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Establishing a heuristic framework for effective attenuation of traffic noise transmission in typical naturally ventilated classrooms in urban schools in Gauteng, South Africa

by

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Declaration

I declare that this research is entirely my own unaided work, except where otherwise stated. All sources referred to are adequately acknowledged in the text and listed.

I accept the rules of assessment of the University of Pretoria and the consequences of transgressing them.

This dissertation is being submitted in partial fulfilment of the requirements for the degree of Philosophiae Doctor (Architecture) at the University of Pretoria.

It has not been submitted before for any degree or examination at any other university.

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Meagan and Craig – *for watching me learn*

Toby – *for loving me and supporting me completely – you are my centre.*

'Academics' in its pure and pristine state (read 'idealised') is all about coming to new discoveries about ourselves and the world around us. All good academic work attempts to find possible answers to unanswered questions, or better answers to incompletely answered questions. That means academic researchers are in the business of explaining the unexplained. They come up with theories to make sense of the world around us and with solutions to practical problems. – Erik Hofstee (2006)

Dedication

To my children, Meagan and Craig,

I hope that one day when you are mature and entrenched in your own families and careers you will never be afraid to start something new and to keep on learning. May life-long learning be a constant undercurrent in your lives.

Abstract

Dissertation title:	Establishing a heuristic framework for effective attenuation of traffic noise transmission in typical naturally ventilated classrooms in urban schools in Gauteng, South Africa
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This study aimed to investigate the possible means of mitigating noise disturbance in naturally ventilated classrooms that are exposed to road-traffic noise. Specifically, the efficacy of façade design, building orientation, distance from the road and noise barriers was tested to achieve a suitable ambient sound pressure level (SPL) in classrooms. The outcome is a heuristic framework to assist school infrastructure planners and architects in the early stages of a project to choose suitable acoustic interventions.

The context was the urbanised province of Gauteng, South Africa, where many new schools are needed and where urbanisation has enveloped many previously suburban schools in traffic noise. Classrooms are typically naturally ventilated with open windows that allow noise in. This increases the classroom ambient noise level which has potentially negative effects on the occupants' health, well-being and academic outcomes.

A computer model of a typical classroom, based on data collected at four Gauteng schools, was used to experiment with various sound attenuation interventions. The modelled results showed that the façade construction material is acoustically inconsequential due to the compromising effect of large openings. A suitable classroom ambient noise level (40 dBA) was only achieved for a building modelled without a barrier at the maximum distance modelled, which was 136 m from the road, provided that the building was perpendicular to the road.

Barriers of varying heights (1.5 m – 7 m) were inserted, either at the school boundary (12 m from the centre of the road) or 3 m from the classroom façade. With a barrier, the closest distance from the road at which the target SPL was achieved was at 42.5 m with a 5.5 m high barrier. As the distance from the road to the building increased, the height of the barrier required decreased. Considering a maximum practical barrier height of 3.5 m, the ideal SPL was only achieved for a classroom at least 51 m from the road. Barriers inserted 3 m from the façade were more effective than barriers at the school boundary.

A significant SPL decrease (≥ 6 dB) was, however, achieved in classrooms as close as 17 m from the road with the insertion of a barrier (≥ 2 m high), and a suitable signal-to-noise ratio was achieved for a classroom 17 m from the road with a 2.5 m high barrier. These findings are particularly useful for application in existing schools with limited space.

The findings provided a data set that was used to develop a heuristic framework as guidance for planners in the early stages of school infrastructure design.

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List of abbreviations

ANC	Active Noise Control
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BB	Building Bulletin
CIBSE	Chartered Institution of Building Services Engineers
dBA	A-weighted decibel level
dB	decibel – unit of sound level measurement
IBT	Innovative building technology
IEQ	Indoor Environment Quality
L_{eq}	Equivalent continuous sound pressure level [dBA]
LA_{max}	Maximum A-weighted sound level over a given time period
NBR	National Building Regulations
NBRI	National Building Research Institute
SANS	South African National Standards
SNR	Sign-to-noise ratio (dB)
SPL	Sound pressure level (dB or dBA)
STI	Speech Transmission Index
WHO	World Health Organization

List of terms

In the context of this thesis, these terms have the following meaning:

Ambient sound pressure level

The background sound level in a given situation at a given time, usually consisting of many sources. In the context of this research, it excludes sound generated by the users of the classroom, such as talking.

Apparent sound reduction index (*R´*):

Ten times the logarithm to the base 10 of the ratio of the sound power W_1 incident on the element to the sound power transmitted into a receiving room, if, in addition to the sound power W_2 radiated by the element, sound power W_3 radiated by flanking elements or by other components is significant (SANS 140-5, 1998):

$$R = L_{eq,1,s} - l_{eq,2} + 10\ log\left(\frac{S}{A}\right) - 3dB \text{(dB)} \quad [1]$$

Apparent sound reduction index (*R´*$_{tr,s}$):

A measure of the airborne sound insulation of a building element when the sound source is traffic noise and the outside microphone position is on the test surface. The formula given below accounts for reflecting effects, area of specimen, absorption of receiving room (SANS 140-5, 1998):

$$R = 10\ log\left(\frac{W_1}{W_2+W_3}\right) \text{(dB)} \quad [2]$$

Equivalent continuous sound pressure level (*L*$_{eq}$):

The value of the sound pressure level of a continuous steady sound that, within a specified time interval T_m, has the same mean-square sound pressure as a sound under consideration whose level varies with time and is given using the following equation (SANS 10103, 2008):

$$L_{eq,T} = 10\ log\left[\frac{1}{T_m}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}dt\right] \text{(dB)} \quad [3]$$

Where:

$L_{eq,T}$ is the equivalent continuous sound pressure level, determined over time interval T_m that starts at $\mathbf{t_1}$ and ends at t_2, in decibels;

$p_A(t)$ is the instantaneous sound pressure level of the sound signal, in pascals;

p_o is the reference sound pressure (p_o = 20 µPa)$L_{Aeq,T}$ is the a-weighted equivalent continuous sound pressure level.

Innovative building technology — Novel or innovative building construction systems that are not the conventional brick and mortar construction type that is typically used in South Africa. This is often in the form of lightweight insulated panels.

Level difference (*D*): The difference, in decibels, between the outdoor sound pressure level (L_1) and the space and time averaged sound pressure level (L_2) in a receiving room (SANS 140-5, 1998):

$$D = L_1 - L_2 \text{ dB} \quad [4]$$

Normalised level difference ($D_{2m,n}$): Level difference, in decibels, corresponding to the reference absorption area in the receiving room (SANS 140-5, 1998).

Normalised level difference (traffic) ($D_{2m,n}$): Level difference, in decibels, where traffic noise is the sound source, corresponding to the reference absorption area in the receiving room (SANS 140-5, 1998).

L_{10} — A statistical descriptor of the sound level exceeded for 10% of the time of the measurement period.

L_{90} — A statistical descriptor of the sound level exceeded for 90% of the time of the measurement period.

L_m — Average traffic noise level in a straight lane.

Learner outcomes: This term, or similar references to user or occupant outcomes, refers to the successful performance of learners/users/occupants of a space. This could refer to academic performance and well-being.

Noise: Noise is considered to be any unwanted sound. However, noise level and sound pressure level are used interchangeably in this thesis.

Outdoor-indoor transmission class (OITC): A one-number rating of the sound-blocking ability of a partition, door, window, etc., calculated in accordance with ASTM E1332 from measurements of one-third-octave band sound pressure levels and sound absorption made in a laboratory and in accordance with ASTM E90 (ANSI/ASA S12.60-2010/Part 1).

Signal to noise ratio (SNR): The difference in sound level between a signal noise (such as a person speaking) and the background (ambient) noise level.

Sound reduction index (*R*-value): Also referred to as 'sound transmission loss' is an indication of the resistance of a particular element to the transmission of sound. It is ten times the logarithm to the base 10 of the ratio of the sound power W_1 incident on the element to the sound power W_2 transmitted through the element (SANS 140-5,1998):

$$R = 10\,log\left(\frac{W_1}{W_2}\right) \text{ dB [5]}$$

Sound Transmission Class (STC): A one-number rating of the sound-blocking ability of a partition, door, window, etc., calculated in accordance with ASTM E413 from measurements of one-third-octave band sound pressure levels and sound absorption made in a laboratory and in accordance with ASTM E90 (ANSI/ASA S12.60-2010/Part 1).

Standardised level difference ($D_{2m,nT}$): Level difference, in decibels, corresponding to a reference value of the reverberation time in the receiving room (SANS 140-5, 1998):

$$D_{2m,nT} = D_{2m} + 10\,log\left(\frac{T}{T_0}\right) \text{ (dB) [6]}$$

Where: T_0 = 0.5 s

Standardised level difference (traffic) ($D_{tr,2m,nT}$): Level difference, in decibels, where traffic noise is the source, corresponding to a reference value of the reverberation time in the receiving room (SANS 140-5, 1998):

$$D_{tr,2m,nT} = D_{2m} + 10\,log\left(\frac{T}{T_0}\right) \text{ (dB) [7]}$$

Where: T_0 = 0.5 s

Well-being: General health of a person, whether is be physiological, behavioural, mental or pshychological, as it relates to the ability of the person to perform expected tasks.

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Chapter 1: Introduction

The aim of this study was to quantify the efficacy of modelled noise attenuation interventions in order to achieve suitable ambient noise levels inside a classroom while maintaining adequate natural ventilation by means of openable windows.

Excessive classroom noise affects the well-being and academic performance of learners, as well as the health and well-being of teachers (Kristiansen, Lund, Persson, Shibuya, Nielsen & Scholz, 2014). Well-being in this sense is a broad term referring to physiological and psychological health; for example, noise disturbance can cause increased blood pressure (a physiological effect) or annoyance (a psychological effect). The ingress of outdoor noise can prove to be a disturbance and distraction for learners, which has been shown to negatively affect educational outcomes (Klatte, Bergström & Lachmann, 2013).

Currently, it is common practice, indeed recommended practice, for South African school classrooms to be ventilated by means of openable windows (Department of Basic Education, 2013). For schools that are located near to outdoor noise sources, the potential problem exists that, when windows are open, the sound insulation value of the classroom envelope is compromised. Sound transmitted from outdoors through open windows increases the ambient sound level in the classroom, making auditory communication difficult. Effective attenuation of outdoor noise can reduce this negative effect and thus contribute to improving the education outcomes.

Current means of dealing with outdoor noise disturbance at a user level include the closing of windows, which results in inadequate ventilation for occupants (Montazami, Wilson & Nicol, 2012). To counter this, mechanical devices, such as fans, room air cleaners or air conditioners are often installed retroactively. These have several potential disadvantages. Firstly, these devices also contribute to the ambient noise level, as demonstrated in the study by Ehrlich and Gurovich (2004) where the ventilation system noise level limit of 35 dBA could not be achieved in all classrooms. Secondly, these devices are costly to install, operate and maintain. Thirdly, mechanical devices are not always correctly specified for the intended use and, while they may provide some thermal comfort, they often do not improve air quality or vice versa. Poor indoor air quality (IAQ) carries the risk of spread of airborne diseases (Patterson, Morrow, Kohls, Deignan, Ginsburg & Wood, 2017) and lack of attentiveness associated with increased carbon dioxide levels (Myhrvold, Olsen & Lauridsen, 1996; Wargocki & Wyon, 2007).

Mitigating outdoor noise transmission can be achieved by increasing the sound insulating value of the façade, or by attenuating the sound before it reaches the façade, or a combination of both. The sound insulation value of the façade refers to the fraction of incident sound that will be transmitted through the façade. This is determined by the façade design in terms of materials and openings. Outdoor attenuation can be achieved by means of various interventions such as screens (barriers) between the noise source and the receiver, increasing the sound absorption of the ground between the noise source and the receiver, or increasing the distance between the source and the receiver. It is most likely that the effective solution lies in a combination of such interventions.

This study seeks to identify practical interventions to employ to overcome potential noise problems without compromising natural ventilation in urban South African schools, taking into consideration the local context and regulations. The intended outcome of this research is to model and quantify effective means of mitigating the noise disturbance in a South African classroom in the situation where disruptive outdoor noise – particularly road-traffic noise in urban areas – is transmitted through natural ventilation apertures. The results, developed into heuristic guidelines, can be useful for decision-makers at the pre-planning phase of school infrastructure and in the concept design phase but does not necessarily nullify the need to employ the skills of a professional acoustic consultant. The modelled results provide parameters which can be used to aid in the selection of suitable attenuation interventions for a particular scenario. The evidence established will be useful for both retrofitting as well as new design situations, and for determining the feasibility of a site when choosing a location for a new school.

Two aspects of noise attenuation are considered in this study:

a) the building envelope (façade) design to reduce the sound energy transmitted through the envelope into the classroom; and

b) outdoor noise attenuation interventions to reduce the sound energy arriving at the building envelope.

A number of different solutions were tested separately and in combination using acoustic modelling software. In this way, all other potential influencing variables were controlled.

1.1 Background

1.1.1 Urbanisation pressure on infrastructure

This study was conducted in the context of Gauteng Province, the smallest and most urbanised province in South Africa with the highest population density.

The rapid urbanisation of populations and expansion of cities is a global phenomenon characterising the twenty-first century (Department of Cooperative Governance and Traditional Affairs, 2016). Much of the projected growth is expected to occur in Asia and Africa (UN Department of Economic and Social Affairs, 2018). In South Africa, 63% of the population growth is expected to occur in city regions, with the majority of this increase set to occur in Gauteng (Le Roux, Arnold, Makhanya & Mans, 2019).

