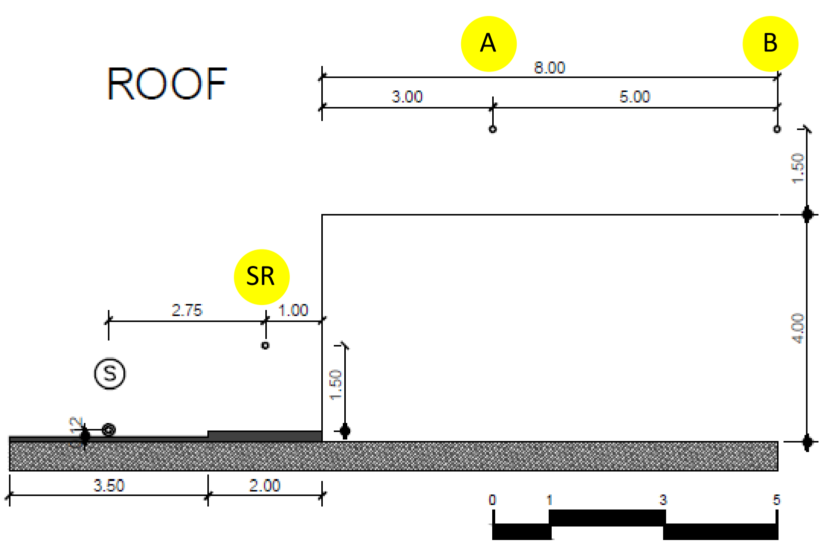


Figure 49: A baseline street-to-roof configuration.

Thirty-three configurations of design tools were constructed and physically measured in the anechoic chamber using the 1:10 scale model, and the same set of configurations was analyzed in the ODEON acoustic simulation software. Each configuration had the same building materials, street structure and acoustic properties matched between the 1:10 scale model tested in the AC and in ODEON. The 1:10 scale model building and design tool materials, such as building facade, substrate layers, and vegetation layers, were selected based on literature. The building design tool input material parameters in ODEON (Table 7) were described differently, owing to the limit of the software calculation.

The 1:10 scale model of the street-to-roof configuration tested in the anechoic chamber consisted of a one-lane asphalt road, 2-m wide asphalt sidewalk, one-storey unglazed brick building and various types of design tools, which can be interchanged on the ROOF model. The design tool materials which were used for the 1:10 design tool models are listed below:

- Earth berm (B); artificial glass, 50 mm high polyurethane (PU) as a berm substrate
- Green roof (GR); artificial glass, 10 mm polyurethane (PU)
- Overhang (OH); 16 mm acrylic sheet
- Guard barrier (G), and Wall (W); 4 mm acrylic sheet

Figure 50 below shows a matrix of 11 single-design tool configurations

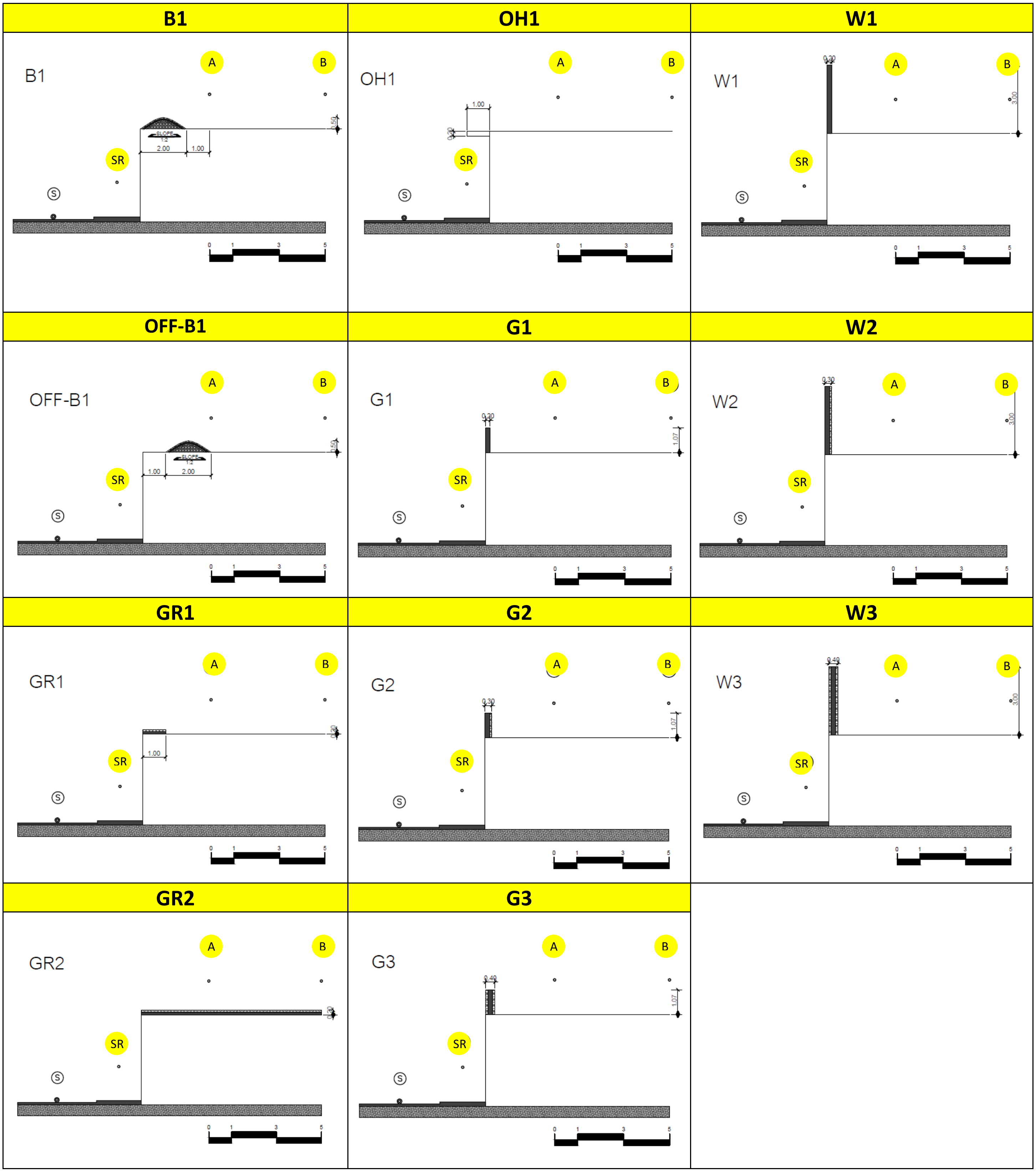


Figure 50: Single-design tool configurations.

Three off-set guard configurations, four double- and four triple-design tool configurations.

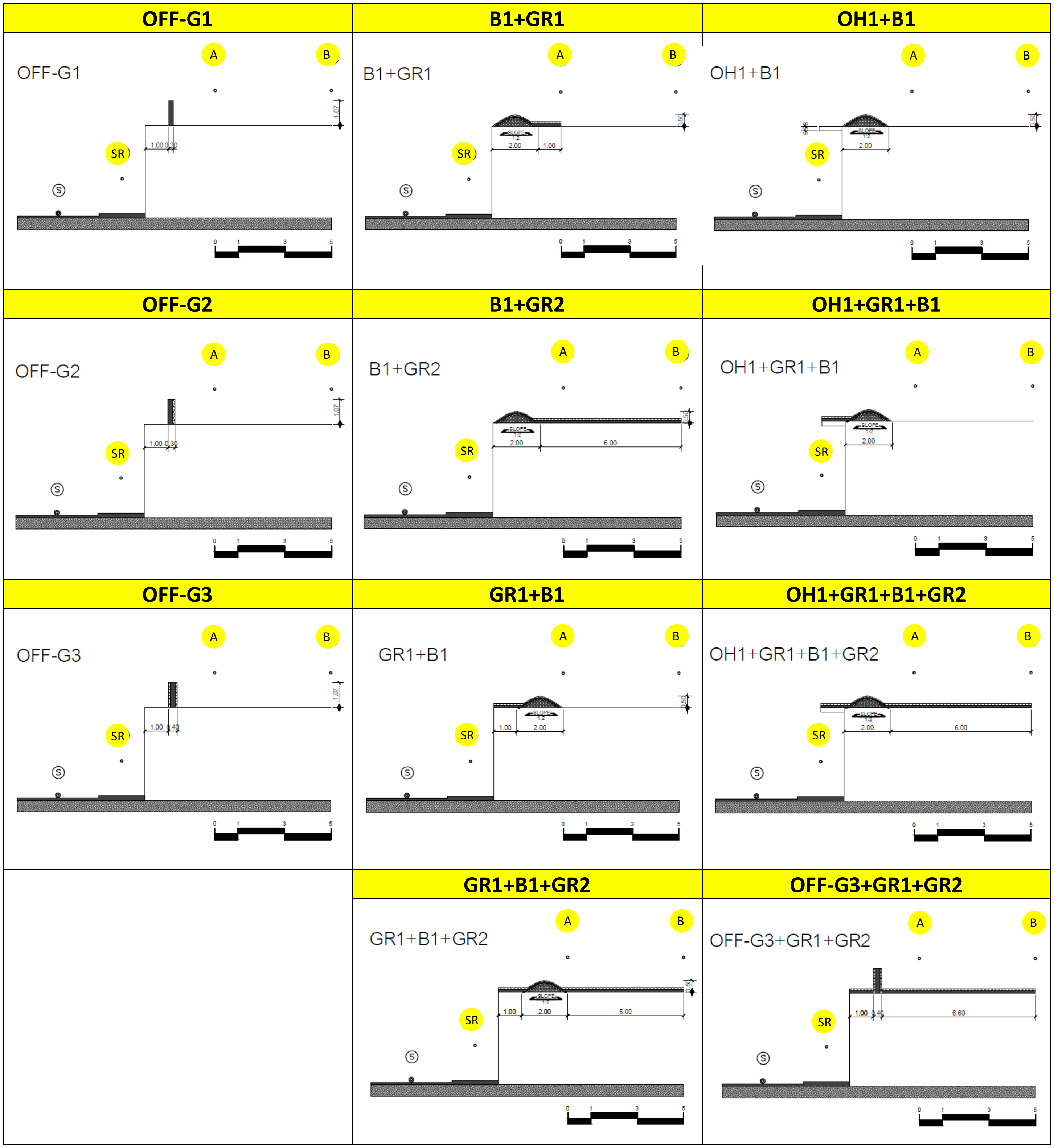


Figure 51: Off-set guard configurations, double- and triple-design tool configurations.

The complex configuration, which is the combination of three or more design tools.

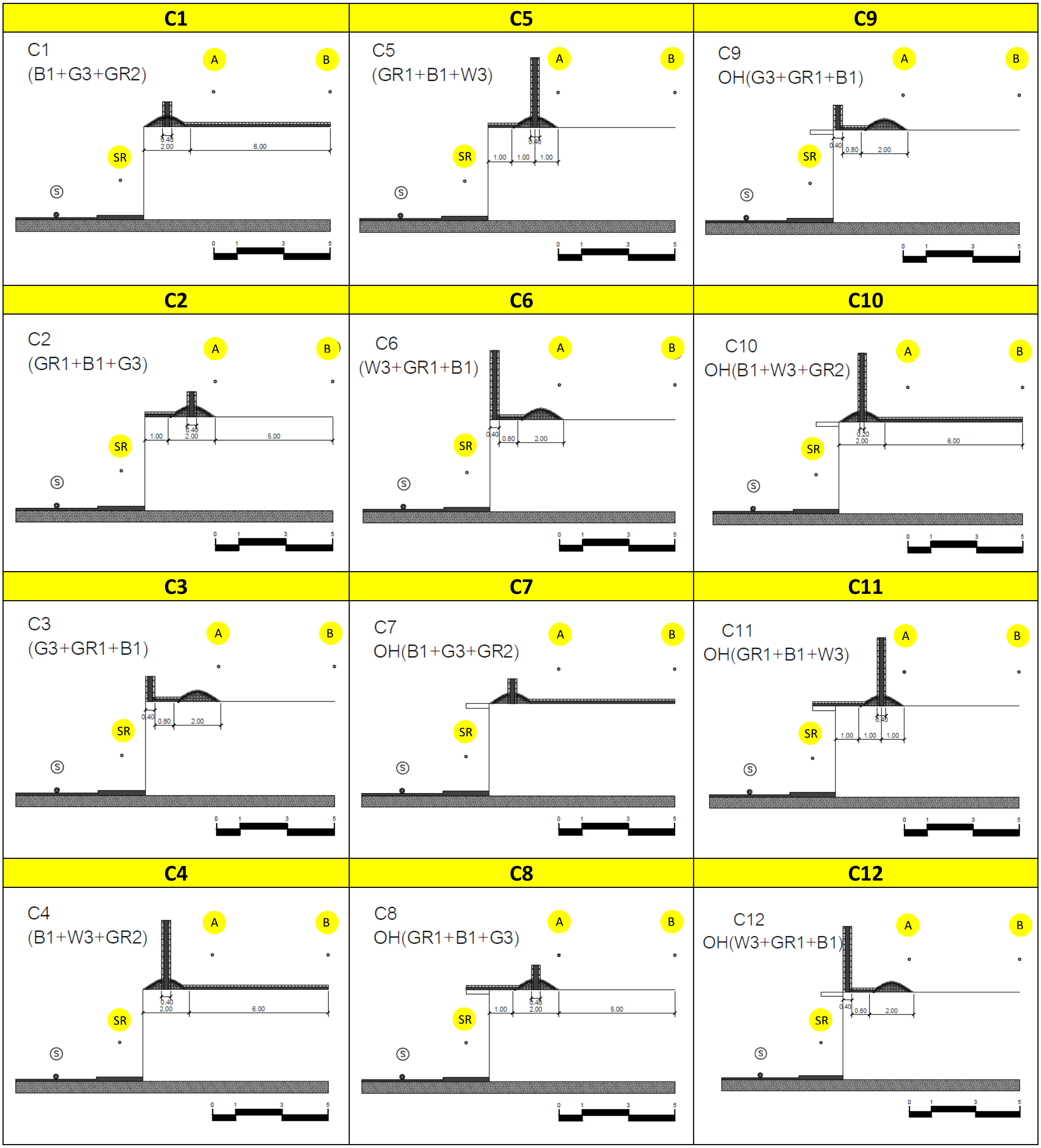


Figure 52: Complex configurations.

2.2.1 Design Tools Manufactured for the 1:10 Scale Model Test in the Anechoic Chamber

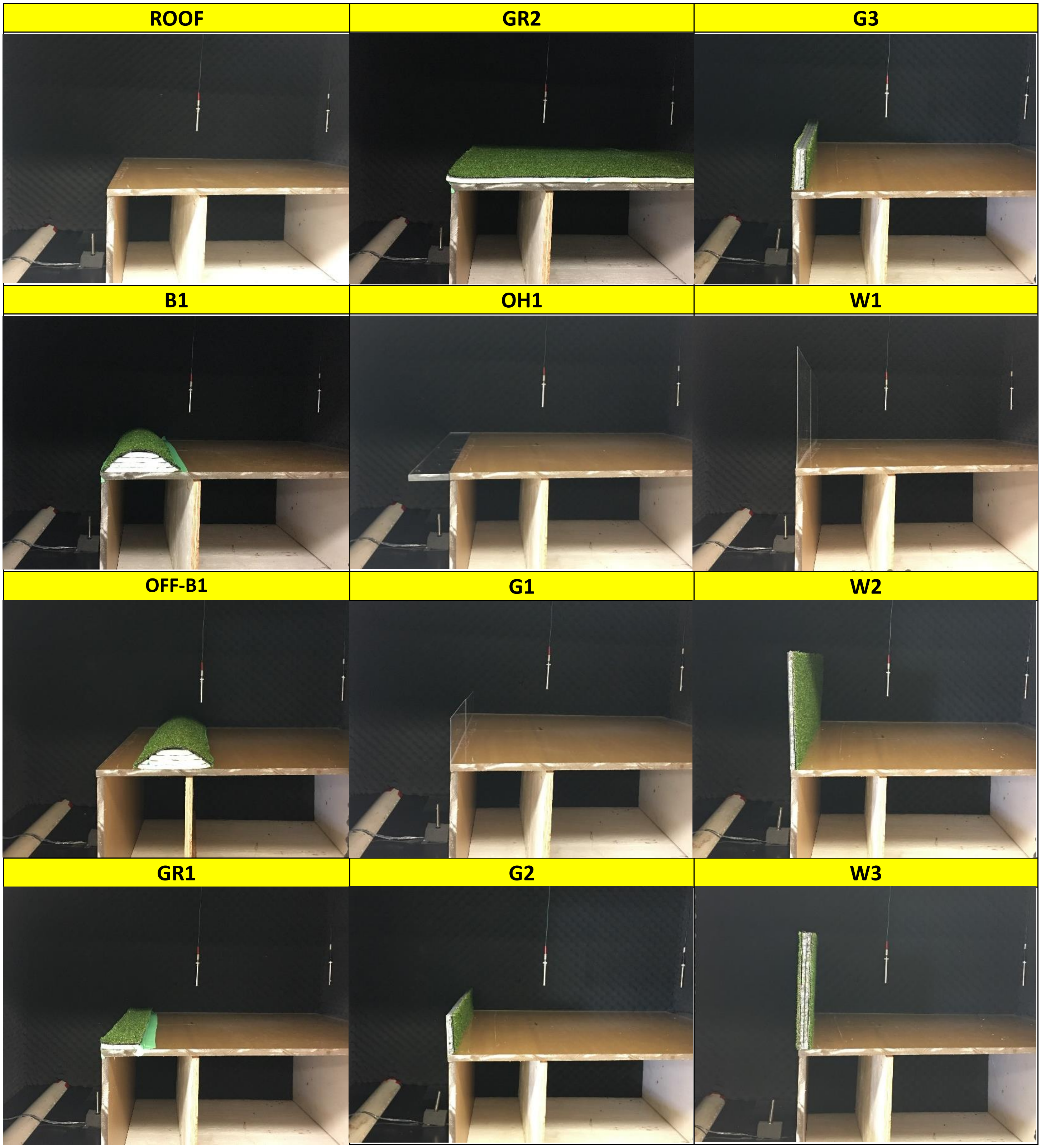


Figure 53: ROOF and single-design tool configurations for the 1:10 scale model tested in the anechoic chamber.

2.2.2 Design Tool Parameters Set-up for the ODEON Simulation Model

The design tool material parameters for the 35 permutations for ODEON are listed below.

Table 7: ODEON material parameter inputs for all design tool materials.

	ROOF	B1	OFF-B1	GR1	GR2	OH1	G1	G2 _G3		W1	W2		W3	
								G	V		G	V	G	V
α	1012	15101	15101	15101	15101	101	101	101	15101	101	101	15101	101	15101
SC	0.05	0.9	0.9	1.0	1.0	0.5	0.05	0.05	1.0	0.05	0.05	1.0	0.05	1.0
TC	0.0	0.1	0.1	0.1	0.5	0.1	0.3	0.3	0.5	0.3	0.3	0.5	0.3	0.5
TP	norm.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.
*SC	0.05	0.3	1.0	0.15	0.015	0.3	0.05	0.05		1.0	0.05		1.0	

	B1+GR1	B1+GR2	GR1+B1	OH1+B1		OH1+GR1+B1		OH1+GR1+B1+GR2		OFF-G1	OFF-G2_OFF-G3		OFF-G3+GR1+GR2	
				OH	B	OH	V	OH	V		G	V	G	V
α	15101	15101	15101	101	15101	101		101	15101	101	101	15101	101	15101
SC	1.0	1.0	1	0.5	1.0	0.5		0.5	1.0	0.05	0.05	1.0	0.05	1.0
TC	0.1	0.1	0.1	0.1	0.1	0.1		0.1	0.1	0.3	0.3	0.5	0.3	0.5
TP	ext.	ext.	ext.	ext	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.
*SC	0.3	1.0	0.05	0.5		0.05		1.0		1.0	0.05		0.3	

	C1		C2		C3 _ C4		C5		C6		C7		
	G	V	G	V	G	V	G	V	G	V	G	V	OH
α	101	15101	101	15101	101	15101	101	15101	101	15101	101	15101	101
SC	0.05	1.0	0.05	1.0	0.05	1.0	0.05	1.0	0.05	1.0	0.05	1.0	0.5
TC	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5	0.1
TP	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.
*SC	0.5		0.05		1.0		0.5		0.9		0.4		

	C8			C9			C10			C11			C12		
	G	V	OH	G	V	OH	G	V	OH	G	V	OH	G	V	OH
α	101	15101	101	101	15101	101	101	15101	101	101	15101	101	101	15101	101
SC	0.05	1.0	0.5	0.05	1.0	0.5	0.05	0.8	0.05	0.05	1.0	0.5	0.05	0.8	0.5
TC	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.8	0	0.3	0.5	0.1	0.3	0.6	0.1
TP	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.	ext.
*SC	1.0			0.5			1.0			1.0			1.0		

α Absorption coefficient

SC Scattering coefficient

TC Transparency coefficient

TP Type; Normal Exterior Fractional Transmission

Table 8: Material absorption coefficient lists for the ODEON model design tool materials.

#91	Boundary box							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	0.90000	0.95000	0.90000	0.85000	1.00000	0.95000	0.97500	0.97500
#101	Overhang, Guard, Wall - smooth unpainted concrete (Bobran,1973)							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	0.01000	0.01000	0.01000	0.02000	0.02000	0.02000	0.05000	0.05000
#109	Asphalt (Jang et al, 2014)							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	0.05000	0.05000	0.05000	0.05000	0.04000	0.04000	0.05000	0.05000
#1012	Brick facade, unglazed (Jang et al, 2014)							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	0.03000	0.03000	0.01000	0.03000	0.02000	0.05000	0.07000	0.07000
#15101	Vegetated layer, Berm (Jang et al,2014)							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
	0.65000	0.65000	0.70000	0.73000	0.68000	0.63000	0.75000	0.70000

The ODEON absorption coefficient inputs of all materials was created based on a full-scale material measured in a previous study (Yang et al., 2013). The coefficient was correlated with the 1:10 scale model materials tested in AC within a 0.09 dB deviation at all frequency bands. The scattering coefficient of all materials was selected based on the roughness of the surface materials and on a guide to scattering coefficients in the ODEON manual. The values between 0 and 1 are the values for the size of diffuse scattering of its surface. A small number of scattering coefficients show a small area of diffused vectors after surface reflection, while a large number, such as a 0.8, show large area of diffused vectors (see Table 7).

The transparency coefficient is another input value for the ODEON material parameters. A zero value is assigned to a solid wall, assuming that no sound energy goes through that solid surface, or that 100% of the energy is neither reflected nor absorbed by the material. The ODEON manual suggests that 0.95 transparency coefficient (TC) shouldn't apply to any surfaces. The material name "0" should be assigned for a total transparency surface like an open window. Finally, types (TP), which refers to the type of surface-based calculation for the scattering method, were assigned to have a "normal" or "exterior" meaning for surface properties in terms of surface scattering. If "normal" is selected, a reflection-based scattering method is used for the surface scattering calculation. In this research, which deals with the outdoor sound propagation in a street canyon, the type (TP) mostly selected for the scattering calculation was "exterior," for deriving the results that have less diffraction applied at a low-frequency range for the outdoor surface calculation.

2.3 Rooftop Design Program

2.3.1 East Hastings Building Configuration and Source Set-up in ODEON Software

The E. Hastings Street rooftop site was selected for investigation in part because the selection of test measurements were available and there is a high exposure to traffic noise. Given the form of building and rooftop, the street noise level was affecting the viability of rooftop use. The purpose was then to analyze the area of use, based on the outcomes of the rooftop measurements after installing the best sound attenuation technologies.

The E. Hastings Street rooftop site was modelled with ODEON computer simulation software to predict an application of the design tools to maximize a rooftop zone equal to or less than 55 dBA. These acoustic design tools were tested in the real-world acoustic environment of a busy urban street. A mapping of background road traffic noise at E. Hastings Street (Figure 54) by Connelly (2011) was used in the set-up of the street traffic noise source in the ODEON model. The 3D site geometry was built in SketchUp software and transferred to ODEON to run a prediction. All materials assigned in ODEON used absorption and scattering coefficients of actual building materials. Table 8 lists the absorption coefficients of the site-model materials.

An area of 5 x 5 m^2, 1.5 m above the road surface, was selected for calculation of grid response results for source set-up in ODEON. The 1.5 m height represents the normal height of a standing human. The visualized colored-grid response result in the ODEON simulation software shows the result just at the individual octave frequency band, such as at 500 Hz. However, from the ASCII output under “Options” on the main toolbar in ODEON, the results can be exported and opened in MS Excel, where the SUM dBA at each grid can be retrieved.

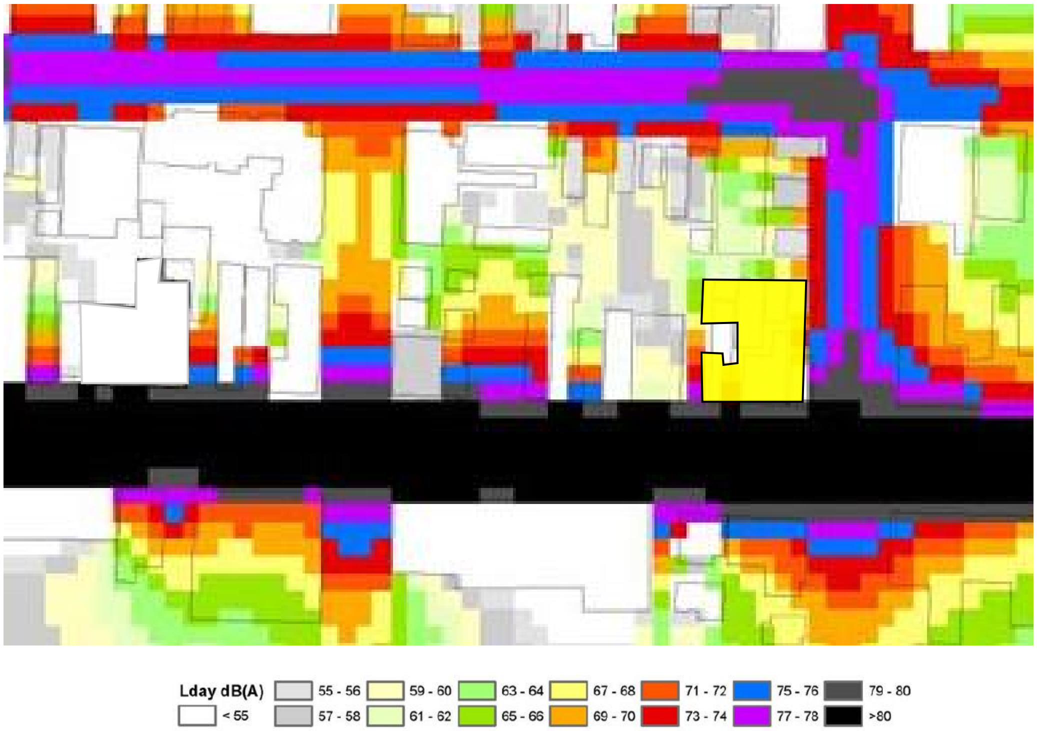


Figure 54: Road traffic noise level at the site location. (Connelly, M., 2011)

Table 8: Absorption coefficients of the materials used in the E. Hastings site ODEON model.

Materials List	Absorption Coefficients by frequency band (Hz)					
	125	250	500	1K	2K	4K	Avg
Asphalt (Jang et al., 2014)	**0.05**	**0.05**	**0.05**	**0.04**	**0.04**	**0.05**	**0.05**
Heavy glass (for Guard and Wall)	**0.21**	**0.09**	**0.05**	**0.04**	**0.06**	**0.04**	**0.08**
Brick facade, unglazed (Jang et al., 2014)	**0.03**	**0.01**	**0.03**	**0.02**	**0.05**	**0.07**	**0.04**
Green roof and berm (Connelly, M., 2011)	**0.31**	**0.31**	**0.5**	**0.61**	**0.7**	**0.67**	**0.52**
Vegetated facade (Akbarnejad, 2017)	**0.27**	**0.27**	**0.35**	**0.37**	**0.41**	**0.91**	**0.43**
Boundary box	**0.95**	**0.9**	**0.85**	**1.0**	**0.95**	**0.975**	**0.94**

In the ODEON model, unglazed brick is the material for the building wall assembly, and it is also used for the overhang material as part of the building structure. Heavy glass represents the guard and wall design tool technologies. Asphalt is selected for the street and sidewalk material. For the boundary box, the former absorption coefficients identified in the firat part of this studywere used for the ODEON materials set-up parameters. However, the values for the real absorption coefficients of the green roof, berm and vegetated facade were updated using the past research data and applied to the ODEON materials list. For the green roof and berm absorption coefficients, the *in-situ* test data of the sedum plant on substrate depth were selected. The substrate depth varied from 125–200 mm after two seasons of establishment (Connelly, M., 2011). A 100% coverage of the Golden Pothos living wall with 100 mm substrate (Akbarnejad, 2017) was selected for the vegetated facade absorption coefficient.

The boundary area modeled in the ODEON is in a square-shaped box of 85 m x 76 m x 50 m. The boundary box encloses the building configuration, the neighbouring buildings and the traffic lanes of E. Hastings St. and Heatley Ave. The traffic noise from the street north of the building was ignored in the simulation, because the density of the traffic is light and the traffic noise exposure level is considered low. Moreover, the trees on the sidewalk and wind effect are not counted in the measurement. The selected E. Hastings site has a rooftop area of 928 square meters, with a total building edge length of 155 meters. Figures 55 and 56 illustrate the SketchUp model of the East Hastings rooftop site.

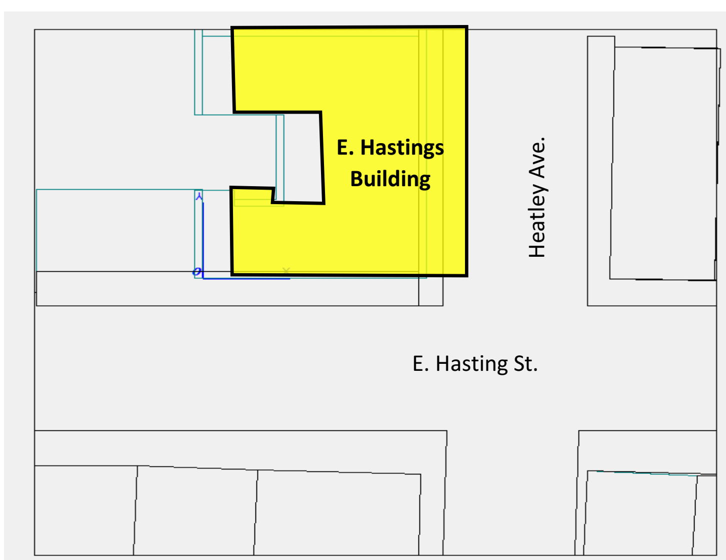


Figure 55: Plan view of E. Hastings building configuration model in ODEON.

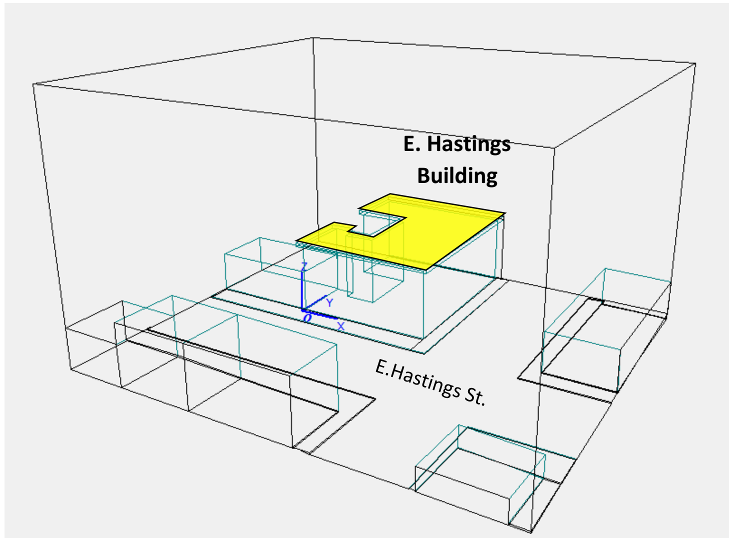


Figure 56: Perspective view of E. Hastings building configuration model in ODEON.

For the traffic source set-up, an array of Omni speakers was placed representing one lane of traffic. Six line-source omni arrays were placed on six lanes of E. Hastings Street and four line-source arrays were placed on Heatley Ave. The distance between each Omni speaker was 75 cm and the height above the road surface was 30 cm, which represents the noise from car and truck engines. Figure 57 illustrates the traffic source in plan view.

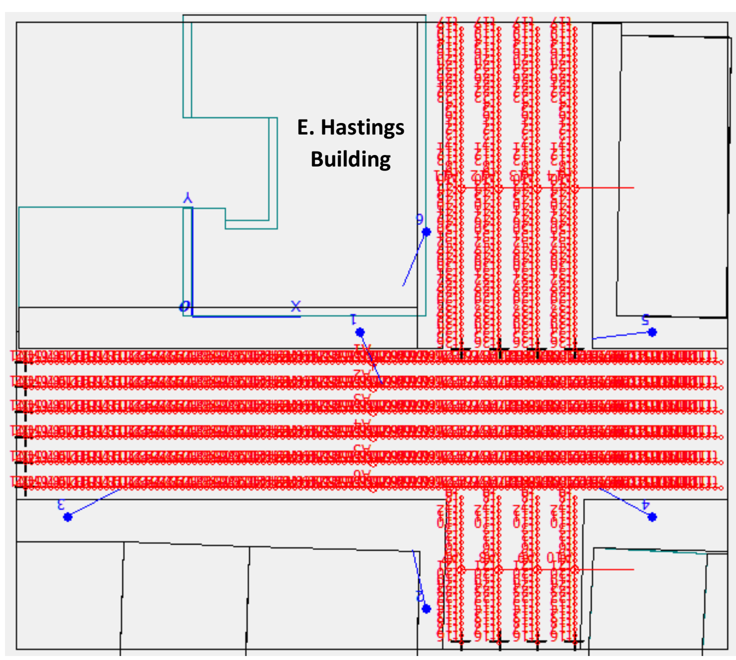


Figure 57: Omni array source set-up of E. Hastings configuration in the ODEON model.

2.3.2 Design Tools Selected for E. Hastings Rooftop Investigation

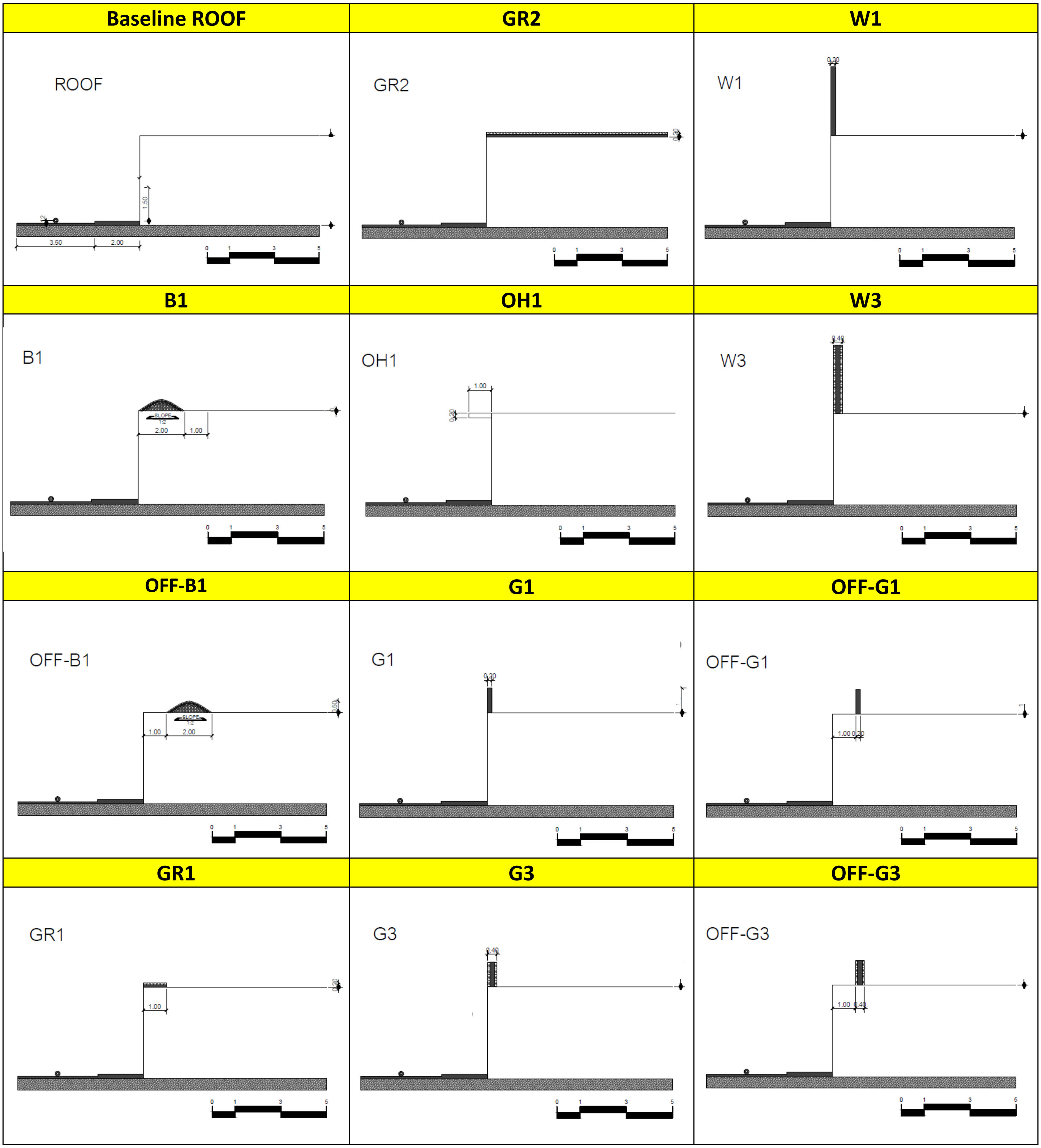


Figure 58: E. Hastings St. ROOF with single-design tool configurations.

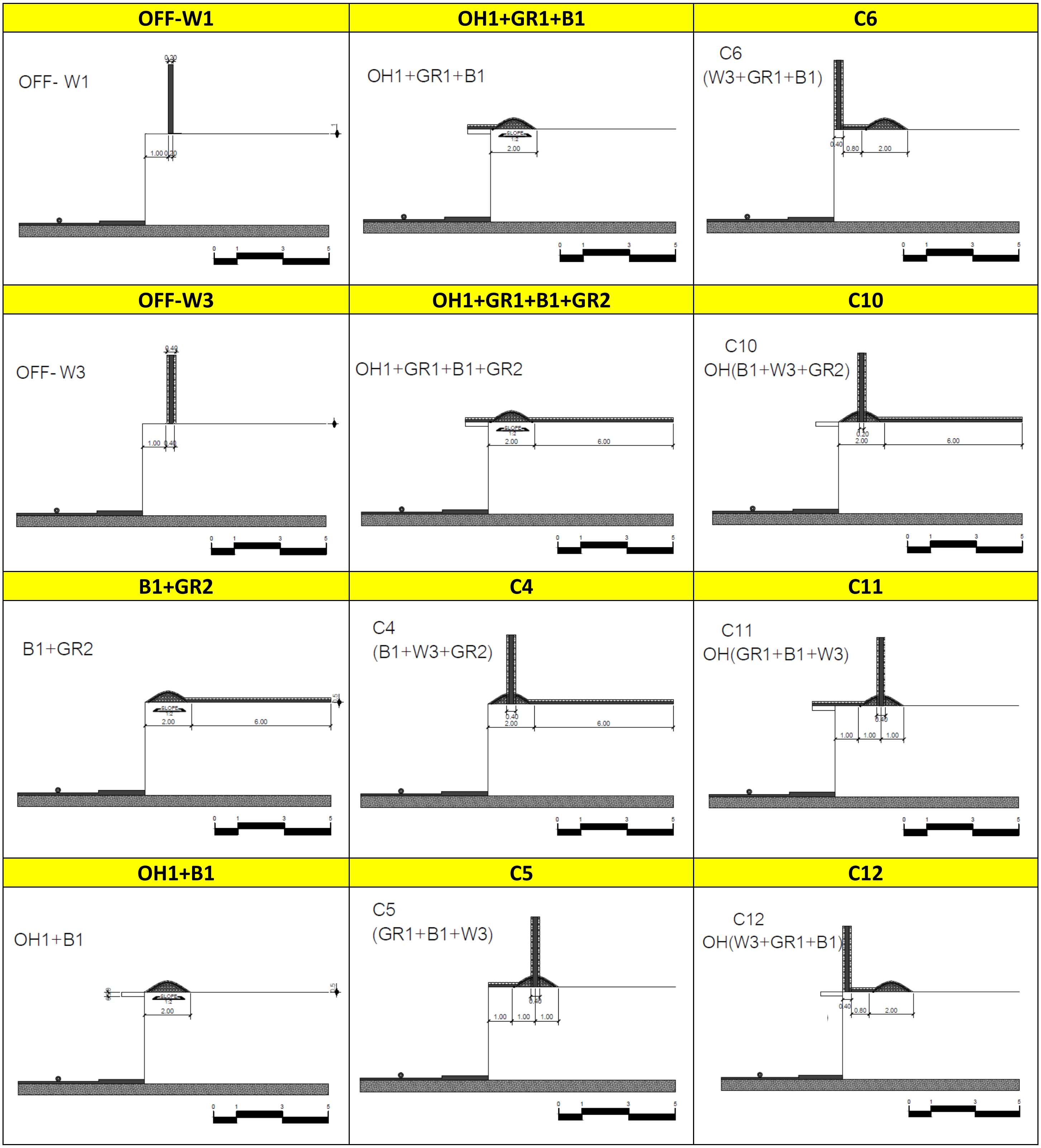


Figure 59: E. Hastings St. ROOF with double- and complex-design tool configurations.

Applying design tool technologies to a real site on E. Hastings Street is the final achievement for developing the design application of this research. After the 23 selected design tools had been applied and tested on a selected site (E. Hastings site), the calculation by ODEON acoustic simulation software was carried out to deliver a predicting SPL (dBA) at 1.5 m above the selected rooftop plane. Figures 58 and 59 illustrate the configurations evaluated, the total of 23 selected design tools, and the baseline ROOF model.

The grid response calculation function in the ODEON software provides a comprehensive view of the sound pressure level for the whole area of the roof, which can then be analyzed in terms of sonic subzones. The grid response calculation on a 2.5 x 2.5 meter grid was calculated to obtain an SPL grid. The design tools to be used on the E. Hastings site were selected based on their performance with an increase in noise attenuation. Thirteen single-design tool, two double-design tool, two triple-design tool and six complex-design tool configurations were selected for investigating on-site. The goal in evaluating a rooftop acoustic environment and creating an acoustic subzone for a site design program is to create an outdoor living space that meets the WHO criterion for an SPL less than 55 dBA.

CHAPTER 3

RESULTS AND ANALYSIS

3.1 Line Source 1:10 Scale Model in the Anechoic Chamber

The successful model that gave results closest to the real traffic source properties was the 5th set-up: 6 tweeters in 4" PVC pipe with the pink noise spectrum input, as determined in the Methodology chapter. The results obtained from developing a model of a line source on a 1:10 scale in the anechoic chamber represented propagation of one lane of traffic noise in a free field. All sound pressure level measurements were evaluated in the one third octave band from 630–20K Hz and then converted back to the real-world scale from 63–2K Hz. The measured noise spectra at six receiver positions (20–120 cm) of the test signal emitted from a pipe source showed the reasonable agreement of 3 dB attenuation and 6 dB attenuation per doubling of the distance. This indicates that sounds from the pipe source could represent the characteristic of traffic noise to be used in a scale model street-to-roof configuration.

Table 9: Noise level at different receiver positions from the line-source scale model measured in the anechoic chamber.

(Hz)	63	80	125	200	250	315	400	500	630	800	1000	1250	1600	2000	Receiver @ (cm)
Sound Pressure Level (dB)	35	45	58	79	71	74	63	60	59	57	58	45	42	34	20
	31	41	60	74	69	70	61	58	57	52	53	42	40	30	40
	32	37	56	75	64	66	57	59	53	49	48	38	36	26	60
	31	35	55	70	65	62	55	57	53	48	48	37	35	26	80
	30	36	52	71	64	61	55	57	50	48	47	36	33	22	100
	27	34	51	70	63	59	54	55	52	48	46	32	28	21	120

Table 9 lists the spectra of the pipe source noise signal measured in the one-third octave wide band at the six different receiver locations from the source, and the measured ambient noise level inside the anechoic chamber. Figure 60 shows the noise spectra at the 60 cm receiver and normalized at 1K Hz, mapped with the traffic noise spectrum from ISO717–1 and different research studies. In Figure 60, the measured SPL of noise from the tweeter-pipe source was plotted within the frequency boundaries of Berglund's study, except for the frequencies below 100 Hz, beyond 2K Hz and at 200 Hz. The trend line of this model line source is similar to the trend line of Tang's study (2005).

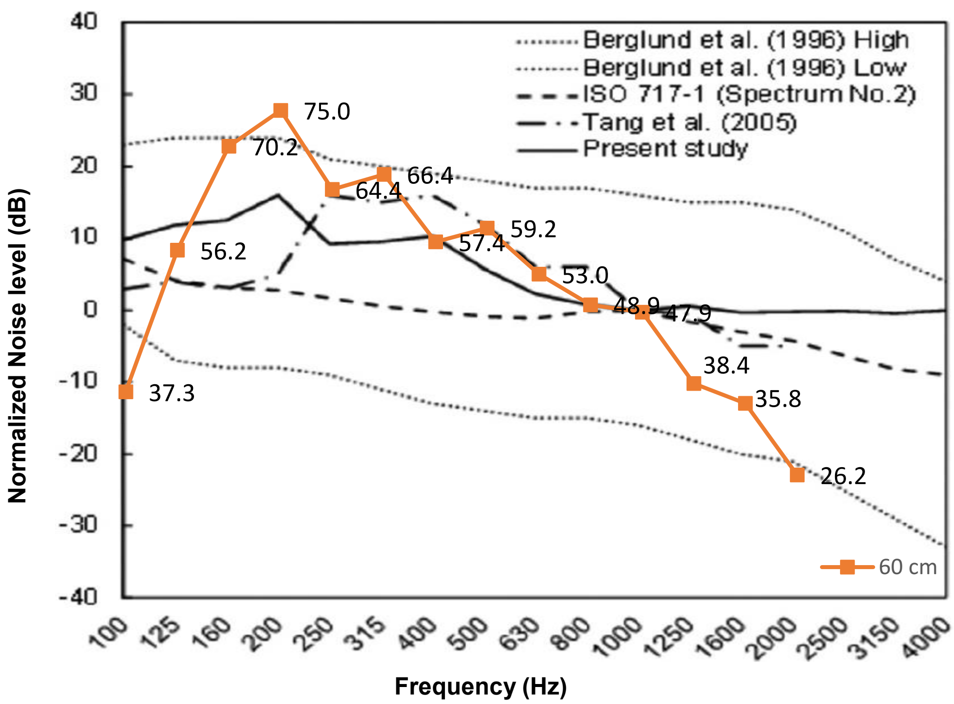


Figure 60: Noise spectra of the source model measured at 60 cm away from the source compared to the traffic spectrums in other studies.

The comparison of the line source model sound pressure level at the six receiver positions as a function of the distance from source, and the reference lines of 3 dB and 6 dB attenuation are plotted in graphs (Figures 61 and 62). They illustrate the alignment of attenuation over the distance, at frequencies from 63–2K Hz between the model and the theory. Most of the attenuation shows 3 dB attenuation over doubling the distance, except in the high frequency range, where the attenuation is closer to 6 dB over doubling the distance.

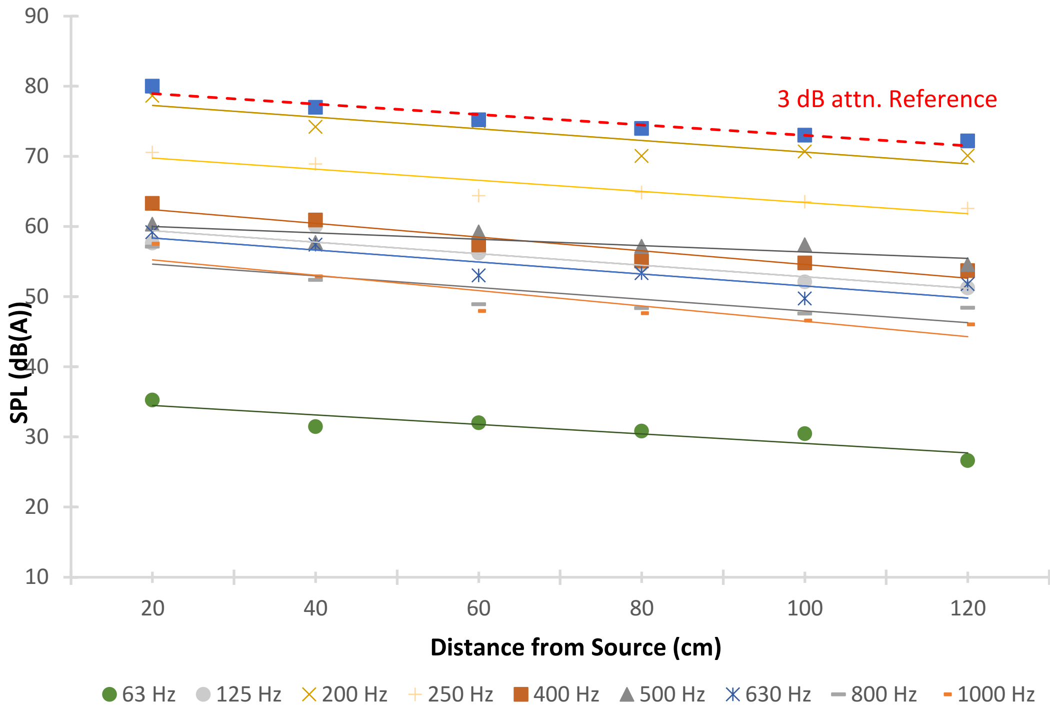


Figure 61: SPL as a function of distance from the source in the frequency range that shows 3 dB attn. per doubling the distance.

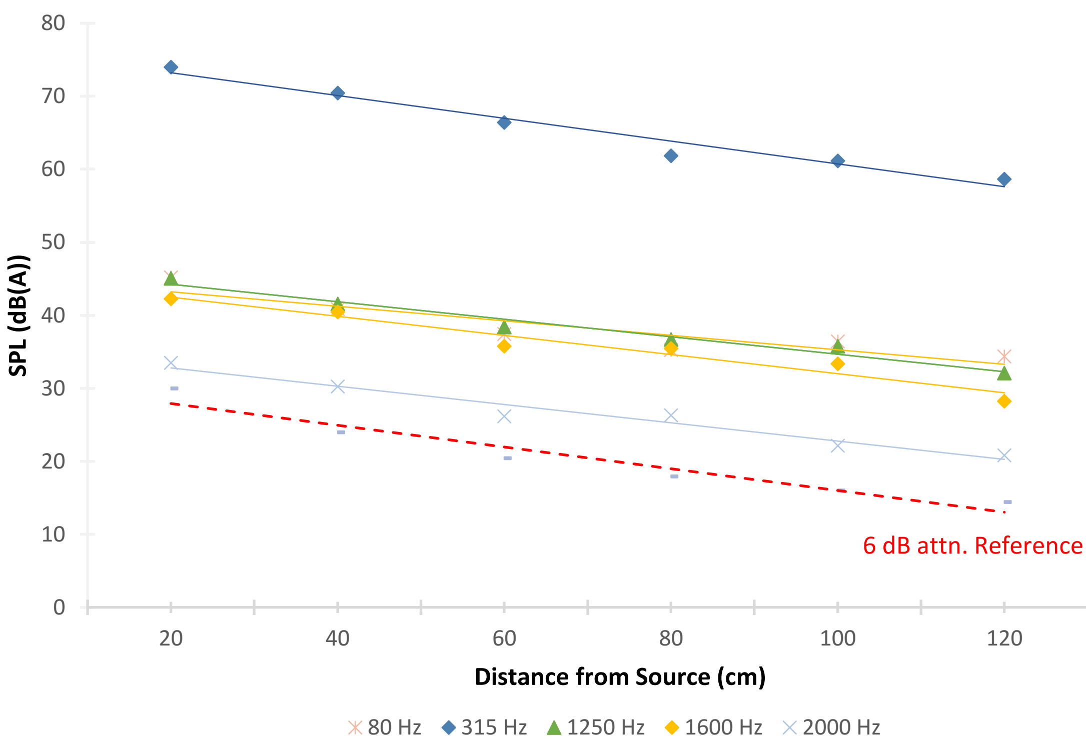


Figure 62: SPL as a function of distance from the source in the frequency range that shows 6 dB attn. per doubling the distance.

3.1.1 Baseline ROOF Model in 1:10 Scale Model and ODEON Simulation Model

A model of a one-lane street-to-roof configuration was constructed on a 1:10 scale and similarly constructed in an ODEON simulation model (shown in Figure 63), to study the noise propagation to the rooftop space. The results obtained using the ODEON calibrated simulation model and scale model were compared. Comparisons of the sound spectrum at three receiver positions are graphed and shown in Figure 64. The ODEON results at the street receiver had been normalized to the results of the 1:10 scale model, since physical measurement should be more reliable. Consequently, the Source Receiver (SR) spectrum results from both the AC and ODEON tests show the same line-trend at all band frequencies.

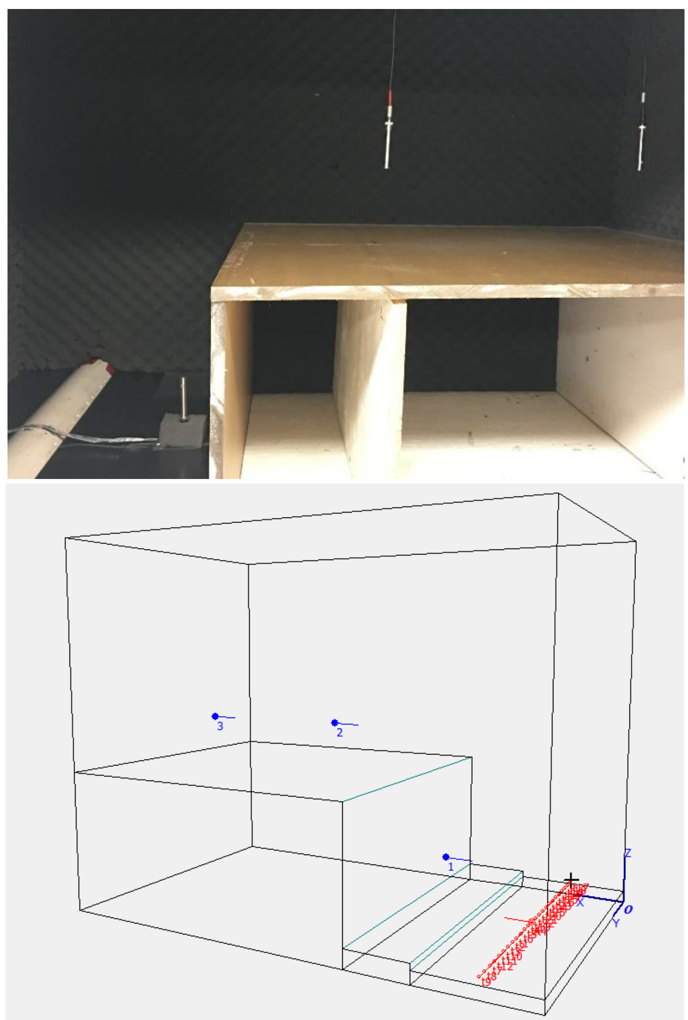


Figure 63: A 1:10 baseline scale model in the AC vs. a baseline simulation model in ODEON.

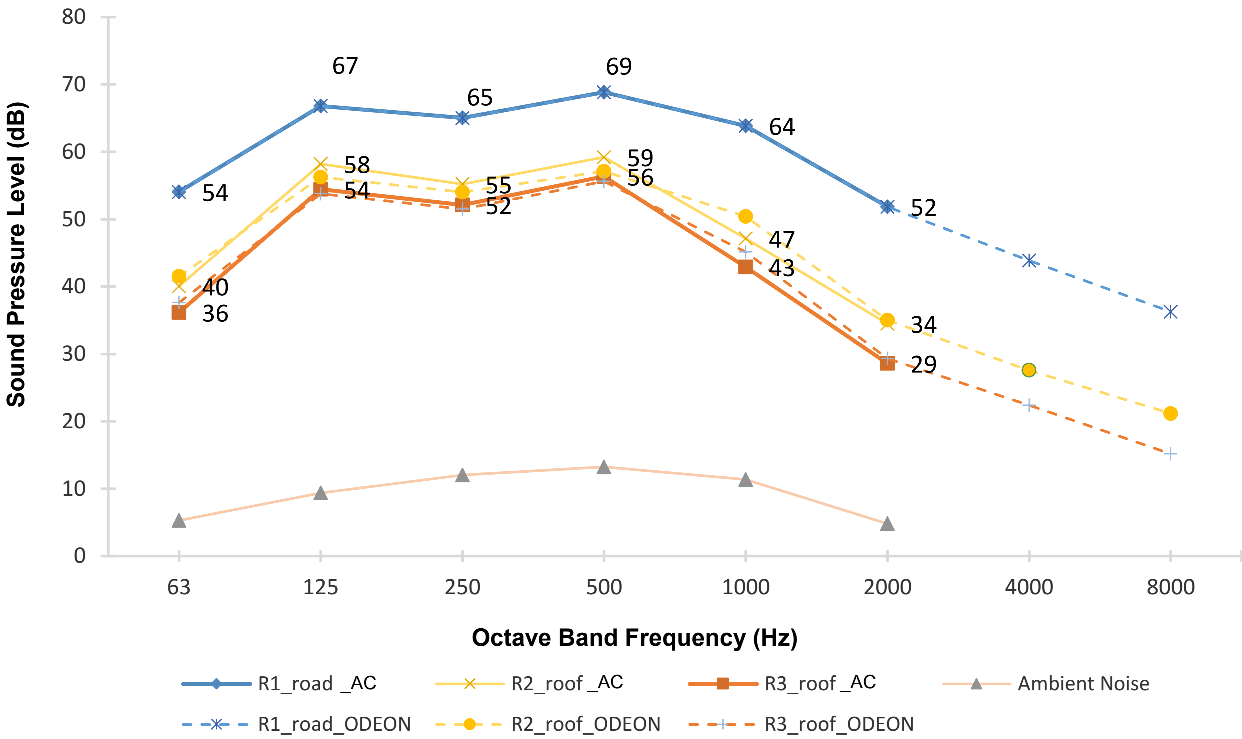


Figure 64: The baseline ROOF configuration spectrum analysis of the 1:10 scale model and ODEON.

In Figure 64, all the test results are showing in a one-octave-wide band. The frequency response result for the 1:10 scale model is measured and scaled down to the frequency range from 63–2K Hz, while in ODEON, the frequency range from 63–8K Hz is wider due to the software capability. The solid lines are the results from the 1:10 scale AC measurement; the dotted lines are the results from the ODEON simulation. Blue, yellow and orange color-lines represent the noise spectra levels at the Source Receiver (SR), Receiver A and Receiver B, respectively. The three different receiver locations show a similar noise reduction trend. Moreover, the attenuation at each frequency band for both models is similar to the noise reduction trend at all bands. The frequency responses of the measured signals in the 1:10 scale AC model reach a high peak at 500 Hz, which is the same as the high peak of the frequency responses in the ODEON simulation model. The dominant frequency is at mid-range from 500–1000 Hz, and the noise level decreases over the high range (>1000 Hz). Another peak frequency for both models is shown at a low frequency, 125 Hz. The SPLs in dB at three receiver positions are shown in Table 10.

Table 10: The baseline ROOF configuration spectrum results of the scale model and ODEON simulation model.

R	1:10 AC							
	Frequency	**63**	**125**	**250**	**500**	**1000**	**2000**	**SUM dB(A)**
SR_road	SPL (dB)	54	67	65	69	64	52	68.4
A_roof		40	58	55	59	47	34	57.2
B_roof		36	54	52	56	43	29	54.2

R	ODEON									
	Frequency	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**SUM dB(A)**
SR_road	SPL (dB)	54	67	65	69	64	52	44	36	68.6
A_roof		42	56	54	57	50	35	28	21	56.6
B_roof		38	54	52	56	45	29	22	15	54.6

Figure 64, comparing the spectrum frequency responses for both model methods, at Receiver A, the ODEON model was minimally under-predicting the sound level at the low-frequency range (125–500 Hz). The numbers were off less than 1 dB; however, this was not the case at 63 Hz, where the sound level predicting by ODEON was slightly higher. At mid-range (500–1000 Hz), the graph minimally shows an over-prediction. The peak of the off-spectrum was shown at a 1000 Hz: 50.5 dB showed in ODEON and 47.1 dB showed in the AC. Receiver B showed a similar trend to Receiver A, but the scale model spectrum results compared to the ODEON results were closer than the spectrum results of Receiver A.

The total weighted sound pressure dB(A) of all one-octave frequencies was evaluated at all three receivers. For the Source Receiver in the scale model test, the total SPL was measured at 68.4 dBA, while the ODEON simulation generated a total SPL of 68.6 dBA, which is only a 0.2 dB(A) difference in prediction at the street level. At Receiver A on the rooftop, the difference in total dBA is 0.6, where the higher value (57.2 dBA) is shown in the scale model measurement. Lastly, at Receiver B, the simulation result in ODEON showed a nominally higher total of 0.4 dBA above the 1:10 scale model measurement, a difference less than the microphone precision of 1 dB. In terms of sound attenuation from the first receiver (SR) to Receivers A and B, the building configuration and air absorption have influenced the sound pressure measured at different receiver locations. The attenuation at A from SR was 11.2 dBA measured in the AC and 12 dBA predicted in ODEON. At the further receiver, B, the attenuation showed higher reduction, as it was measured the attenuation by 14.2 dBA in the 1:10 scale model and by 14 dBA in ODEON.

3.2 Noise Attenuation by Design Tools

The noise attenuation of the baseline and 33 design tool configurations were evaluated using a 1:10 scale model and comparing the results with the results obtained from the ODEON acoustic simulation model. The total dBA difference between measurements in ODEON and the 1:10 scale model in the anechoic chamber at Receiver A and Receiver B was less than 2.7dB(A) across all configurations. The noise attenuation in a one-octave-wide band from 63 to 2K Hz for the scale model cases and from 63 to 8K Hz for the ODEON simulation model showed a similar trend. The attenuation values are listed in Tables 12 to 15; the spectrum analysis for thirty-three design-tool configurations is illustrated in the appendices.

The performance of the 1:10 scale mode and the ODEON simulation model in predicting the results is evaluated by the difference in SPL between Receiver A and B (See Table 11). The difference at Receiver A, of 24 out of 33 design tools, was less than or equal to 1 dB. The remaining 9 design tools differed in the range of 1.1 dB to 2.7 dB. The average difference at A was 0.7 dB. For the measurements at B, 19 out of 33 design tools showed a difference of less than or equal to 1 dB, while 14 design tools differed in the range from 1.3 dB to 2 dB. The average difference at B was -0.2 dB; the negative number shows that ODEON mostly over-predicted the results at Receiver B.

Table11: The differences in sound pressure level at Receiver A and Receiver B between the AC and ODEON models.

Design Tools	Code	Design Tools	Difference between 1:10 scale model – ODEON	
			@Receiver A	@Receiver B
	ROOF	**Baseline configuration**	0.8	-0.2
Single	**B1**	Berm1 (0.6 m. height)	0.7	-0.6
	OFF-B1	Off-set Berm1 (1m. away)	0.5	-0.9
	GR1	Green roof1 (1m.)	0.3	0.8
	GR2	Green roof 2 (full area)	0	0.7
	OH1	Overhang1 (1m.)	0.7	-0.7
	G1	Guard1 (1.07m. height)	1.6	-1.3
	G2	Guard2 (inner side veg. layer)	0.7	-1.4
	G3	Guard3 (both side veg. layers)	0.7	0.1
	OFF-G1	Off-set Guard1 (1m. away)	1.1	-0.8
	OFF-G2	Off-set Guard2 (1m. away)	-0.1	-1.3
	OFF-G3	Off-set Guard3 (1m. away)	-0.8	-0.8
	W1	Wall1 (3m. height)	0.4	-0.8
	W2	Wall2 (inner side veg. layer)	0.5	-0.9
	W3	Wall3 (both side veg. layers)	0.8	-1.5
Double & Triple	**B1+GR1**	Berm1+Green roof1	1.2	-0.6
	B1+GR2	Berm1+Green roof2	-0.2	-0.3
	GR1+B1	Green roof1+Berm1	0.3	-1.6
	OH1+B1	Overhang1+Berm1	0	-1.3
	OH1+GR1+B1	Overhang1+Green roof1+ Berm1	0	-1.6
	OH1+GR1+B1+GR2	Overhang1+Green roof1 +Berm1+Green roof2	0.7	-1.9
	OFF-G3+GR1+GR2	Off-set Guard3+Green roof1+Green roof2	0.7	0.6
Complex	**C1_(B1+G3+GR2)**	Berm1+Guard3+Green roof2	0	1.7
	C2_(GR1+B1+G3)	Green roof1+Berm1+Guard3	0.2	-0.4
	C3_(G3+GR1+B1)	Guard3+Green roof1+Berm1	1	2
	C4_(B1+W3+GR2)	Berm1+Wall3+Green roof2	1.6	1.5
	C5_(GR1+B1+W3)	Green roof1+Berm1+Wall3	1	-0.9
	C6_(W3+GR1+B1)	Wall3+Green roof1+Berm1	1.1	-0.2
	C7_OH(B1+G3+GR2)	Overhang (Berm1+Guard3+Green roof2)	1.3	0.4
	C8_OH(GR1+B1+G3)	Overhang (Green roof1+Berm1+Guard3)	0.6	1
	C9_OH(G3+GR1+B1)	Overhang (Guard3+Green roof1+Berm1)	0.5	1.5
	C10_OH(B1+W3+GR2)	Overhang (Berm1+Wall3+Green roof2)	2.7	1.3
	C11_OH(GR1+B1+W3)	Overhang (Green roof1+Berm1+Wall3)	1.9	-0.2
	C12_OH(W3+GR1+B1)	Overhang (Wall3+Green roof1+Berm1)	2.4	1.5
Average			0.7	-0.2

Design Tools	Code	Design Tools	SPL (dBA)			A-B attn	ATTENUATION [dB(A)]				
			Source	Receiver A	Reciever B		Receiver A 3 m from roof	Increased attn @ A	Receiver B 8 m from roof	Increased attn @ B	Increased attn over distance
	ROOF	**Baseline configuration**	**68.4**	**57.2**	**54.2**	**3**	**11.2**	**na**	**14.2**	**na**	**na**
Single	**B1**	Berm1 (0.6 m. height)	**68.2**	**56.1**	**51.9**	4.2	12.1	**0.9**	16.3	**2.1**	1.2
	OFF-B1	Off-set Berm1 (1m. away)	**68.5**	**56.4**	**53.1**	3.3	12.1	**0.9**	15.4	**1.2**	0.3
	GR1	Green roof1 (1m.)	**68.2**	**55.9**	**53.7**	2.2	12.3	**1.1**	14.5	**0.3**	-0.8
	GR2	Green roof 2 (full area)	**68.1**	**55.5**	**52.2**	3.3	12.6	**1.4**	15.9	**1.7**	0.3
	OH1	Overhang1 (1m.)	**68.9**	**55.9**	**51.1**	4.8	13	**1.8**	17.8	**3.6**	1.8
	G1	Guard1 (1.07m. height)	**68.2**	**54.6**	**49.7**	4.9	13.6	**2.4**	18.5	**4.3**	1.9
	G2	Guard2 (inner side veg. layer)	**68.7**	**54.8**	**51.7**	3.1	13.9	**2.7**	17	**2.8**	0.1
	G3	Guard3 (both side veg. layers)	**68.6**	**53.6**	**52.1**	1.5	15	**3.8**	16.5	**2.3**	-1.5
	OFF-G1	Off-set Guard1 (1m. away)	**68.5**	**53.2**	**49.9**	3.3	15.3	**4.1**	18.6	**4.4**	0.3
	OFF-G2	Off-set Guard2 (1m. away)	**68.8**	**53.7**	**50.1**	3.6	15.1	**3.9**	18.7	**4.5**	0.6
	OFF-G3	Off-set Guard3 (1m. away)	**68.5**	**53.6**	**52.5**	1.1	14.9	**3.7**	16	**1.8**	-1.9
	W1	Wall1 (3m. height)	**68.2**	**52.4**	**48.8**	3.6	15.8	**4.6**	19.4	**5.2**	0.6
	W2	Wall2 (inner side veg. layer)	**68.4**	**52.6**	**49.7**	2.9	15.8	**4.6**	18.7	**4.5**	-0.1
	W3	Wall3 (both side veg. layers)	**68.6**	**52.6**	**48.7**	3.9	16	**4.8**	19.9	**5.7**	0.9
Double & Triple	**B1+GR1**	Berm1+Green roof1	**68.4**	**54.7**	**51.1**	3.6	13.7	**2.5**	17.3	**3.1**	0.6
	B1+GR2	Berm1+Green roof2	**68.3**	**54.5**	**49.9**	4.6	13.8	**2.6**	18.4	**4.2**	1.6
	GR1+B1	Green roof1+Berm1	**68.3**	**55.5**	**50.8**	4.7	12.8	**1.6**	17.5	**3.3**	1.7
	OH1+B1	Overhang1+Berm1	**69.1**	**52.9**	**49.7**	3.2	16.2	**5**	19.4	**5.2**	0.2
	OH1+GR1+B1	Overhang1+Green roof1+ Berm1	**69.4**	**52.3**	**48.3**	4	17.1	**5.9**	21.1	**6.9**	1
	OH1+GR1+B1+GR2	Overhang1+Green roof1 +Berm1+Green roof2	**69.7**	**52**	**46.8**	5.2	17.7	**6.5**	22.9	**8.7**	2.2
	OFF-G3+GR1+GR2	Off-set Guard3+Green roof1+Green roof2	**68.5**	**54.1**	**51.7**	2.4	14.4	**3.2**	16.8	**2.6**	-0.6
Complex	**C1_(B1+G3+GR2)**	Berm1+Guard3+Green roof2	**67.7**	**51.8**	**51.4**	0.4	15.9	**4.7**	16.3	**2.1**	-2.6
	C2_(GR1+B1+G3)	Green roof1+Berm1+Guard3	**67.6**	**53.6**	**51.7**	1.9	14	**2.8**	15.9	**1.7**	-1.1
	C3_(G3+GR1+B1)	Guard3+Green roof1+Berm1	**67.4**	**52**	**53.2**	-1.2	15.4	**4.2**	14.2	**0**	-4.2
	C4_(B1+W3+GR2)	Berm1+Wall3+Green roof2	**67.7**	**50**	**49.2**	0.8	17.7	**6.5**	18.5	**4.3**	-2.2
	C5_(GR1+B1+W3)	Green roof1+Berm1+Wall3	**67.6**	**48.1**	**50.6**	-2.5	19.5	**8.3**	17	**2.8**	-5.5
	C6_(W3+GR1+B1)	Wall3+Green roof1+Berm1	**67.7**	**49.4**	**49.6**	-0.2	18.3	**7.1**	18.1	**3.9**	-3.2
	C7_OH(B1+G3+GR2)	Overhang(Berm1+Guard3+Green roof2)	**67.8**	**52.3**	**49.2**	3.1	15.5	**4.3**	18.6	**4.4**	0.1
	C8_OH(GR1+B1+G3)	Overhang(Green roof1+Berm1+Guard3)	**67.7**	**51.4**	**51.4**	0	16.3	**5.1**	16.3	**2.1**	-3
	C9_OH(G3+GR1+B1)	Overhang(Guard3+Green roof1+Berm1)	**67.5**	**51.2**	**51.9**	-0.7	16.3	**5.1**	15.6	**1.4**	-3.7
	C10_OH(B1+W3+GR2)	Overhang(Berm1+Wall3+Green roof2)	**67.8**	**49.9**	**48.5**	1.4	17.9	**6.7**	19.3	**5.1**	-1.6
	C11_OH(GR1+B1+W3)	Overhang(Green roof1+Berm1+Wall3)	**67.7**	**47.6**	**49**	-1.4	20.1	**8.9**	18.7	**4.5**	-4.4
	C12_OH(W3+GR1+B1)	Overhang(Wall3+Green roof1+Berm1)	**67.7**	**49.7**	**49.8**	-0.1	18	**6.8**	17.9	**3.7**	-3.1

Table12: The increase in attenuation of 33 design tool configurations measured in the anechoic chamber using the 1:10 scale model method.