Urbanisation places an increased demand on infrastructure. The effect of this urban growth is already evident in Gauteng with the growth of informal settlements around cities and the densification of cities.

This study pertains to two related aspects of this growing urbanisation and pressure on infrastructure. On the one hand, the growing population places a demand on access to schools (Parliamentary Monitoring Group, no date). On the other hand, urbanisation is accompanied by an increase in traffic volumes – as evidenced by the increase in vehicle ownership in Gauteng (Department of Transport, 2014) – and the resultant noise pollution (Lin, Peng, Tsai, Chang & Chen, 2018). This study considers effective ways to manage noise pollution in urban schools in Gauteng.

1.1.2 South African school infrastructure and design

Attention to school infrastructure is not new. However, the environment both within and around the classroom is changing and infrastructure needs to respond. In 1975 the CSIR published a short paper on school infrastructure design in response to changing education methods (National Building Institute, 1975). Reading this paper, it is interesting to note how the descriptions of evolving pedagogy in the 1970s[1] could easily be used to describe current

[1] "Teaching in South Africa has always been and will, for the predictable future, remain classroom orientated. However, methods of teaching are slowly changing and many innovations are now appearing in the primary school, e.g. variable size grouping, team teaching, integrated day, etc. Schools must therefore provide teaching spaces that are essentially class oriented but allow for innovation in teaching practice and educational organization." (NBRI Information sheet, 1975, page 2)

evolving teaching methods, such as the flipped classroom (Zuber, 2016), whereby learning occurs in group settings with discussion and participation, as opposed to a traditional lecture-type teaching style. This draws attention to the fact that school infrastructure design norms should be continuously responding to changes in teaching, technology and context (Robinson & Munro, 2014). What may have constituted a suitable classroom design in one decade may well be outdated in the next (Ramma, 2007).

This calls into question the suitability of our school infrastructure norms for the current and evolving schooling environment in South Africa. It raises concerns regarding the design of new schools, as well as the adaptation of existing schools, which were built according to outdated norms, to ensure that they remain suitable spaces for education.

Apart from the changing teaching approaches and technology, with their bearing on classroom design, the urban dynamics of the neighbourhood setting of schools also plays a role in the efficacy and suitability of the teaching environment. A number of schools in Gauteng that were originally located in residential suburban neighbourhoods now find themselves in commercial or industrial districts, or adjacent to main traffic routes as urbanisation changes the character of cities. An example of this phenomenon in the City of Tshwane, Gauteng, is Pretoria Secondary School, built in 1938 amongst houses and parks but now enveloped within the central business district on one of the major traffic routes into the city – the comparison is evident in the photographs in Figure 1-1.

A potential issue that arises from this change in setting is that these schools are now subject to increased traffic noise. Since most of these schools are naturally ventilated by means of openable windows, it is likely that noise from outdoor activities, particularly road-traffic noise, will penetrate the classrooms and pose a hindrance to effective teaching and learning (Karami, Cheraghi & Firoozabadi, 2012).

Figure 1-1: The site of Pretoria Secondary School in aerial photographs taken in 1948[2] (left) and 2020[3] (right)

Effective educational outcomes can be defined as "the acquisition of knowledge, skills and values … articulated in the curriculum" (Spaull, 2015). According to the Constitution of the Republic of South Africa (1996), it is the right of every child to receive a decent education and it is the duty of the National Department of Basic Education (DoBE) to ensure that this is achieved. Ensuring an education entails more than providing a teacher and curriculum. Teaching and learning take place in a context and that context – the infrastructure as well as

[2] https://repository.up.ac.za/bitstream/handle/2263/60293/Strip07-05%2893597%29.jpg?sequence=5&isAllowed=y [accessed 7 July 2020]

[3] https://www.google.co.za/maps

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the environment – needs to be suitable for the task. An ideal physical classroom environment may be described as one in which there is adequate space for learners and educators to perform the necessary activities, and in which the indoor environment quality (IEQ) does not hinder the optimal performance of the learners and educators. In other words, the temperature, humidity, sound level, light quality and air quality are suitable for the number of occupants and type of activities occurring in the classroom.

South Africa is more than two decades into a new democracy, in which equal access to education for all has been made a priority. Because of past inequalities, many schools had inadequate physical facilities – hundreds being poorly constructed and without electricity, water or sanitation. This led to the development of the *National policy for an equitable provision of an enabling school physical teaching and learning environment* in 2010 (Department of Basic Education, 2010), followed by the publication of the *Regulations relating to minimum uniform norms and standards for public school infrastructure* (Department of Basic Education, 2013) (hereafter referred to as “the Regulations”), which are legally binding.

The Regulations are held up as the minimum standard to which all public school infrastructure is to conform – whether the school is large or small, primary or secondary, ordinary or special needs. It provides guidance regarding the basic infrastructure requirements of schools in South Africa. Aspects of infrastructure covered in the Regulations range from the suitability of toilets to the physical space to be provided in classrooms, as well as factors influencing the indoor environment quality.

The motivation behind the Policy and the Regulations is not only to make all infrastructure equal (at least at a minimum level) but it is ultimately aimed at improving the education outcomes. Quality basic education is the Outcome 1 of the government’s 2014-2019 Medium-Term Strategic Framework (The Presidency, 2014). It has been shown that the physical classroom environment has an impact on the performance and outcomes of learners (Woolner, Thomas & Tiplady, 2018). Overcrowding in classrooms, as well as noise, poor lighting and poor air quality, can negatively affect a learner’s ability to concentrate and perform optimally (Amsterdam, 2013).

1.1.3 The importance of Indoor Environment Quality (IEQ)

Since the majority of time spent at school is spent indoors, the indoor environment quality (IEQ) is arguably as important as the physical infrastructure. IEQ is defined by the USA National Institute for Occupational Safety and Health (NIOSH) as referring to “the quality of a building’s environment in relation to the health and wellbeing of those who occupy space within it" (National Institute for Occupational Safety and Health, 2013) and includes the thermal, visual, acoustic and air quality conditions (Frontczak & Wargocki, 2011).

An indication of the well-being of occupants in a classroom environment can be measured in terms of the educational outcomes, using performance tests as indicators. Extensive longitudinal studies in other countries, as well as numerous case studies over the last few decades, provide evidence that the IEQ in classrooms has a significant effect on the health and academic performance of occupants, using parameters such as memory and comprehension (Marchand, Nardi, Reynolds & Pamoukov, 2014; Haverinen-Shaughnessy, Shaughnessy, Cole, Toyinbo & Moschandreas, 2015). There are a number of factors that can influence a learner's outcomes and well-being. Thus, classroom design should be approached holistically (Woolner & Hall, 2010).

1.1.4 Classroom acoustics and ventilation

Though all factors of IEQ are important to ensure a suitable classroom environment, this study focuses on the management of noise and ventilation. It is well-established that the quality of classroom acoustics has a significant impact on the learner performance, including indicators such as reading skills, auditory perception, reading comprehension, episodic memory, long-term memory as well as certain health effects such as raised blood pressure and myocardial infarction (Hygge, Boman & Enmarker, 2003; Dockrell & Shield, 2006; Matheson, Clark, Martin, van Kempen, Haines, Barrio, Hygge & Stansfeld, 2010; Söderlund, Sikstrom, Loftesnes & Sonuga-Barke, 2010; Seabi, Cockcroft, Goldschagg & Greyling, 2012; Paunovic, Belojevic & Jakovljevic, 2013). The acoustic condition of the classroom environment should not be neglected in school planning – indeed it is one of the most important design considerations (Association of Australasian Acoustical Consultants, 2010).

Research in the field of classroom acoustics, considering evidence-based research as well as international norms and standards, is in general agreement that classroom ambient noise levels should not exceed 35 dBA in order to achieve a suitable signal-to-noise ratio (SNR) of +15 dBA (Van Reenen & Karusseit, 2017). The SNR refers to the level difference between the ambient (background) noise level and the signal level, which in a classroom setting is typically the teacher's voice. Logic, as well as evidence-based research, dictates that the higher the ambient noise level in a classroom is, the harder it will be for the learners to hear the teacher. Furthermore, additional vocal effort on the part of the teacher is required, resulting in vocal strain and fatigue (Kristiansen *et al.*, 2014).

In order to keep ambient noise levels as low as possible, potential sources of noise in the classroom environment need to be kept to a minimum. Noise in a classroom can come from a number of different sources, such as noise from adjacent classrooms, mechanical ventilation, aircraft noise and road-traffic noise. There is evidence that different types of noise can result in different exposure effects. For example, traffic noise may affect reading comprehension while speech noise can affect working memory (Clark, Martin, Van Kempen, Alfred, Head, Davies, Haines, Lopez, Matheson & Stansfeld, 2006; Dockrell & Shield, 2006; Connolly, Dockrell, Shield, Conetta, Mydlarz & Cox, 2019).

In the context of the increasing urbanisation and consequent increase in traffic volumes, this research is considering the mitigation of intrusive road-traffic noise in classrooms. Numerous case studies have shown that traffic noise influences learner academic performance and well-being (Hygge, Evans & Bullinger, 2002; Clark *et al.*, 2006; Ana, Shendell, Brown & Sridhar, 2009; Paunovic *et al.*, 2013; Silva, Oliveira & Silva, 2016). According to the World Health Organization (World Health Organization, 2011), traffic noise is becoming a significant health threat and is considered one of the top environmental stressors. Not only are education outcomes affected, but noise in schools has been cited as a major public health risk (Ana *et al.*, 2009; World Health Organization, 2011). Traffic noise is found to be a significant contributor to noise in schools the world over (Ana *et al.*, 2009; Karami *et al.*, 2012; Nzilano, 2018; Kapetanaki, Konstantopoulou & Linos, 2018).

In schools that are located close to disturbing external noise sources, such as airports or busy roads, occupants are likely to close windows in an effort to block out the noise. In so doing, the natural ventilation supply is also shut off (Montazami *et al.*, 2012).

Ventilation is required to supply fresh air to and remove polluted air from an indoor space. The amount of fresh air required in a room depends on the number of occupants in the room. Classrooms typically have a high occupant density with up to 40 learners allowed in a typical South African classroom (Department of Basic Education, 2013). Research shows a strong correlation between indoor air quality (IAQ) and performance in terms of learners' concentration and memory skills (Coley, Greeves & Saxby, 2007; Bako-Biro, Clements-Croome, Kochhar, Awbi & Williams, 2012). Inadequate ventilation in classrooms leads to carbon dioxide (CO_2) concentration levels that are above the acceptable norms (Clements-Croome, Awbi, Bako-Biro, Kochhar & Williams, 2008; Bako-Biro *et al.*, 2012).

Sufficient ventilation can be achieved by passive or active means. Passive ventilation makes use of natural air movement through apertures in the building envelope to exchange indoor and outdoor air. Active ventilation makes use of equipment that mechanically forces air into and out of a particular space. Mechanical ventilation requires an energy supply and the design and installation of equipment.

While mechanical ventilation offers a good solution when windows are closed, there is an environmental and a financial cost to be considered. Financially, there is the initial cost of the equipment and installation, as well as the running and maintenance costs. The carbon emissions associated with running the equipment on coal-based electricity, as well as the noise generated by the equipment, are environmental costs to consider. Some research in schools has shown that air conditioners contribute significantly to the ambient noise levels to the extent that noise limits are exceeded (Knecht, Nelson, Whitelaw & Feth, 2002; Ehrlich & Gurovich, 2004). These costs position natural ventilation as a responsible design decision. However, in a noisy outdoor environment, open ventilation apertures potentially compromise a suitable ambient noise level. Thus, careful consideration of the design of classrooms in this regard is necessary.

1.2 Problem context

This study is conducted in the context of South Africa, and in particular Gauteng Province. Though the potential issue of external noise disturbance in classrooms can occur at any location, this study focuses on Gauteng – the smallest, yet most urbanised and highly populated province of South Africa.

The urbanisation of the South African population has led to a great need for additional school infrastructure in or around urban centres. According to data provided by the Gauteng Department of Education (GDE), there are a total of 3 065 public and independent schools operating in Gauteng (2018 data); 119 new and replacement schools have been identified, 14 of which are scheduled for completion before the end of 2020. For a province that constitutes only 1.5% of the country’s land area, this is a high number of new and replacement schools and is indicative of the population density and intense urbanisation. Schools in urban areas are potentially vulnerable to exposure to the sounds of the city – traffic and industrial noise. Thus, the acoustic treatment of new and existing schools in urban areas is relevant in South Africa.

As mentioned previously, school design in South Africa is as a minimum based on the *Regulations relating to minimum uniform norms and standards for public school infrastructure* (Department of Basic Education, 2013). A number of South African guidelines for school design pre-dating the Regulations also provide guidance on school infrastructure design. For example, the NBRI Information Sheet (National Building Institute, 1975), the National Building

Research Institute Technical Report Series on School Building Design (a series of 22 reports issued in South Africa during the 1960s), and of course the National Building Regulations.

All these documents, both new and old, primarily focus on the physical infrastructure, facilities, premises and space norms, with limited attention given to IEQ.

An interview with the Gauteng Department of Education Infrastructure Planning and Property Management Directorate (February 2018) revealed that currently noise exposure does not feature strongly, if at all, when choosing locations for new schools. Furthermore, it is not common to employ acoustic specialists on public school projects, and architects are generally ill-equipped to provide technical acoustic solutions. Urbanisation and the expansion of the central business districts of many South African cities, particularly in Gauteng, has resulted in many schools that were previously suburban schools now finding themselves in busy urban environments. Urban schools are typically exposed to high traffic noise which is problematic (Xie & Kang, 2013). Such schools are likely to be in need of acoustic interventions, whether in the form of building envelope isolation or outdoor noise attenuation, or a combination of both.

The number of schools that are subject to traffic noise exposure in Gauteng is not known, although anecdotal evidence indicates that noise transmitted through open windows in schools in urban centres is a problem. Existing research on the topic of noise in Gauteng schools is limited. A study by Ramma of noise levels in primary school classrooms in Johannesburg, Gauteng, concludes that the ambient noise level in classrooms generally exceeds the accepted norm of 35 dBA, and that traffic is the top external noise source (Ramma, 2007).

In South Africa, most public school classrooms are naturally ventilated – usually by means of cross-ventilation through open windows on two opposite walls of the classroom. Natural ventilation by means of openable windows and permanent wall vents is a requirement of the Regulations (Department of Basic Education, 2013, Section 18, paragraph 7). Schools built prior to the implementation of the Regulations would have been designed according to older norms, such as the NBRI School Building series, which only refers to natural ventilation (Van Straaten, Richards, Lotz. & Van Deventer, 1965). Ventilation is important since air quality has a significant effect on the alertness and performance of learners (Haverinen-Shaughnessy, Moschandreas & Shaughnessy, 2011; Twardella, Matzen, Lahrz, Burghardt, Spegel, Hendrowarsito, Frenzel & Fromme, 2012). An adequate supply of fresh air not only ensures alertness but has the added benefit of minimising the risk of transmission of airborne diseases, particularly with reference to tuberculosis in South Africa (Seabi *et al.*, 2012; Patterson *et al.*, 2017).

However, natural ventilation implies that certain portions of the building envelope are open to the outside, whether directly or indirectly, which presents a problem when it comes to acoustic isolation from outdoor noise as any opening in the envelope will facilitate sound transmission. Limited attention has been given to this issue. The only mention of noise control in the NBRI series is with reference to the site location, recommending that school sites should not be on main traffic ways, and, in terms of landscaping, recommending that vegetation be used to protect against wind, sun, noise and dust. While the Regulations mention indoor acoustics, outdoor-indoor noise attenuation is not discussed, save to recommend that schools be located away from noise sources. A number of land uses that are to be avoided are listed, including railway stations, taxi ranks and busy roads – these are potential sources of outdoor noise. However, the Regulations offer no guidance in the event that a school cannot practically be located anywhere other than adjacent to one of these land uses. Furthermore, the requirement that schools be accessible means that they are likely to be located on or close to major transit routes, which increases the potential that they are located close to environmental noise sources.

A potential problem exists that, in the case where a school is located close to an outdoor noise source and employs natural ventilation in the form of openable windows as the primary means of achieving suitable air quality in classrooms, the ambient noise level in the classrooms will exceed the suitable level for speech intelligibility. It is likely that road-traffic noise will contribute to the ambient sound level in classrooms in highly urbanised areas, such as Gauteng. It has been noted by other researchers in the field of acoustics that increasing urbanisation is leading to increasing ambient noise levels and a consequent need to address sound insulation in buildings (Batungbakal, Konis, Gerber & Valmont, 2013; Lee, 2016).

A number of different interventions can be applied to mitigate outdoor noise transmission into a building. For example, noise barriers, absorbent surfaces, distancing the receiver from the source, or improving the sound insulation of the building. However, the extent of their application and their efficacy, separately or in combination, is a complex matter requiring expert engineering. Guidelines on the topic are often qualitative or performance-based, and much of the research literature on the topic is in the form of case studies considering a single intervention. For example, South African regulations state that “noise and reverberation should … be reduced to a minimum” and “acoustic conditions should … facilitate clear communication” (Department of Basic Education, 2013) and in another South African standard an ambient noise level in classrooms is set to be 40 dBA (SABS Standards Division, 2008), yet in neither are guidelines provided as to how to achieve these conditions, such as the recommended heights of barriers or the distance that a classroom should be located from a noise source to ensure the set ambient level is achieved.

Infrastructure investment decisions are made at very early planning stages prior to engagement with expert consultants and designers. Quantitative guidance for the lay architect regarding the extent and feasibility of noise attenuation interventions is lacking. The result, potentially, is that acoustic problems emerge only after sites have been selected and schools have been designed and are operational. The cost of correcting problems by retrofitting interventions is high – not only in terms of specialist consultant fees and material installation but also in terms of interference with the regular activities of the school.

For existing schools that now find themselves in a noisy environment, outdoor noise mitigation solutions are limited due to site constraints. The result is often that windows are sealed up and mechanical ventilation systems installed. This is costly in terms of installation as well as operational costs. Furthermore, mechanical ventilation also contributes to the ambient noise level.

Though a diligent planner may consider basic acoustics theory, designers are often ill-equipped to provide suitable solutions. As noted by Batungbakal *et al.* (2013), "Improved acoustic design guidance for building enclosures is needed to increase awareness of acoustic quality and its influence on occupant comfort.… While advances in design tools and façade performance criteria primarily focus on daylighting, thermal performance and ventilation, acoustic design is often not the highest priority." The design limitations and site constraints add further complexity to acoustic solutions.

1.3 Problem statement

Architects and school infrastructure planners in South Africa are poorly equipped to make good scenario-specific decisions regarding outdoor sound attenuation interventions and envelope sound insulation solutions to achieve suitable ambient sound levels in naturally ventilated classrooms that are subject to road-traffic noise. **There is a lack of quantitative guidance for basic acoustic design solutions to attenuate outdoor noise in the context of urban schools exposed to road-traffic noise**.

Designers – and ultimately the classroom users – will benefit from quantitative evidence that provides guidance for noise control.

1.4 Aim

The aim of this study is to establish heuristic guidelines by quantifying the effect of modelled noise attenuation interventions under various conditions with the goal of achieving a suitable ambient sound level in naturally ventilated classrooms that are exposed to road-traffic noise, thus ensuring suitable acoustic and ventilation conditions.

1.5 Research questions

The main research question that needs to be answered to achieve the aim is:

What interventions are appropriate and effective to attenuate road-traffic noise that is transmitted into a typical naturally ventilated classroom in Gauteng in order to achieve a suitable indoor ambient sound level?

This question has four components or sub-questions. The answers to the sub-questions help define the main question and provide the input required to answer it, as illustrated in Figure 1-2. The sub-questions are:

- What is a typical naturally ventilated classroom design in Gauteng?
- What is a suitable ambient sound level in a classroom?
- What is the nature of problem noise (traffic) in the context of this study?
- What are the noise attenuation interventions that can be employed?

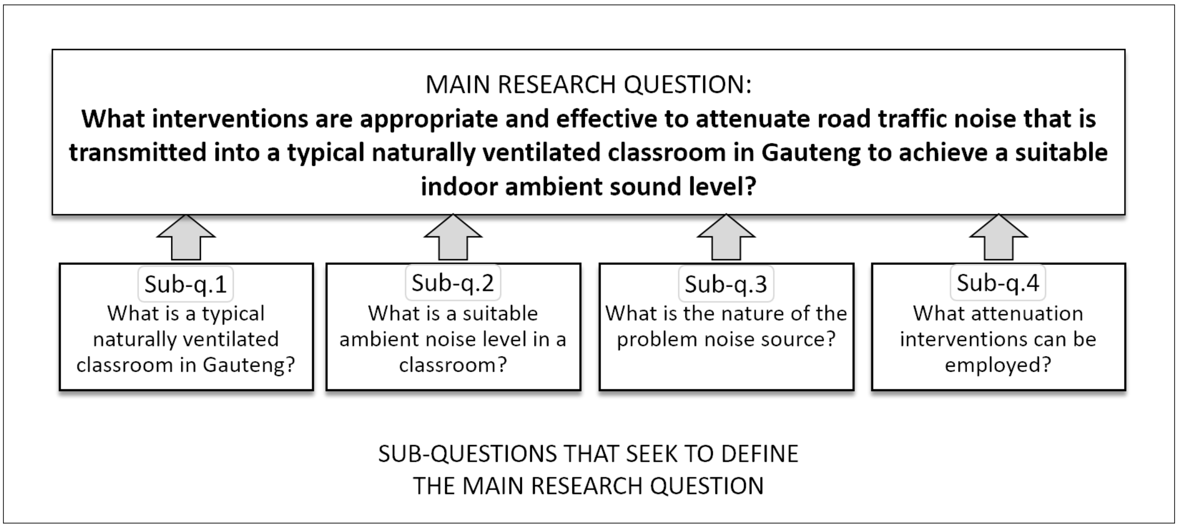


Figure 1-2: Relationship of research questions

1.6 Objectives

In order to quantify the effect of the efficacy of outdoor-indoor noise attenuation interventions, the following objectives need to be met, corresponding to each research, as illustrated in Figure 1-3:

Main Objective: Measure and compare the effect of various attenuation interventions to determine which achieve the target noise level in the presence of the traffic-noise problem.

Sub-objective 1: Determine the dimensions and natural ventilation design for a typical South African classroom.

Sub-objective 2: Define the suitable ambient noise level in a classroom.

Sub-objective 3: Identify and characterise the traffic noise problem.

Sub-objective 4: Determine what attenuation interventions are possible options to investigate within the context of the study.

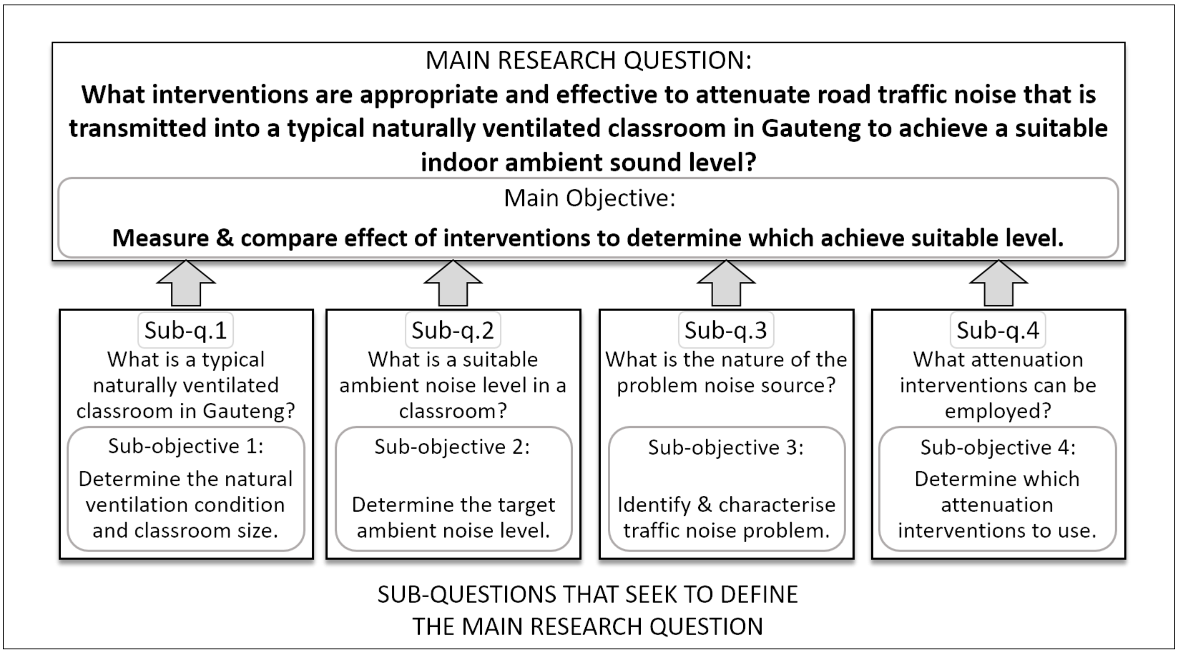


Figure 1-3: Research objectives corresponding to research questions

1.7 Rationale and relevance of the study

The desired outcome of this research is to enable the effective management of intrusive traffic noise under natural ventilation conditions in old and new school infrastructure in urban areas in South Africa.

The Regulations stipulate that classrooms should be naturally ventilated by means of permanent wall vents and openable windows (Department of Basic Education, 2013). This is a good principle, particularly in South Africa. Mechanical ventilation and air-conditioning require financial resources for the installation and operation. These resources, as well as the required energy resources, are not always available or reliable in the South African context. Additionally, the climate in South Africa, particularly in Gauteng, is conducive to natural ventilation. Thus, passive ventilation through the openable windows, as suggested in the Regulations, is a sensible and economically feasible solution and should be supported. However, open ventilation apertures make the classroom vulnerable to the effect of outdoor noise transmission.

Unnecessary costs of retrofitting acoustic or ventilation solutions, or of over-designed solutions, can be avoided if suitable design solutions can be identified at the outset of an infrastructure project, based on quantitative guidelines.

The findings of this study provide parameters to guide designers and decision-makers in selecting the most suitable means for attenuating traffic noise transmission into classrooms with open windows. This may be in the form of a barrier of a certain design and position or it may relate to the position, orientation or façade design of the classroom building.

A solution that enables good natural ventilation, as well as a suitable acoustic environment, will benefit the occupants, eliminating potential environmental hindrances to optimal performance. Occupants will benefit directly from an improved environment and ultimately, the country will benefit from the improved education outcomes that are possible if education is provided in a suitable and conducive learning environment.

1.8 Research design

The research design is both investigative and experimental in nature, making use of qualitative as well as quantitative data.