Design Tools	Code	SPL (dBA)			Normalized to 1:10 scale source level				A-B attn	ATTENUATION [dB(A)]				
		Source	Reciever A	Reciever B	Source dif.	AC Source	Reciever A	Reciever B		Receiver A 3 m from roof	Increased attn @ A	Receiver B 8 m from roof	Increased attn @ B	Increased attn over distance
	ROOF	**68.6**	**56.6**	**54.6**	**0.2**	**68.4**	**56.4**	**54.4**	**2**	**12**	**na**	**14**	**na**	na
Single	**B1**	67.8	55	52.1	-0.4	**68.2**	**55.4**	**52.5**	2.9	12.8	**0.8**	15.7	**1.7**	0.9
Single	**OFF-B1**	68.2	55.6	53.7	-0.3	**68.5**	**55.9**	**54**	1.9	12.6	**0.6**	14.5	**0.5**	-0.1
Single	**GR1**	68.1	55.5	52.8	-0.1	**68.2**	**55.6**	**52.9**	2.7	12.6	**0.6**	15.3	**1.3**	0.7
Single	**GR2**	68.2	55.6	51.6	0.1	**68.1**	**55.5**	**51.5**	4	12.6	**0.6**	16.6	**2.6**	2
Single	**OH1**	69	55.3	51.9	0.1	**68.9**	**55.2**	**51.8**	3.4	13.7	**1.7**	17.1	**3.1**	1.4
Single	**G1**	70.3	55.1	53.1	2.1	**68.2**	**53**	**51**	2	15.2	**3.2**	17.2	**3.2**	0
Single	**G2**	70.2	55.6	54.6	1.5	**68.7**	**54.1**	**53.1**	1	14.6	**2.6**	15.6	**1.6**	-1
Single	**G3**	68.7	53	52.1	0.1	**68.6**	**52.9**	**52**	0.9	15.7	**3.7**	16.6	**2.6**	-1.1
Single	**OFF-G1**	69	52.6	51.2	0.5	**68.5**	**52.1**	**50.7**	1.4	16.4	**4.4**	17.8	**3.8**	-0.6
Single	**OFF-G2**	70.1	55.1	52.7	1.3	**68.8**	**53.8**	**51.4**	2.4	15	**3**	17.4	**3.4**	0.4
Single	**OFF-G3**	69.7	55.6	54.5	1.2	**68.5**	**54.4**	**53.3**	1.1	14.1	**2.1**	15.2	**1.2**	-0.9
Single	**W1**	69	52.8	50.4	0.8	**68.2**	**52**	**49.6**	2.4	16.2	**4.2**	18.6	**4.6**	0.4
Single	**W2**	70	53.7	52.2	1.6	**68.4**	**52.1**	**50.6**	1.5	16.3	**4.3**	17.8	**3.8**	-0.5
Single	**W3**	67.2	50.4	48.8	-1.4	**68.6**	**51.8**	**50.2**	1.6	16.8	**4.8**	18.4	**4.4**	-0.4
Double & Triple	**B1+GR1**	71.4	56.5	54.7	3	**68.4**	**53.5**	**51.7**	1.8	14.9	**2.9**	16.7	**2.7**	-0.2
Double & Triple	**B1+GR2**	67	53.4	48.9	-1.3	**68.3**	**54.7**	**50.2**	4.5	13.6	**1.6**	18.1	**4.1**	2.5
Double & Triple	**GR1+B1**	68.5	55.4	52.6	0.2	**68.3**	**55.2**	**52.4**	2.8	13.1	**1.1**	15.9	**1.9**	0.8
Double & Triple	**OH1+B1**	72	55.8	53.9	2.9	**69.1**	**52.9**	**51**	1.9	16.2	**4.2**	18.1	**4.1**	-0.1
Double & Triple	**OH1+GR1+B1**	70.6	53.5	51.1	1.2	**69.4**	**52.3**	**49.9**	2.4	17.1	**5.1**	19.5	**5.5**	0.4
Double & Triple	**OH1+GR1+B1+GR2**	71.4	53	50.4	1.7	**69.7**	**51.3**	**48.7**	2.6	18.4	**6.4**	21	**7**	0.6
Double & Triple	**OFF-G3+GR1+GR2**	67.9	52.8	50.5	-0.6	**68.5**	**53.4**	**51.1**	2.3	15.1	**3.1**	17.4	**3.4**	0.3
Complex	**C1_(B1+G3+GR2)**	67.5	51.6	49.5	-0.2	**67.7**	**51.8**	**49.7**	2.1	15.9	**3.9**	18	**4**	0.1
Complex	**C2_(GR1+B1+G3)**	69.9	55.7	54.4	2.3	**67.6**	**53.4**	**52.1**	1.3	14.2	**2.2**	15.5	**1.5**	-0.7
Complex	**C3_(G3+GR1+B1)**	67	50.6	50.8	-0.4	**67.4**	**51**	**51.2**	-0.2	16.4	**4.4**	16.2	**2.2**	-2.2
Complex	**C4_(B1+W3+GR2)**	68.2	48.9	48.2	0.5	**67.7**	**48.4**	**47.7**	0.7	19.3	**7.3**	20	**6**	-1.3
Complex	**C5_(GR1+B1+W3)**	68.9	48.4	52.8	1.3	**67.6**	**47.1**	**51.5**	-4.4	20.5	**8.5**	16.1	**2.1**	-6.4
Complex	**C6_(W3+GR1+B1)**	68.6	49.2	50.7	0.9	**67.7**	**48.3**	**49.8**	-1.5	19.4	**7.4**	17.9	**3.9**	-3.5
Complex	**C7_OH(B1+G3+GR2)**	70.3	53.5	51.3	2.5	**67.8**	**51**	**48.8**	2.2	16.8	**4.8**	19	**5**	0.2
Complex	**C8_OH(GR1+B1+G3)**	69.4	52.5	52.1	1.7	**67.7**	**50.8**	**50.4**	0.4	16.9	**4.9**	17.3	**3.3**	-1.6
Complex	**C9_OH(G3+GR1+B1)**	70.1	53.3	53	2.6	**67.5**	**50.7**	**50.4**	0.3	16.8	**4.8**	17.1	**3.1**	-1.7
Complex	**C10_OH(B1+W3+GR2)**	69.6	49	49	1.8	**67.8**	**47.2**	**47.2**	0	20.6	**8.6**	20.6	**6.6**	-2
Complex	**C11_OH(GR1+B1+W3)**	69.5	47.5	51	1.8	**67.7**	**45.7**	**49.2**	-3.5	22	**10**	18.5	**4.5**	-5.5
Complex	**C12_OH(W3+GR1+B1)**	69.5	49.1	50.1	1.8	**67.7**	**47.3**	**48.3**	-1	20.4	**8.4**	19.4	**5.4**	-3

Table13: The increase in attenuation of 33 design tool configurations measured in ODEON using the computer simulation method.

RECIEVER A_on the roof top level, 1.5 m. above the level, 3 m. away from the building edge																		
Scale Model Tested in Anachoic Chamber (AC)								ODEON Acoustic Computer Simulation										
Design Tool	Frequency							Design Tool	Frequency									
	63	125	250	500	1000	2000	SUM dB(A)		63	125	250	500	1000	2000	4000	8000	SUM dB(A)
ROOF	**40.0**	**58.2**	**55.2**	**59.2**	**47.1**	**34.5**	**57.2**	**ROOF**	**41.5**	**56.3**	**54.0**	**57.1**	**50.5**	**35.1**	**27.6**	**21.2**	**56.4**
B1	38.3	57.5	54.1	58.1	45.2	33.5	56.1	**B1**	41.0	55.5	53.2	55.7	50.3	33.7	25.5	19.5	55.4
OFF-B1	39.3	57.4	54.4	58.5	44.6	32.6	56.4	**OFF-B1**	42.5	55.4	52.5	56.3	50.3	33.0	23.6	19.4	55.9
GR1	39.5	59.4	54.2	57.8	45.2	33.7	55.9	**GR1**	41.2	55.7	53.3	55.9	50.5	35.1	27.0	20.7	55.6
GR2	39.5	58.7	56.4	57.1	44.3	31.0	55.5	**GR2**	41.6	55.9	53.3	55.7	50.6	35.7	27.3	21.1	55.5
OH1	38.1	58.7	53.9	57.8	46.1	33.9	55.9	**OH1**	39.2	55.4	52.4	56.0	49.4	36.0	26.9	20.7	55.2
G1	40.1	57.5	54.0	56.5	42.5	31.2	54.6	**G1**	39.6	52.3	49.7	53.5	47.3	34.7	26.4	20.0	53
G2	38.7	57.3	53.5	56.4	45.7	32.0	54.8	**G2**	39.0	55.3	54.1	55.1	43.3	25.8	17.9	16.1	54.1
G3	38.0	57.3	54.0	54.8	44.9	32.0	53.6	**G3**	36.8	53.6	52.5	54.6	43.8	31.3	23.3	16.7	52.9
OFF-G1	37.8	57.1	53.4	54.8	41.9	30.2	53.2	**OFF-G1**	38.6	50.6	47.7	52.8	45.9	33.1	23.4	17.1	52.1
OFF-G2	37.0	56.5	52.9	55.6	41.8	29.6	53.7	**OFF-G2**	39.4	51.9	49.1	54.3	48.0	35.0	25.9	19.2	53.8
OFF-G3	36.6	55.6	53.9	55.0	44.1	32.2	53.6	**OFF-G3**	39.1	56.1	54.7	55.1	44.3	26.0	18.3	16.6	54.4
W1	36.9	58.8	52.9	53.5	41.7	30.6	52.4	**W1**	38.5	51.2	48.7	52.5	46.0	32.2	23.8	17.7	52
W2	34.5	58.2	52.3	53.7	44.1	31.8	52.6	**W2**	36.1	53.7	51.6	53.6	43.5	31.5	23.6	17.6	52.1
W3	34.3	57.6	51.0	54.0	43.9	31.8	52.6	**W3**	35.5	53.3	51.6	53.2	42.7	28.1	19.8	13.6	51.8
B1+GR1	37.7	55.0	54.7	56.4	44.4	31.9	54.7	**B1+GR1**	40.2	52.2	50.0	53.9	46.5	28.0	18.5	16.8	53.5
B1+GR2	38.1	56.4	54.8	56.2	43.3	31.2	54.5	**B1+GR2**	40.5	54.9	52.3	55.2	49.6	34.6	25.2	19.3	54.7
GR1+B1	39.1	56.5	53.5	57.7	42.9	32.3	55.5	**GR1+B1**	41.1	54.9	52.5	55.8	50.1	35.6	27.0	20.7	55.2
OH1+B1	35.7	54.7	51.5	54.3	44.8	32.2	52.9	**OH1+B1**	37.7	52.0	48.7	53.8	43.6	28.6	18.0	16.4	52.9
OH1+GR1+B1	35.8	54.9	51.6	53.8	43.6	32.5	52.3	**OH1+GR1+B1**	36.2	51.0	47.6	53.6	45.6	33.9	25.2	18.6	52.3
OH1+GR1+B1+GR2	35.4	54.2	53.8	53.1	43.0	30.1	52	**OH1+GR1+B1+GR2**	35.7	50.2	46.8	52.1	43.0	27.9	17.1	15.5	51.3
OFF-G3+GR1+GR2	36.5	54.2	54.7	55.6	45.3	27.3	54.1	**OFF-G3+GR1+GR2**	36.6	54.5	53.0	54.9	45.1	31.0	22.9	16.2	53.4
C1_(B1+G3+GR2)	38.5	51.7	52.9	53.0	43.4	26.0	51.8	**C1_(B1+G3+GR2)**	37.6	53.2	50.9	53.8	41.8	29.6	21.9	15.5	51.8
C2_(GR1+B1+G3)	38.2	50.6	52.5	55.6	43.6	26.3	53.6	**C2_(GR1+B1+G3)**	39.9	55.1	52.8	54.5	43.2	26.1	18.6	16.7	53.4
C3_(G3+GR1+B1)	39.2	52.8	53.9	53.1	43.3	24.0	52	**C3_(G3+GR1+B1)**	37.2	52.5	50.7	52.7	41.5	28.3	21.5	15.2	51
C4_(B1+W3+GR2)	34.9	50.9	50.4	51.5	41.3	21.1	50	**C4_(B1+W3+GR2)**	35.8	50.5	48.3	49.3	37.3	17.0	7.5	4.7	48.4
C5_(GR1+B1+W3)	34.5	48.9	51.1	49.3	35.6	20.4	48.1	**C5_(GR1+B1+W3)**	34.4	49.3	46.6	48.4	34.9	11.9	3.9	0.6	47.1
C6_(W3+GR1+B1)	37.6	49.6	51.0	50.8	39.8	23.5	49.4	**C6_(W3+GR1+B1)**	35.7	50.5	48.3	49.5	36.2	12.1	4.5	1.4	48.3
C7_OH(B1+G3+GR2)	39.2	52.9	53.3	53.3	44.9	28.4	52.3	**C7_OH(B1+G3+GR2)**	36.5	54.3	50.5	52.1	39.8	22.4	15.3	13.5	51
C8_OH(GR1+B1+G3)	38.1	49.3	52.3	52.8	42.5	26.3	51.4	**C8_OH(GR1+B1+G3)**	36.6	54.2	50.3	51.9	40.3	22.6	15.6	13.9	50.8
C9_OH(G3+GR1+B1)	40.2	51.6	52.7	52.2	43.1	24.3	51.2	**C9_OH(G3+GR1+B1)**	36.3	54.3	50.3	51.6	39.7	22.4	14.8	12.9	50.7
C10_OH(B1+W3+GR2)	36.4	52.9	52.0	50.1	43.3	22.8	49.9	**C10_OH(B1+W3+GR2)**	34.3	51.3	47.0	48.3	35.8	14.1	6.2	3.0	47.2
C11_OH(GR1+B1+W3)	34.9	46.8	50.0	48.9	36.7	19.8	47.6	**C11_OH(GR1+B1+W3)**	31.9	49.4	44.8	47.1	34.6	10.4	1.9	-2.1	45.7
C12_OH(W3+GR1+B1)	38.5	49.2	50.9	51.2	40.3	24.2	49.7	**C12_OH(W3+GR1+B1)**	33.7	51.2	46.6	48.3	36.2	11.7	4.5	1.4	47.3

Table14: Spectrum measurements of 33 design tools configurations at Receiver A in the anechoic chamber using the 1:10 scale model method and ODEON method.

RECIEVER B_on the roof top level, 1.5 m. above the level, 8 m. away from the building edge																	
Scale Model Tested in Anachoic Chamber (AC)								ODEON Acoustic Computer Simulation									
Design Tool	Frequency							Design Tool	Frequency								
	63	125	250	500	1000	2000	SUM dB(A)		63	125	250	500	1000	2000	4000	8000	SUM dB(A)
ROOF	**36.2**	**54.4**	**52.1**	**56.3**	**42.9**	**28.6**	**54.2**	**ROOF**	**37.6**	**53.8**	**51.5**	**55.6**	**45.2**	**29.4**	**22.4**	**15.2**	**54.4**
B1	35.8	54.3	49.3	53.9	40.9	26.6	51.9	**B1**	38.3	52.4	50.0	53.5	43.3	27.6	19.0	11.9	52.5
OFF-B1	35.8	53.7	52.9	54.9	42.8	28.0	53.1	**OFF-B1**	40.2	53.2	51.4	54.7	42.2	22.4	12.6	10.5	54
GR1	36.2	54.6	50.8	56.0	41.1	27.2	53.7	**GR1**	38.7	52.8	50.2	53.8	44.3	29.6	21.1	14.0	52.9
GR2	35.0	53.9	49.8	54.5	39.7	23.0	52.2	**GR2**	37.9	51.9	49.1	52.3	44.0	29.8	21.5	14.4	51.5
OH1	32.9	53.1	49.6	53.1	39.3	24.7	51.1	**OH1**	36.0	51.6	48.6	53.1	43.0	30.3	21.2	14.0	51.8
G1	37.0	54.0	50.2	51.0	40.2	23.7	49.7	**G1**	37.7	50.5	47.9	51.9	42.9	30.6	22.3	15.4	51
G2	36.3	52.7	52.3	53.4	40.8	26.1	51.7	**G2**	37.9	54.3	53.0	54.4	39.3	23.0	14.4	12.1	53.1
G3	34.9	53.4	52.4	53.6	42.7	25.8	52.1	**G3**	36.0	53.0	52.0	54.1	39.4	27.7	19.4	12.4	52
OFF-G1	35.7	53.4	50.6	51.2	40.4	26.1	49.9	**OFF-G1**	37.5	49.5	46.5	51.8	41.9	29.1	19.5	12.7	50.7
OFF-G2	34.9	53.3	49.6	51.7	40.4	26.3	50.1	**OFF-G2**	37.6	49.9	47.0	52.3	42.6	30.1	21.3	14.3	51.4
OFF-G3	35.7	54.3	53.1	53.9	43.6	25.4	52.5	**OFF-G3**	37.8	55.0	53.5	54.3	39.1	21.9	13.8	11.7	53.3
W1	32.6	53.7	48.5	50.4	37.5	18.7	48.8	**W1**	36.4	49.0	46.6	50.5	41.8	28.8	20.0	13.2	49.6
W2	33.0	46.3	49.9	51.6	39.2	24.1	49.7	**W2**	34.5	52.3	50.3	52.5	38.9	28.3	20.4	13.6	50.6
W3	31.6	46.5	49.0	50.5	38.1	22.6	48.7	**W3**	33.3	51.2	49.8	52.2	36.7	24.1	15.5	8.7	50.2
B1+GR1	35.2	53.8	49.5	53.0	40.7	26.8	51.1	**B1+GR1**	38.5	50.5	48.2	52.3	41.9	24.0	14.2	12.2	51.7
B1+GR2	34.6	53.9	49.7	51.5	39.4	23.8	49.9	**B1+GR2**	36.5	50.3	47.2	51.5	41.3	27.9	18.1	11.1	50.2
GR1+B1	34.9	53.7	49.8	52.5	40.9	27.0	50.8	**GR1+B1**	38.5	51.8	49.3	53.6	43.7	29.6	20.8	13.7	52.4
OH1+B1	31.6	51.6	47.6	51.7	38.0	23.2	40.7	**OH1+B1**	35.7	50.1	46.7	52.1	39.5	24.4	13.5	11.3	51
OH1+GR1+B1	31.1	52.2	47.5	50.1	37.1	22.1	48.3	**OH1+GR1+B1**	34.0	48.9	45.2	51.5	40.8	29.2	20.6	13.6	49.9
OH1+GR1+B1+GR2	31.9	51.7	47.8	48.1	35.6	21.0	46.8	**OH1+GR1+B1+GR2**	33.2	47.8	44.2	49.6	38.4	23.6	12.8	10.8	48.7
OFF-G3+GR1+GR2	33.7	52.9	52.2	53.6	39.4	21.9	51.7	**OFF-G3+GR1+GR2**	34.8	52.9	51.3	53.0	39.6	26.3	18.3	11.3	51.1
C1_(B1+G3+GR2)	32.7	53.7	52.0	53.1	38.8	25.7	51.4	**C1_(B1+G3+GR2)**	35.7	51.6	49.2	51.8	36.9	25.6	17.6	10.6	49.7
C2_(GR1+B1+G3)	33.3	52.5	52.4	53.1	42.3	26.9	51.7	**C2_(GR1+B1+G3)**	38.7	53.9	51.4	53.6	37.9	21.7	13.4	11.2	52.1
C3_(G3+GR1+B1)	34.2	49.6	53.1	55.3	40.5	27.1	53.2	**C3_(G3+GR1+B1)**	37.1	52.8	51.2	53.3	38.4	25.7	18.9	11.8	51.2
C4_(B1+W3+GR2)	33.2	48.0	50.7	51.0	35.1	24.7	49.2	**C4_(B1+W3+GR2)**	34.6	49.8	48.0	48.6	31.9	14.9	6.9	4.4	47.7
C5_(GR1+B1+W3)	29.8	46.1	51.6	52.2	40.4	26.8	50.6	**C5_(GR1+B1+W3)**	37.8	53.2	51.1	53.0	35.1	18.4	6.9	4.4	51.5
C6_(W3+GR1+B1)	34.6	44.0	49.9	51.7	36.3	26.0	49.6	**C6_(W3+GR1+B1)**	36.0	51.5	50.2	51.1	32.3	15.4	6.2	3.9	49.8
C7_OH(B1+G3+GR2)	32.9	51.7	51.5	50.6	35.7	26.1	49.2	**C7_OH(B1+G3+GR2)**	34.2	52.2	48.3	50.1	34.9	19.3	11.2	8.8	48.8
C8_OH(GR1+B1+G3)	32.5	49.7	51.0	53.4	40.2	26.3	51.4	**C8_OH(GR1+B1+G3)**	35.7	53.7	50.0	51.7	35.9	18.3	10.6	8.4	50.4
C9_OH(G3+GR1+B1)	33.8	48.2	51.5	54.0	39.1	26.5	51.9	**C9_OH(G3+GR1+B1)**	35.8	53.9	49.9	51.5	36.1	20.1	11.2	8.9	50.4
C10_OH(B1+W3+GR2)	32.2	48.3	50.9	50.0	33.8	24.7	48.5	**C10_OH(B1+W3+GR2)**	33.8	51.2	47.3	48.2	32.4	14.8	6.9	4.4	47.2
C11_OH(GR1+B1+W3)	27.3	45.4	51.4	50.3	38.1	25.0	49	**C11_OH(GR1+B1+W3)**	34.4	52.4	48.6	50.5	33.5	15.6	4.9	2.2	49.2
C12_OH(W3+GR1+B1)	33.6	44.3	50.1	51.8	36.1	26.1	49.8	**C12_OH(W3+GR1+B1)**	33.4	51.6	48.0	49.5	31.7	14.6	5.3	2.7	48.3

Table15: Spectrum measurements of 33 design tool configurations at Receiver B in the anechoic chamber using the 1:10 scale model method and ODEON method.

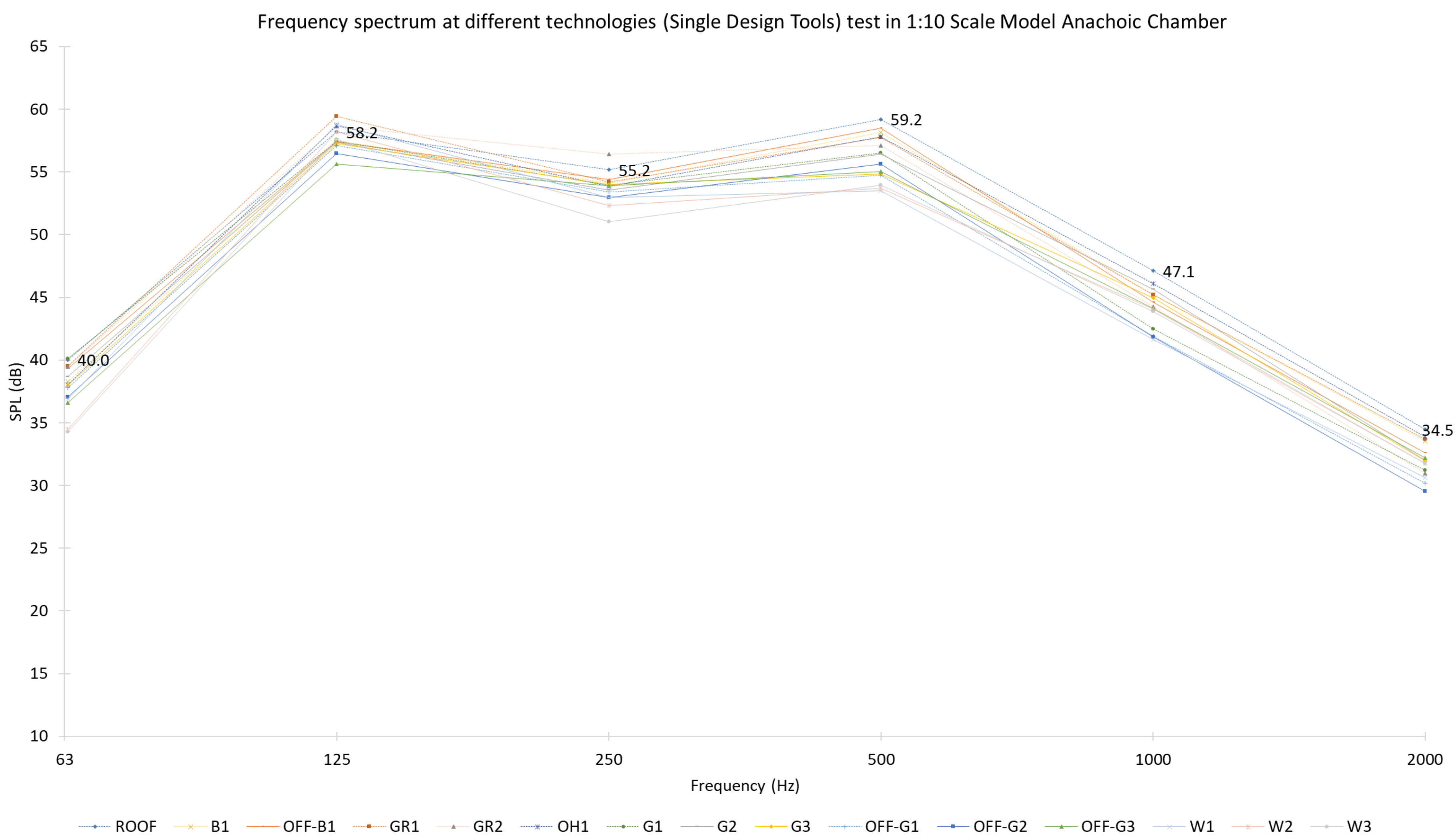


Figure 65: Receiver A noise reduction spectrum analysis for single- design tool configurations measured in the anechoic chamber using the 1:10 scale model method.

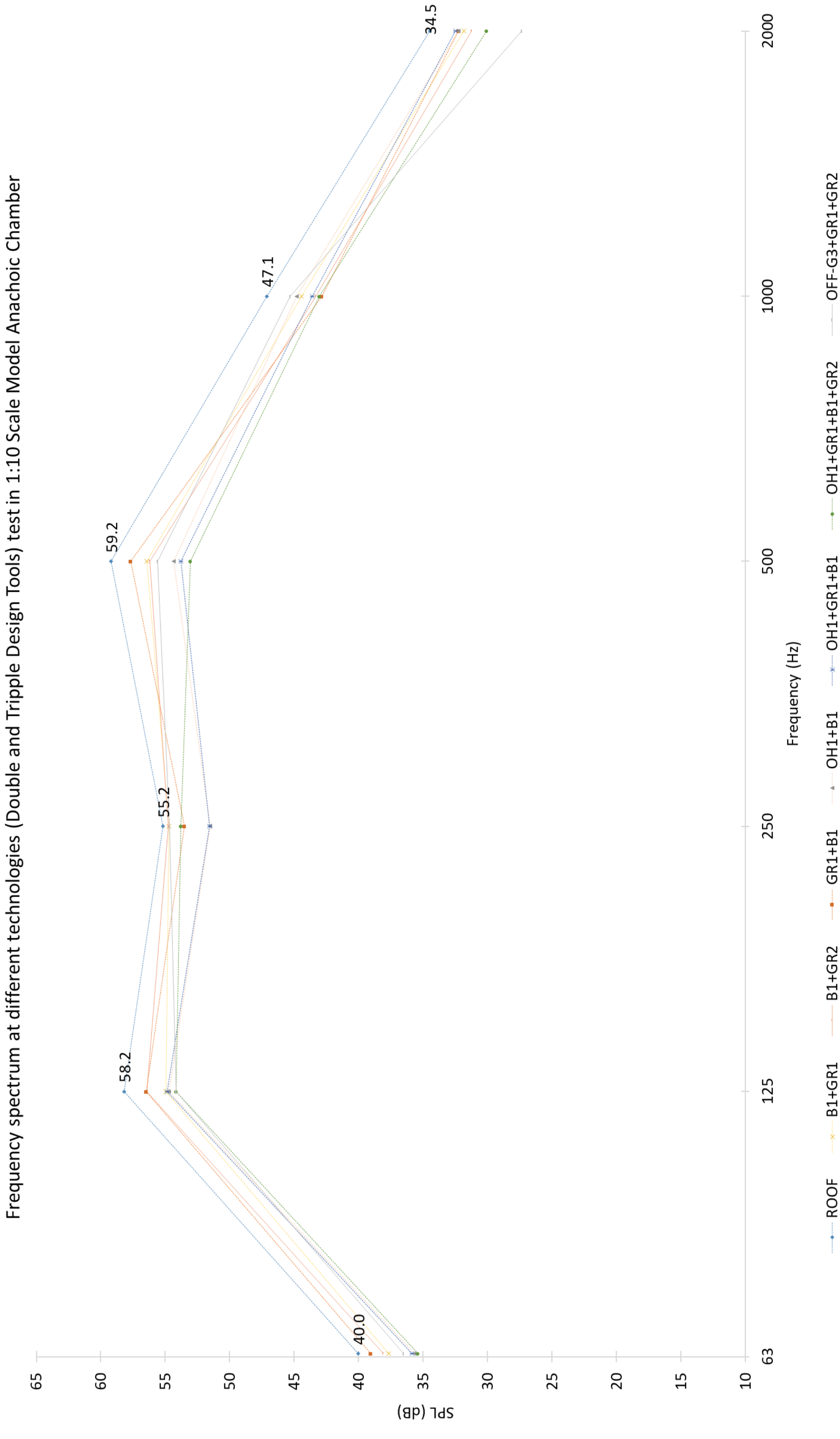


Figure 66: Receiver A noise reduction spectrum analysis for double- and triple-design tool configurations measured in the anechoic chamber using the 1:10 scale model method.