1.8.1 Research instruments

Four research instruments were used to meet the objectives. As illustrated in Figure 1-4, these are:

- Modelling (software)
- Literature review
- Surveys
- Site measurements

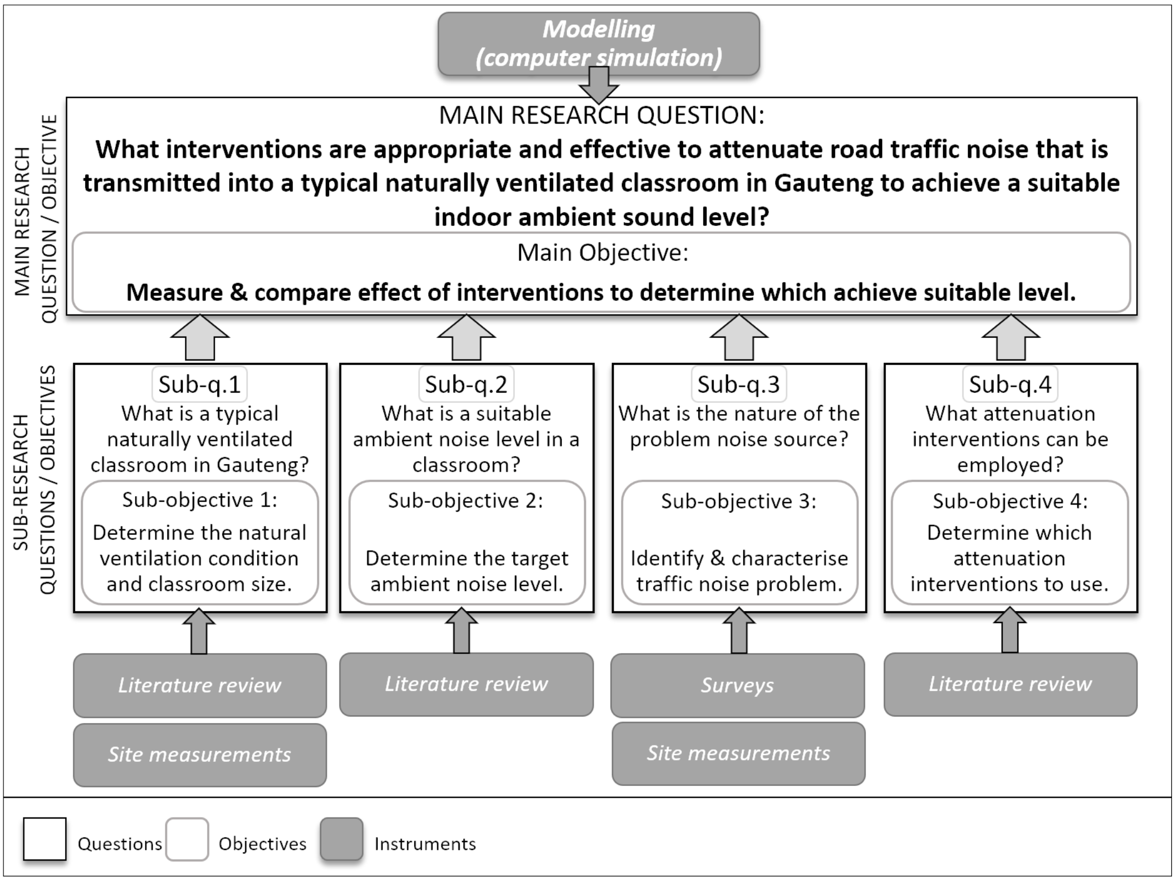


Figure 1-4: Research instruments used to answer research questions

Modelling, using acoustic software, was used to measure the effect of various noise attenuation interventions. This is towards meeting the main objective of determining the most effective noise attenuation interventions. This instrument is quantitative and experimental.

A virtual experimental scenario including a noise source (road) and a receiver point inside a standardised (typical) classroom with open windows was set up in the modelling software. The sizes of the windows and openings were determined through a review of literature and regulations pertaining to classroom ventilation design, as well as a survey of a selection of actual classrooms in South Africa. The sound pressure level (SPL) at the classroom receiver point was considered as the dependent variable which was tested against the target SPL in the classroom. The acceptable target SPL (40 dBA) was determined through a review of acoustic literature and regulations pertaining to classroom ambient noise levels, thus meeting the third objective.

Possible sound attenuation interventions were treated as independent variables in the experimental environment. Various scenarios were created in the model, changing one variable at a time in order to measure the effect on the dependent variable. The independent variables determined through a review of acoustic theory and literature were:

- Building façade (material and composition)
- Building location (distance from source)
- Building orientation relative to source
- Building floor level (ground or first floor)
- Barrier length
- Barrier height
- Barrier position relative to source and receiver
- Barrier alternatives (crowning, shape, double barriers, topographical barrier)

The type of source noise used in the model was determined by means of surveys (qualitative data) and on-site sound level measurements (quantitative data). Although the acoustic modelling software used standardised traffic noise calculation methods, actual measurements of traffic noise at selected school sites were used to determine and validate the modelled sound levels.

The surveys and site measurements additionally provided confirmation of the noise problem experienced by schools located close to busy roads and provided a baseline against which to measure results of possible interventions in the future.

On-site sound pressure level measurements were taken at three locations at four selected urban schools to measure the traffic noise at the boundary, outside a classroom façade and inside a classroom with open windows. The noise level at the boundary provided data regarding the source noise; the façade noise level informed how much of the source noise was reaching the building, and the level inside the classroom indicated the sound transmission through the façade.

Two survey instruments were used – a province-wide survey and a teacher questionnaire. The first was a province-wide electronic survey distributed to all schools in Gauteng to find out how many schools are subject to disruptive outdoor noise and how common the problem of traffic noise is. The second was a questionnaire for teachers in selected schools where on-site measurements were taken. Participants of the survey and questionnaire provided qualitative data regarding the perceived noise condition in urban schools. Quantitative data from on-site measurements provide an objective baseline against which to compare and validate the perceived noise levels on the one hand, and the simulated noise levels on the other hand.

Each of these research instruments is discussed in further detail in Chapter 3.

1.8.2 Selection of sites

Four schools were selected for on-site sound level measurements and qualitative research (teacher questionnaires). These were selected from the list of all registered schools provided by the Gauteng Department of Education (GDE), including both public and independent schools. The GDE identified a number of school sites that are known to be subject to high environmental noise. Other sites were identified by virtue of their location, being situated adjacent to busy roads. The main criterion for the selection of sites was that they be adjacent to a major road.

Because the research is primarily conducted with the aid of computer simulation, a large sample of schools was not necessary. A suitable number of different scenarios could be created by means of the simulation. However, in order to validate the simulation, it was decided that at least three school study sites would be selected and that, at each of the selected schools, at least one classroom would be selected for the study.

1.8.3 Data analysis

Quantitative data collected from the model include the input values of each independent variable and the resultant values of the dependent variable for each scenario. The values were analysed and assessed for compliance against the target classroom ambient sound level. The outcome is a summary of scenarios that are deemed to satisfy the target classroom ambient sound level.

Simple statistics were used to represent the qualitative data.

1.9 Ethical considerations

Although the study was low-risk in terms of ethical considerations, ethics permission was still required. Ethics approval for conducting the survey, questionnaires and on-site measurements was obtained from the University of Pretoria, the Council for Scientific and Industrial Research (sponsor), the Gauteng Department of Education, as well as the principals of the selected schools.

Although it was necessary for the sound level measurements to be taken during normal school hours, no direct participation from the learners was required. The purpose of the study and the questionnaire was explained to the participating teachers and participation was voluntary. No sensitive personal or private information was collected as survey data.

The names of individual participants and participating schools will not be disclosed in any publication resulting from this research. The schools that were used as case study sites were assigned the letters A, B, C and D for reference in this document.

1.10 Scope and delimitations

This study considers the effect of acoustic interventions in a typical naturally ventilated classroom in Gauteng. Although there may be numerous potential solutions, this study is limited in scope in order to focus on options that may be reasonably considered and applied in Gauteng and within the practical limitations of this study.

The focus is on noise control rather than ventilation solutions. Thus, the exploration of ventilation solutions is limited to establishing a typical natural ventilation (window) design, based on case study examples and the Regulations, and mechanical ventilation or alternative natural ventilation designs are not explored.

It is also acknowledged that window design is not only determined by ventilation requirements but also natural daylight requirements. While natural daylight is important to consider in classroom design, it is excluded from the subject of this study. While sound transmission can occur more easily through glazing than through the surrounding construction, solutions, such as double glazing, are available to effectively limit sound transmission while maintaining daylighting requirements. Thus the natural daylight requirement for classrooms does not compromise acoustic insulation in the same way that natural ventilation through open windows does.

The scope of this study is limited to ordinary primary or secondary schools in the province of Gauteng, South Africa. Only normal[4] classrooms, compliant with the Regulations (Department of Basic Education, 2013), were used for acoustic modelling and on-site measurements.

This study only considered the airborne sound transmission in the horizontal direction through the vertical envelope (the wall). For the purposes of this exercise, it was assumed that noise was not transmitted through the roof or floor construction. The effect of impact sound from activities on the floor above was excluded from the study, as well as sound transmission from adjacent classrooms or other user-generated noise.

The focus of this study was on outdoor-indoor sound transmission only. Though it is acknowledged that reverberation is an important consideration for speech intelligibility in a classroom, this study did not consider reverberation or acoustic treatment inside the classroom, except where it was applied in the set-up of the acoustic model. There is a significant body of research available in this regard, as discussed in the works by Subramaniam and Ramachandraiah (2006), Klatte, Bergström and Lachman (2013), and Klattte, Lachmann and Meis (2010), Breitsprecher (2011) and Yang and Bradley (2009), which is to be considered in conjunction with the results of this study when designing classroom environments. All interior surfaces in the simulation were standardised to represent a reverberation time of 0.5 seconds in the model. This must be taken into consideration when drawing conclusions from this research.

This study was limited to the assessment of road-traffic noise. The model used had only one noise source, which was the road. Other potential sources of noise and the contribution of other roads were ignored; in other words, the main road was assumed to be the dominating source of noise.

Schools close to airports were not considered for this study as air-traffic noise is unusually disturbing and schools that are subject to frequent air-traffic noise should receive special attention (Xie & Kang, 2013; Institute of Acoustics & Acoustics & Noise Consultants, 2015, p. 9).

The scope of this study is limited to investigating architectural means of attenuating traffic noise between the source and the receiver. Only interventions that are available for implementation within the school premises, including at the boundary, and related to physical infrastructure and design are considered. It excludes interventions that reduce the generation

[4] A normal classroom is defined as one that is used for regular teaching subjects, as opposed to a special classroom, which is one used for subjects such as art, drama or music.

of noise at the source, such as vehicle-noise emission control or road design, and alternative interventions, such as noise-cancelling devices.

Acoustic interventions are limited to the insertion of barriers, the location of the building (up to 136 m from a road), and façade treatment.

Masonry walling is the most common construction method seen in urban schools, however, some are found constructed from light-weight prefabricated panels. Furthermore, the South African government promotes the use of alternative building methods that are quick to erect and cost-effective, which are often in the form of light-weight panels. Thus, façade treatment is limited to two options, namely a 220 mm masonry wall or a light-weight panel construction. The opening window sections are assumed to be sliding sash or horizontal pivot windows, which offer the least effect of directionality on ventilation and sound transmission.

The aim is to achieve suitable ambient sound levels in a classroom. Thus, the focus is on assessing the equivalent continuous sound pressure level over a broad spectrum. Although the modelling software accounts for the typical frequency spectrum of traffic noise, frequency is not discussed specifically in this study.

Certain factors that affect sound propagation, such as meteorology (temperature, humidity and wind) and atmospheric absorption were excluded as their effect is either relatively negligible over the distances considered or are too variable to reasonably consider.

1.11 Assumptions

A number of assumptions were made as a basis for this study. Assumptions include information, conditions, or background knowledge used in this study and assumed to be true, yet not examined in detail in this study.

Though it is acknowledged that other sources of external noise do occur, road-traffic noise is assumed here to be the dominant source of outdoor noise in the experiments. Dynamic traffic is assumed on a level, tarred road. In other words, the traffic is not of a stop-start nature. The traffic speed is assumed to be 60 km/h with two lanes of traffic in either direction.

The school site is assumed to be flat and level with the road, except where the topography is seen as a type of barrier and is changed as an independent variable.

The ventilation requirements discussed assume outdoor air is pollutant-free. This study is limited to the consideration of ventilation only and does not consider air quality, although air quality in terms of carbon dioxide concentration is discussed as an indicator of ventilation efficacy.

There is very little local data available regarding the soundscape in Gauteng. However, it is assumed that the Gauteng city region is comparable to other urban centres in the world and that the soundscape, particularly in terms of traffic noise, is similar.

The schools and classrooms that were selected as study sites are assumed to be representative of a typical Gauteng school.

When analysing the effect of noise attenuation interventions, it is assumed that a change of 3 dB is a perceptible change and that a change of 6 dB is a significant change in sound level.

Unless otherwise stated, sound levels discussed refer to the A-weighted equivalent continuous sound pressure level in A-weighted decibels (dBA). The decibel unit (dB) is used when discussing a level change as the difference between two sound levels is not to be weighted.

Several assumptions are also made in the modelled environment, such as the ground absorption and the number of reflections. These are set out in detail in section 5.1.

1.12 Limitations

The study was limited in that it was neither practical nor feasible to conduct a number of experimental interventions on an actual site. Thus, acoustic modelling software was used, in which an unlimited number of experimental scenarios can be created.