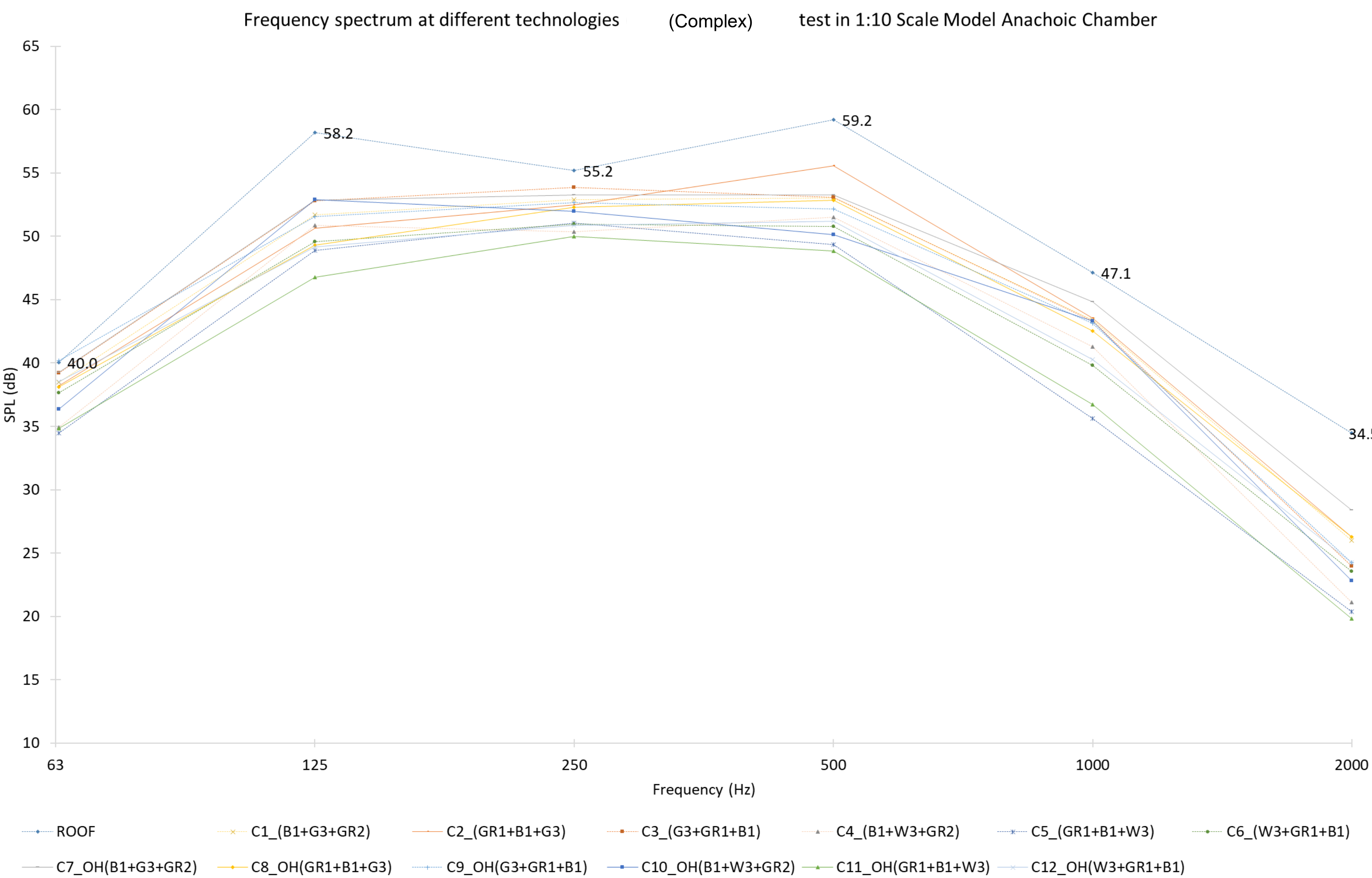


Figure 67: Receiver A noise reduction spectrum analysis for complex-design tool configurations measured in the anechoic chamber using the 1:10 scale model method.

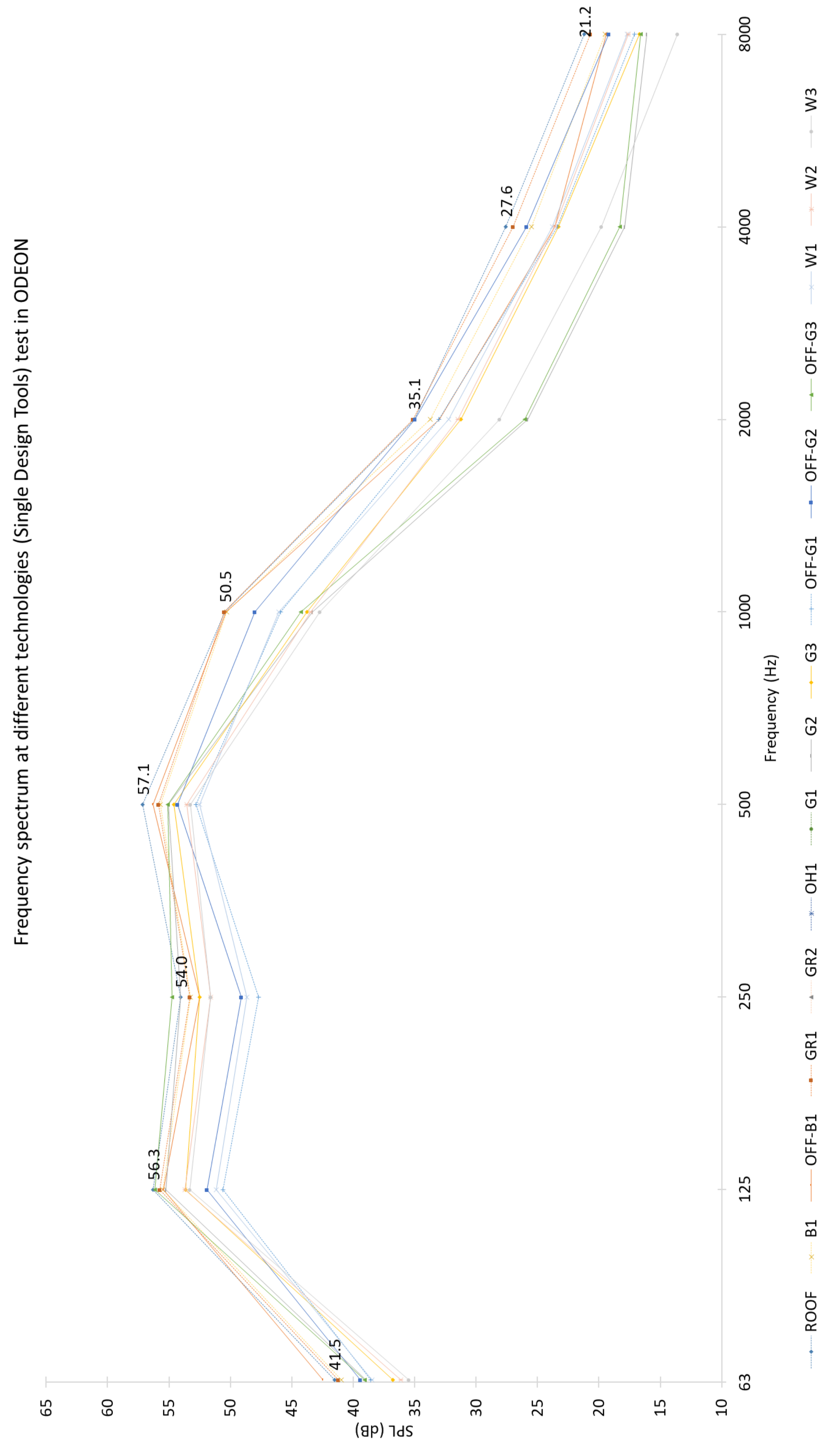


Figure 68: Receiver B noise reduction spectrum analysis for single-design tool configurations measured in the ODEON computer simulation.

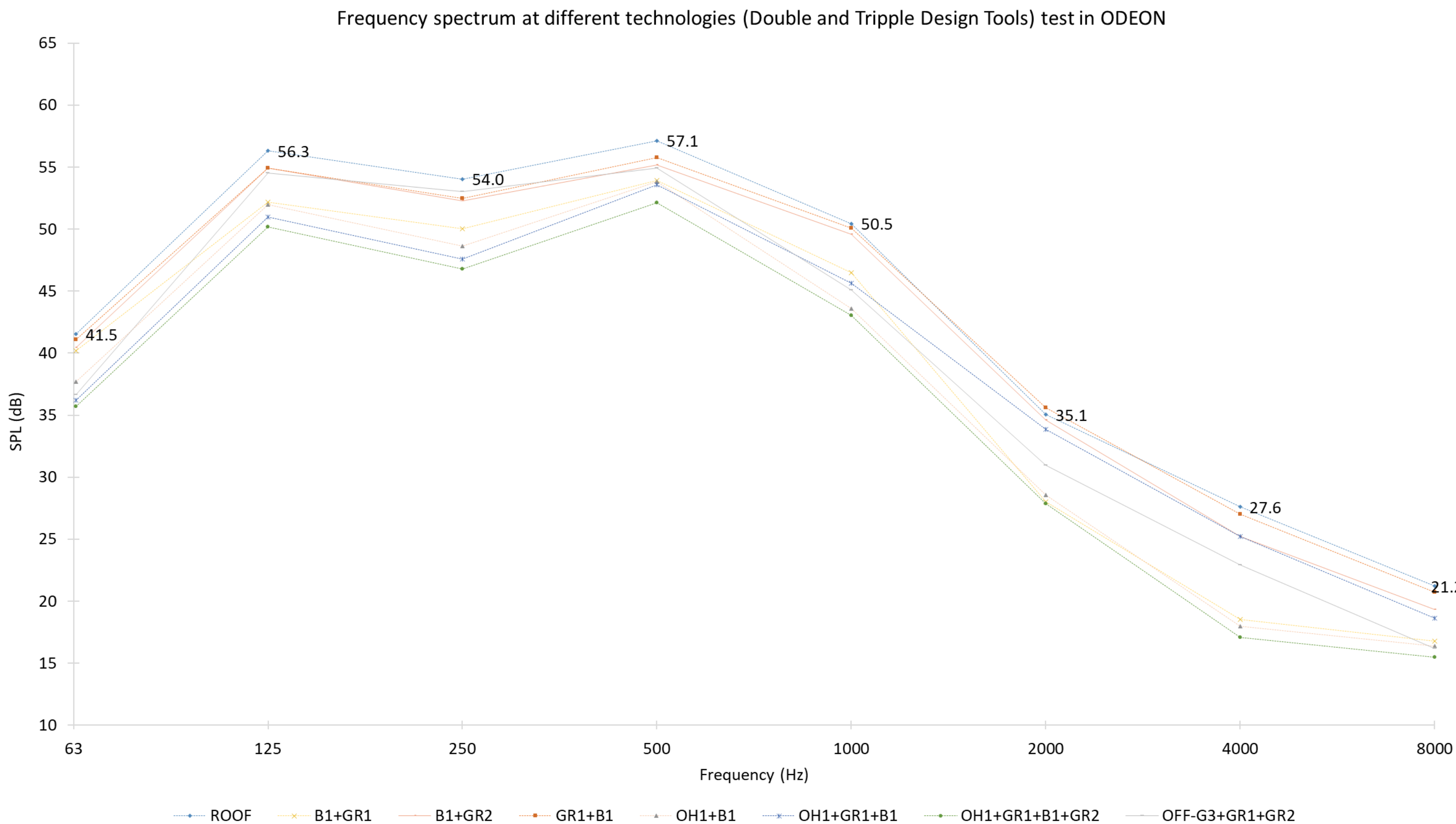


Figure 69: Receiver B noise reduction spectrum analysis for double- and triple design tools configuration measured in the ODEON computer simulation.

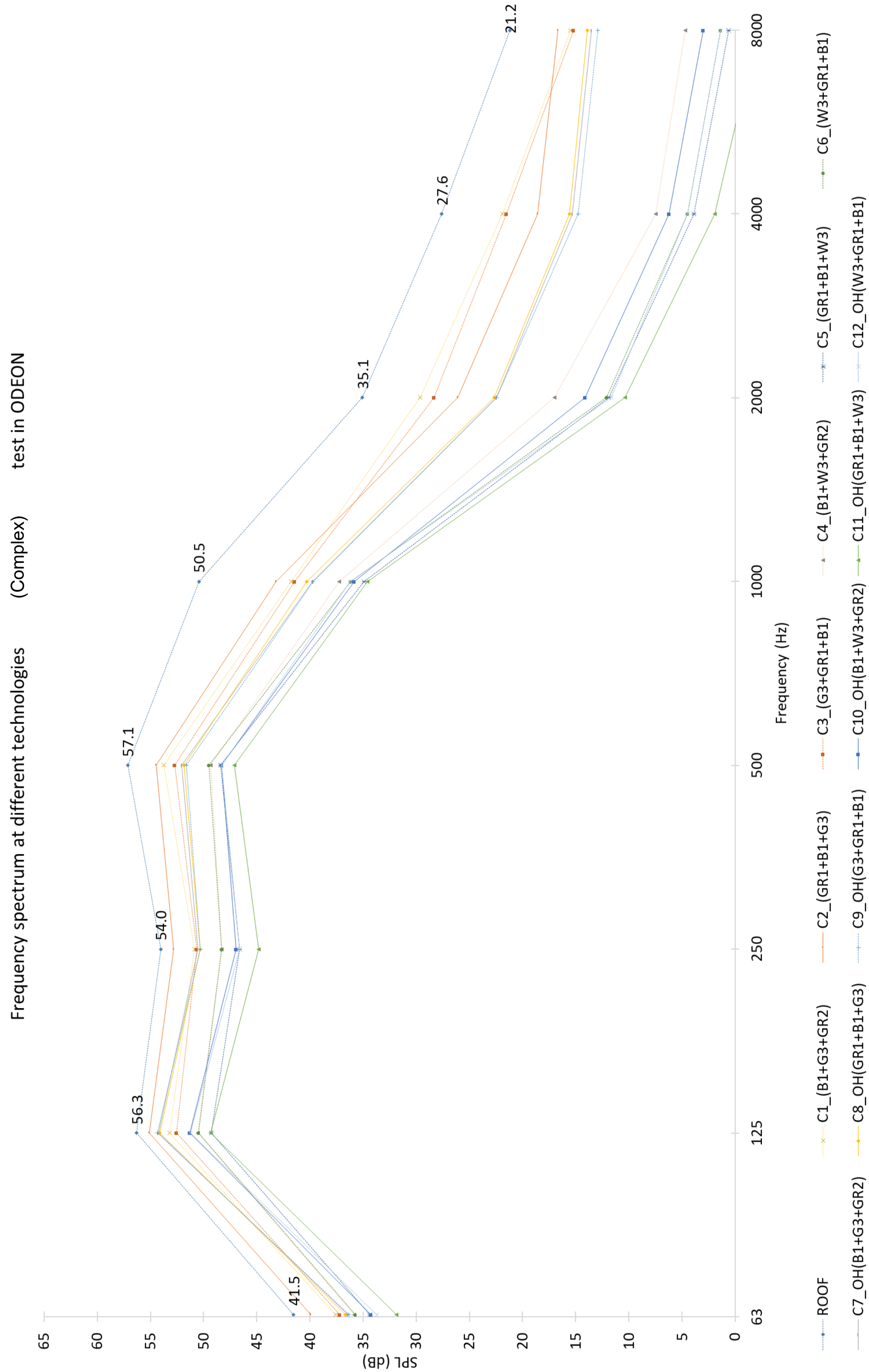


Figure 70: Receiver B noise reduction spectrum analysis for complex-design tool configurations measured in the ODEON computer simulation.

The analysis of the total dBA results showed a good alignment between the 1:10 scale model in the anechoic chamber and the ODEON computer simulation model. Tables 16–18 illustrate the average differences in SPL predicted by the two models at receivers A and B over the 33 design tool configurations. Overall, ODEON under-predicted by 1 dB at the single-design tool groups and at the double- and triple-design tool groups. A zero average difference showed at complex configurations.

At single-design tool configurations, ODEON under-predicted the results within 0–3 dB. For double- and triple-design tool configurations, ODEON under-predicted the results again at the same average difference as in single-design tool results. Therefore, there was a mixed trend in prediction at complex configurations for the average difference shown in both positive and negative values. ODEON under-predicted the results within 1–2 dB and over-predicted by 1 dB.

Table 16: The analysis of total dBA difference in two model results of AC to ODEON for single-design tool configurations.

dBA	Receiver		ROOF	Single configuration														
				B1	OFF-B1	GR1	GR2	OH1	G1	G2	G3	OFF-G1	OFF-G2	OFF-G3	W1	W2	W3	
Total	A	AC	63	62	62	62	62	62	61	61	61	60	60	60	61	60	60	
		ODEON	61	60	60	60	60	60	57	60	59	56	58	60	56	58	58	
	B	AC	59	58	59	59	58	57	57	58	58	57	57	59	56	55	54	
		ODEON	59	57	58	57	56	56	55	59	58	55	55	59	54	57	56	
Diff	A	AC to ODEON	2	2	2	2	2	2	4	1	2	4	3	0	4	2	2	
	B	AC to ODEON	1	1	1	2	2	1	1	-1	0	2	1	0	2	-2	-2	
Avg. Difference at A & B			1	1	1	2	2	1	3	0	1	3	2	0	3	0	0	1

Similar trend (within ±2dB) Over predicting (2-(6) dB)

Table 17: The analysis of total dBA difference in two model results of AC to ODEON for the double- and triple- design tools.

dBA	Receiver		Double & Triple configuration							
			B1+GR1	B1+GR2	GR1+B1	OH1+B1	OH1+GR1+B1	OH1+GR1+B1+GR2	OFF-G3+GR1+GR2	
Total	A	AC	60	61	61	59	59	59	60	
		ODEON	57	60	60	57	57	55	59	
	B	AC	57	57	57	56	55	54	58	
		ODEON	56	55	57	55	54	53	57	
Diff	A	AC to ODEON	3	1	1	2	2	3	1	
	B	AC to ODEON	2	2	0	0	1	2	0	
Avg. Difference at A & B			2	2	1	1	2	3	1	1

Similar trend (within ±2dB) Over predicting (2-(6) dB)

Table 18: The analysis of total dBA difference in two model results of AC to ODEON for complex-design tool configurations.

dBA	Receiver		Complex configuration												
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	
Total	A	AC	58	58	58	56	55	55	58	57	57	57	54	55	
		ODEON	58	59	57	54	53	54	57	57	57	54	52	54	
	B	AC	58	58	58	55	56	54	56	57	57	55	55	55	
		ODEON	56	58	57	54	57	56	55	57	57	54	56	55	
Diff	A	AC to ODEON	0	-1	1	2	2	1	1	-1	0	3	1	1	
	B	AC to ODEON	2	0	1	1	-2	-1	1	0	0	1	-1	0	
Avg. Difference at A & B			1	-1	1	1	0	0	1	0	0	2	0	1	0

Similar trend (within ±2dB) Over predicting (2-(6) dB)

The colored code analysis showed an outstanding prediction trend between the two models. The similar trend within a ±2 dBA difference (green color) accounted for 90% of results shown over 33 design tool technologies. The remaining 10% was over-predicted within 2–6 dBA, meaning that ODEON was under-predicting the situation, which mostly occurred at Receiver A in all configuration tests.

3.2.1 Frequency Spectrum Analysis

Table 19: The analysis of the SPL difference in two model results of AC to ODEON for single-design tool configurations.

Hz.	Range	Receiver	Diff	ROOF	B1	OFF-B1	GR1	GR2	OH1	G1	G2	G3	OFF-G1	OFF-G2	OFF-G3	W1	W2	W3	
125	LOW	A	AC to ODEON	2	2	2	4	3	3	5	2	4	6	5	0	8	4	4	
		B	AC to ODEON	1	2	0	2	2	2	3	-2	0	4	3	-1	5	-6	-5	
250		A	AC to ODEON	1	1	2	1	3	1	4	-1	1	6	4	-1	4	1	-1	
		B	AC to ODEON	1	-1	1	1	1	1	2	-1	0	4	3	0	2	0	-1	
Arg. Differnce at Low Range				1	1	1	2	2	2	4	0	1	5	4	-1	5	0	0	2
500	MID	A	AC to ODEON	2	2	2	2	1	2	3	1	0	2	1	0	1	0	1	
		B	AC to ODEON	1	0	0	2	2	0	-1	-1	0	-1	-1	0	0	-1	-2	
1000		A	AC to ODEON	-3	-5	-6	-5	-6	-3	-5	2	1	-4	-6	0	-4	1	1	
		B	AC to ODEON	-2	-2	1	-3	-4	-4	-3	1	3	-2	-2	5	-4	0	1	
Arg. Differnce at Mid Range				-1	-1	-1	-1	-2	-1	-1	1	1	-1	-2	1	-2	0	0	-1
2000	HIGH	A	AC to ODEON	-1	0	0	-1	-5	-2	-3	6	1	-3	-5	6	-2	0	4	
		B	AC to ODEON	-1	-1	6	-2	-7	-6	-7	3	-2	-3	-4	3	-10	-4	-2	
Arg. Differnce at High Range				-1	-1	3	-2	-6	-4	-5	5	-1	-3	-5	5	-6	-2	1	-1

Table 20: The analysis of SPL difference in two model results of AC to ODEON for double- and triple-design tool configurations.

Hz.	Range	Receiver	Diff	[illegible]	[illegible]	[illegible]	[illegible]	OH1+GR GR2 1+B1	OH1+GR1 OH1 +B1+GR2	OFF-G3+ G1 GR1+GR2	G2	G3	OFF-G1	OFF-G2	OFF-G3	W1	W2	W3
125	LOW	A	AC to ODEON	2	2	2	4	3	3	5	2	4	6	5	0	8	4	4
		B	AC to ODEON	1	2	0	2	2	2	3	-2	0	4	3	-1	5	-6	-5
250		A	AC to ODEON	1	1	2	1	3	1	4	-1	1	6	4	-1	4	1	-1
		B	AC to ODEON	1	-1	1	1	1	1	2	-1	0	4	3	0	2	0	-1
Arg. Differnce at Low Range				1	1	1	2	2	2	4	2	1	5	4	-1	5	0	0
500	MID	A	AC to ODEON	2	2	2	2	1	2	3	1	0	2	1	0	1	0	1
		B	AC to ODEON	1	0	0	2	2	0	-1	-1	0	-1	-1	0	0	-1	-2
1000		A	AC to ODEON	-3	-5	-6	-5	-6	-3	-5	2	1	-4	-6	0	-4	1	1
		B	AC to ODEON	-2	-2	1	-3	-4	-4	-3	1	3	-2	-2	5	-4	0	1
Arg. Differnce at Mid Range				-1	-1	-1	-1	-2	-1	-1	-1	1	-1	-2	1	-2	0	0
2000	HIGH	A	AC to ODEON	-1	0	0	-1	-5	-2	-3	6	1	-3	-5	6	-2	0	4
		B	AC to ODEON	-1	-1	6	-2	-7	-6	-7	3	-2	-3	-4	3	-10	-4	-2
Arg. Differnce at High Range				-1	-1	3	-2	-6	-4	-5	-2	1	-3	-5	5	-6	-2	1

Table 21: The analysis of SPL difference in two model results of AC to ODEON for complex-design tool configurations.

Hz.	Range	Receiver	Diff	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	W1	W2	W3
125	LOW	A	AC to ODEON	2	2	2	4	3	3	5	2	4	6	5	0	8	4	4
		B	AC to ODEON	1	2	0	2	2	2	3	-2	0	4	3	-1	5	-6	-5
250		A	AC to ODEON	1	1	2	1	3	1	4	-1	1	6	4	-1	4	1	-1
		B	AC to ODEON	1	-1	1	1	1	1	2	-1	0	4	3	0	2	0	-1
Arg. Differnce at Low Range				1	1	1	2	2	2	4	0	1	5	4	-1	0	0	0
500	MID	A	AC to ODEON	2	2	2	2	1	2	3	1	0	2	1	0	1	0	1
		B	AC to ODEON	1	0	0	2	2	0	-1	-1	0	-1	-1	0	0	-1	-2
1000		A	AC to ODEON	-3	-5	-6	-5	-6	-3	-5	2	1	-4	-6	0	-4	1	1
		B	AC to ODEON	-2	-2	1	-3	-4	-4	-3	1	3	-2	-2	5	-4	0	1
Arg. Differnce at Mid Range				-1	-1	-1	-1	-2	-1	-1	1	1	-1	-2	1	2	0	0
2000	HIGH	A	AC to ODEON	-1	0	0	-1	-5	-2	-3	6	1	-3	-5	6	-2	0	4
		B	AC to ODEON	-1	-1	6	-2	-7	-6	-7	3	-2	-3	-4	3	-10	-4	-2
Arg. Differnce at High Range				-1	-1	3	-2	-6	-4	-5	5	-1	-3	-5	5	6	-2	1

In addition to the analysis of total dBA, a more detailed analysis considers three frequency spectrum ranges: low, mid and high frequencies. The values of the differences in predicting the results were compared and analyzed to find out the difference between the ODEON and 1:10 scale model. In general, the results of single-design tools aligned with the 1:10 scale model at low frequencies (125 Hz–250 Hz). ODEON under-predicted relative to the 1:10 scale model by an average of ±2 dB. In the mid-frequency range (500 Hz–1000 Hz), ODEON over-predicted by 1 dB and, at 2000 Hz (high range), over-predicted by only 1 dB. (See Table 19.)

The single-design tools had the most reliable prediction by ODEON at low, mid and high frequencies. At the low frequency range, the average of the differences in SPL at receivers A and B over 33 design tools showed the best prediction at the Guard (G2) configuration, Wall with the inner side vegetated (W2) configuration, and Wall with both sides vegetated (W3) configuration. Then ODEON under-predicted by 1 dB at the Baseline ROOF, Berm (B1) and Off-set Berm (OFF-B1) configurations, but at the Off-set Guard with both sides vegetated configuration (OFF-G3), over-predicted by 1 dB. At mid frequency, ODEON over-predicted at most of the configurations. The Wall with inner side vegetated (W2) and Wall with both sides vegetated (W3) configurations showed no difference in the average of the differences. At high frequency (2000 Hz), 90% of the configurations showed over-prediction in the SPL by ODEON. The over-prediction values varied from (-1) – (-6) dB.

In Table 20 for the double- and triple-design tool configurations, ODEON under-predicted the results by 2 dB at the low range. At mid and high frequencies, ODEON over-predicted by 1 dB and 2 dB, respectively. At the low-frequency range, the most reliable prediction showed at the green roof and berm (GR1+B1) configurations. At the off-set guard with both sides vegetated + full area of green roof (OFF-G3+GR1+GR2) configuration, the average difference in prediction was 1 dB. At mid range, ODEON, on the other hand, over-predicted the results from -1 – (-2) dB. At 2000 Hz, the mixed prediction showed the difference values varying from -4 – (3) dB.

The resulting prediction for complex configurations showed a good alignment between two models at the low- and mid-frequency ranges. However, at high frequency, ODEON under-predicted the results by 6 dB on average across all complex configurations. The highest off-value was 11 dB, which showed at the C6 (W3+GR1+B1) configuration. At low range, ODEON under- and over-predicted the results within (-2) – 2 dB. ODEON under-predicted the results at mid range in this configuration group. The over-prediction values varied from 1–3 dB.

3.2.2 Increased Noise Attenuation of 33 Design Tool Investigations

Attenuation in dB over distance and due to barriers of various geometries, between the source and receivers, is a critical matrix to understand. The attenuation values of design tools can be applied to other sites. The noise attenuation values of the design tools were analyzed based on the results obtained at the three receiver positions measured in the 1:10 scale model and in the ODEON simulation model. The attenuation values of the single-design tool, double- and triple-design tools, and complex-design tools from the street level receiver to Receivers A and B on the roof were compared between the scale model and ODEON model. Table 22 summarizes the results.

Table 22: Increased attenuation of 33 design tool configurations in the AC and ODEON.

The increase attenuation summary table

Design Tools	Code	Design Tools	Increased attn @ A		Increased attn @ B	
			AC	ODEON	AC	ODEON
	ROOF	Baseline configuration	na	na	na	na
Single	B1	Berm1 (0.6 m. height)	0.9	0.8	2.1	1.7
	OFF-B1	Off-set Berm1 (1m. away)	0.9	0.6	1.2	0.5
	GR1	Green roof1 (1m.)	1.1	0.6	0.3	1.3
	GR2	Green roof 2 (full area)	1.4	0.6	1.7	2.6
	OH1	Overhang1 (1m.)	1.8	1.7	3.6	3.1
	G1	Guard1 (1.07m. height)	2.4	3.2	4.3	3.2
	G2	Guard2 (inner side veg. layer)	2.7	2.6	2.8	1.6
	G3	Guard3 (both side veg. layers)	3.8	3.7	2.3	2.6
	OFF-G1	Off-set Guard1 (1m. away)	4.1	4.4	4.4	3.8
	OFF-G2	Off-set Guard2 (1m. away)	3.9	3	4.5	3.4
	OFF-G3	Off-set Guard3 (1m. away)	3.7	2.1	1.8	1.2
	W1	Wall1 (3m. height)	4.6	4.2	5.2	4.6
	W2	Wall2 (inner side veg. layer)	4.6	4.3	4.5	3.8
	W3	Wall3 (both side veg. layers)	4.8	4.8	5.7	4.4
Double & Triple	B1+GR1	Berm1+Green roof1	2.5	2.9	3.1	2.7
	B1+GR2	Berm1+Green roof2	2.6	1.6	4.2	4.1
	GR1+B1	Green roof1+Berm1	1.6	1.1	3.3	1.9
	OH1+B1	Overhang1+Berm1	5	4.2	5.2	4.1
	OH1+GR1+B1	Overhang1+Green roof1+ Berm1	5.9	5.1	6.9	5.5
	OH1+GR1+B1+GR2	Overhang1+Green roof1 +Berm1+Green roof2	6.5	6.4	8.7	7
	OFF-G3+GR1+GR2	Off-set Guard3+Green roof1+Green roof2	3.2	3.1	2.6	3.4
Complex	C1_(B1+G3+GR2)	Berm1+Guard3+Green roof2	4.7	3.9	2.1	4
	C2_(GR1+B1+G3)	Green roof1+Berm1+Guard3	2.8	2.2	1.7	1.5
	C3_(G3+GR1+B1)	Guard3+Green roof1+Berm1	4.2	4.4	0	2.2
	C4_(B1+W3+GR2)	Berm1+Wall3+Green roof2	6.5	7.3	4.3	6
	C5_(GR1+B1+W3)	Green roof1+Berm1+Wall3	8.3	8.5	2.8	2.1
	C6_(W3+GR1+B1)	Wall3+Green roof1+Berm1	7.1	7.4	3.9	3.9
	C7_OH(B1+G3+GR2)	Overhang(Berm1+Guard3+Green roof2)	4.3	4.8	4.4	5
	C8_OH(GR1+B1+G3)	Overhang(Green roof1+Berm1+Guard3)	5.1	4.9	2.1	3.3
	C9_OH(G3+GR1+B1)	Overhang(Guard3+Green roof1+Berm1)	5.1	4.8	1.4	3.1
	C10_OH(B1+W3+GR2)	Overhang(Berm1+Wall3+Green roof2)	6.7	8.6	5.1	6.6
	C11_OH(GR1+B1+W3)	Overhang(Green roof1+Berm1+Wall3)	8.9	10	4.5	4.5
	C12_OH(W3+GR1+B1)	Overhang(Wall3+Green roof1+Berm1)	6.8	8.4	3.7	5.4

Selected spectrum analysis graphs of the design tool configurations are illustrated below, but the spectrum analyses of all 33 configurations are shown in the Appendices. The analysis was divided into sections by looking at each receiver position: SR (Source Receiver on the sidewalk), Receiver A and Receiver B (receivers on the rooftop). Three groups categorized by the number of design tools used in the configuration, named single group, double and triple group, and complex group, explain the increased attenuation results under the analysis of the three receivers.

Source receiver (SR) results analysis

The Source receiver (SR) position was mainly set for source normalization, that is, to calibrate the ODEON simulation results. However, comparing the results of both models helps with understanding the sound effect for street pedestrians on the sidewalk when the roof technologies have been installed. The results showed that the overhang (OH) configurations with single-, double- and triple-design tool placements increased SPL at the street level compared to the street level SPL of the baseline ROOF configuration. The reflection due to an overhang's rigid material placed horizontally parallel to the street strongly influenced the noise level for street pedestrians on the sidewalk. Moreover, off-set design tool configurations, such as OFF-B1, OFF-G1, OFF-G3 in single and double-design tool configurations, showed a higher SPL at the street level as well. On the other hand, for the complex configurations where more than two design tools were combined, the complex-design tools influenced the SPL at the pedestrian level by reducing the loudness at the street sidewalk up to 1 dBA. A spectrum analysis of the OH1 configuration result is shown in Figure 71.

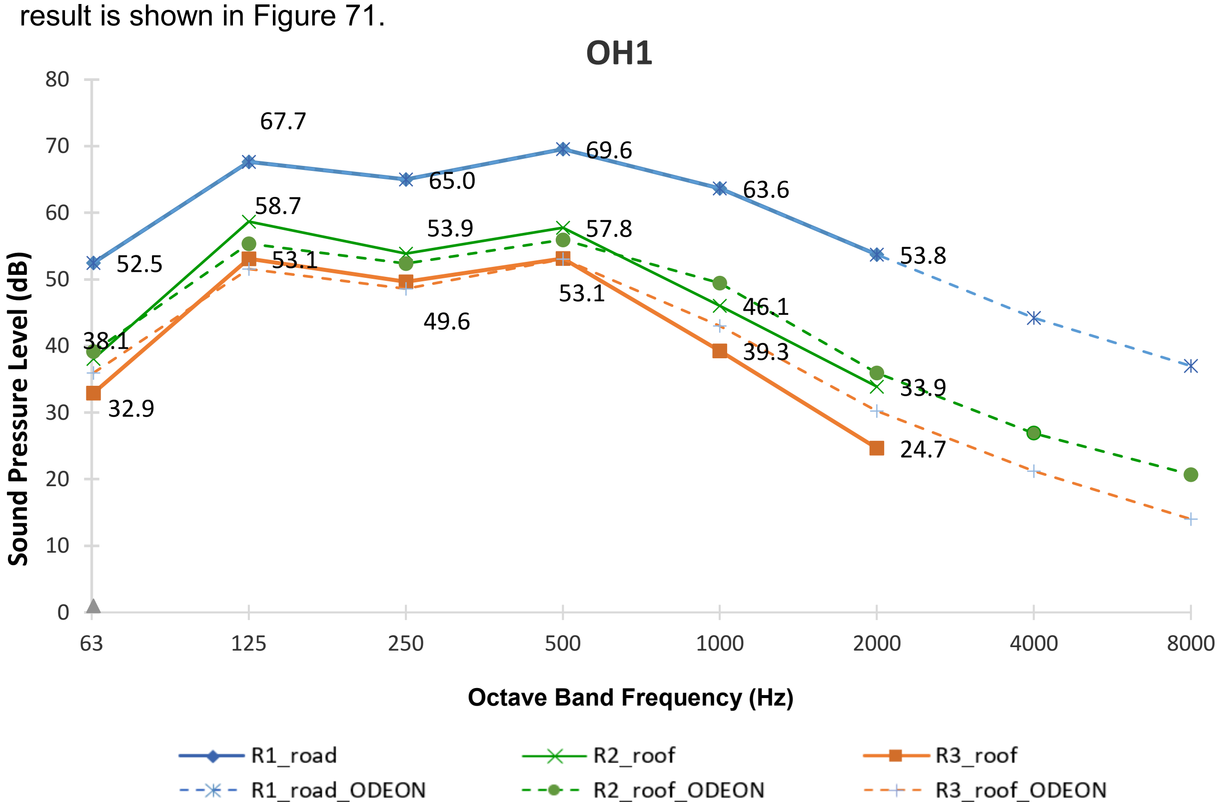


Figure 71: The OH1 design tool configuration spectrum analysis

Receiver A – Single-design tool configuration results analysis

For the results at Receiver A, located on the rooftop level, 3 m away from the building edge, all 33 design tool configurations showed a positive value of increased attenuation from 0.6–10 dBA. The vegetated layer on both sides of 3 m high rigid wall configuration (W3) showed the highest increased attenuation (4.8 dBA) in both the 1:10 scale model and ODEON simulation model for a single-design tool configuration group. Figure 72 illustrates the measurement and simulation results of W3 in the 63–8K Hz wide band frequency spectrum for both models. The ODEON results showed a higher attenuation at almost every frequency band except at 63 Hz and 250 Hz. The predicted SPL in the ODEON model was slightly higher than the measurement in the AC. On the other hand, at Receiver B, the ODEON results showed a lower attenuation for all frequencies except at 1000 Hz, where the higher attenuation showed.

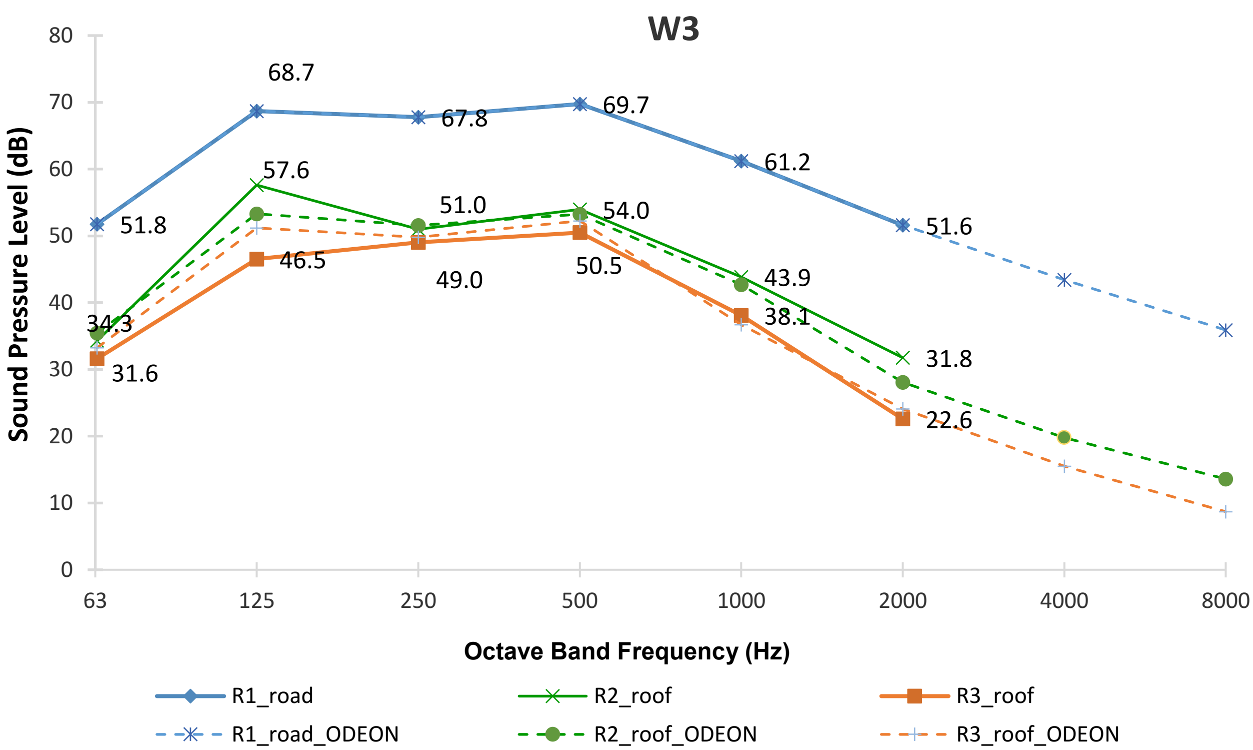


Figure 72: The W3 design tool configuration spectrum analysis.

The results for the single-design tool configurations for the berm and green roof technologies (B1, OFF-B1, GR1, GR2) appeared to have the lowest attenuation in this single-design group, for both the scale model and ODEON simulation model. The increased attenuation varied from 0.6–1.4 dBA. The overhang (OH) configurations showed a relatively low increased attenuation (1.7–1.8 dBA) in ODEON and the AC test, respectively. G3, with vegetation on both sides of the 1.07 m high guard, showed the highest attenuation in a single-design guard configuration (G1–G3): 3.7–3.8 dBA. The absorption on both sides of the vegetated guard lowers the SPL at Receiver A located behind the design tool technology. For attenuation that depends on a height of the barrier, the higher the barrier, the higher the attenuation shown (in the case of wall and guard configurations). For the off-set guards (OFF-G1, OFF-G2, OFF-G3), the attenuation trend was smaller compared to the guard placed at the edge.

Receiver A – Double- and triple-design tool configuration results analysis

Overhang cases with double- and triple-design tools with the combination of berm and green roof configurations provided the highest attenuation in this group (4.2–6.5 dBA), owing to a shallow protection and high mass of absorption surface area of the berm and green roof substrate. The highest attenuation in this group was from the OH1+GR1+B1+GR2 configuration (6.4–6.5 dBA in ODEON and AC, respectively). (See the spectrum analysis in Figure 74.) The smallest increased attenuation in this group was shown in the GR1+B1 configuration; the results showed as 1.1 dBA in ODEON and 1.6 dBA in the AC, which is close to the results for the single-design configurations with the green roof design tool.

Receiver A – Complex–design tool configuration results analysis

The complex configurations that had the highest increase in attenuation were at C5 and C11, which are the combination of green roof, berm, and both-sides-vegetated high wall (C5) and the same combination with the addition of an overhang included in the configuration (C11). C11 yielded an increased attenuation result of 8.9 dBA and 10 dBA in the scale model and ODEON model, respectively, and C5 yielded the increased attenuation results of 8.3 dBA and 8.5 dBA. A spectrum analysis of the C11 configuration result is shown in Figure 73. The trend at Receivers A and B between the results in ODEON and the AC model fluctuated. The differences in the trend between the AC and ODEON wide-frequency band results were apparent. At 125 Hz, the ODEON results showed a couple of decibels higher, while at 250 Hz, ODEON showed a smaller SPL compared to the AC model at both Receiver A and Receiver B. However, the total dBA increases in attenuation of this configuration for ODEON and the AC model did not show much difference (8.9 dBA for the scale model and 10 dBA for the ODEON model). In fact, the differences were less than 3 dBA, in which the loudness would not be noticeable. For these configurations (C5 and C11), the high wall with two sides vegetated (W3) was placed closer to the Receiver A, resulting in a higher attenuation behind the acoustic shading zone.

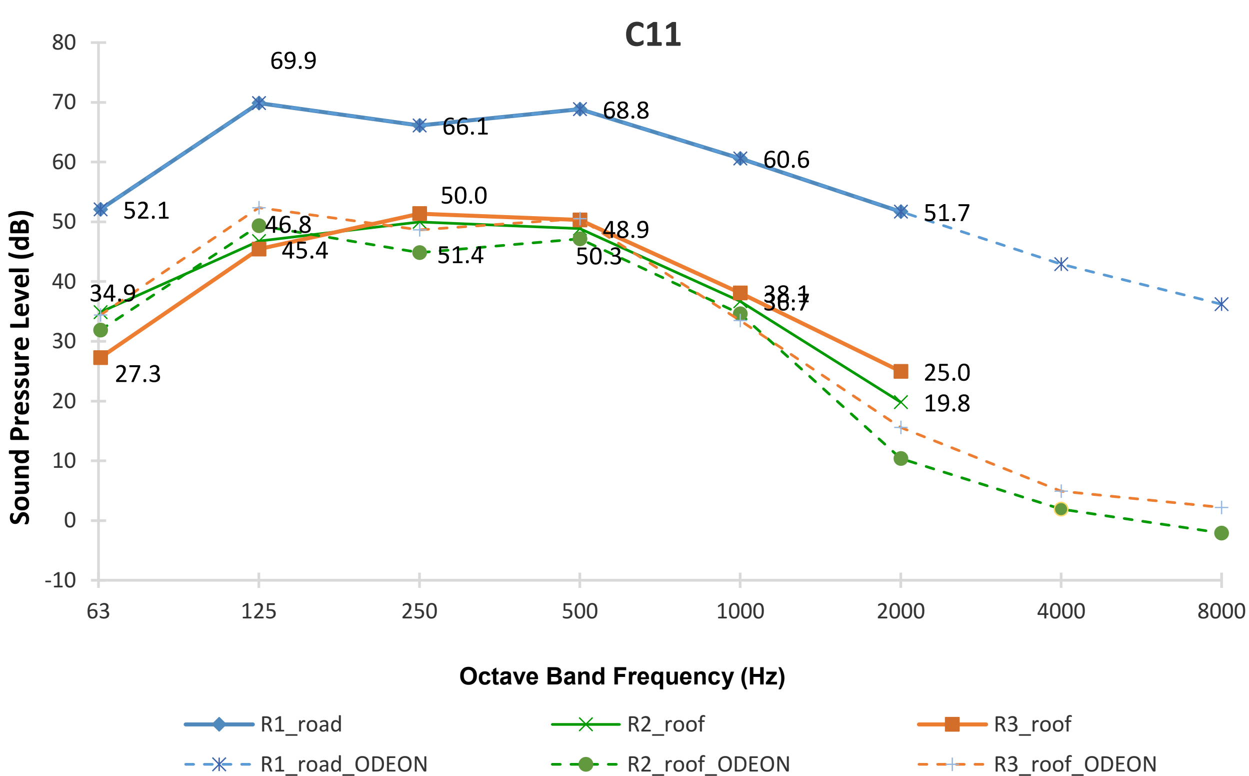


Figure 73: The C11 design tool configuration spectrum analysis.

The second-highest increased attenuation in this group was from the C6 and C12 configurations. The increased attenuation values for the C12 configuration equalled 6.8 dBA and 8.4 dBA for the AC and ODEON models, respectively, while the C6 configuration model provided 7.1–7.4 dBA attenuation. These two configurations were comprised of the same design tool combinations as C5 and C11, which showed the highest attenuation in this group, but the location of W3 was different. The High Wall (W3) was placed at the building edge closer to the source, resulting in slightly smaller increased attenuation compared to those of C5 and C11. On the other hand, the complex configurations that included a low guard barrier vegetated on both sides (G3) showed considerably less increased attenuation; attenuations varied between 2.2 and 5.1 dBA.

<u>Receiver B – Single-design tool configuration results analysis</u>

In the results for single-design tool configurations at Receiver B, the highest attenuation was shown in the high-wall categories (W1–W3). The increased attenuation varied from 3.8–5.7 dBA. The berm and green-roof categories (B1, OFF-B1, GR1) had the least impact for street noise-to-roof attenuation. The one-meter-wide green roof (GR1) showed the smallest attenuation, 0.3 and 1.3 dBA for the scale model and ODEON model, respectively, because the small mass and small area of the absorption surface made the low-profile design tools, or small-size design tools, showed a smaller increase in attenuation. In contrast, for the full area green-roof configuration (GR2), Receiver B showed higher attenuation. The scale model and ODEON model showed increased attenuation of 1.7 dBA and 2.6 dBA, respectively. The area of the green roof covering the roof to the location of Receiver B enabled increased attenuation at the further away receiver from the source. For the low-guard categories (G1–G3 and OFF-G1, OFF-G2, OFF-G3), the results showed a moderate increased attenuation varying from 1.2 dBA to 4.5 dBA. The OFF-G3 configuration showed the smallest attenuation in this category.

Receiver B – Double- and triple-design tool configuration results analysis

The greatest attenuation over 33 configurations at Receiver B showed in the OH1+GR1+B1+GR2 configuration, 8.7 dBA in the scale model results and 7 dBA in the ODEON simulation model results. The combination of overhang, full area green roof, and berm yielded the best in increased attenuation at the further receiver (Receiver B) on a rooftop. Figure 74 below illustrates the spectrum analysis results of the OH1+GR1+B1+GR2 configuration in both the 1:10 scale model and ODEON prediction model in a wide-spectrum band.

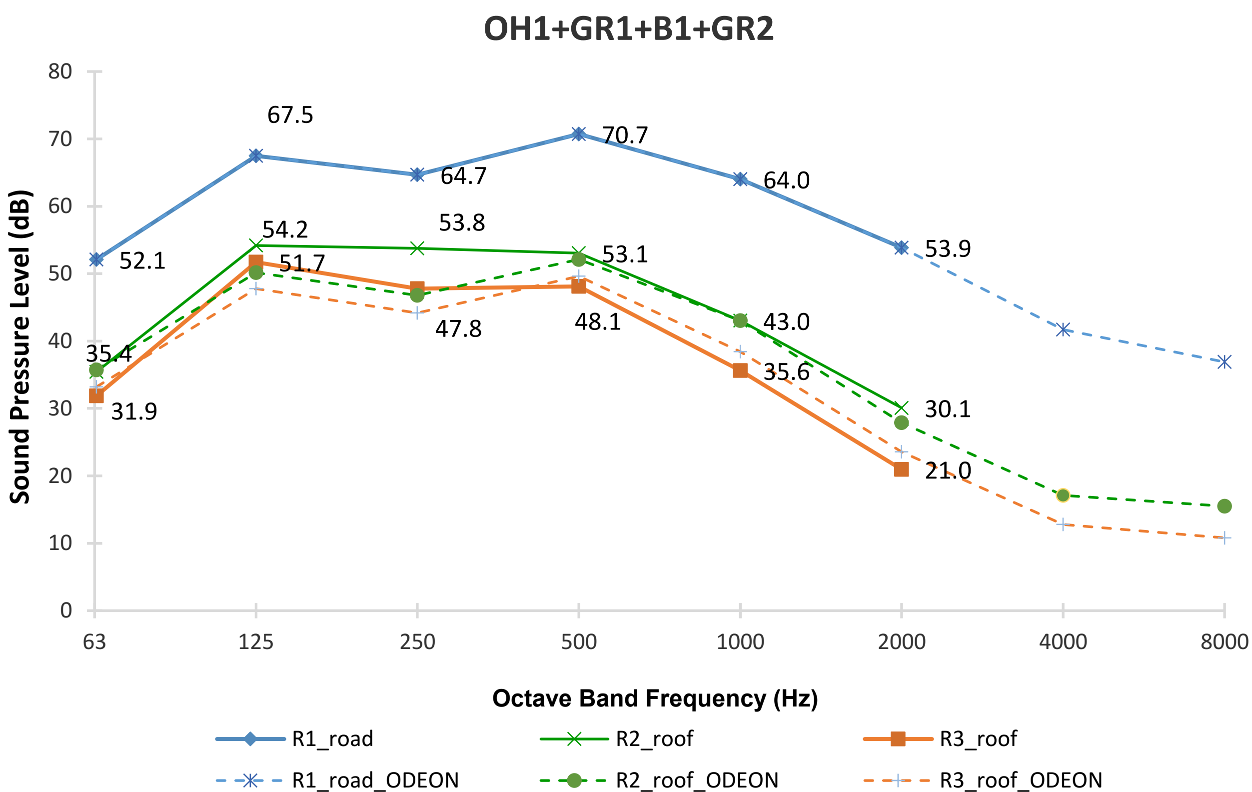


Figure 74: The OH1+GR1+B1+GR2 design tool configuration spectrum analysis.

<u>Receiver B – Complex-design tool configuration results analysis</u>

The highest attenuation values for the complex configurations were shown by the C4 and C10 configurations at Receiver B. The complex configurations with the combination of both-sides-vegetated high wall (W3), full area green roof (GR2), and the addition of an overhang (OH1) showed the highest attenuation at 4.3 dBA measured in scale model and 6.6 dBA predicted by ODEON. C7, which is the complex combination of overhang, berm, both-sides-vegetated low guard, and full area green roof showed the third highest increased attenuation for this complex group. Figure 75 shows the spectrum analysis of the C7 configuration. It is noticeable that the effects of the design tools in attenuating sound propagation from the street have not shown a huge impact at Receiver B (far field), compared to at Receiver A (near field). Unlike Receiver A's attenuation, the highest increased attenuation at Receiver B was from the double- and triple-design tool configurations. The OH1+GR1+B1+GR2 configuration measured 8.7 dBA in the 1:10 scale model.

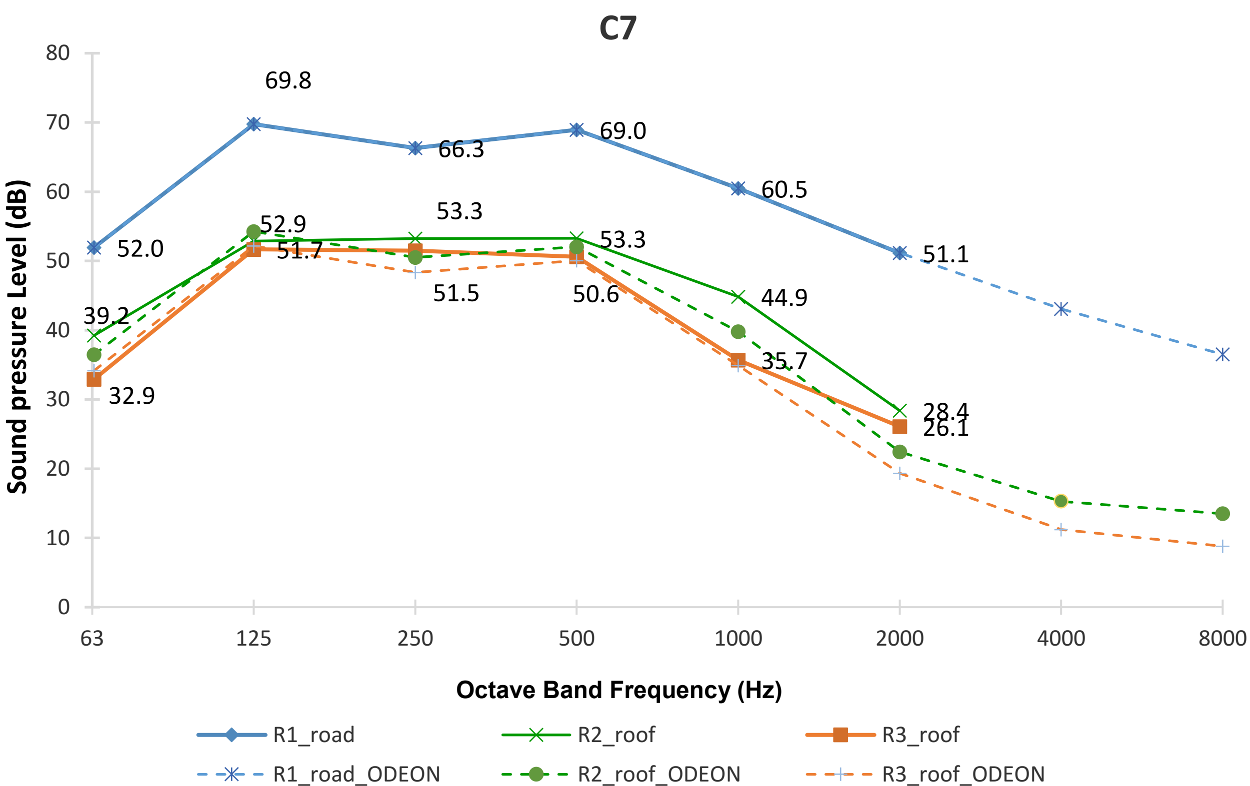


Figure 75: The C7 design tool configuration spectrum analysis.

The "C7" complex configuration with the combination of overhang (OH1), berm (B1), both-sides-vegetated shallow guard (G3), and full area green roof (GR2) showed a similar trend in the 1:10 scale model (AC) and ODEON model. For the ODEON prediction model, the trend was close to the scale model at low- and mid-frequency ranges, except at 250 Hz the scale model under-predicted an attenuation.

3.3 Rooftop Design Results

3.3.1 E. Hastings Building Configuration and Source Set-Up in ODEON Acoustic Simulation

Once the geometry and material set-up for the E. Hastings building configuration model was completed in the ODEON simulation software, the SPL grid response calculation was generated. Figure 76 illustrates the grid response calculations at 500 Hz by the ODEON simulation model.

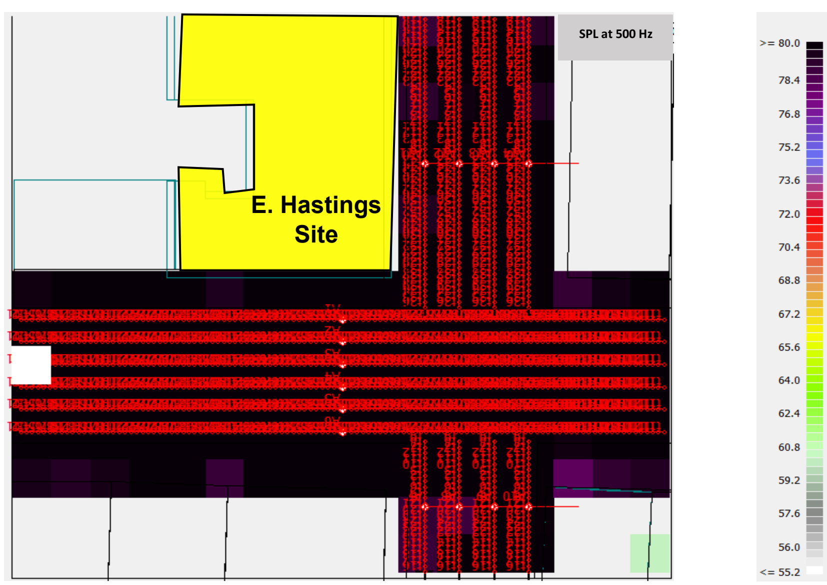


Figure 76: Colored grid response to SPL at 500 Hz resulting after the line source arrays had been assigned in ODEON.

Figure 77, referenced from Connelly, M (2011), illustrates the real background traffic noise data for the E. Hastings site, with the Lday in dBA shown at the boundary area of the simulation. The black area on the E. Hastings main road, as identified in the noise map, shows a noise level above 80 dB(A). East Hastings St. is the main truck route used for servicing downtown Vancouver. Apart from the busy road traffic as a main truck route during slow traffic hours, commuters during rush hours and local, lightweight industrial activities are the other noise sources in this sonic environment.

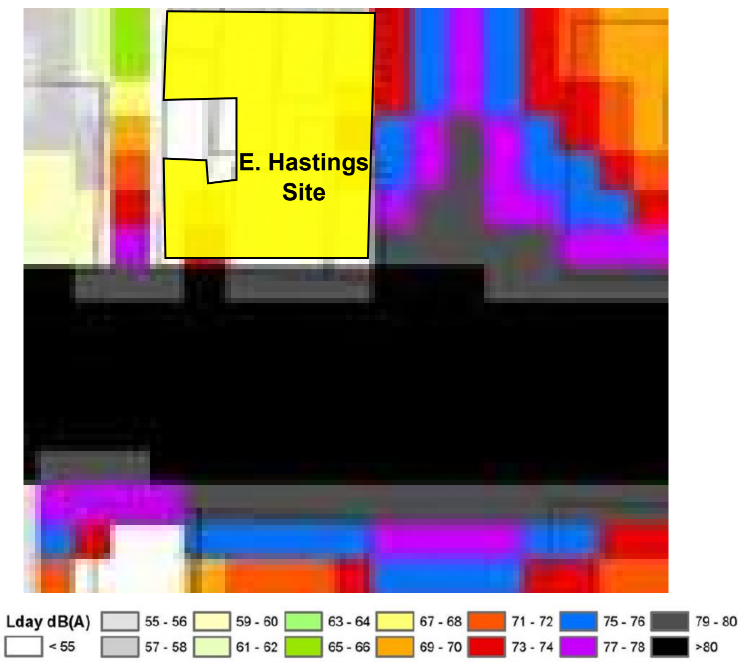


Figure 77: Lday (dB(A)) street background traffic noise SPL at the same location referenced from Connelly (2011).

Figure 78 illustrates the colored grid response of the total dBA of street noise source calculations analyzed from ASCII output—the street plan view. The source model grid result table analyzed from ASCII output can be found in the appendices.

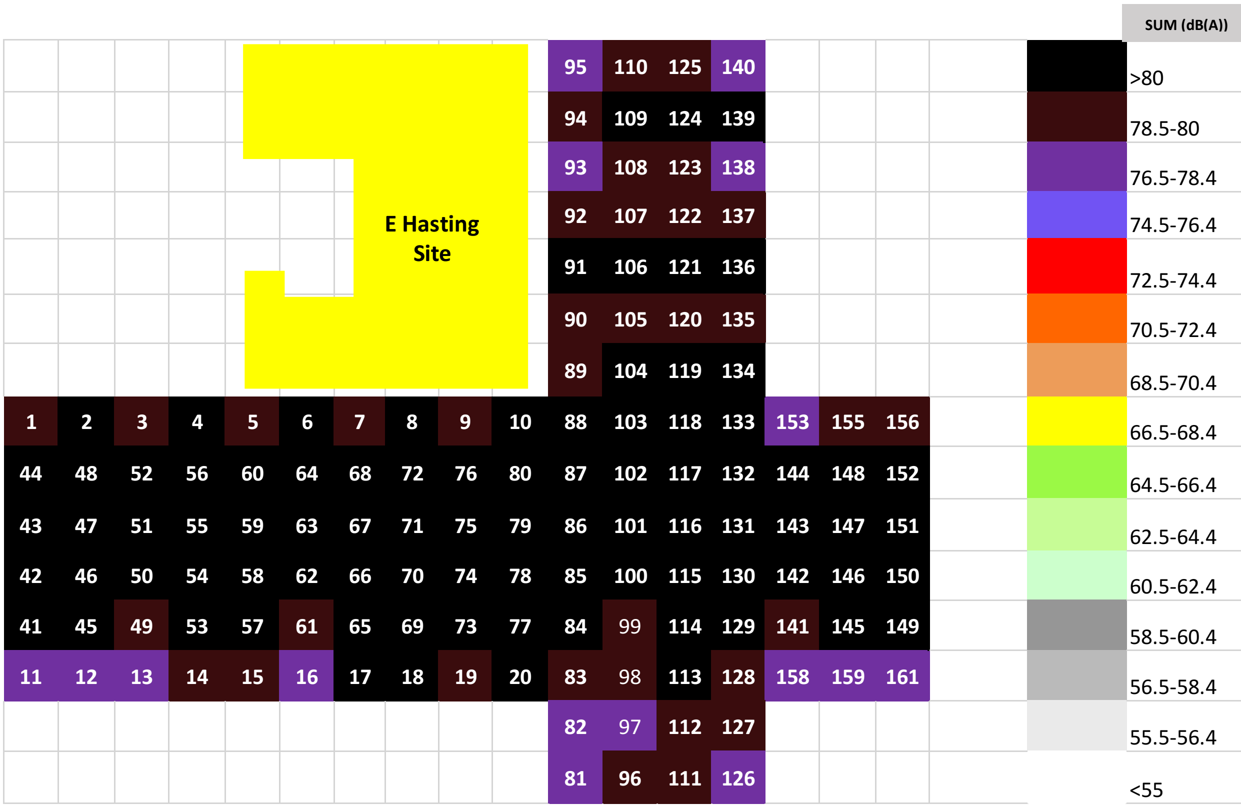


Figure 78: Total dB(A) colored grid response of the street source model analyzed from ASCII output.

The total dBA colored grid result from ODEON corresponds with Figure 77: Lday (dB(A)) street background traffic noise SPL at the same location referenced from Connelly (2011) shown in Figure 78. Therefore, the line source array set-up can efficiently be used as a traffic source model for E. Hastings Street and Heatley Avenue in the ODEON acoustic simulation software. Also, the source model can represent traffic at this selected site's acoustic environment and can be used for further calculations when applying the design tools to the E. Hastings building site in the ODEON simulation.

3.3.2 Creating Sonic Subzones from 23 Selected Design Tools for the E. Hastings Rooftop

Figures 79–81 illustrate the colored grid response results of the parametric model in an urban context, generated by the ODEON computer acoustic simulation software to predict the sound attenuation of design tool technologies. A total of 24 configurations of design tools on the building roof are illustrated. The colored scale represents the range of sound pressure levels in dBA at the measuring grid surfaces.

The results of a 2.5 x 2.5 m grid response calculation of 24 configurations, including a baseline E. Hastings site, are illustrated. For each configuration, a colored scale representing a different SPL, from <53.3 to >78.3 dBA, is also shown with each result. The black color represents a SPL above 80 dBA, while the white color represents a SPL under 55.2 dBA. Orange represents a SPL at 67.5 dBA.

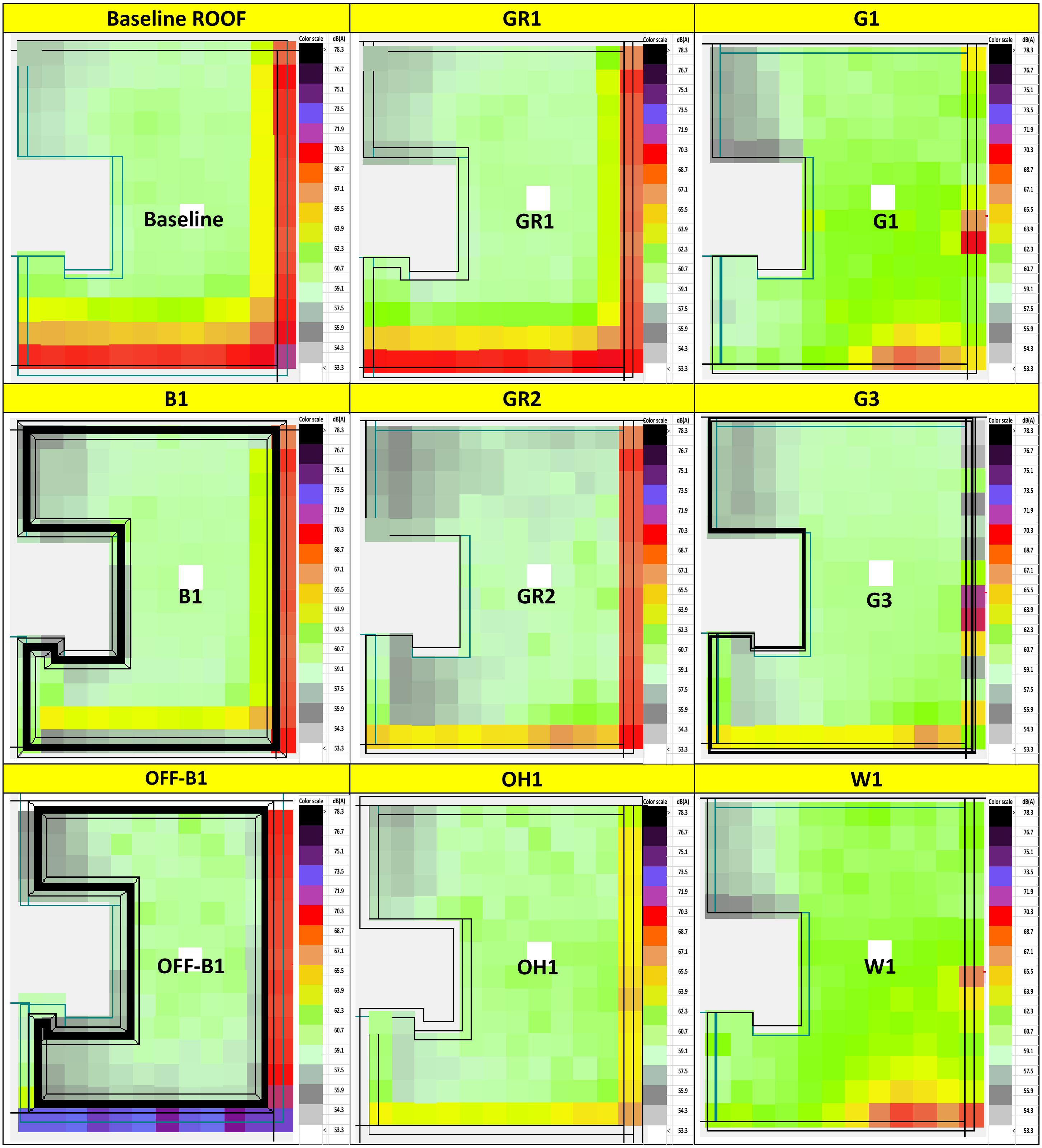


Figure 79: Sonic subzones of the E. Hastings building ROOF and 8 single-design tool configurations on the rooftop.

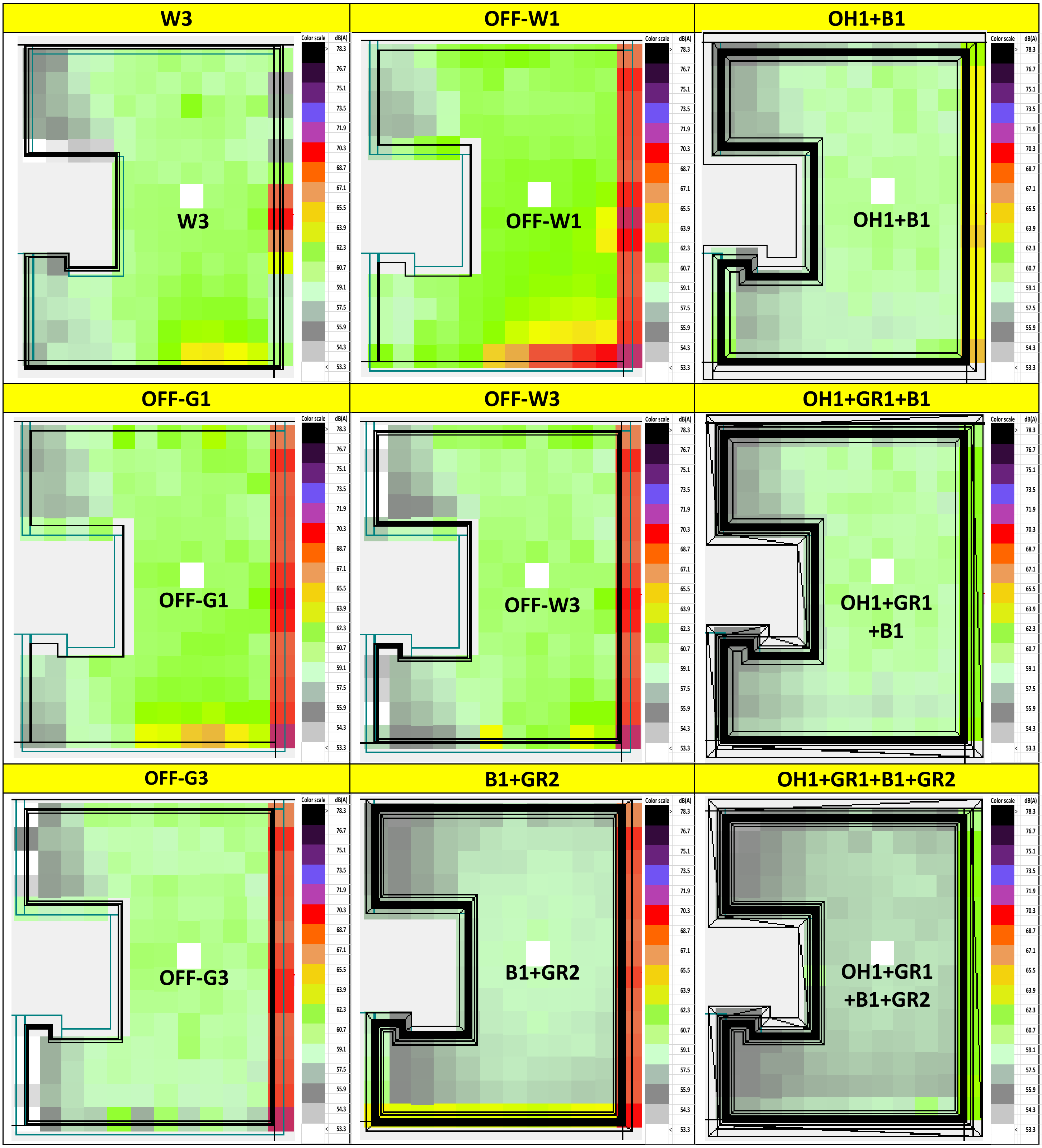


Figure 80: Sonic subzones of 5 single-, 2 double- and 2 triple-design tool configurations on the rooftop.