The results of the modelled experiment are limited by the capability of the software. For example, the calculation of traffic noise within the software, using the German standard RLS-90, includes assumptions of ground absorption, and thus ground absorption could not be manipulated in the model. This is a limitation of the study. However, the assumed ground condition is reflective, representing the worst-case scenario. The limitation in software capacity was mitigated as much as possible in the selection of the software.

Because the model was developed with specific controlled variables, such as the noise source, topography and ground absorption, the results are not strictly applicable to any school site. However, the intention of this study was to establish heuristic guidelines which do not replace the skills and services of acoustic specialists.

A limitation was also experienced in that only one sound level meter was available for on-site measurements. This meant that indoor and outdoor measurements could not be conducted simultaneously to establish the transmission across the façade. As discussed in the methodology chapter, this was overcome by taking 30-minute measurements indoors and outdoors during the same hour.

1.13 Document outline

This document is set out as follows.

Chapter 1 provides the background to the problem statement, motivating the need for the study in the global and local context. A brief overview of the methodology is given, noting limitations, delimitations and assumptions.

This introductory chapter begins setting the scene by discussing urbanisation and the demand that this places on infrastructure. This chapter draws the link between urbanisation, traffic noise and school infrastructure and introduces these issues in the context of South Africa with a focus on the impact on schools, particularly in the province of Gauteng.

The background gives the reader insight into the relevance of the study, particularly as to why the indoor environment quality (IEQ) is important to consider in classroom design, and why traffic noise is identified as a significant noise source to consider.

The chapter introduces the problem, the goal and objectives and the related research questions.

Chapter 2 discusses literature and evidence provided by other studies to establish the principles of school design, ventilation and acoustics that are relevant to this study.

The first section is a brief historical overview of schooling and school design that introduces the theories applied in school design, specifically regarding the indoor environment quality and, more specifically, acoustics and ventilation.

The subsequent sections set out to establish what is already known in terms of ventilation and acoustics requirements in a classroom context, and to identify possible gaps. The purpose is to collect background information to be used in answering the research questions. The basic theories of ventilation and acoustics provide the background for the research topic. A review of standards and literature is used to establish what has been done before to address traffic noise intrusion in naturally ventilated spaces. Gaps in this body of knowledge, or gaps in the application of knowledge, are identified. Literature and standards regarding attenuation interventions are reviewed to conclude which variables and acoustic parameters are relevant to consider for this study.

Chapter 3 discusses the research design and methods introduced in Chapter 1 in more detail. A review of methods employed by other studies, as well as relevant norms and standards for measuring noise, is conducted to establish the methods most suitable for measuring noise and collecting data for this study.

Each of the four research instruments is described in detail and their purpose within the research design are discussed.

Chapter 4 reports on and discusses the research findings of the sub-objectives, which establish the variables to be applied in achieving the main objective.

Chapter 5 provides a report on the research process and findings of the main research objective. This was done through modelling. The modelling assumptions and rationale are explained in detail and the findings documented and briefly discussed.

Chapter 6 is a discussion chapter. Here the meaning of the data and analysis is discussed with reference to the research question and the findings are applied to the examples of the selected schools.

Chapter 7 provides a conclusion to this body of work. It summarises the purpose, method, results, and meaning of the work done. Finally, based on the discussion in Chapter 5, recommendations for applying the findings are given, as well as recommendations for further research.

Chapter 2: Review of relevant literature and theory

This chapter reviews literature, including regulations, norms and standards pertaining to school infrastructure design in general, and ventilation and acoustics specifically. The purpose is to set the scene for conducting the research.

Firstly, the origin of the classroom and its evolution in design over the years is considered, establishing the current requirements for design in terms of noise and ventilation and the reasoning behind it.

Secondly, the basic theory and design principles of ventilation and acoustics respectively are discussed. Existing literature and regulations are explored to establish the design criteria that are relevant for this study in terms of both acoustic and ventilation design targets. A review of literature on the topic of noise and ventilation establishes the landscape of the current body of knowledge and regulations pertaining to noise attenuation, ventilation requirements and possible solutions where the criteria seem to be mutually exclusive. This is discussed in general and in a classroom setting.

Finally, noise attenuation options are discussed, establishing the key attenuation factors that are relevant to consider in the current research.

2.1 School design theory

2.1.1 A brief history of formalised schooling and standardised school infrastructure

The concept of school has evolved over the centuries. The history of schooling developed as civilisation changed, starting with hunter-gatherer children, who learnt life lessons as they played and participated in the community. Agriculture and later industrialisation saw children being used as labourers. It is argued that this was the beginning of formal schooling – institutional learning and discipline. In some cases, religious institutions advanced the concept of formally schooling children. Universal compulsory schooling began to emerge in the seventeenth century (Gray, 2011).

As public education began to be standardised, so the school infrastructure became standardised. The conventional school model originated in the 19th century, in which learners are rigidly organised in classes, facing to the front to receive instruction (Bates, 2015; Gray, 2017). In order to ensure equality and access for growing populations, schools have been standardised over time. By the 1930s the typical classroom in America (and much of the rest of the world) was a rectangular room designed to house the maximum number of learners in rows (Baker, 2012). This model has gone relatively unchallenged for over a century. While the overall school design evolved slightly in the years after World War 2, the basic rectangular classroom layout has largely remained entrenched.

As far back as the end of the 1800s, attention has been given to suitable school design, including the indoor environment (Baker, 2012). Most countries today have standards for school infrastructure. An examination of school design norms in a number of countries reveals that in varying degrees the same issues are covered. Broadly speaking, standards include matters relating to classroom size, ablution facilities, accessibility, lighting, ventilation, acoustics, site location, services and connectivity.

Since the 1970s there has been a growing realisation globally that the physical environment has a significant impact on learner outcomes and that the physical environment also has a role to play in facilitating pedagogical change (Baker, 2012; Barrett, Davies, Zhang & Barrett, 2015; Kasmuri, Zubir & Hormias, 2017; Woolner, Thomas & Tiplady, 2018). The evolution of pedagogy is leading some countries to re-think classroom design. For example, the New Zealand Ministry of Education recognises the need to change design requirements in line with changing education and teaching methods (Ministry of Education, 2017). Current trends in teaching, such as the flipped classroom (Zuber, 2016), the 'unwalled' classroom (Deed & Lesko, 2015) and Teaching 4.0 (Abdelrazeq, Janssen, Tummel, Richert & Jeschke, 2016; Davis, 2017), are moving away from teacher-centred learning, making use of technology and increased learner interaction. These pedagogical changes have an implication for design, as can be seen in the illustration in Figure 2-1 and in the images comparing traditional and flexible learning spaces in Figure 2-2 and Figure 2-3. The Classroom 4.0 or smart learning environments require more space for flexibility. Byers and Lippman (2019) caution that classroom design should follow evidence and that the evidence base for classroom design needs to be increased. This view is also evident in research conducted for the Innovative Learning Environments and Teacher Change (ILETC) project in Australia (Imms, Mahat, Byers & Murphy, 2017). While the design of Classroom 4.0 is yet to be firmly formulated, the indoor environment needs in terms of lighting, ventilation (per person) and ambient sound level remain unchanged based on a large body of evidence.

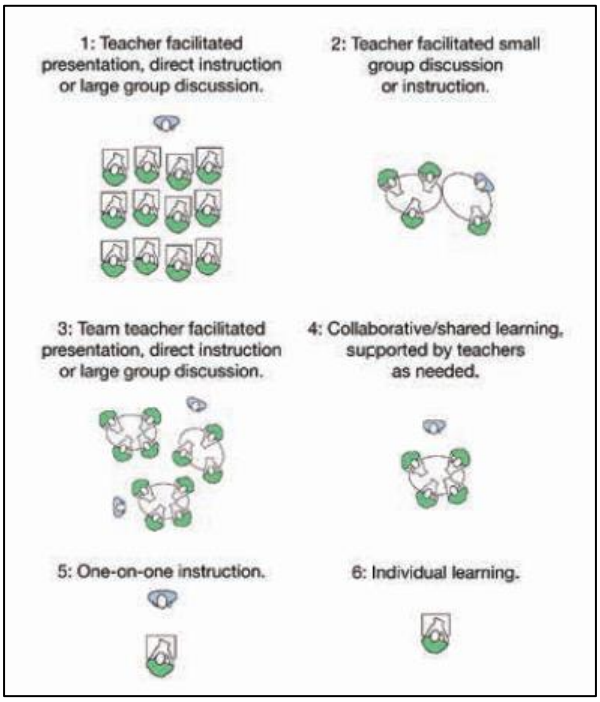


Figure 2-1: Illustration by Immes et al. (2017) of spatial arrangement for different modes of learning

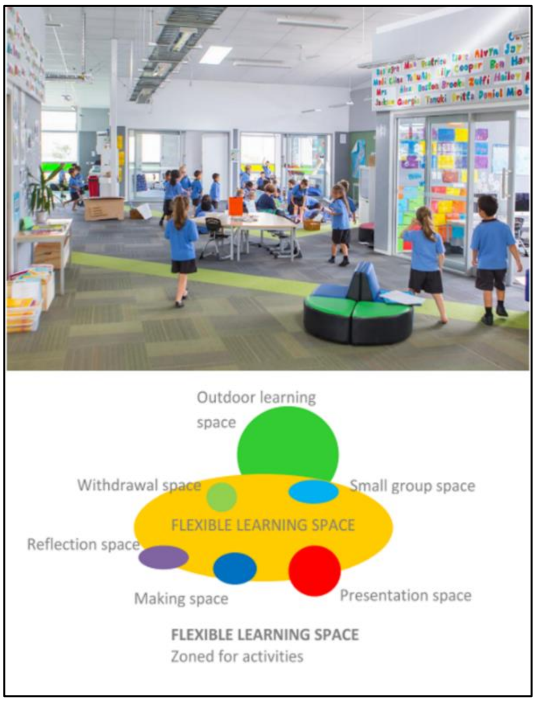


Figure 2-2: Example of a flexible learning space in a modern school in New Zealand (Ministry of Education, 2016)

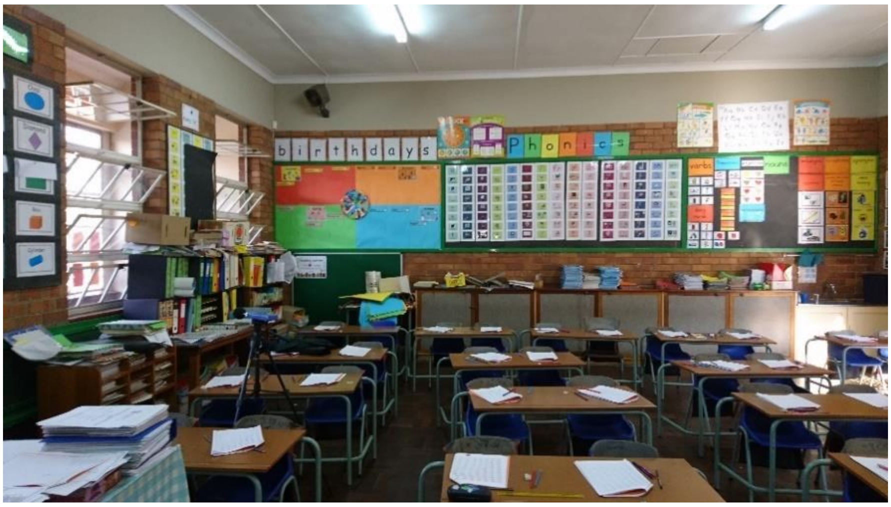


Figure 2-3: Example of a traditional classroom space in South Africa (author's own photo)

2.1.2 Schooling and school infrastructure in South Africa

In South Africa, compulsory schooling was introduced after the formation of the Union in 1910 (Thomas & Shimahara, 2018). Colonial heritage meant that schools generally followed the rectangular "face-the-front" classroom norm (Uduku, 2018). The earliest found official norms and standards developed for South African school infrastructure is the series of twenty-two

Technical Reports of the National Building Research Institute, published in the 1960s. However, many schools, particularly in the former homelands, were not constructed or maintained in accordance with such guidelines.

In 1994, the new democratic government of South Africa inherited a large number of schools with inferior infrastructure (Department of Basic Education, 2010). The Constitution of South Africa (1996) affords everyone the right to education, as well as the right to an environment that promotes health and well-being. The Tirisano plan was implemented in 2000 to transform and improve education. Nine priorities were identified, including the physical condition of schools (Department of Education, 2001). In 2007 the South African Schools Act was amended, incorporating Section 5A, making provision for the development of norms and standards for school infrastructure (Republic of South Africa, 2000). In 2010 the *National policy for an equitable provision of an enabling school physical teaching and learning environment* was gazetted (Department of Basic Education, 2010). This policy recognised the importance of suitable infrastructure to support education and aimed to define an enabling environment. The policy is enforced through the *Regulations relating to minimum uniform norms and standards for public school infrastructure*, gazetted in 2013 (Department of Basic Education, 2013).

Today, the design of public schools in South Africa is subject to the recommendations of these Regulations. The ambition of the Regulations is to ensure the provision of “relevant, effective, responsive, inclusive and sustainable teaching and learning school infrastructure” (Department of Basic Education, 2013). Minimum requirements for the classroom size, indoor environment, provision of water and sanitation, energy, media facilities and more are included. The Regulations assume a teacher-centred approach to learning, with an allocation of 1 m^2 per learner and 7 m^2 for a teacher, and limit the number of learners per class to 40.

The Regulations do not specifically discuss the construction and materials to be used for school infrastructure, except to condemn the use of mud, asbestos and other ‘inappropriate’ materials. In 2013 there was a cabinet resolution to increase the use of innovative building technologies (IBTs) for public social infrastructure, including schools. IBTs refer to any building construction method or system other than traditional masonry construction and that is not covered by the National Building Regulations (Centre for Research and Housing Innovation, 2017). Although IBTs boast many advantages, there is very little evidence-based research confirming the performance of IBTs in terms of the indoor environment quality, such as acoustic and thermal performance.

The need for innovation in education in South Africa has been identified as a priority, yet the uptake is slow (Van der Elst, 2016). The significant backlog in conventional schools has resulted in a drive to build more schools. The current Regulations address the conventional school model. The Regulations focus largely on the physical facilities of schools with only short sections pertaining to aspects of the indoor environment quality (IEQ).

The lack of attention to IEQ in South African classroom design is reflected in the small pool of research pertaining to IEQ in South African schools. The few studies on school indoor environments in South Africa confirm that thermal comfort, ventilation and acoustic requirements are not adequately regulated and enforced in South African schools (Ramma, 2007; Motsatsi & Gibberd, 2015; Wiese, 2018).

While the Regulations recommend natural ventilation that it is more energy and cost efficient, specific deemed-to-satisfy design solutions or performance-based requirements are not provided. Likewise, for acoustic conditions, the Regulations merely require that conditions facilitate clear communication "as far as reasonably practicable" (Department of Basic Education, 2013, sec. 8).

Because ventilation – whether natural or mechanical – can potentially become a source of noise, and because both ventilation and noise are important elements of a suitable classroom environment, it is necessary to have a clear understanding of the performance requirements for both, and to coordinate the design solutions to achieve the respective requirements.

2.2 Ventilation

This section discusses the basic theories relating to natural ventilation, particularly in a classroom context, and considers the ventilation requirements in a classroom based on literature and norms and standards.

2.2.1 Basic ventilation theory

Ventilation has two main purposes, which are a) to provide suitable air quality (fresh air) and b) to aid in managing thermal comfort (CIBSE, 2005). Ventilation is described as "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space" (ASHRAE Standing Project Committee 62.1, 2019).

Natural ventilation, sometimes referred to as passive ventilation, employs naturally occurring air movement, such as wind, thermal or diffusion effects, without the use of mechanically driven air movement (ASHRAE Standing Project Committee 62.1, 2019). These air movements bring fresh air into a building and extract stale air. Rather than filtering indoor air and returning it to the building interior by mechanical means, outdoor fresh air is brought into the building through deliberate openings in the envelope to dilute the indoor air and 'used' indoor air is passively extracted from the building.

Ventilation, being necessarily defined as air movement, is measured in terms of airflow. Because the amount of fresh air required is dependent on the number of people (occupancy) in a particular space, airflow is often measured in terms of litres (of fresh air) per second per person (L/s/p). This is relatively easy to achieve in the design of mechanical ventilation systems, whereby the correct amount of air can be delivered into a space. Mechanical ventilation makes use of energy to power equipment that moves air in and out of a space, sometimes combined with systems that cool, warm, humidify and clean the air. These systems can be accurately tuned to provide specific amounts of fresh air.

Natural ventilation, where possible, has become the preference of green building designers, striving to achieve improved sustainability and energy efficiency in buildings. Apart from the economic and energy-saving benefits of natural ventilation, there is some evidence that naturally ventilated buildings produce better user outcomes, such as good health and productivity (Huang, Huand, Lin & Hwang, 2015). However, to achieve adequate ventilation by passive means requires effort on the part of the designer.

With natural ventilation, it is not possible to be very specific regarding the airflow rate as this is dependent on uncontrollable and inconsistent natural factors such as wind speed, air pressure and temperature. Because it is difficult to determine the airflow rate in passive systems, the concentration of carbon dioxide (CO_2) in the indoor air is often used as an indicator of the efficacy of natural ventilation (Ministry of Education, 2017). While guidelines for mechanical systems specify the airflow rate in terms of L/s/p, natural ventilation design guidelines often specify the CO_2 concentration level in parts per million (ppm), or the recommended size of ventilation openings (such as windows) required to achieve sufficient fresh air supply in the building.

Various design techniques can be employed to create natural air movement from outdoors to indoors and out again. Every technique relies on openings in the building envelope to allow for air movement through the building fabric. The efficacy of natural ventilation depends on the size and position of ventilation openings. The larger the open area in a facade, the more air can flow through it.

The three basic types of natural ventilation strategies are single-sided ventilation, cross-ventilation and stack ventilation. These are briefly described below:

> **Single-sided ventilation**: openings are only present on one side of a space. Single-opening single-sided ventilation relies on wind turbulence and requires a large opening. Double-opening single-sided ventilation makes use of openings on one side of a space but at different heights. The stack effect assists in creating air movement and is thus more effective than single opening ventilation (CIBSE, 2005).
>
> **Cross-ventilation** makes use of windows on opposite sides of a space. Efficacy relies on wind. In both cross-ventilation and single-sided ventilation, the depth of the room plays a significant role in the efficacy of the system.
>
> **Stack ventilation** uses differences in density (created by the buoyancy of warmer air) to drive air movement. Air movement is in a vertical direction. A ventilation chimney, double facade or a ventilation atrium are examples of stack ventilation.

Cross- or stack ventilation systems are likely to require smaller openings than single-sided ventilation, which requires large openings to achieve the same ventilation rates (Institute of Acoustics & Acoustics & Noise Consultants, 2015). The design of a window itself affects ventilation efficacy and thus is a factor in determining the required opening size (CIBSE, 2005). For example, a horizontal pivot window allows for better airflow through it than louvre windows.

Trickle ventilators provide ventilation through very small openings. The efficacy, however, is highly dependent on the pressure difference across the openings (Ling, 2001) and would not be suitable for ventilating a large space with a high occupancy rate.

2.2.2 Ventilation requirements for classrooms

There is a significant body of research establishing the negative effects of poor classroom ventilation on learning outcomes and health. Low ventilation rates lead to a decrease in attentiveness (Coley *et al.*, 2007) and directly correlate to performance outcomes and negative health effects, such as asthma, tiredness, fainting, slower work speed, poor concentration and poor standardised test performance (Haverinen-Shaughnessy *et al.*, 2011; Bako-Biro *et al.*, 2012; Al-Hubail & Al-Temeemi, 2015).

The high occupancy level in classrooms increases the ventilation requirement. While the air supply per person remains constant, the high occupancy level implies that the required air change rate per hour for an occupied classroom is high. It has been shown that increasing the airflow from 3 L/s/p to 8.5 L/s/p can improve learners' performance and speed in schoolwork

(Wargocki & Wyon, 2007). Efficacy of classroom ventilation systems (both natural and mechanical) has been studied by others. Case studies in different countries, such as Italy (De Giuli, Da Pos & De Carli, 2012), Kuwait (Al-Hubail & Al-Temeemi, 2015), England (Bako-Biro *et al.*, 2012) and the United States (Haverinen-Shaughnessy *et al.*, 2011) have shown that inadequate classroom ventilation is a widespread occurrence. It is found that natural ventilation often fails because windows are closed by users to keep out cold draughts, dust and noise (Al-Hubail & Al-Temeemi, 2015; Angelopoulos, Cook, Iddon & Porritt, 2016). However, when suitably designed and operated correctly it is possible to achieve good ventilation with natural systems (Al-Rashidi, Loveday & Al-Mutawa, 2012).

To achieve and maintain the high ventilation rate required for the high occupancy rate in classrooms by natural means is not always easy. However, it has been proven successful even in very hot climates, such as Kuwait (Al-Rashidi *et al.*, 2012), and in climates with cold winters, such as England (Angelopoulos *et al.*, 2016), and is beneficial in terms of energy efficiency (Wang, Zhao, Kuckelkorn, Liu, Liu & Zhang, 2014). In a climate such as that of Gauteng, South Africa, natural ventilation is suitable since the climate is relatively mild, with low to medium amounts of heating and cooling required (Conradie, Van Reenen & Bole, 2018).

Because of the significant impact of ventilation on user outcomes, ventilation requirements and recommendations for classrooms are addressed in the norms, standards or regulations of many countries. These are either performance-based, using flow rate (L/s/p) or CO_2 concentration levels as a performance indicator, or deemed-to-satisfy, using opening size (as a percentage of the floor area) as a measure.

Performance-based regulations specify the performance to be achieved by any means, whereas deemed-to-satisfy regulations prescribe a certain design solution which is considered to achieve suitable ventilation. Examples of norms and standards that are prescriptive or deemed-to-satisfy are listed in Table 2-1.

Table 2-1: List of natural ventilation guidelines, norms, standards or regulations in various countries by type

Country	Standard (norm, regulation or guideline)	Type of requirement	
		Performance-based	Deemed-to-satisfy
World Health Organisation	WHO policy on TB infection control in health-care facilities, congregate settings and households	✓ (L/s/p)	
South Africa	SANS 10400: Part O		✓ (% opening area)
United Kingdom	BB101	✓ (L/s/p & CO2)	✓ (% opening area)
United States	ASHRAE 62.1		✓ (% opening area)
New Zealand	Designing Quality Learning Spaces	✓ (L/s/p & CO2)	
Rwanda	Child Friendly Schools Infrastructure Standards and Guidelines		✓ (minimum opening area)

The World Health Organization (WHO) does not have ventilation requirements for classrooms as such. However, it does have guidelines for airborne infection control for congregate settings, which may be applied to schools (World Health Organization, 2009; Centers for Disease Control and Prevention, 2014; Richardson, Morrow, Kalil, Bekker & Wood, 2014). Accordingly, the recommended ventilation rate is 12 air changes per hour (ACH), which can be equated to approximately 1 000 ppm CO_2 or 8.6 L/s/p (Richardson *et al.*, 2014).

The *Building Bulletin 101* (BB 101) provides regulatory support for the United Kingdom building regulations regarding ventilation in schools (Department for Education, 2006). The BB 101 goes into some depth in terms of performance requirements. It stipulates that the ventilation rate in classrooms should be at least 3 L/s/p and the CO_2 levels should be maintained at a maximum average of 1 500 ppm throughout the school day. The minimum daily average ventilation rate should be 5 L/s/p and there should be capability to achieve a rate of 8 L/s/p when occupied, thus maintaining a CO_2 concentration of approximately 1 000 ppm. This correspondence between ventilation rate and CO_2 concentration has been confirmed by research (Santamouris, Synnefa, Assimakopoulos, Livada, Pavlou, Papaglastra, Gaitani, Kolokotsa & Assimakopoulos, 2008). The potential to achieve these performance requirements by natural ventilation has been demonstrated by means of computational fluid dynamics (CFD) simulations (Angelopoulos *et al.*, 2016).

The effect of window type, in terms of opening section design, is acknowledged and tabulated in BB 101, enabling the designer to make an informed selection regarding window design. According to Table 7 of BB 101, horizontal centre-pivot or sliding sash windows provide the best ventilation. This is supported in the CIBSE manual for natural ventilation (CIBSE, 2005).

Dampers, louvres and roof ventilators are also discussed, though this is beyond the scope of the current discussion.

The American national standard, *Ventilation for acceptable indoor air quality*, provides specific ventilation rates for different occupancies for mechanical ventilation (ASHRAE Standing Project Committee 62.1, 2019, sec. 6). However, it is not possible to ensure specific ventilation rates when relying on natural ventilation. Rather, it provides guidance in terms of the openable window area as a factor of the floor area. According to this, a naturally ventilated classroom (with a maximum occupancy of 35) should have operable wall openings that open directly to the outdoors with an unobstructed openable area that is at least 2.5 – 4% of the net usable floor area (depending on the window height to width ratio).

In addition, this standard provides guidance regarding the size of the room relative to the ventilation openings and design. For single-sided ventilation (i.e. window on one side of the room only) the horizontal distance from the ventilation opening should not be more than twice the height of the space. For double-sided natural ventilation (i.e. windows on opposite sides of the space) the maximum distance from an opening should not be more than five times the ceiling height of the space. With certain exceptions, naturally ventilated spaces are to also have mechanical ventilation unless the openings are permanently open. This combats the situation in which windows are closed by users (for example, to prevent dust or noise from entering), leaving the space with no fresh air supply. From this, it can be learned that a certain minimal amount of permanent trickle ventilation should be present.

As part of the *Designing quality learning spaces* series of the New Zealand Ministry of Education, the *Indoor air quality and thermal comfort* document (Ministry of Education, 2017) provides design guidance and technical requirements for this aspect of school design. According to this document, the average CO_2 concentration in a classroom should not exceed 1 500 ppm and should be maintained at approximately 1 200 ppm or less. The peak at any time during the occupied period should not exceed 3 000 ppm; ventilation design should enable occupants to purge a space to achieve a concentration of 1 000 ppm within 10 minutes.

According to the New Zealand guidelines, a suitable ventilation rate (equivalent to 4 ACH, providing approximately 8 L/s/p) will be exceeded by opening windows. A number of ventilation design options are discussed, such as various window designs to maximise airflow (horizontal pivots and sliding sashes being promoted as best-practice options), cross-ventilation, single-sided ventilation, assisted and mixed-mode ventilation. This design guide acknowledges the need to consider location and local conditions. This document provides good theory and performance-based regulations, but does not provide a deemed-to-satisfy design solution.