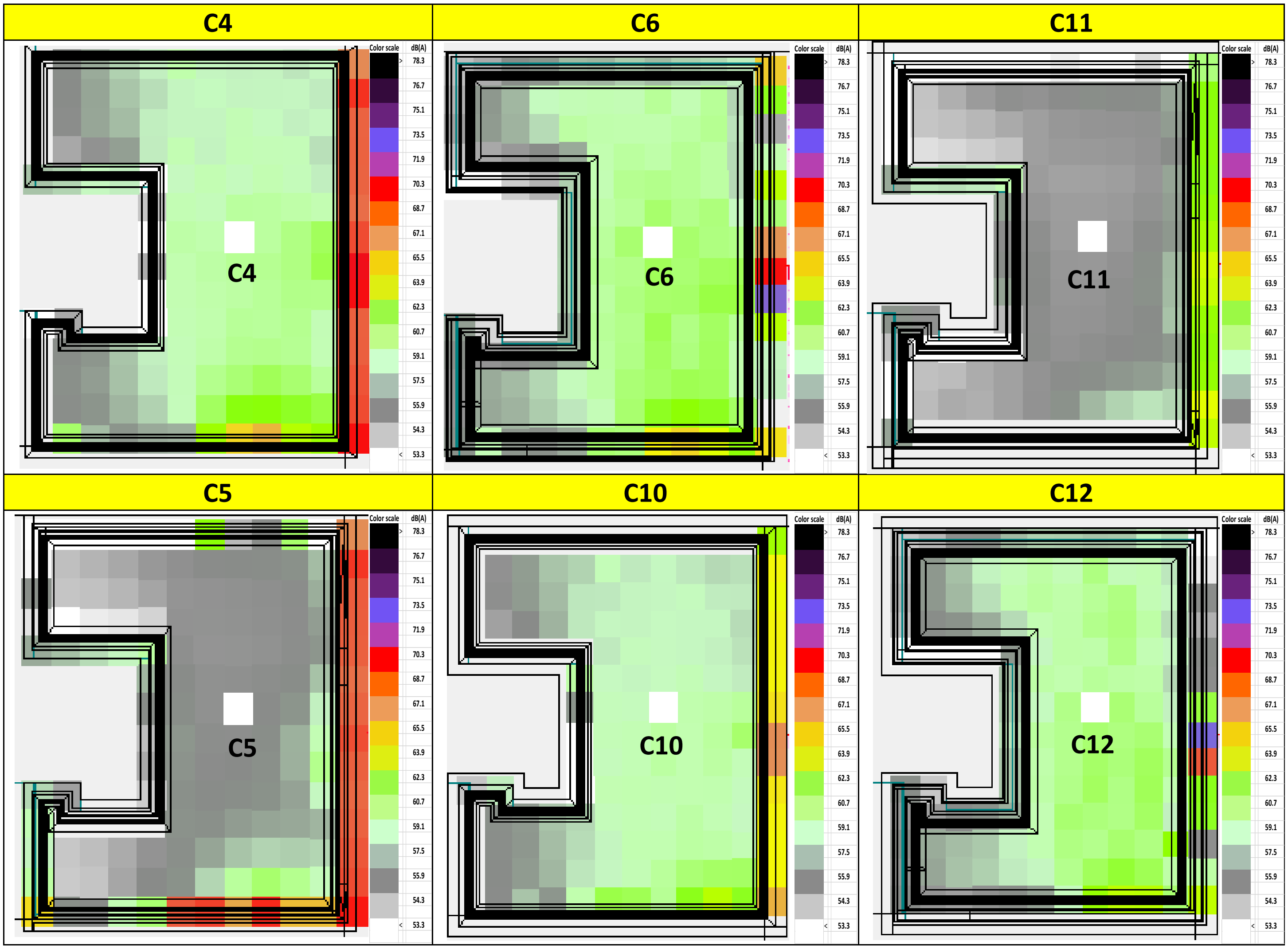


Figure 81: Sonic subzones of 6 complex-design tool configurations on the rooftop.

Then, the data from the grid response calculation were plotted according to the zone of interest, as shown in Table 23. Eight sonic subzones analyzed from the predicted SPL values are shown in Figure 82, a reference diagram of the top view of the E. Hastings roof. The attenuation by the design tools at each zone was analyzed and input into a data table (Table 23). The columns illustrated an average SPL in dBA at 8 sonic subzones and the reduction of SPL due to the design tools compared to the baseline ROOF configuration. Twenty-four rows represented the baseline ROOF and 23 design tool configurations.

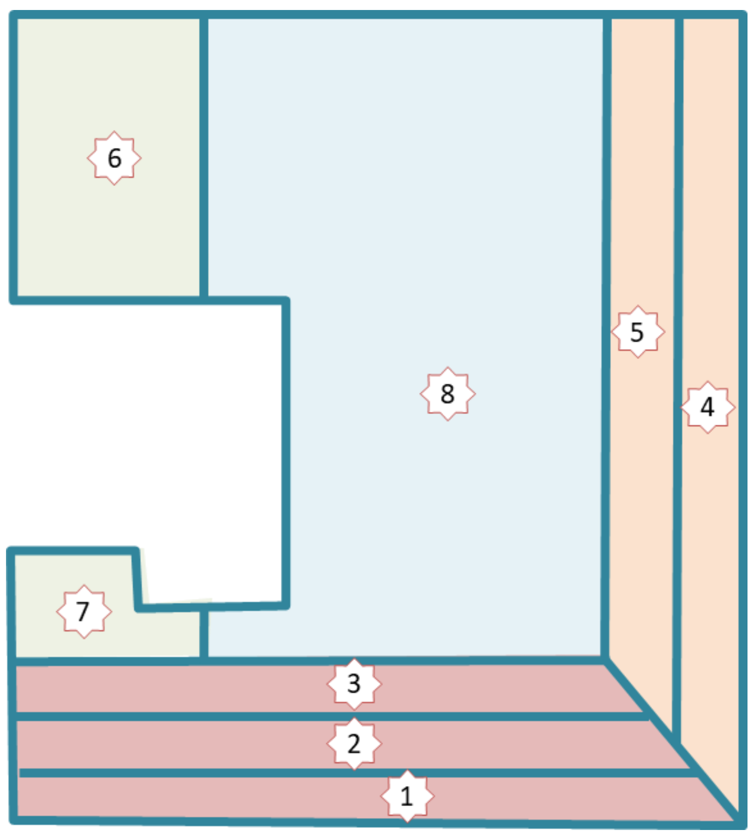


Figure 82: The zone diagram of the E. Hastings rooftop for sonic subzone analysis.

Table 23: Sonic Subzone Analysis of 24 configurations of SPL (dBA) and its attenuation from zones 1 – 8.

	Parameter Zone	High Density Traffic Zone						Low Density Traffic Zone				Courtyard Zone				Living Zone	
	Technology	1	Attn@1	2	Attn@3	3	Attn@4	4	Attn@2	5	Attn@5	6	Attn@6	7	Attn@7	8	Attn@8
	Baseline ROOF	70	(dBA)	66	(dBA)	63	(dBA)	70	(dBA)	64	(dBA)	58	(dBA)	62	(dBA)	61	(dBA)
Single	GR1	70	1	66	1	62	1	69	1	64	1	58	0	61	1	61	1
	GR2	66	4	58	8	58	6	69	2	58	7	57	2	58	5	58	3
	OH1	65	6	59	7	59	5	65	5	62	3	58	1	59	4	61	0
	B1	58	12	65	1	60	3	68	2	64	1	58	0	59	4	59	2
	OFF-B1	73	-3	58	8	58	5	69	1	58	7	58	1	58	4	60	2
	G1	64	6	61	5	62	2	63	7	62	2	58	0	59	3	62	-1
	G3	66	5	60	6	61	3	65	5	60	5	59	-1	60	3	59	2
	OFF-G1	64	7	60	6	61	2	68	2	60	4	57	1	59	3	61	0
	OFF-G3	61	9	59	7	59	5	68	2	59	5	59	-1	59	4	60	2
	W1	64	6	61	5	62	1	62	8	62	3	57	1	61	1	62	-1
	W3	63	8	60	7	60	3	68	3	60	4	57	2	57	6	61	1
	OFF-W1	64	6	61	5	63	1	69	1	62	2	57	1	59	3	62	-1
	OFF-W3	62	8	59	7	59	4	69	2	59	5	57	2	57	6	60	2
Double	B1+GR2	64	7	58	9	57	6	68	2	58	6	56	2	56	6	59	3
	OH1+B1	59	11	58	8	58	6	64	6	59	6	57	1	57	6	59	2
	OH1+GR1+B1	59	12	58	8	58	6	63	8	59	6	58	1	57	6	59	2
	OH1+GR1+B1+GR2	58	12	56	10	57	7	63	8	58	7	56	2	56	6	58	4
Complex	C4 (B1+W3+GR2)	62	8	59	8	58	5	69	2	59	6	57	2	56	6	59	3
	C5 (GR+B1+W3)	64	6	57	9	56	7	69	2	57	7	54	4	54	8	55	7
	C6 (W3+GR1+B1)	62	8	59	8	58	5	68	3	58	6	58	1	57	6	59	2
	C10 OH(B1+W3+GR2)	61	9	58	8	58	6	65	5	58	7	57	1	56	6	58	3
	C11 OH(GR+B1+W3)	54	17	57	10	56	7	63	7	57	8	54	4	54	8	55	6
	C12 OH(W3+GR1+B1)	62	9	58	8	58	5	67	3	58	7	58	1	57	6	59	2

A summary of sonic subzone investigation by zone of 23 design tool configurations is presented in this section. The Baseline ROOF configuration which modelled from the existing conditions of the building environment at the building site was measured in ODEON giving the SPL (dBA) results at 1.5 m height from the rooftop. The rooftop without any design tools for sound mitigation has a high noise exposure at roof level as shown in Figure 83. The roof edge next to street at high and low-density traffic subzone, zone 1 and zone 4, the SPL is 70 dBA. While zone 2, zone 3 and zone 5, the SPL decreased slightly due to attenuation over the distance averaging at 66 dBA, 63 dBA and 64 dBA respectively. Zone 6 and 7, which are the area at the opposite site of the building edge connected to the courtyard located the furthest away from the traffic, illustrate an average SPL of 58 and 62 dBA respectively. Lastly, the middle area of the roof called as living zone, zone 8, a moderated average SPL of 61 dBA shows.

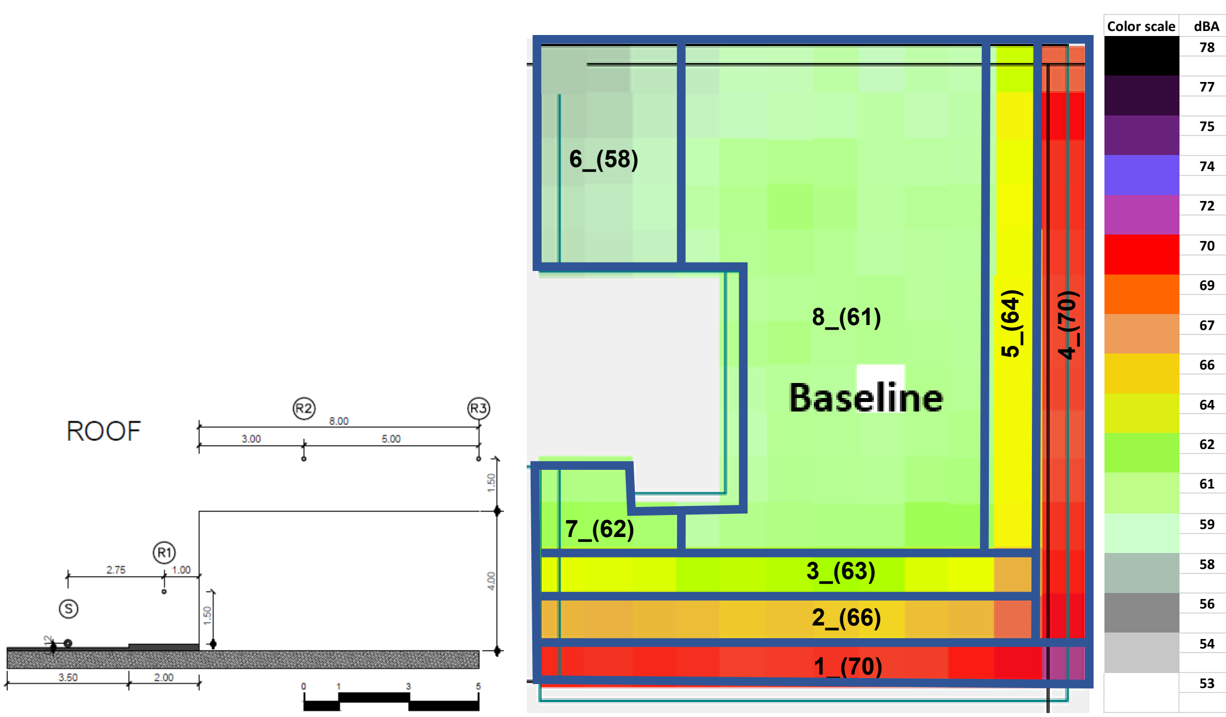


Figure 83: Sonic Subzone of Baseline ROOF configuration.

Number in front of the bracket is a zone number, number inside the bracket is the average SPL in dBA at each zone.

High Density Traffic Zone

The highest attenuation among 8 sonic subzones happened in this zone since it is the first area next to the edge diffraction. At single-design tool configurations, the different design tools provided -3 to 12 dB in attenuation. The highest attenuation for the single-design tools group is berm (B1), providing 12 dB attenuation from the measured SPL of 58 dBA at zone 1. In the double- and triple-design tools cases, more than 10 dB attenuation are shown. The highest reduction at sonic subzone 1 is at C11 (A complex configuration with a combination of overhang, full area green wall, berm and high vegetated wall), as illustrated in Figure 84. An average SPL of 53 dBA accounted for 17 dB attenuation was shown. A criterion for outdoor recreation space with SPL at or below 55 dBA is possible in zone 1, 6, 7 and 8 with installing C11 design tools at edge.

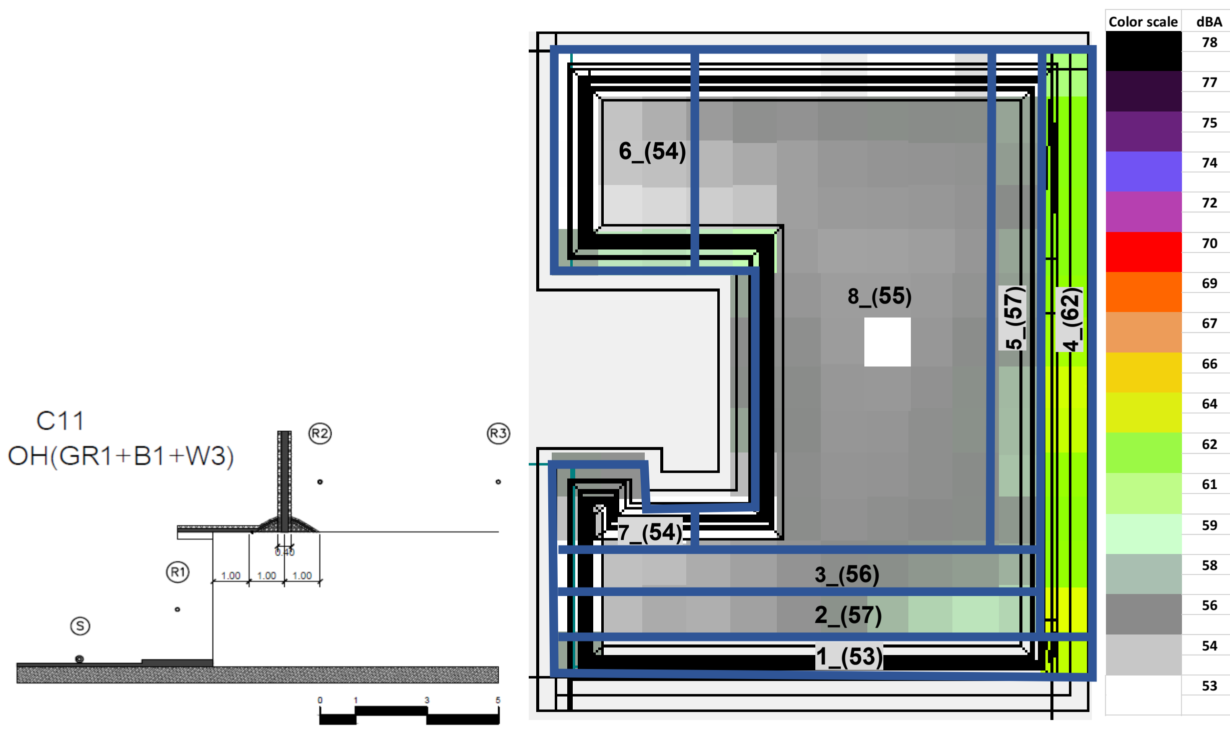


Figure 84: Sonic Subzone of C11 OH(GR1+B1+W3) configuration,

Number in front of the bracket is a zone number, number inside the bracket is an average SPL in dBA at each zone

The best performance in mitigating the traffic sound in sonic zone 2 is OH1+GR1+B1+GR2 configuration, as illustrated in Figure 85. Almost 10 dB attenuation from 66 dBA to 56 dBA is modelled after an overhang, berm and full area green roof had installed on the roof edge. The C11 configuration which showed the highest attenuation at zone 1 also showed 10 dB reduction at this sonic subzone. The design tool configuration that given a second-high attenuation value at this zone is B1+GR2 configuration. For this case, GR2 represented a full area of green roof influences the noise reduction at this zone.

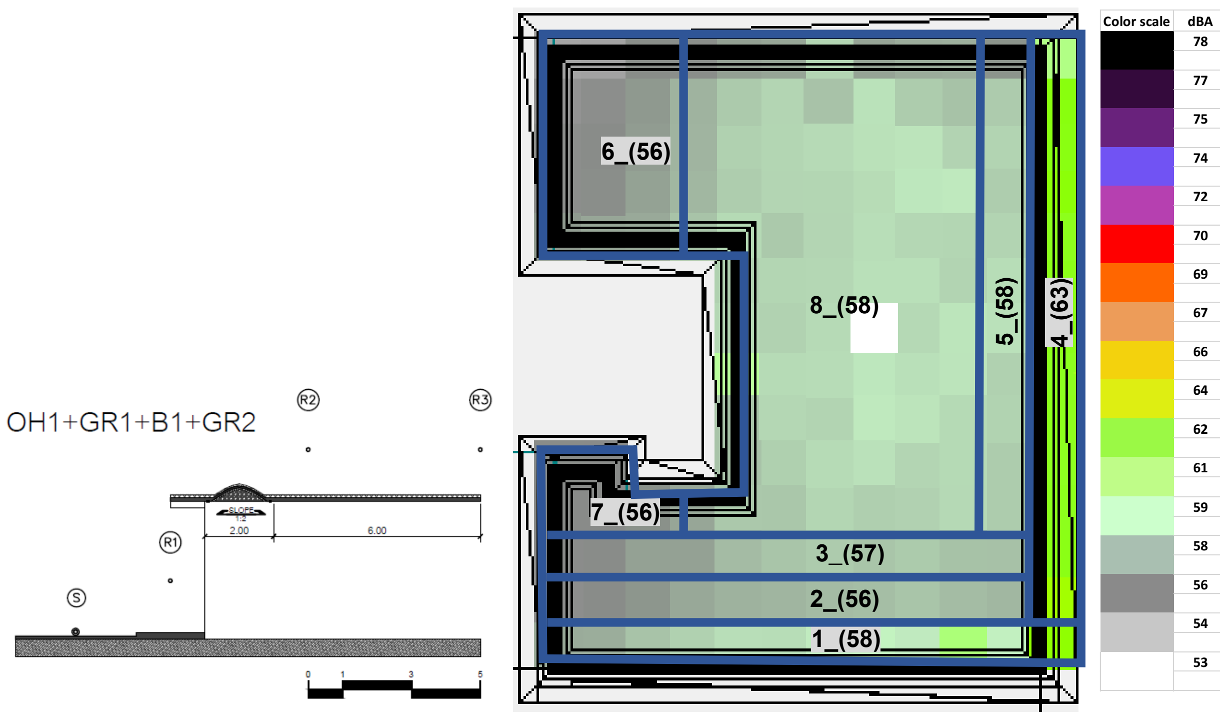


Figure 85: Sonic Subzone of OH1+GR1+B1+GR2 configuration,

Number in front of the bracket is a zone number, number inside the bracket is an average SPL in dBA at each zone

At sonic subzone 3, the furthest zone away from high density traffic, 7 dB attenuation was modelled with OH1+GR1+B1+GR2, C5 and C11 configurations. These are the configurations that have the best attenuation at this zone.

Low Density Traffic Zone

Zone 4 at low density traffic zone is situated next to the building edge above 4 traffic lanes of Heatley Avenue. An attenuation, due to the building design tools, moderately influences the SPL reduction at this zone. The highest SPL reduction is provided by the triple-design tool configurations, OH1+GR1+B1 and OH1+GR1+B1+GR2. An attenuation of 8 dB from 70 dBA to 63 dBA was modelled. The color grid response results of OH1+GR1+B1 illustrated at Figure 86.

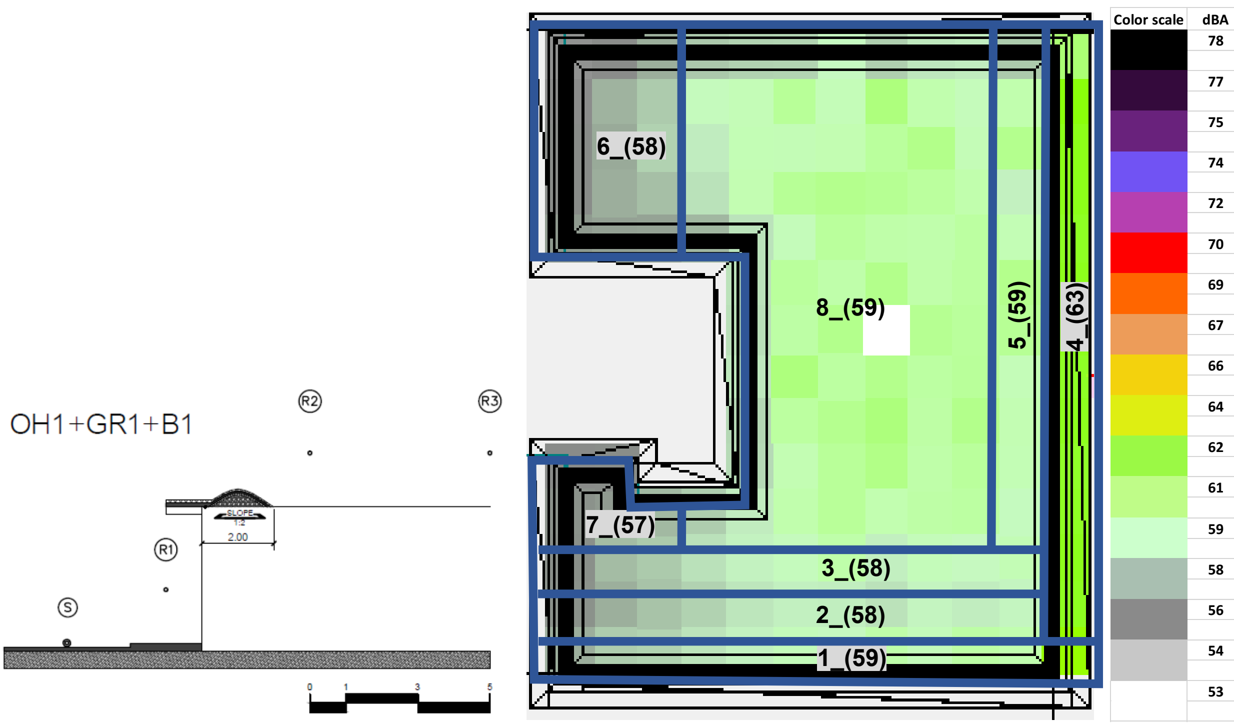


Figure 86: Sonic Subzone of OH1 +GR1+B1 configuration,

Number in front of the bracket is a zone number, number inside the bracket is an average SPL in dBA at each zone

At the receiving area on the roof second next to the sub road; Heatley Avenue, zone 5, C11 configuration showed the highest attenuation again. 8 dB reduction from 64 dBA to 57 dBA with the overhang, green roof, berm and both side vegetated high wall, is shown. Therefore, 7 dB noise attenuation is shown in many configurations such as GR2, OH1+GR1+B1+GR2, C5, C10 and C12. It is noticing that almost all of the configurations consisted of green roof technology.

<u>Courtyard Zone</u>

Only small attenuation is shown at this sonic subzone 6 since the zone located at a far back of the building from the traffic noise source. The highest reduction was providing by C5 (GR+B1+W3) and C11 (OH1+GR1+B1+W3). Figure 87 below shows the color grid response results of C5 configuration on the E. Hastings building site.

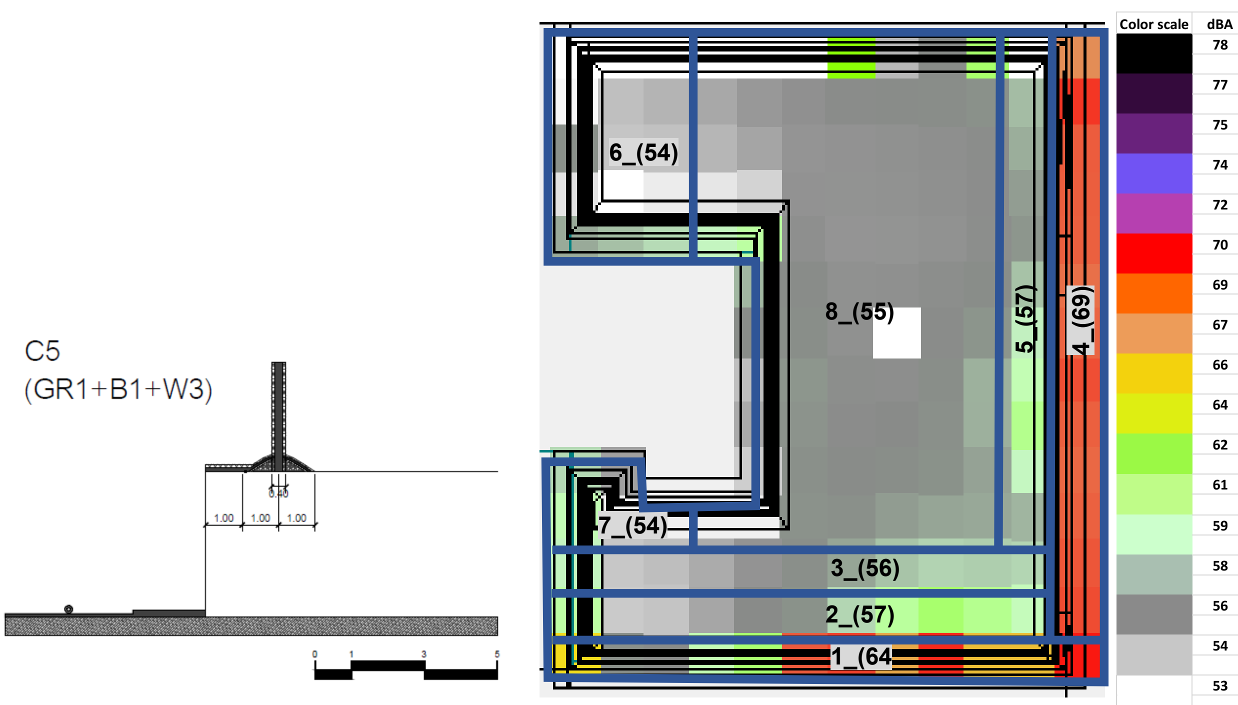


Figure 87: Sonic Subzone of C5, GR1+B1+W3 configuration,

Number in front of the bracket is a zone number, number inside the bracket is an average SPL in dBA at each zone

Sonic subzone 7 in the courtyard zone is located further away from the main E. Hastings Street on the left side of the building. At single configurations, a lower attenuation below 5 dB were expected. Moreover, 6 dB attenuation can be achieved at W3 configuration, all double- and triple-design tool configurations and complex configurations. The highest attenuation at this zone was modelled with C5 and C11 corresponding to the results at zone 6, 8 dB attenuation can be perceived. Therefore, it possible to create an outdoor recreation space where SPL is below 55 dBA with this design tool configuration at this zone, average SPL at this zone modelled with C5 and C11 configuration was 54 dBA.

Living Zone

The biggest area in the middle of the roof is called as a living zone, sonic subzone 8. This zone can make the best use of the space for various type of recreation activities since it has the largest area on roof. The design tool configurations that showed the highest attenuation is C5 (GR1+B1+W3) and C11 (OH1+GR1+B1+W3) which 6 dB attenuation can be achieved. Figure 84 shows the color grid response results of C11 configuration. An average SPL at this zone was shown at 55 dBA for the roof with a combination of those design tools (C5 and C11). However, at this zone, a few configurations results in a negative value attenuation, such as G1, W1 and OFF-W1 where those design tools are made of a high reflecting material. A single-design tool configuration did not give a good result in term of sound reduction when comparing to a Baseline ROOF configuration. Double- and triple-design tool configurations showed a moderate attenuation of 2 to 4 dB at this zone.

LIMITATION

In this research investigation, several design tools used for the rooftop sound attenuation were selected based on the goal to bring nature to the building. The criteria for size selection of those design tools followed recommendations and a common-building practices which were referenced in published literatures the field of living architecture. Therefore, not all potential solutions were examined. Further, the scope of the selection was limited to those design tools that could be model at 1:10 scale with accuracy in material representation. Two different methods were verified to determine the sound attenuation results by the design tool technologies. One was a 1:10 physical scale model in the anechoic chamber, and the other was a computer simulation in the ODEON acoustic modelling software. Modelling procedures for both models are discussed in detail in the Methodology chapter. This section briefly reviews the limitations in both modelling techniques.

Physical scale modelling was the primary method used in this research. For several decades, many research studies have used this model methodology to solve acoustic problems. The scale modelling method is straight-forward and, accurately predicts the results, since the measurements can be taken physically. The relationship between the size of the model object, and the wavelength of sound was taken into consideration for the model size, the measurement set-up and, the acoustical characteristic of representative materials. The size of the anechoic chamber limits the area surrounding of the scale model and creates a boundary which does not exist in reality.

The ODEON acoustic simulation model was the other method in the research methodology used to investigate the increase in attenuation by the design tools, in the comparison to the scale model method. The actual scale model size and frequency range from 63 Hz–8K Hz were modelled in ODEON. For the investigation of the E. Hastings rooftop design, only the ODEON calculations were relied on to determine the attenuation by the design tools. In the simulation model, the calculations represent the ideal condition, while calculations from the scale model are taken from physical measurements. Even though the differences in prediction of the total dBA would not be audible in terms of human hearing, caution is needed. The differences low amplitude at the highest and lowest frequency bands of the line source spectrum may be perceivable.

DISCUSSION

Rooftop gardens are widely constructed for a living space as part of amenity zones for city residential buildings and commercial buildings, At the same time, the urban environment has been significantly degraded from urbanization. Noise pollution has become a major problem of cities. Consequently, the World Health Organization (WHO) recommends an SPL of noise below 55 dBA for a amenity space in an urban area, which benefits the occupants in terms of their physical and mental health.

The objective of this research was to identify the living architecture design tools that most significantly attenuate noise from street level. The findings would then govern the design of a rooftop space to reduce the sound pressure level to the acceptable range recommended by WHO for an outdoor living space. Living architecture, such as a green roof, berm, and living wall, are the keys to success. An overhang is another design tool used in this investigation. It is not considered as a living architecture, but, as part of the flat roof structure of a vegetated layer, an overhang on top or below under the soffit could also act as a horizontal living architecture. Six building components—green roof (GR), berm (B), guard (G), wall (W) and overhang (OH) were evaluated. The outcome of this research was finding and using the building technologies that could be used on rooftop areas.

Overall, in the investigation of the design tools, a small difference in the predicted total dBA, from (-1.9)–2.7 dBA, was shown by the two model methods (Table 11, Page 85), meaning that measurements from both models had a high reliability and could accurately predict the noise attenuation effects by the design tools. The highest off-differences appeared with the complex configurations, which is where the (-0.9)–2.7 dBA difference was seen. At single-design tool configurations, the differences were ±1.6 dBA. With both the physical scale model and ODEON simulation model, the more design tools added to the configuration, the higher chance of error was shown in predicting the attenuation results. However, the two model methods gave similar results for predicting the sound attenuation of the technologies on the rooftop. The findings from this investigation were assurance that the two prediction models could be trusted and could be used in the next part of the research to apply the design tool technologies to a specific site on E. Hasting Street.

In analyzing the design tool investigation results, it can be concluded that an increase in attenuation is a function of the surface area absorption and the number of design tools used in the configuration. The closer the design tool is to the receiver position, the better the attenuation. The off-set design tools, including the off-set berm, off-set guard technologies and the 1 m wide green roof (GR1), showed the smallest attenuation in the single-design tool configurations, especially at Receiver B. The reason for that would be that the sound energy had been modified twice: first, by the diffraction over the hard building edge and, secondly, by the scattering on the vegetation surface causing a number of rays to be scattered toward both receivers. The sound energy still presents at Receiver B, due to the complexity of the sound paths. However, for the configurations that comprised the building edge of a solid material, such as OH1, OFF-B, OFF-G etc., the SPL at pedestrian level tended to be louder. This could be because the building edge diffraction made the sound energy, once it hit the solid edge, bounce back to the street pedestrian sidewalk.