Turning to Africa for an example, the Rwandan guidelines for school infrastructure prescribe a minimum openable window area of 5 m^2, with airflow maximised by cross-ventilation (Rwanda Ministry of Education, 2009). This is a deemed-to-satisfy design solution and equates to approximately 10% of the floor area of a minimally sized classroom.

2.2.3 Ventilation requirements in South African schools

In South Africa, the *Regulations relating to minimum uniform norms and standards for public school infrastructure* (Department of Basic Education, 2013) – applicable to all South African public schools – do not provide technical detail regarding ventilation requirements for classrooms. Rather, the Regulations recommend that natural ventilation should be employed by means of permanent wall vents and windows with opening sections and that natural ventilation requirements and all relevant laws be taken into consideration. No further guidance regarding the performance or deemed-to-satisfy solutions is provided and no specific laws are referenced.

All buildings in South Africa are subject to design compliance with the National Building Regulations, which are enforced through the application of the South African National Standard number 10400. According to the SANS 10400, education spaces are classified as occupancy class A3 – place of instruction. Part O of SANS 10400 deals with lighting and ventilation. According to this, for the occupancy class A3, the basic minimum requirement for ventilation is that the total opening area of a ventilation aperture (whether window or door) must be at least 5% of the floor area of the room (with a minimum area of 0.2 m^2). Alternatively, if a ventilation flue is used, the opening area must be at least 2% of the floor area. This is a deemed-to-satisfy solution and a minimum requirement. It is noted that the natural lighting requirement in terms of SANS 10400 Part O calls for a glazed area of at least 10% of floor area. This implies that half the windows are to be openable for ventilation.

Guidance regarding classroom ventilation design in South Africa is also found in *Technical Report 9* (Van Straaten, Richards, Lotz & van Deventer, 1965). This is part of the old National Building Research Institute Technical Report Series pertaining to school building design published in the 1960s. Though this report is not enforceable, the series was sponsored by the provincial administration at the time and may be considered good-practice guidelines.

Technical Report 9 provides extensive discussions on natural ventilation design. The efficacy of natural ventilation is dependent on a number of factors, such as the indoor-outdoor temperature difference and local wind strength and direction. Both performance-based and deemed-to-satisfy guidelines are provided. It can be generally summarised that the required ventilation rate for a classroom is 30 cfm per person (or approximately 14 L/s/p), which can be equated to 0.07 m^2 of window area per person (Van Straaten, Richards, Lotz & Van Deventer, 1965).

Considering that there can be up to 40 learners per class, the occupancy rate is high, requiring a high ventilation rate. There is little evidence regarding the efficacy of these deemed-to-satisfy regulations and guidelines in the South African context. With reference to CO_2 levels, a study in classrooms in Cape Town, South Africa, found that a CO_2 level of not more than 1 000 ppm is necessary to achieve safe indoor air quality in naturally ventilated classrooms (Richardson *et al*., 2014). This is in line with regulations of other nations and the WHO, but does not make reference to the deemed-to-satisfy solutions offered by local regulations. A case study by Motsatsi and Gibberd on indoor environment quality in a South African classroom found that CO_2 levels are high in naturally ventilated classrooms assessed (Motsatsi & Gibberd, 2015).

2.2.4 Ventilation: pertinent issues within the context of the current study

International regulations are mixed in terms of deemed-to-satisfy and performance-based requirements. The American standards for natural ventilation are limited to deemed-to-satisfy requirements in terms of window area relative to room size, while the British and New Zealand regulations speak to the performance requirements, leaving the achievement of such performance up to the designer.

The South African regulations, norms and standards in terms of natural ventilation for classrooms are limited to the deemed-to-satisfy minimum requirements of the National Buildings Regulations (in accordance with SANS 10400 Part O), while the *Regulations relating to minimum uniform norms and standards for public school infrastructure* require natural ventilation yet provide no criteria.

Because natural ventilation is dependent on local factors, such as climate and wind direction, it is almost impossible to expect a generic deemed-to-satisfy design solution to meet performance requirements. For this reason, it would generally be better to apply performance requirements, provided that the efficacy of the design can be established.

Very little research has been done in South Africa regarding the ventilation conditions in schools. That which has been done is in the form of case studies assessing indoor environmental conditions but does not refer to window or ventilation design (Richardson *et al.*, 2014; Motsatsi & Gibberd, 2015). Many case studies, whether local or international, are not clear on whether windows are open or closed during the study or do not control for temporal variation in window-opening conditions. There is a gap in the evidence in this regard, making it almost impossible to determine what an 'ideal' ventilation design is for a naturally ventilated classroom in Gauteng.

2.3 Acoustics

This section considers existing literature, including regulations, and discusses the theories relating to acoustics and noise control, particularly in a classroom context. The purpose of this section is to provide background information and theory and discusses ideal sound conditions for a classroom.

2.3.1 Basic acoustics background and theory

Acoustics is described as "a science that deals with the production, control, transmission, reception, and effects of sound" (Merriam-Webster Inc, 2019).

Sound is transmitted as a longitudinal wave of compressions and rarefactions in gasses, liquids or solids, although it can be a transverse wave in solids. Sound is perceived by the human ear due to the physical phenomenon of waves of air pressure causing the eardrum to vibrate. As such, sound is technically measured in terms of pressure (Pa). However, the common unit of measurement for the loudness of sound is the decibel (dB), which is the sound pressure level (SPL) with reference to the threshold of human hearing on a logarithmic scale. Because the decibel is a logarithmic unit, a perceived doubling of sound level is represented by a 10 dB increase in SPL, while an increase in loudness of less than 3 dB is barely perceivable by the human ear (Cowan, 2016); a change in sound pressure level of 6 dB is considered significant perceived change (McShefferty, Whitmer & Akeroyd, 2015).

In the built environment, it is important to control sound levels because of the effects it can have on people as users of the built environment. Noise, a term often used when discussing sound, is defined as unwanted sound and not necessarily sound above a specified level. Noise affects people in two basic ways. Firstly, sound levels above a certain limit can cause hearing damage, referred to as noise induced hearing loss (NIHL). Secondly, sound can be disturbing in that it can cause irritation, distraction, tiredness and stress, thus influencing human behaviour and well-being (Stansfeld & Matheson, 2003; World Health Organization, 2018).

In the context of this study, the second effect is of more interest. Sound from outside the classroom is unlikely to be of such a level as to result in hearing loss; however, numerous studies demonstrate that intrusive outdoor noise disrupts classroom activities and outcomes (Matheson *et al.*, 2010; Paunovic *et al.*, 2013). A meta-analysis of research regarding the effects of noise on school children by Paunovic (2013) lists increased temporal hearing shift, sleep disturbances, impaired learning ability and stress symptoms as some of the negative outcomes. Other literature studies (Bluyssen, 2017; Van Reenen & Karusseit, 2017) cite the negative effects on annoyance, stress, social behaviour, reading skills, spelling, memory, comprehension, speech perception, auditory processing, attention or concentration and voice strain. The effects of noise in the classroom, as well as the extent of the effects, seems to vary depending on the type of noise and the age and ability of the learners. Research by Dockrell and Shield (2006) and Klatte *et al*. (2013), which provide evidence that different types of noise have differing effects on the performance of school children. Younger learners and those with language or learning differences (including second language learners) seem to have more difficulty hearing in noise (Abikoff, Courtney Szeibel & Koplewicz, 1996; Anderson, Kritzinger & Pottas, 2019; Nelson, Kohnert, Sabur & Shaw, 2005; Peng & Wang, 2016). Types of noise that have been studied in relation to their effect include air traffic noise, road traffic noise, white noise, music, speech and random noise (Connolly *et al*., 2019; Hygge *et al*., 2002; Hygge *et al*., 2003; Söderlund *et al*., 2010;). For these reasons, it is relevant to consider the different aspects of noise and understand the impact on the design of the built environment.

Sound can be described in terms of its loudness, frequency, impulsivity and fluctuation or temporal variation. The human perception of sound is influenced by all these characteristics (Willemsen & Rao, 2010; Wunderli, Pieren, Habermacher, Vienneau, Cajochen, Probst-Hensch, Roosli & Brink, 2016), as well as the period of exposure.

To describe environmental noise generally, taking these factors into account, the equivalent continuous sound pressure level (L_{eq}) is calculated. This is a single figure that represents the total sound energy experienced over a particular period of time in decibels (dB) and is the mean-square sound pressure of the environmental noise under consideration (SABS Standards Division, 2008). The L_{eq} also represents the sound pressure level over the full sound spectrum and thus is not frequency-specific.

When discussing environmental noise, the sound pressure level is usually A-weighted and time-weighted in order to more accurately represent the human perception of sound. This is known as the A-weighted equivalent continuous sound pressure level ($L_{Aeq,T}$) over a specified time period (T).

The $L_{Aeq,T}$ is usually used when referring to environmental noise. While other statistical descriptors of sound are sometimes used, such as the L_{10} when measuring traffic noise, most standards, regulations and guidelines relating to environmental noise (whether indoor or outdoor) use the $L_{Aeq,T}$ to describe the noise limit. What does vary to some extent across different sources is the time period for which the $L_{Aeq,T}$ is referenced. In most standards, the time period is defined as night and day periods. However, in certain environments the time period is more narrowly defined, depending on the use.

2.3.2 Sound transmission

Sound, as we normally perceive it, is transmitted through air (gas). However, sound waves can also travel through liquids and solids. The ability of a material or element to resist or transmit sound can generally be referred to as sound insulation.

There are a number of metrics used in industry to describe the insulating ability of materials[5]. For example, most American standards refer to the sound transmission class (STC) – a single number rating indicating the sound-blocking ability of a material over a broad frequency spectrum (Acoustical Society of America, 2010), while many other English-speaking countries refer to the sound reduction index (R-value), which provides an insulating value in decibels for each octave band. In South Africa the R-value is used, which indicates the amount of sound transmitted (in dB) per octave band (International Organization for Standardization, 1998).

The sound reduction index is established in a laboratory set-up as per SANS 140-1 (1997). The apparent sound reduction index (R´) and the level difference (D) are alternate metrics for the sound insulating ability of a separating element that takes influencing factors such as room absorption, source character or flanking noise into account (International Organization for Standardization, 1998). Specific measurement conditions result in variations of these two metrics. For example, there are specific variations for each when traffic noise is the source sound. The apparent sound reduction index when traffic noise is the source ($R'_{tr,s}$) is measured with the outside microphone position on the surface of the test element; the standardised level difference when traffic noise is the source ($D_{tr,2m,nT}$) takes the reverberation time of the

[5] See Appendix C for a detailed list of descriptors for sound transmission

receiving room into account and is measured with the outside microphone 2 m in front of the test element (International Organization for Standardization, 1998).

If the sound reduction index of a partition element is known and the sound pressure level of a sound source is known, the calculation of the sound pressure level on the receiving side of the partition is a matter of simple arithmetic. For example, if the sound source is 70 dB at a frequency of 1 000 Hz and the sound reduction index (R-value) of a partition element is 20 dB at 1 000 Hz, then the sound pressure level on the receiving side of the element will be 50 dB at 1 000 Hz (assuming no flanking sound occurs).

Generally, a dense material, such as a masonry wall, will have a relatively high R-value. For example, a plastered double-skin brick wall (230 mm) will provide R-values of 41 – 61 dB over the frequencies of 100 – 4 000 Hz. However, the isolation integrity of any element is significantly compromised by a single component that has a lower R-value. Thus, a masonry wall with a window in it will have a decreased R-value, particularly if that window is open. Any aperture in an element – whether an open window or door, or small gaps around closed windows or doors – will significantly reduce the insulating effect of the envelope element as a whole.

This means that in a classroom that is naturally ventilated by means of openable windows, as most South African classrooms are, outdoor noise is likely to be transmitted into the indoor space and influence the ambient noise level in the classroom.

The transmission of disruptive outdoor noise through the classroom envelope can be minimised by ensuring that the separating elements (walls, floor and ceiling) have a high sound insulating ability. Sound can be transmitted through a separating element by means of mass transmission (by which particles of the element vibrate), co-incidence (by which a panel element is excited by sound waves at a certain incident angle, making the element virtually transparent) and resonance (by which particle vibration is amplified at certain frequencies) (Lawrence, 1970), and is dependent on material properties and the frequency of the incident sound. Thus, when considering the sound transmission through a building envelope, it is necessary to know the ability of each material component to resist sound transmission.

2.3.3 Sound attenuation

Another way of minimising the transmission of disruptive outdoor noise is to attenuate the noise outdoors, thus decreasing the magnitude of the incident noise at the building envelope. A number of factors play a role in outdoor sound attenuation. In theory, sound decays over distance at a rate of 6 dB for every doubling of distance (Lawrence, 1970). Although in a realistic scenario this is seldom the case, the point remains that the magnitude of the source noise and the distance of the receiver from the source are primary considerations in sound attenuation. However, the effect of screening, topography, terrain, weather and orientation can also influence the sound attenuation. The effect of all these factors acting simultaneously is a complex calculation.

In the context of this study, two main options for attenuating outdoor noise inside school classrooms are explored. These are either to increase the insulation of the envelope or to decrease the incident sound (Acoustical Society of America, 2010). The best option, of course, is to locate a school away from sound sources such as busy roads. This is proposed by many of the regulations studied, such as the *Building Bulletin 93 – Acoustic design of schools: performance standards* (BB 93) (Department for Education, 2015) and the South African *Regulations relating to minimum uniform norms and standards for public school infrastructure* (Department of Basic Education, 2013). Determining a suitable distance from a noise source depends on the character and magnitude of the source and the sound insulation value of the envelope. An upper noise level limit of 60 dB ($L_{Aeq,30min}$) at the boundary of a school is suggested (Department for Education, 2015), although this will depend on the building envelope design, screening and distance from the source.