The findings of the double- and triple-design tool configuration analysis suggest that, the more design tools added and the more area coverage of the design tools on roof toward the receiver positions, the better effects of noise mitigation were shown. Especially at configurations with an overhang (OH) at roof edge, the greater increase in attenuation at Receiver B, which was further away from the building edge, showed significantly. The complex configurations, C4, C7, and C10 (Figure 88), showed the highest predicting results at Receiver B for both models. Receiver B showed the largest increase in attenuation in those configurations because it relied on the high mass absorption of the full area of the green roof, which was used in all configurations mentioned above. The absorption area of the material affects the noise attenuation results; hence, having the absorption material over the receiving zone would mitigate noise propagation effectively.

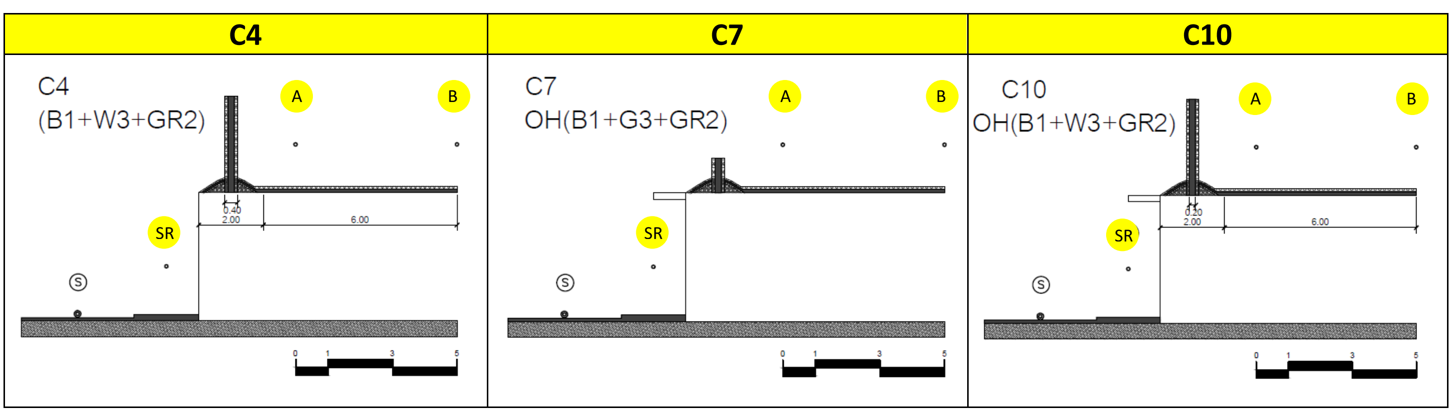


Figure 88: Complex configurations that showed the highest increased attenuation at Receiver B in the design tools investigation.

In the ODEON simulation model results from the E. Hastings rooftop design program, the most effective design tool configuration was C11, OH(GR1+B1+W3). This configuration was comprised of a 1 m wide overhang with a green roof covering the top of the overhang, a berm next to it with a green wall in the middle of the berm; a 3 m high wall, vegetated on both sides. (see Figure 89). For this configuration, the predicted SPL at 1.5 m above the rooftop surface showed the smallest values, meaning that it had the highest attenuation among all the configurations. At 8 different sonic subzones, 53– 62 dBA could be expected. The attenuation of 4–17 dB could be obtained when considering the reduction of the loudness after the design tools have been installed, compared to the existing building site without any noise mitigation technologies.

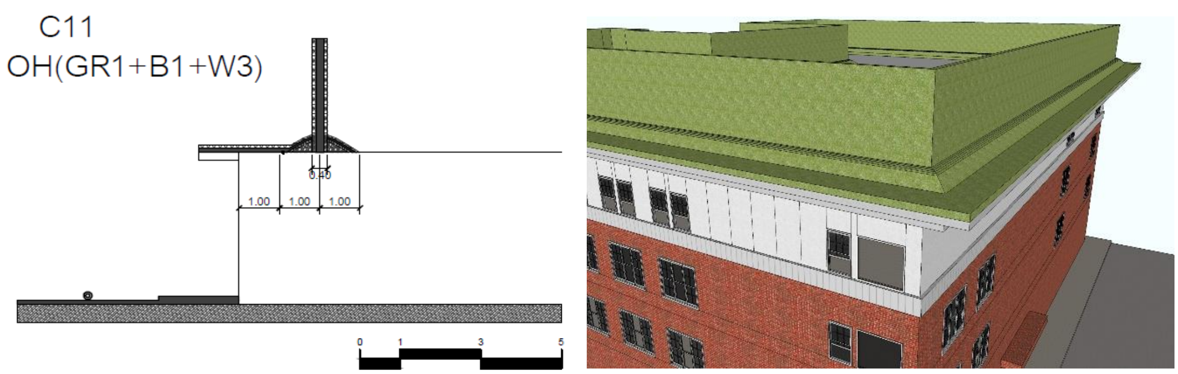


Figure 89: C11, OH(GR1+B1+W3) configuration.

The site for the rooftop design program investigation was selected based on the worst-case scenario of a street in Vancouver, so that the loudest road could be used in the simulation for the research investigation. However, if we are considering a more common level of traffic noise in the Vancouver mainland area, with an average level of traffic noise, the more options for design tool configurations will be achievable to satisfy the maximum 55 dB noise level criterium for outdoor living areas recommended by WHO. Most of the double- and triple-design tool configurations comprised of a full area green roof, and most of the complex configurations, such as OH1+GR1+B1+GR2, C5 and C11, can comprise a rooftop space that meets the need for a pleasant sound environment for the users.

The second-best configuration that attenuated traffic noise in the ODEON simulation model results was C5 (GR1+B1+W3) (Figure 90). The same set of design tools as in the C11 configuration, except the lack of overhang, showed as good attenuation as C11. However, without an overhang solid barrier, acoustic zones 1 and 4, which are the areas on the roof next to the main road and sub-road, were illustrated by orange to red color hues, which represent high noise levels ranging from 64–70 dBA. The analysis of the design tool layouts hints at how powerful an overhang is in attenuating traffic noise at the rooftop building edge next to the road.

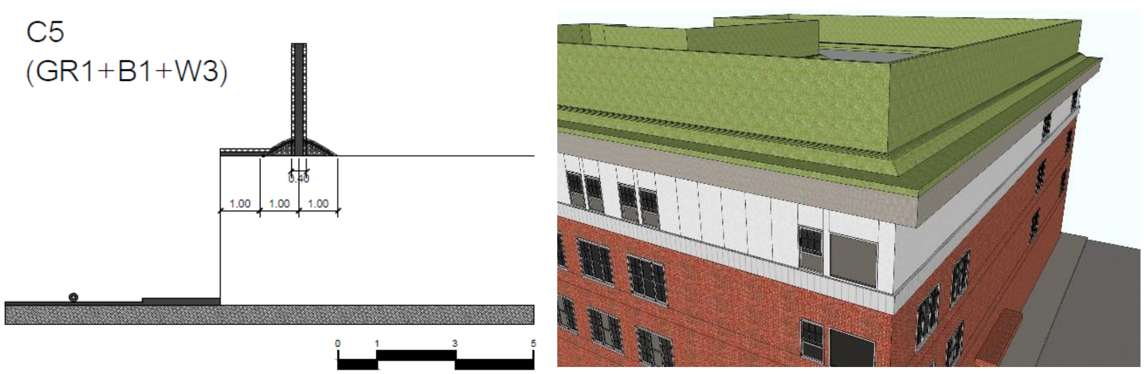


Figure 90: C5, (GR1+B1+W3) configuration.

One thing to note is that, it is likely the performance in yielding a good attenuation prediction for both the C5 and C11 configurations was from the W3 design tool. Because of the 3 m high wall with the large absorption area of vegetated layers on both sides, a large amount of sound energy is attenuated over the path through to the receiver area. However, in real-world building practice, the use of a 3 m high wall with vegetation layers would have several drawbacks for the user in terms of the cost for construction, maintenance and view blockage, for example. Therefore, the configuration that would be the answer for the users might be the triple configurations comprised of OH1+GR1+B1+GR2. Figure 91 illustrates the OH1+GR1+B1+GR2 configuration. The acoustic performance is comparable to a simpler design tool construction.

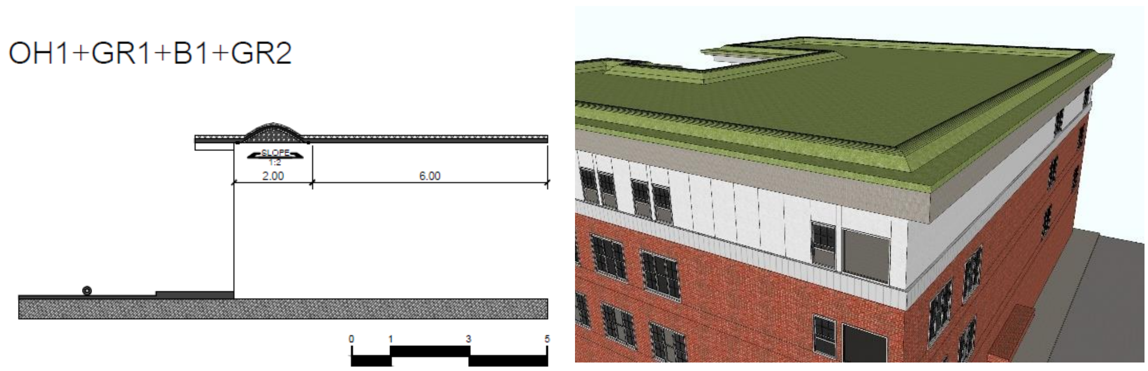


Figure 91: OH1+GR1+B1+GR2 configuration.

CONCLUSION AND OUTCOMES

A research framework was established for investigating living architecture design tools for the attenuation of street level noise at the rooftop level. The two parts of the investigation were completed: one was to investigate the design tools, and the other was to create the design program for a rooftop space using the design tools. The later could be used to develop a design guideline for the community. For the first method, the measurements were carried out in the anechoic chamber using the 1:10 physical scale model with construction materials that had representational absorption coefficients of a real-world material; prediction of the same model were evaluated with ODEON acoustic simulation software. The second method was to rely on the ODEON acoustic simulation software to simulate the real building site at E. Hastings Street, and to simulate the traffic source power that represented a stream of traffic flow at that street. The materials were similar to those referenced from other studies.

For the design tool investigation, 33 design tool technologies comprised of a green roof, berm, overhang, 1.07 m high guard, and 3 m high wall, with and without a vegetated layer, were simulated and their attenuation prediction results were measured in both the physical scale model and ODEON computer simulation model. The experimental results on the design tool configurations measured in both models showed a similar trend in the total dBA sound pressure level results and the frequency spectrum results at three receivers located at street level and at two locations on the rooftop.

The conclusion from the design tool investigation is that the effect on noise reduction increased with an increase in the number of design tools that made up the configurations. As well, the area of the absorption material of the design tools, such as the green roof and green wall, influenced the total noise reduction on the rooftop. The design tool configurations that included an overhang effected a good noise reduction at Receiver B, which was positioned further away from the rooftop edge. The closer the design tools are to the receiver position, the better the attenuation that results.

The second part of the investigation was to apply the design tools to the real site E. Hastings Street to create habitable space which meet the WHO recommendation, less than 55 dBA of traffic noise. The attenuation functions also rely on the number of the design tools per configuration and the area of absorption materials over the path from source to receiver. The ODEON acoustic simulation model was the only method for this part of the investigation. The 2.5 x 2.5 m grid response results from ODEON ASCII output were acquired and the colored-range of SPL at the 8 different sonic subzones were illustrated. The findings could be used to implement a guideline for the use of living architecture design tools for a rooftop space and to design a community rooftop to be an acoustically friendly living space for the city.

FUTURE WORK

Sounds produced by nature, including those generated by water, wind, storms and sounds of living organisms such as birds, insects, and humans are considered the speakers of nature. In the early world, only nature controlled the soundscape harmony. Now the world of soundscapes has changed. A city environment bends the traditional way of natural sounds into an all-time lo-fi condition, where background noise created by all kinds of vehicles and people's activities is greater than the background of natural sounds.

Figure 92: Natural Sounds, reprinted from List of natural sounds. (Google, n.d., Retrieved January 27, 2017)

The natural acoustics	Geophony	Sound of water	Oceans, seas, rivers, streams, rain
		Sound of air	Wind
	Biophony	Sound of birds	Sparrow
		Sound of insects	Flies
Human made acoustics	Anthrophony	Sound and society	Town, urban, parks
		Mechanical sounds	Machines, aircraft, constructions...

Figure 93: Urban sound classification. (Wang, K., 2004)

Introducing natural sounds back into the city soundscape is a pleasant way of balancing the harmony of the soundscape on rooftops. The high level of sound diffracted from street vehicles and sounds of mechanical systems which are usually placed on rooftops creates a huge, dominant excess of low-frequency sound waves, which normally can be attenuated by material absorption on purposely designed rooftops. However, with natural sounds, such as the high-pitched song of birds inhabiting the green roof, would bring high- and mid-frequencies to the rooftop space which could balance some of those low-frequency noises effectively.

Integrating natural sounds may creatively mask traffic noise and create sound balance on the rooftop space, adding an aural esthetic to improve the rooftop acoustic environment. Associated with each tool would be an algorithm to apply to a specific site. Applying psychoacoustic parameters will illustrate the satisfaction from human sound perception on the rooftop soundscape, because “The subjectively felt noise quality does not only depend on the A-weighted sound pressure level, but also on other psychoacoustical parameters such as loudness, roughness, sharpness, etc.” (Genuit and Fiebig, 2005). An A-weighted SPL could be mapped with psychoacoustic parameters to predict sound quality, as well as annoyance, of sound events on rooftops in future work.

Acoustic auralization in ODEON is a useful application to simulate natural sounds for integrating into the acoustic environment in a model simulation. The anechoic audio recording could have an acoustic impulse response to the natural sounds created. “Multi-source auralization makes it possible to create soundscapes and realistic virtual sound environments based on the ODEON model convolved with anechoic recordings” (Soundscapes and multi-source auralization, ODEON). Therefore, the natural sounds audio recording of water drops, waterfalls, wind, foliage and birds and insects would be available from the acoustic library to investigate further. The whole design simulation of the rooftop soundscape with simulated inputs from living architecture design tools and natural sounds could easily be achieved using an ODEON simulation model in future work.

APPENDICES

Measurement Tools for the Scale Model Test in the Anechoic Chamber

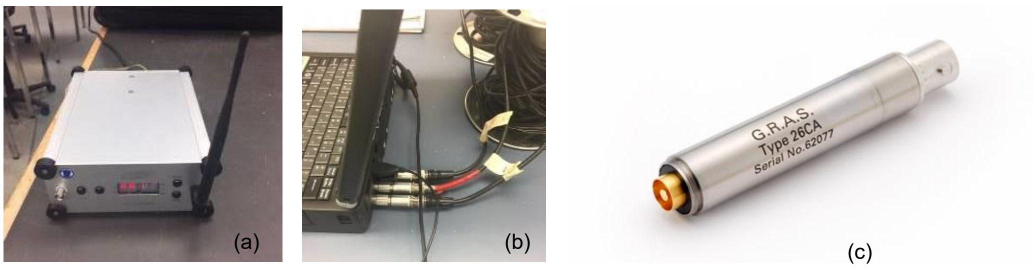
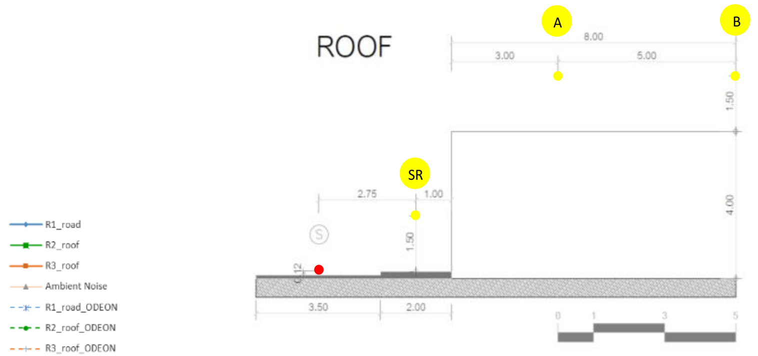


Figure 94: (a) Sound generator/sound amplifier, (b) A Soundbook with 3 channel outputs, (c) 1/2" microphones (G.R.A.S. 26CA).

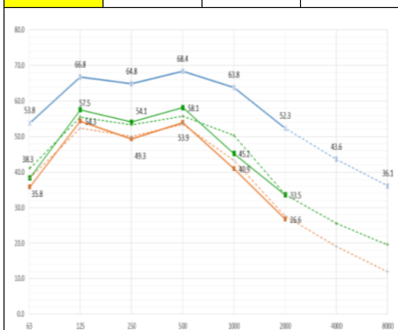
Spectrum Attenuation by Design Tools (dBA)

Table 24: Attenuation by design tool spectrum analysis for ROOF and single-design tool configurations.

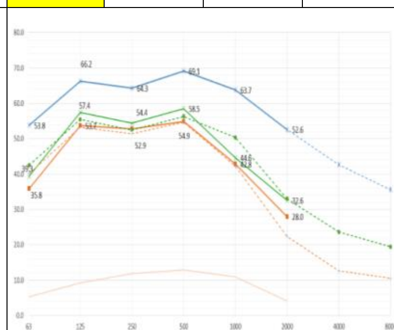
ROOF			
	68.4	57.3	54.2
	68.6	56.4	52.5



B1			
	68.2	56.1	51.9
		55.4	52.5

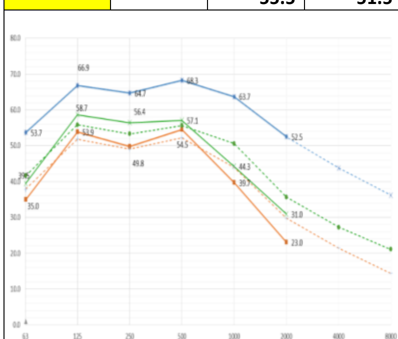


OFF-B1			
	68.5	56.4	53.1
		55.9	54

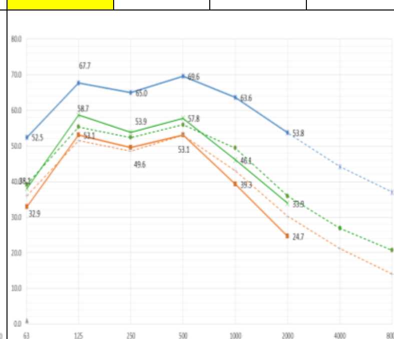


GR1			
	68.2	55.9	53.7
		55.6	52.9

GR2			
	68.1	55.2	52.2
		55.5	51.5



OH1			
	68.9	55.9	51.1
		55.2	51.8



G1			
	68.2	54.6	49.7
		53	51

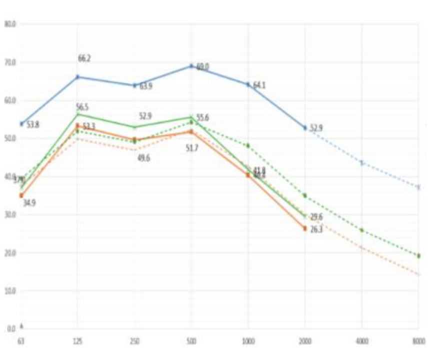
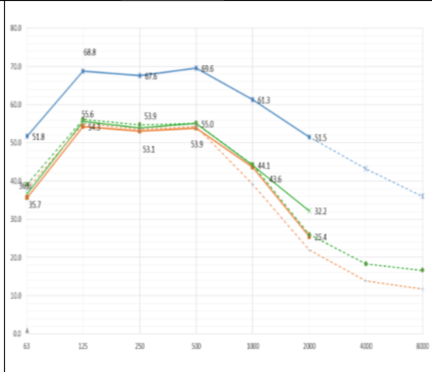
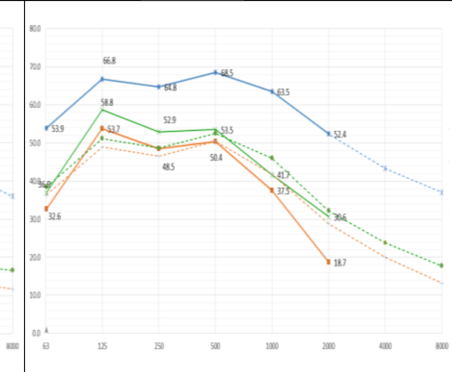
G2			
	68.7	54.8	51.7
		54.1	53.1

G3			
	68.6	53.6	52.1
		52.9	52

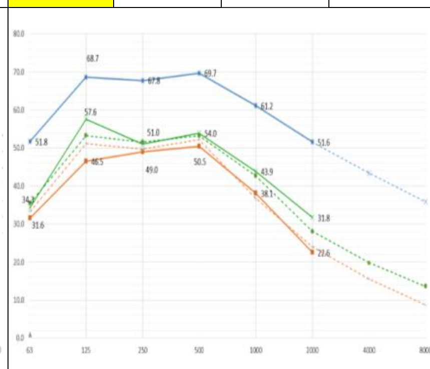
OFF-G1			
	68.5	53.2	49.9
		52.1	50.7

Table 25: Attenuation by design tool spectrum analysis for double-and triple-design tool configurations.

OFF-G2	**68.8**	**53.7**	**50.1**	**OFF-G3**	**68.5**	**53.6**	**52.5**	**W1**	**68.2**	**52.4**	**48.8**
		53.8	**51.4**			**54.4**	**53.3**			**52**	**49.6**

W2	**68.4**	**52.6**	**49.7**	**W3**	**68.6**	**52.6**	**48.7**	**B1+GR1**	**68.4**	**54.7**	**51.1**
		52.1	**50.6**			**51.8**	**50.2**			**53.5**	**51.7**


B1+GR2	**68.3**	**54.5**	**49.9**	**GR1+B1**	**68.3**	**55.5**	**50.8**	**OH1+B1**	**69.1**	**52.9**	**49.7**
		54.7	**50.2**			**55.2**	**52.4**			**52.9**	**51**



OH1+GR1 +B1	**69.4**	**52.3**	**48.3**	**OH1+GR1 +B1+GR2**	**69.7**	**52**	**46.9**	**OFF-G3+ GR1+GR2**	**68.5**	**54.1**	**51.7**
		52.3	**49.9**			**51.3**	**48.7**			**53.4**	**51.1**

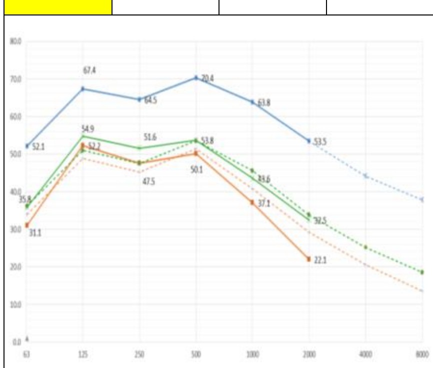
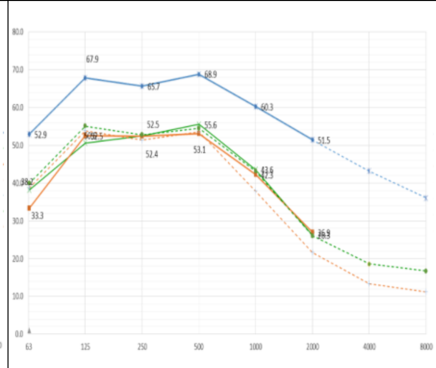
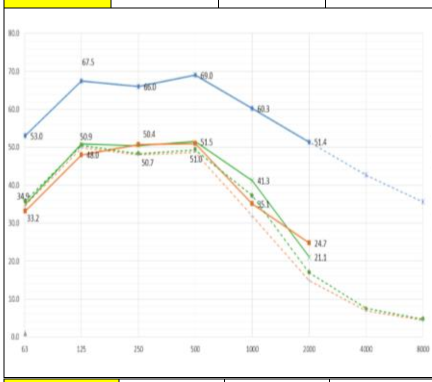
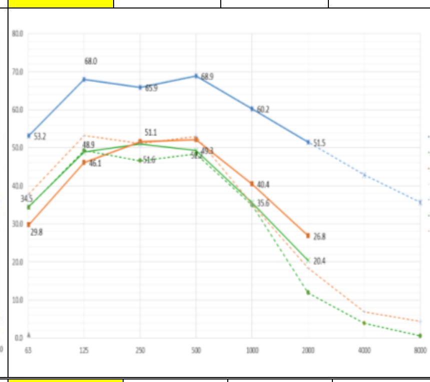
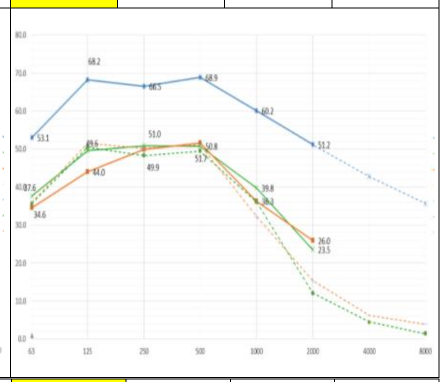


Table 26: Attenuation by design tool spectrum analysis for complex-design tool configurations.

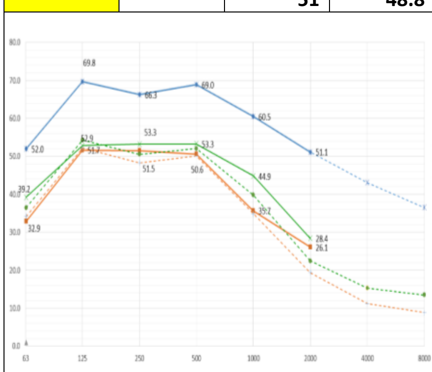
C1	**67.7**	**51.8**	**51.4**	**C2**	**67.6**	**53.6**	**51.7**	**C3**	**67.4**	**52**	**53.2**
		51.8	**49.7**			**53.4**	**52.1**			**51**	**51.2**

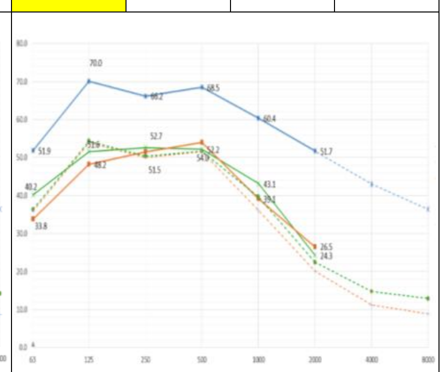




C4	**67.7**	**50**	**49.2**	**C5**	**67.6**	**48.1**	**50.6**	**C6**	**67.7**	**49.4**	**49.6**
		48.4	**47.7**			**47.1**	**51.5**			**48.3**	**49.8**

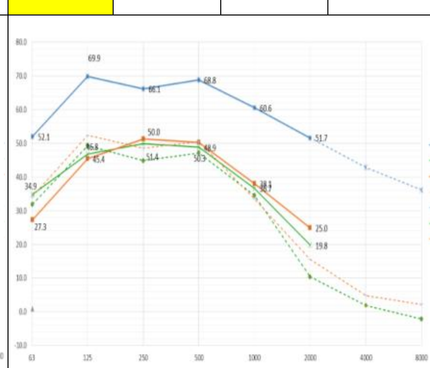
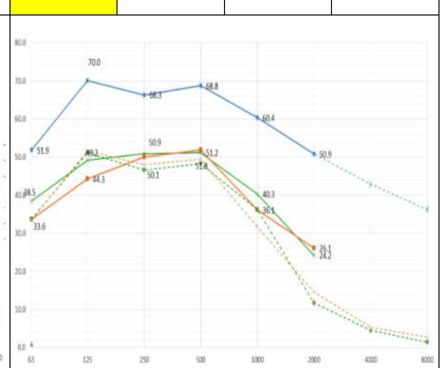




C7	**67.8**	**52.3**	**49.2**	**C8**	**67.7**	**51.4**	**51.4**	**C9**	**67.5**	**51.2**	**51.9**
		51	**48.8**			**50.8**	**50.4**			**50.7**	**50.4**





C10	**67.8**	**49.9**	**48.5**	**C11**	**67.7**	**47.6**	**49**	**C12**	**67.7**	**49.7**	**49.8**
		47.2	**47.2**			**45.7**	**49.2**			**47.3**	**48.3**

Site Seclection

This research site is on a loud and busy street in Vancouver, British Columbia, Canada. The chosen site in Vancouver, on East Hasting street, has been selected to be the experimental site. The acoustical data of the background noise includes the road traffic noise level above 80 Lday dB (A).

From mapping the background road traffic noise by Connelly, M (2011), and the satellite imagery of street maps, began the illustration of the sonic environment on the street and surroundings (Figure 95). The proposed rooftop site is on a 4-storey-building: Union Gospel Mission building, located at 601 E. Hastings St., Vancouver, BC V6A 1J7. The building is at the corner of East Hastings St. and Heatley Ave. The size of rooftop, roof style, building facade and building height influence the traffic noise propagation on the roof. The sound pressure level at the rooftop of the chosen building is calculated based on the reference data from a road noise map of the downtown Vancouver area by Connelly (2011).

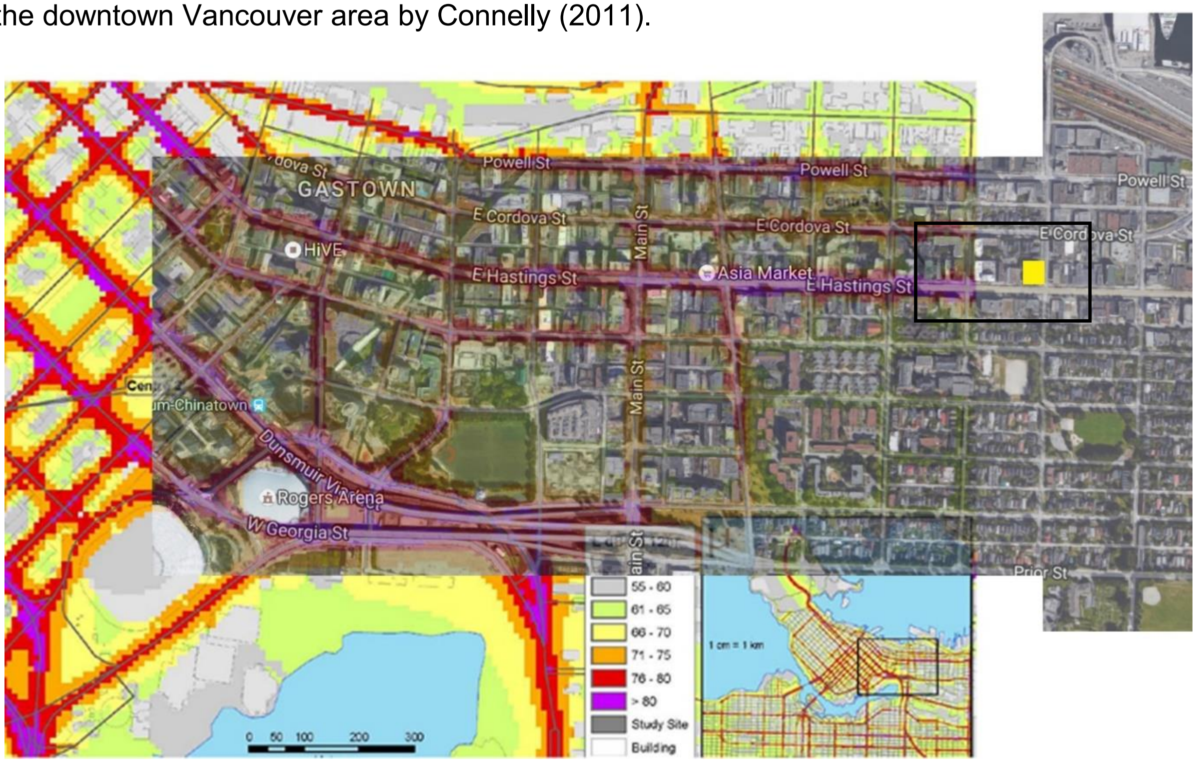


Figure 95: Road traffic noise level mapping on a Google map in the downtown Vancouver area.

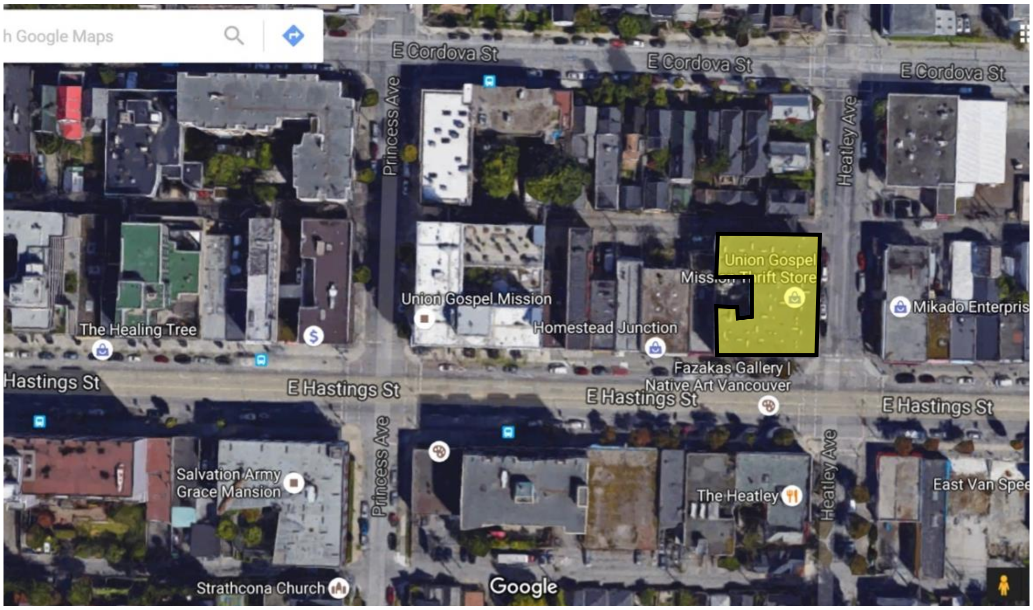


Figure 96: The top view of the site and its surroundings.

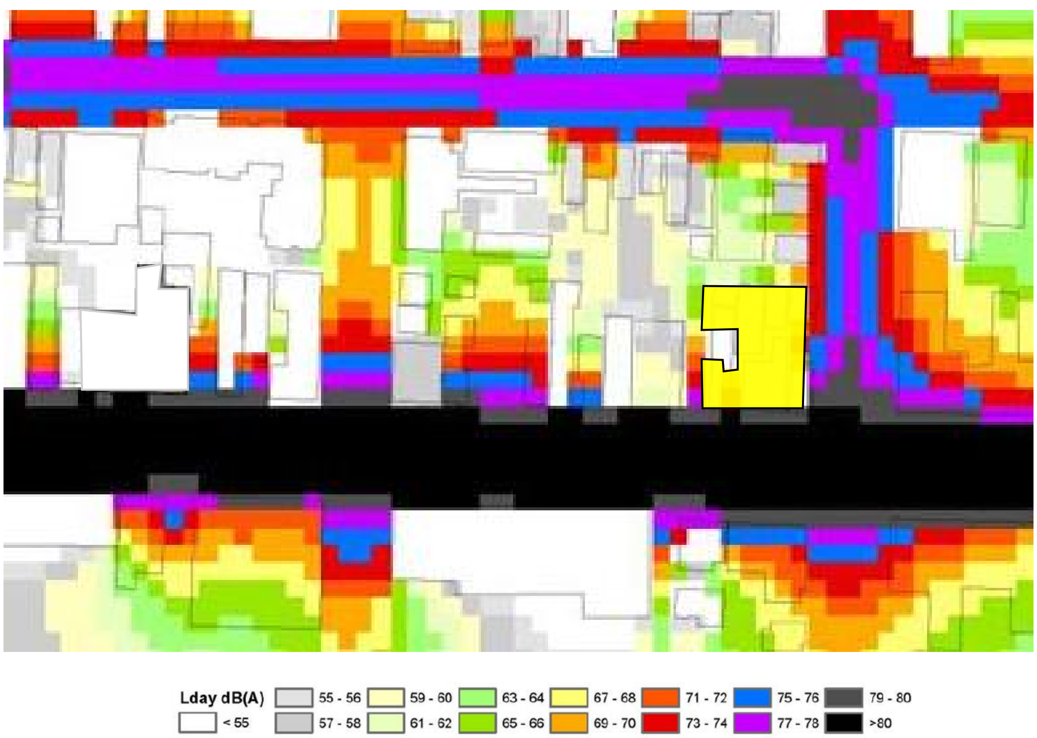


Figure 97: Road traffic noise level at the site location. (Connelly, M., 2011)

In Figure 96, the closer look at noise context maps generated on 5 m grids with 2 dB intervals shows the finer details of sound power level at the loudest series of street blocks on the six-lane E. Hastings St., which exceeds 80 Lday dB (A).

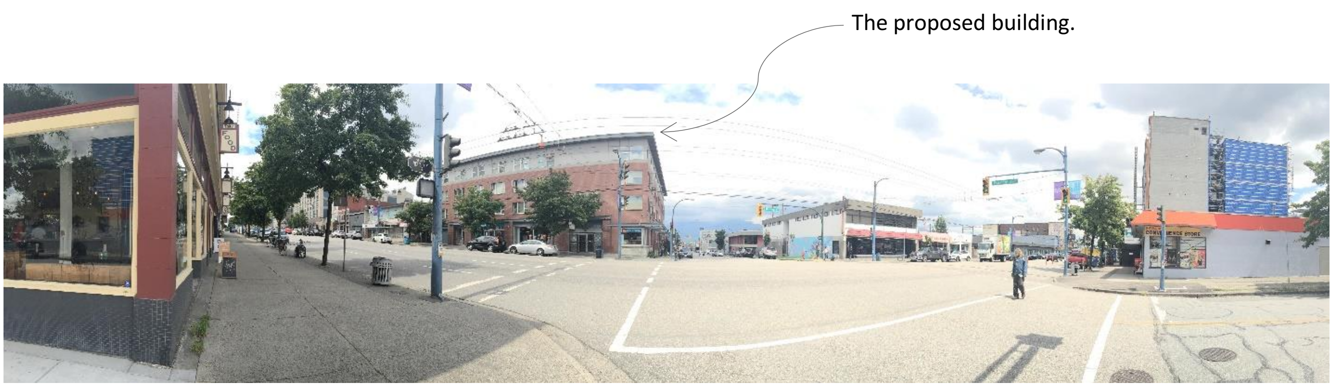


Figure 98: A perspective view of the building site at E. Hastings St. and Heatley Ave.

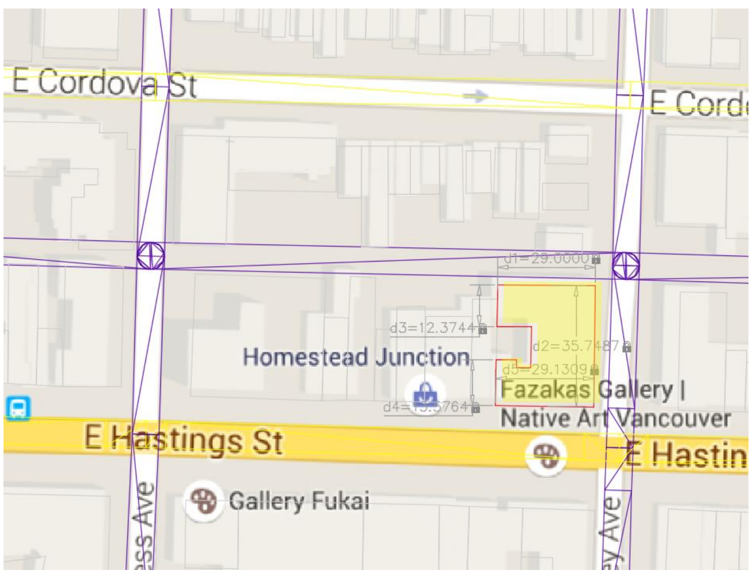


Figure 99: The rooftop site plan and its surroundings.

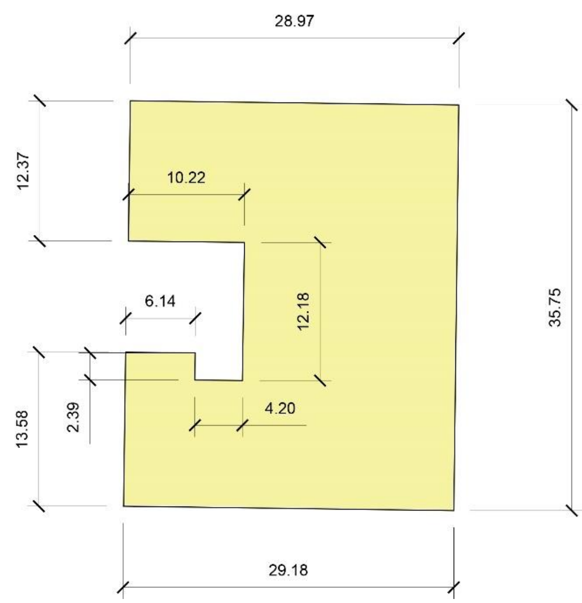


Figure 100: The rooftop site dimension.

The building plan has a rectilinear-shaped rooftop with a square section cut off for a courtyard on the third floor. The building is set back from East Hastings Street and Heatley Avenue with a 3 m and 2 m sidewalk, respectively. Noise levels on the North street of the block (service road) are in the range of 59–72 Lday dB(A). The South street is E. Hastings which is exposed to the highest level of traffic noise above 80 Lday dB(A), and the East street is Heatley Ave. where the noise level at the road intersection ranges from 73–80 Lday dB(A). The service road at the north elevation of the building is considered quiet. The building area is 928 square meters with a total length of 155 meters. The 8-meter-high street trees are on the sidewalk, spaced roughly at 10 meters apart.

In the model experimentation, the traffic noise from the North street of the building is ignored in the test, since the traffic noise exposure level is considered low and the density of the traffic is light. The only concern in these tests is on the main roads on the South street (E. Hastings St.) and the East street (Heatley Ave.), where the high level of traffic noise occurs. The trees on the sidewalk and the wind effect are not considered in the experiment.

Grid Response ASCII Output Table

					A Weight						
Grid	63	125	250	500	**500**	1000	2000	4000	8000	**Sum**	**Color**
1	55.7	72.7	72	80	77	72.5	62	54.6	46.4	**78.5**	
2	59	74.8	73	81.1	78.1	72.8	62	55.1	46.6	**79.4**	
3	59.2	75	73	80.5	77.5	71.9	62.6	55.9	47.5	**78.8**	
4	59.6	74.9	73.1	81.8	78.8	75.2	64.8	56.6	48.4	**80.5**	
5	59.6	75	73.2	81.5	78.5	73.2	63.1	56.6	49.4	**79.7**	
6	59.9	75.3	73.6	79.8	76.8	72.3	63.1	56.8	49.4	**78.4**	
7	60.4	75.9	74.2	83.2	80.2	75.7	65.4	56.8	50.2	**81.6**	
8	61.4	77	75.3	82.4	79.4	73.7	63.7	57	51.2	**80.7**	
9	62.1	77.5	75.7	80.7	77.7	73.5	63.3	57.1	50.7	**79.4**	
10	61.9	77.4	75.7	83.9	80.9	76.2	65.6	57.6	51.2	**82.3**	
11	54.8	71.5	70.9	79.9	76.9	72.7	61.3	54.4	44.9	**78.4**	
12	58.7	74.3	72.4	79.6	76.6	72.6	61.1	54.3	45.4	**78.2**	
13	58.8	74.2	72.4	79.9	76.9	71.4	61.6	55.3	47.2	**78.2**	
14	58.9	74.3	72.4	81	78	74	62.5	55.5	47.5	**79.6**	
15	59	74.4	72.6	80.7	77.7	73.5	62.4	55.6	47.7	**79.2**	
16	59.3	74.8	72.9	79.2	76.2	71.3	62	56	49.1	**77.1**	
17	60	75.6	73.9	81.8	78.8	74.3	63.3	55.8	49	**80.3**	
18	61.5	77.3	75.6	82.4	79.4	74.3	63.5	56.7	48.5	**80.7**	
19	62.5	78	76.1	80.6	77.6	72.7	62.8	57	50.3	**79.2**	
20	61.9	77.4	75.6	82.4	79.4	74.7	64	56.1	50.3	**80.9**	
41	58	75.1	73.8	81.5	78.5	74.3	63.8	56.5	48.7	**80**	
42	59.6	76.8	75.3	83.3	80.3	75.7	65.7	57.5	49	**81.7**	
43	60	77	75.5	83.9	80.9	75.7	65	57.8	50.1	**82.2**	
44	59.1	76.2	74.7	82.9	79.9	75.6	64.5	57.7	49.4	**81.4**	
45	60.3	76.3	74.4	82.4	79.4	74.1	64.4	56.8	50.1	**80.7**	
46	61.2	77.3	75.4	84	81	75.6	65	58.8	50.2	**82.2**	
47	61.4	77.5	75.6	83.9	80.9	76	66	57.7	50.9	**82.3**	
48	60.9	76.9	75	83.1	80.1	74.3	65.6	57.3	50.9	**81.3**	
49	60.7	76.2	74.4	81.1	78.1	73.8	64.2	57.8	49.6	**79.7**	
50	61.9	77.2	75.5	81.5	78.5	75.1	65	58.8	51.1	**80.4**	
51	62.1	77.5	75.6	81.7	78.7	75.3	65.8	59	51.7	**80.7**	
52	61.5	76.8	75	81.2	78.2	74.5	66.1	58.1	50.6	**80.1**	
53	60.9	76.4	74.6	84.2	81.2	77.2	65.7	57.4	52	**82.7**	
54	61.8	77.3	75.4	86.1	83.1	78.1	66.8	57.9	52.7	**84.3**	
55	62	77.5	75.7	86.8	83.8	77.8	66.6	58.3	52.9	**84.8**	
56	61.4	76.9	75.1	85.8	82.8	77.8	66.4	59.3	52.4	**84.1**	
57	60.8	76.3	74.6	83.4	80.4	74.2	65.5	58	51.9	**81.5**	
58	61.9	77.4	75.6	84.6	81.6	75.2	66	59.9	52.5	**82.6**	
59	62.1	77.6	75.8	84.7	81.7	76	66.9	58.8	53.2	**82.9**	
60	61.5	77	75.2	83.7	80.7	74.7	66.4	58.3	53.2	**81.8**	
61	61	76.5	74.8	80.8	77.8	74	65	58.6	51.3	**79.7**	
62	62	77.5	75.8	81.7	78.7	75.5	65.3	59.6	52.9	**80.7**	
63	62.2	77.8	76	81.4	78.4	75.8	66.4	59.5	53.3	**80.7**	
64	61.7	77.2	75.4	81.4	78.4	74.8	66.5	59.1	52.4	**80.4**	
65	61.4	77	75.2	84.9	81.9	77.2	65.8	57.6	53.7	**83.2**	
66	62.3	77.8	76	86.6	83.6	78.5	67.4	58.5	54.6	**84.8**	
67	62.4	78	76.2	87.2	84.2	78.3	67	58.7	54.7	**85.2**	
68	62	77.5	75.7	86.4	83.4	78.1	66.8	59.8	54.3	**84.5**	

					A Weight						
Grid	63	125	250	500	**500**	1000	2000	4000	8000	**Sum**	**Color**
69	62	77.6	75.9	84.1	81.1	74.7	65.7	58.4	53.6	**82.1**	
70	62.6	78.2	76.4	85.1	82.1	75.4	66.2	60.4	54	**83**	
71	62.8	78.4	76.6	85	82	76.2	67.2	59.1	54.6	**83.2**	
72	62.5	78	76.3	84.2	81.2	74.8	66.7	58.9	54.7	**82.3**	
73	62.5	78	76.3	84.2	81.2	74.8	66.7	58.9	54.7	**80.1**	
74	62.8	78.3	76.5	81.9	78.9	75.8	65.6	60	54.1	**81**	
75	63.1	78.6	76.8	82	79	76.1	66.4	60	54.7	**81.2**	
76	62.9	78.4	76.6	82	79	75.4	66.8	59.7	53.7	**81**	
77	62.1	77.6	75.8	85.1	82.1	77.3	65.9	57.8	54.2	**83.4**	
78	62.6	78.1	76.3	86.9	83.9	78.6	67.5	58.9	55.4	**85.1**	
79	62.9	78.4	76.7	87.5	84.5	78.6	67.1	58.9	55.2	**85.5**	
80	62.5	78.1	76.3	86.6	83.6	78.2	66.9	60	54.9	**84.7**	
81	58.2	73.5	71.8	79.2	76.2	70.7	60.2	53.7	48.2	**77.4**	
82	59.2	74.5	72.8	79.3	76.3	71.4	61.1	55.4	49.8	**77.7**	
83	59.5	74.9	73.1	81.4	78.4	73.4	62.3	55.8	49.3	**79.7**	
84	60.9	76.5	74.6	84	81	74.3	65.8	58.4	53.6	**82**	
85	61.9	77.4	75.6	84.9	81.9	75.1	66	60.1	53.4	**82.9**	
86	62.1	77.6	75.8	84.9	81.9	75.8	67.1	58.8	54.1	**82.9**	
87	61.5	77	75.2	83.9	80.9	74.5	66.6	58.6	54.3	**82**	
88	61	76.6	74.9	83.1	80.1	74.1	65.5	58.5	51.4	**81.3**	
89	60.3	75.6	73.9	81.1	78.1	73.5	62.4	56.8	50.3	**79.6**	
90	59.9	75.3	73.5	79.7	76.7	73.1	62	56.5	50.3	**78.5**	
91	60.1	75.6	73.8	83.1	80.1	74	65.3	56.3	48.7	**81.2**	
92	59.9	75.4	73.7	80.6	77.6	72.6	61.4	55.8	48.9	**79**	
93	59.4	74.8	73	79.4	76.4	72	60.9	55.7	49.3	**78**	
94	59.1	74.6	72.7	81.8	78.8	72.7	64.4	54.7	47.7	**79.9**	
95	57.2	73.3	72.1	79.2	76.2	71.8	59.5	53.8	46.4	**77.7**	
96	59.3	75.1	73.5	80.2	77.2	71.3	61	54.7	48.9	**78.4**	
97	59.6	75.2	73.4	79.1	76.1	71.3	62.5	56.3	51	**77.7**	
98	59.6	75.1	73.3	81.1	78.1	73.6	63.2	55.8	50.7	**79.6**	
99	60.4	75.8	74.2	81	78	74.1	64.7	58.7	51.9	**79.8**	
100	61.3	76.8	75	81.5	78.5	75	65	59.3	52.8	**80.4**	
101	61.6	77.1	75.3	81.7	78.7	75.4	65.7	59.3	53.3	**80.7**	
102	60.9	76.3	74.5	82.1	79.1	74.8	66.3	59	52.4	**80.7**	
103	61.2	76.8	75.1	83.1	80.1	75.1	65.3	58.2	51.4	**81.4**	
104	60.7	76.2	74.3	81.7	78.7	73.3	64.4	57.6	51	**80**	
105	60.5	75.9	74.1	80.5	77.5	72.9	63.9	57.2	51.9	**79.1**	
106	60.5	76	74.3	84.2	81.2	75.4	64.9	56.9	50.4	**82.3**	
107	60.3	75.8	74.1	81	78	73	64.1	56.7	51.1	**79.4**	
108	60	75.4	73.7	80	77	72.5	63.4	56.4	51.1	**78.6**	
109	59.8	75.4	73.4	82.7	79.7	74.7	64	56.1	49.2	**81**	
110	58.2	74.5	73.1	80.5	77.5	73.1	61.2	54.5	47.1	**79**	
111	59.7	75	73.4	80.6	77.6	72.5	62	54.7	50.1	**79**	
112	60.1	75.4	73.6	80.2	77.2	73.5	63.8	56.3	51.2	**79**	
113	59.7	75	73.3	82.3	79.3	75	63.7	55	50.9	**80.7**	
114	60.1	75.5	73.8	84.6	81.6	76.6	65.3	57.5	53.1	**82.8**	
115	61	76.5	74.7	86.4	83.4	77.9	66.5	57.5	53.5	**84.5**	
116	61.2	76.7	74.9	87	84	77.8	66.3	57.6	53.3	**84.9**	

					A Weight						
Grid	63	125	250	500	**500**	1000	2000	4000	8000	**Sum**	**Color**
117	60.5	76	74.2	86.3	83.3	77.5	66.3	59.3	53.2	**84.3**	
118	61	76.5	74.8	84.2	81.2	76.5	65.7	58.5	50.9	**82.5**	
119	60.8	76.4	74.7	82.3	79.3	74.7	64.5	57.3	51	**80.8**	
120	60.7	76.3	74.8	81.1	78.1	73.9	64.5	57.6	52	**79.8**	
121	60.6	76.2	74.7	84.4	81.4	75.9	65.1	58.1	50.3	**82.5**	
122	60.4	76	74.4	81.2	78.2	73.4	64.2	56.8	51.1	**79.7**	
123	60.1	75.6	74	80.2	77.2	72.8	63.1	56.6	51.2	**78.8**	
124	59.7	75.4	73.6	82.8	79.8	74.9	63.8	56.4	48.9	**81.1**	
125	58.2	74.5	73.3	80.7	77.7	73.2	61.4	54.8	47.6	**79.2**	
126	59.1	74.8	73.1	80.2	77.2	71.5	61.4	54.8	48.6	**78.4**	
127	60	75.6	73.8	80.2	77.2	73	62.6	56.7	49.7	**78.8**	
128	58.7	74.2	72.4	81.1	78.1	73.1	61.8	55.6	49.2	**79.4**	
129	59.7	75.2	73.4	83.4	80.4	73.5	65.1	57.4	51.9	**81.3**	
130	60.8	76.3	74.4	84.4	81.4	74.5	65.3	59	51.5	**82.3**	
131	61	76.5	74.7	84.2	81.2	75.4	66.5	57.9	52.5	**82.3**	
132	60.3	75.8	73.9	83.2	80.2	73.9	65.9	57.7	52.4	**81.3**	
133	60.3	75.9	74.2	82.8	79.8	74.1	65.3	58.5	50.1	**81**	
134	61.1	76.4	74.6	82	79	74.4	62.8	57.5	50.3	**80.4**	
135	60.6	75.9	74.1	80.3	77.3	73.4	62.5	56.7	50.1	**79.1**	
136	60.5	76.1	74.3	83.2	80.2	73.9	65.7	57.4	48.9	**81.3**	
137	60.4	76.1	74.2	81	78	73.1	61.1	56.9	50.2	**79.4**	
138	59.9	75.5	73.7	79.6	76.6	72.8	61.3	55.7	49.4	**78.4**	
139	59.5	75.2	73.3	82	79	73	64.7	56.5	47.9	**80.2**	
140	57.8	74.2	72.9	79.5	76.5	71.9	59.8	55.2	47.7	**78**	
141	59.3	74.8	73	80	77	72.8	64.2	57.2	49.3	**78.7**	
142	60.7	76.2	74.3	81.3	78.3	74.2	64.5	58.5	50.8	**80**	
143	61	76.5	74.6	81.2	78.2	74.5	65.2	58.5	51.5	**80**	
144	60.2	75.7	73.8	81.6	78.6	73.4	65.5	58	50.4	**80**	
145	58.9	74.6	72.8	82.9	79.9	75.1	64.2	55.9	49.6	**81.2**	
146	60.2	76.1	74.3	84.7	81.7	76.8	66	56.9	51.2	**82.9**	
147	60.5	76.5	74.7	85.2	82.2	77	65.3	56.8	50.6	**83.4**	
148	59.8	75.6	73.7	84.4	81.4	76.5	65.2	58.2	50.4	**82.7**	
149	58	74.9	73.2	82	79	73.5	62.4	54.7	47.4	**80.1**	
150	59.7	76.6	74.7	82.6	79.6	74.5	63.3	57.5	49.1	**80.9**	
151	60	76.8	75.1	82.9	79.9	75.6	64.5	56.3	49.2	**81.4**	
152	59.1	76.1	74	82	79	73.8	63.9	56	49.3	**80.3**	
153	57.8	73.4	71.7	79.3	76.3	69.8	61	54.9	46.6	**77.3**	
155	58.4	73.9	72.1	79.9	76.9	73.4	63.7	55.8	46.5	**78.7**	
156	55.9	73.2	72.5	80.5	77.5	72.5	60.8	53.8	45.9	**78.8**	
158	56.7	72.6	70.9	78.3	75.3	70.2	59.6	53.9	45.9	**76.7**	
159	57.6	72.7	70.9	79.3	76.3	71.3	60.9	53.6	45.1	**77.6**	
161	54.7	71.7	71	79.7	76.7	70.4	59.9	52.9	43.6	**77.7**	

REFERENCES

Akbarnejad, M. (2017). The absorption and scattering characteristics of interior living walls

Albert, D. G., & Liu, L. (2010). The effect of buildings on acoustic pulse propagation in an urban environment. *The Journal of the Acoustical Society of America*, *127*(3), 1335-1346.

Anechoic chamber. (n.d.). In *Wikipedia*. Retrieved from https://en.wikipedia.org/wiki/Anechoic_chamber

Berglund, B., Lindvall, T., & Schwela, D. H. (2008). "Guidelines for community noise." 1999 World Health Organization.

Bennet, K. & Wilkins, S. (2017, February). Building Soil Berms. Retrieved from http://www.extension.umn.edu/garden/landscaping/implement/soil_berms.html

BC Office of Housing and Construction Standards. (2012). BC Building Code (Handrails and Guard). Retrieved from http://www.rdosmaps.bc.ca/min_bylaws/building_inspect/forms/Guard_excerpt.pdf

Connelly, M., & Hodgson, M. (2008, April). Sound transmission loss of green roofs. In *Proceedings of 6th Annual Greening Rooftops for Sustainable Communities Conference*, Baltimore, MD (Vol. 30).

Connelly, M. R. (2011). *Acoustical characteristics of vegetated roofs—contributions to the ecological performance of buildings and the urban soundscape* (Doctoral dissertation, University of British Columbia).

Connelly, M., & Hodgson, M. (2015). Experimental investigation of the sound absorption characteristics of vegetated roofs. *Building and Environment*, *92*, 335-346.

Davies, H. W., Vlaanderen, J. J., Henderson, S. B., & Brauer, M. (2009). Correlation between co-exposures to noise and air pollution from traffic sources. *Occupational and Environmental Medicine*, *66*(5), 347-350.

Dragonetti, L., Van Renterghem, T., & Botteldooren, D. (2011). Scale model study of road traffic noise reduction by planting schemes. In *Forum Acusticum 2011* (pp. 881-885). European Acoustics Association (EAA).

Echevarría Sánchez, G. M., Van Renterghem, T., & Botteldooren, D. (2015). The influence of urban canyon design on noise reduction for people living next to roads. In *10th European Congress and Exposition on Noise Control Engineering (Euronoise 2015)* (pp. 1571-1576).

Engineering Acoustics/Outdoor Sound Propagation. (n.d.) In *Wikibooks*. Retrieved from https://en.wikibooks.org/wiki/Engineering_Acoustics/Outdoor_Sound_Propagation#endnote_HyperPhysics

Genuit, K., & Fiebig, A. (2005). Prediction of psychoacoustic parameters. *Journal of the Acoustical Society of America*, *118*(3), 1874.

Green roofs (n.d.). Retrieved from http://www.greenroofs.com/projects/

Green roofs (n.d.). Retrieved from http://www.cityfarmer.info/?s=Rooftop+Food+Garden+YWCA

Green roof on MEC building. (2006). Retrieved from http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=3a7a036318061410VgnVCM10000071d60f89RCRD

Guillaume, G., & Gauvreau, B. (2014, October). Effect of input data in the impact studies of road traffic noise in a time-domain model. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings* (Vol. 249, No. 7, pp. 1204-1210). Institute of Noise Control Engineering.

Introducing Acoustifence–Reducing Road Noise Using Earth Berm with Foliage and Acoustifence (n.d.). Retrieved from http://www.acoustiblok.com/acoustical_fence.php

Jang, H. S., Lee, S. C., Jeon, J. Y., & Kang, J. (2015). Evaluation of road traffic noise abatement by vegetation treatment in a 1:10 urban scale model. *The Journal of the Acoustical Society of America*, *138*(6), 3884-3895.

Kang, J. (2006). *Urban sound environment*. CRC Press.

Koidan, W., & Hruska, G. R. (1978). Acoustical properties of the National Bureau of Standards anechoic chamber. *The Journal of the Acoustical Society of America*, *64*(2), 508-516.

Koyasu, M., & Yamashita, M. (1973). Scale model experiments on noise reduction by acoustic barrier of a straight line source. *Applied Acoustics*, *6*(3), 233-242.

Leventhall, H. G. (2004). Low frequency noise and annoyance. *Noise & Health*, 6, 59-72.

Lisa, M., Rindel, J. H., & Christensen, C. L. (2004, June). Predicting the acoustics of ancient open-air theatres: the importance of calculation methods and geometrical details. In *Joint Baltic-Nordic Acoustics Meeting* (pp. 8-10).

MacIvor, J. S., & Lundholm, J. (2011). Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. *Ecological Engineering*, *37*(3), 407-417.

Noise Barrier Design Concept – Building of noise barrier. (2010). Retrieved from http://noisesorb.com/3301.html

Nordic void form (2017, February 8). Retrieved from http://www.norseman.ca/products/construction/foundation-infrastructure-foam/nordic-void-form/

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., ... & Rowe, B. (2007). Green roofs as urban ecosystems: ecological structures, functions, and services. *BioScience*, *57*(10), 823-833.

Ossen, D. R., Ahmad, M. H., & Madros, N. H. (2005). Optimum overhang geometry for building energy saving in tropical climates. *Journal of Asian Architecture and Building Engineering*, 4(2), 563-570.

Peng, C., & Lines, J. A. (1995). Noise propagation in the agricultural environment. *Journal of agricultural engineering research*, 60(3), 155-165.

Perini, K., Ottelé, M., Haas, E. M., & Raiteri, R. (2011). Greening the building envelope, façade greening and living wall systems. *Open Journal of Ecology*, *1*(01), 1.

Rehan, R. M. (2015). The phonic identity of the city urban soundscape for sustainable spaces. *HBRC Journal*.

Residential Structural Design Guide. (2000). U.S. Department of Housing and Urban Development. Retrieved from https://www.huduser.gov/portal/publications/residential.pdf

Schafer, R. M. (1993). *The soundscape: Our sonic environment and the tuning of the world*. Inner Traditions/Bear & Co.

Soundscapes and multi-source auralization (n.d.). Retrieved from http://www.odeon.dk/soundscapes-and-multi-source-auralization

Sound Propagation (n.d.). Retrieved from http://www.sfu.ca/sonicstudio/handbook/Sound_Propagation.html

Traffic noise health impacts second only to air pollution, new WHO report says. (2011). Retrieved from https://www.transportenvironment.org/press/traffic-noise-health-impacts-second-only-air-pollution-new-who-report-says

Van den Berg, A. E., Maas, J., Verheij, R. A., & Groenewegen, P. P. (2010). Green space as a buffer between stressful life events and health. *Social Science & Medicine*, *70*(8), 1203-1210.

Van Renterghem, T., & Botteldooren, D. (2009). Reducing the acoustical façade load from road traffic with green roofs. *Building and Environment*, *44*(5), 1081-1087.

Van Renterghem, T., & Botteldooren, D. (2011). In-situ measurements of sound propagating over extensive green roofs. Building and Environment, *46*(3), 729-738.

Van Renterghem, T., & Botteldooren, D. (2012). On the choice between walls and berms for road traffic noise shielding including wind effects. *Landscape and Urban Planning*, *105*(3), 199-210.

Van Renterghem, T., Hornikx, M., Forssen, J., & Botteldooren, D. (2013). The potential of building envelope greening to achieve quietness. *Building and Environment*, 61, 34-44.

Van Renterghem, T., Salomons, E., & Botteldooren, D. (2006). Parameter study of sound propagation between city canyons with a coupled FDTD-PE model. *Applied Acoustics*, *67*(6), 487-510.

Vorländer, M. (2007). Auralization: fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality. *Springer Science & Business Media*.

Wang, K. (2004). *The aesthetic principles of soundscape in architectural design and built environment* (Doctoral dissertation, Texas A&M University).

Wei, W., Van Renterghem, T., & Botteldooren, D. (2015). “An Efficient Method to Calculate Sound Diffraction over Rigid Obstacles.” In *Proc. INTER-NOISE*.

Yang, H., Choi, M., & Kang, J. (2010, June). Laboratory study of the effects of green roof systems on noise reduction at street levels for diffracted sound. In *Proc. INTER-NOISE*.

GLOSSARY AND ABBREVIATIONS

Anechoic chambers are commonly used in acoustics to conduct experiments in nominally "free field" conditions, free-field meaning that there are no reflected signals. All sound energy will be traveling away from the source with almost none reflected back. Common anechoic chamber experiments include measuring the transfer function of a loudspeaker or the directivity of noise radiation from industrial machinery. In general, the interior of an anechoic chamber is very quiet, with typical noise levels in the 10–20 dBA range.

Auralization is the process of rendering a sound field audible. This generally involves convolving an anechoic audio recording with an acoustic impulse response.

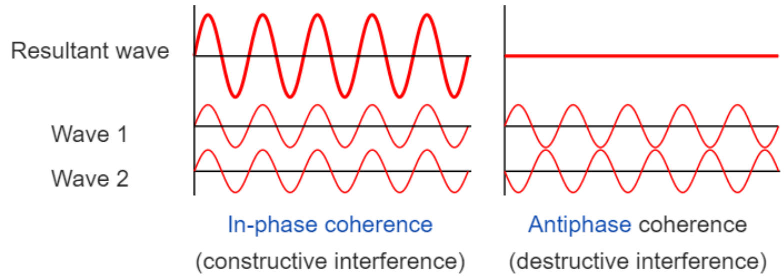
Baseline model is the experimental model representing the standard one-storey building in a local urban context. The building configurations in both the physical 1:10 scale model and the ODEON computer simulation model were constructed with a simple geometry using real-world materials for use in the design tools investigation.

Coherent Vs. Incoherent line source

Coherent line source stands for a set of point sources emitting in-phase signals. For time-domain approaches, a coherent line source is then modelled by introducing a finite number of sound sources with synchronous and identical emission (i.e. the same signal is produced by all point sources with matching time evolution).

Incoherent sources mean that no relation of phase exists between point sources which compose the line source. In time-domain models, an incoherent line source is thus modelled by assigning a random phase at each point source constituting the line source. Consequently, each point source emission is uncorrelated with others point source emissions.

Constructive Vs Destructive interference



Constructive interference occurs when the phase difference between the waves is a multiple of 2π.

Destructive interference occurs when the difference is an odd multiple of π. If the difference between the phases is intermediate between these two extremes, then the magnitude of the displacement of the summed waves lies between the minimum and maximum values.

Green roof is used to describe both ornamental roof gardens and roofs with more naturalistic plants or self-established vegetation. The term, living roof, is increasingly being used instead of green roof in the United Kingdom.

Green wall (Green facade) is an exterior wall of a building that has vegetation growing on it. Masonry and other building materials can become colonised by lichens, mosses, grasses and flowering plants. They may be induced to grow directly against the building fabric or climb trelliswork; geotextiles can also be attached to walls and be planted or seeded.

Natural sounds are sounds produced by natural sources in their normal soundscape. The category includes the sounds of any living organism, from insect larvae to the largest living mammal on the planet, whales, and those generated by natural, non-biological sources.

Noise mitigation or noise control is a set of strategies to reduce noise pollution or to reduce the impact of that noise, whether outdoors or indoors.

ODEON acoustic simulation software is a software application that uses the image-source method combined with a modified ray-tracing algorithm for simulating and measuring the interior acoustics and exterior of buildings. Given a 3D model and materials, the acoustics can be predicted, illustrated and listened to. Sound reinforcement is easily integrated into the acoustic predictions by the ODEON simulation model.

Line source model is a noise source experimental model used to represent the real stream of traffic flow generated by vehicles in laneways. The line source models were constructed in both the physical 1:10 scale model and ODEON computer simulation model for the research investigation.

Lo-Fi soundscape is an abbreviation for low fidelity, that is, an unfavorable signal-to-noise ratio. Applied to soundscape studies, a lo-fi environment is one in which signals are overcrowded, resulting in masking or lack of clarity. Compare: Hi-fi

Low-Speed vehicle: Engine noise is dominant (low frequency, long wave)

High-Speed vehicle: High frequency is dominant (short wave)

Refraction is the change in direction of propagation of a wave due to a change in its transmission medium.

Semi-anechoic chambers aim to absorb energy in all directions. Semi-anechoic chambers have a solid floor that acts as a work surface for supporting heavy items, such as cars, washing machines, or industrial machinery, rather than the mesh floor grille over absorbent tiles found in full anechoic chambers. This floor is damped and floating on absorbent buffers to isolate it from outside vibration or electromagnetic signals. A recording studio may use a semi-anechoic chamber to record music free of outside noise and unwanted reflection reverberations.

Soundscape The sonic environment. Technically, any portion of the sonic environment regarded as a field for study. The term may refer to actual environments, or to abstract construction such as musical compositions and tape montages, particularly when considered as an environment.