The American standard for acoustic performance criteria for schools (ANSI/ASA 12.60-2010/Part 1) provides a table of deemed-to-satisfy outdoor-indoor transmission class ratings for the envelope relative to set outdoor noise levels. However, the insulation is significantly compromised when windows or doors are opened. An envelope design that includes openings such as doors and windows generally provides a sound reduction index of approximately 10 dB (Institute of Acoustics & Acoustics & Noise Consultants, 2015).

Façade transmission and outdoor attenuation are each discussed in the following sections.

2.3.3.1 Façade attenuation

Since sound insulation is largely dependent on material density, light-weight panel systems are likely to be poor insulators. The mass law – a well-established law in the field of sound transmission – states that a doubling of surface density of a separating element should result in a 6 dB increase in sound transmission loss (Lawrence, 1970). In general, any dense homogenous wall, such as a masonry wall, should provide sufficient insulation to allow for suitable indoor sound pressure levels (Institute of Acoustics & Acoustics & Noise Consultants, 2015).

The transmission of sound through a partition element that is made up of more than one type of material – such as a brick wall with a glass window – will be a factor of the sound reduction index and respective area of each material. As a general rule, the sound reduction index of a composite element is determined by the weakest element (Acoustical Society of America, 2010, p. 16).

The introduction of a glazed section in a façade will influence the overall insulation value of the façade. For example, the introduction of a glazed window occupying 20% of a masonry façade can reduce the effective sound reduction across the façade from 45 dB to 22 dB (Ling, 2001, sec. 19). Laboratory experiments measuring the sound transmission through a separating element with closed windows of different sizes show a 5 dB reduction in the sound insulation value for every doubling of the window area (The Building Performance Centre, 2007), demonstrating the effect of the size of the weaker element on the overall façade insulation.

A solution that is commonly offered to increase the sound insulation of building facades with glazed sections is to install double glazing. Double glazing or secondary glazing (a retrofitted pane in front of an existing window) can improve the overall sound insulation of the envelope. Tadeu and Mateus (2001) experimented with this, finding that there is a significant difference in the performance of single or double glazing, but only when the separating air space is greater than 50 mm.

Batungbakal *et al.* (2013) also studied the comparative effect of single and double-skin facades in terms of sound transmission. Using *INSUL* simulation software, they were able to determine that double-glazing offers a slightly improved sound insulation performance but highlighted that this effect is frequency dependent.

Alternative window pane materials have shown that glass is superior to other transparent materials, such as acrylic and polycarbonate of the same thickness (Khidir, Harun, Nor & Razi, 2013). This can be attributed to the higher material density of glass, which is 2 440 kg/m^3 compared to 1 160 kg/m^3 and 1 200 kg/m^3 for acrylic and polycarbonate respectively.

The benefit of double-glazed windows for acoustic insulation in a school context is demonstrated in a comparative study of schools with and without double-glazed windows. Double-glazed windows were shown to effectively reduce background noise; however, the effect is lost when windows are opened for ventilation purposes (Sarantopoulos, Lykoudis & Kassomenos, 2014).

While replacing façade materials and sealing window openings may effectively improve the overall sound insulation of a façade, it can sometimes introduce new acoustic challenges. This was evidenced in a post-intervention study at a school near Manchester airport. In an effort to reduce the transmission of air traffic noise into the classrooms, the existing aluminium panel curtain walls, of which 15% were windows, were replaced with a new curtain wall system with a higher sound insulating ability, resulting in a significant improvement in noise level reduction across the façade. However, to achieve this level of isolation the windows needed to be sealed and a mechanical system was installed to provide fresh air. The noise generated by the mechanical system provided a new challenge – to reduce the ambient noise level (Ehrlich & Gurovich, 2004). Noise from mechanical systems can be due to fan noise or aerodynamic noise in ducts. Compressor noise can also create a source of outdoor noise or structure-borne noise. Care should be taken in the entire design of a mechanical system from an acoustic point of view.

For naturally ventilated spaces, ventilation openings can reduce the overall sound insulation of a façade by approximately 10 – 15 dB (Ling, 2001, p. 49; The Building Performance Centre, 2007, p. 39). The degree to which ventilation openings affect the overall sound insulation of a façade will depend on the ventilation design and the size of the openings in the façade. Ideally, openings should be as small as possible to minimise sound transmission (Ling, 2001), although evidence presented by Walter-Fuller *et al.* (The Building Performance Centre, 2007) indicates that the difference in sound insulation for open sections of different areas is almost negligible.

Laboratory experiments have shown that a double-glazed façade with a 314 mm cavity and ventilating slots is significantly better than single glazing (R_w = 34 dB for single glazing compared to 40 or 47 dB, without or with absorption, respectively) and that a glazed cavity with absorption is best, even better than a non-parallel cavity (Urbán, Roozen, Zat'ko, Rychtarikova, Tomasovic & Glorieux, 2016). However, this study did not consider the efficacy of ventilation and, as has been pointed out previously, a high air exchange rate is required in a high-occupancy context, such as a classroom. Thus, although natural ventilation through double-glazed facades is possible, it is unlikely to prove to be a good solution for a classroom.

The CIBSE manual for natural ventilation offers two possible solutions to reduce noise transfer through ventilation openings: place ventilation openings on the sides of the building that face away from the noise source; or make use of acoustic baffles inside the ventilation opening (CIBSE, 2005). Both of these options can be problematic. Firstly, it may not be practical to orient the building to face ventilation openings away from the outdoor noise source. Secondly, acoustic baffles are only applicable for relatively small openings, such as trickle ventilators, which are unlikely to provide adequate airflow for ventilation and thermal comfort in a classroom.

There is a relationship between airflow, envelope opening size, opening resistance to airflow, and noise transmission. The performance of a wall with a high sound reduction index is dramatically decreased by an opening as small as one percent of the total façade area. Alternative ventilation options often require sound attenuation treatment within the opening at the expense of airflow (Oldham, de Salis & Sharples, 2004).

When considering the combined effectiveness of acoustic attenuation and airflow, it is evident that as the percentage of opening area on a façade increases, the airflow increases but at the same time the acoustic insulation value decreases (De Salis, Oldham & Sharples, 2002). This research by De Salis *et al.* showed that adequate ventilation rates and acoustic insulation in the context of traffic noise can be achieved at certain aperture opening sizes; however, this is highly dependent on an ideal and constant air pressure differential.

Apart from the aperture size, De Salis *et al.* (2002) also considered the effect of screens, acoustic louvres, resonators, treatment of ducted inlets and hybrid systems with reference to relative airflow. It was concluded that, for the lower frequencies produced by traffic noise, screening is not very effective. This was also found to be the case with the application of acoustic louvres inserted into apertures, where an overall reduction of 28 dB (using a double louvre) could be achieved associated with required airflow rates. Quarter wave resonators within the edges of the aperture openings were investigated and, here too, it was found that efficacy decreased with frequency. Ducted ventilation was also considered since ducts provide more opportunity for attenuation due to their extended length and the opportunity to incorporate bends and make use of different geometries. This is made possible by the fact that ducted openings typically do not function as visual openings (windows). It was found that effective attenuation could be achieved at lower frequencies due to the panel absorption effect of the duct walls, and at mid to high frequencies by the application of absorptive duct lining. Also, attenuation over distance contributes to effectiveness. It is noted, however, that increase in length and lining have an effect on airflow.

Ducts provide multiple opportunities for designing attenuators, such as Helmholtz resonators, into the system. However, this may not be applicable or desirable in simple buildings. Active noise control (ANC) is also possible in a ducted system, providing minimal airflow reduction and the opportunity to tune the system to target certain frequencies. De Salis *et al.* argue that the disadvantage of ANC systems is that they are not very effective at responding to time-varying noise and, if not expertly designed, can become a problematic source of noise themselves and have the added disadvantages of requiring energy and maintenance. On the other hand, ANC installed on top of screen walls has been shown to improve the insertion loss of noise barriers (Guo & Pan, 1997).

De Salis *et al.* (2002) conclude that the ideal solution to achieving suitable sound insulation and ventilation simultaneously lies in combining different mechanisms in a hybrid solution that covers the full range of frequencies.

One way to ventilate without a direct opening in the building envelope is to make use of plenum windows. These are double-glazed windows with openings in each side of the cavity that are misaligned. This allows a certain amount of airflow without a direct path for sound transmission through the building envelope. According to the BB 93 design guide (Institute of Acoustics & Acoustics & Noise Consultants, 2015), partially open single glazing or double glazing with opposite opening panes can offer 10 to 15 dB airborne sound insulation, while staggered opening sections can achieve insulation of 20 to 25 dB.

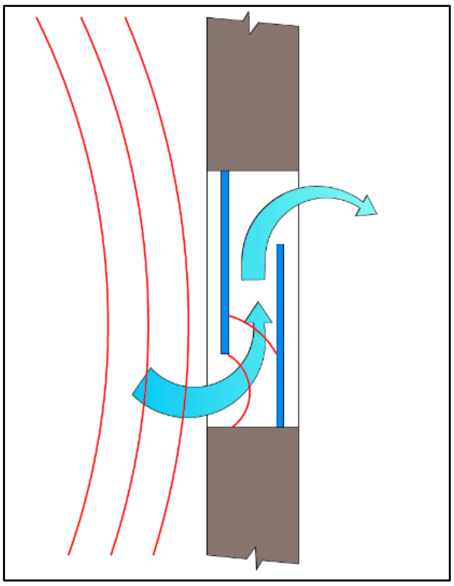


Figure 2-4: Diagrammatic illustration of airflow through plenum window

A study investigating the effectiveness of plenum windows to limit the transmission of traffic noise in Hong Kong was conducted in a laboratory set-up and then on an actual site (Yeung, Ng, Lam, Tang, Lo & Yeung, 2014). It was found that a noise reduction of up to 8 dB can be achieved without compromising ventilation if care is taken in the design. Research by others also suggests that plenum windows are effective and worthy of further investigation and development (Tang, 2017).

Lee (2016) considered the effect of different ventilated cavity designs for glazed curtain walls. The position of ventilation openings, as well as the depth of the cavity, was explored. In terms of noise control, it was found that a cavity of at least 750 mm was significantly more effective than smaller cavity depths while, at the same time, it was noted that glazed cavities potentially grow hot and transfer unwanted heat to the interior of the building. This again highlights the challenge of designing to satisfy all IEQ requirements simultaneously.

Griffiths developed a design tool in 2000, referred to as the acoustics and ventilation design tool (AVDT), to help determine the volume of spaces in the early design stages for optimal acoustic performance (Griffiths, 2007). Motivated by a need to save energy through the application of natural ventilation, and the need for acoustically suitable indoor spaces, the tool calculates the required volume of a space for the use and occupancy (number of people) as well as the suitable volume to ensure good acoustics, based on the reverberation and absorption required. Though this tool closely matches the topic of this study – the quantification of design solutions for optimal acoustics and ventilation – the focus was on the interior space design, while this study is focused on the ingress of outdoor noise into a standardised space and the mechanisms to be employed to minimise noise ingress in spite of employing natural ventilation.

A recent study considered the effectiveness of protrusions on a building façade to decrease noise transmission through windows, with particular reference to traffic noise penetrating high-rise residential buildings. The study found that protrusions – meaning building elements, such as balconies, that protrude above, below or next to windows – are not effective for noise attenuation (Yeung, Ng, Lam, Tang, Lo & Yeung, 2017).

An extensive study into the sound insulation performance of common residential window designs in an open condition was undertaken by Napier University (The Building Performance Centre, 2007). The study explored the sound transmission (between 50 Hz and 5 kHz) through windows in a masonry cavity wall, considering the window type, glazing type, opening design and opening area. Amongst other things, the study investigated the effect of the type of noise and the open area of the window in a laboratory situation.

The findings of the Napier study showed that a doubling of the window area (with closed glazing) reduced sound resistance by 5 dB – in other words, the larger the window area, the more noise was transmitted. However, the resistance was almost nullified once windows were open. It was further discovered that the type of window frame material and window seals had no significant effect once the windows were opened. This is a useful finding and informs the window design for the modelling in this study, since it implies that only the open area and not the details of the window framing need be considered.

The study found a variance of up to 21 dB in the insulation offered by windows, depending on the direction of the noise source and opening design of the window. This finding demonstrates that the window design is relevant to consider, so that the open pane does not assist in diverting the noise into the classroom.

The attenuation effect of the building envelope material was explored by Kim, Barber and Srebric (2017) including the position of openings in the envelope, the size of openings relative to the façade area and indoor boundary conditions. The study by Kim *et al.* is similar to the current research study in that it (1) modelled traffic noise, (2) determined outdoor propagation, (3) assessed transmission through the building envelope, (4) determined indoor sound propagation and (5) evaluated the resultant indoor noise level. The findings of this study confirmed the significant effect that an envelope opening height has on the overall sound transmission of a façade. The current study differs in that it considers outdoor attenuation interventions, rather than focusing on the indoor interventions. The study by Kim *et al.* demonstrates the complexity of factors that influence the perceived sound level at an indoor receiver.

2.3.3.2 Outdoor attenuation

When considering outdoor noise attenuation, there are a number of factors that influence the propagation of sound in an outdoor environment (Lawrence, 1970; Federal Highway Administration, 2017). These include:

i) geometric divergence (distance between source and receiver)
ii) orientation
iii) ground absorption or reflection
iv) topography
v) atmospheric (air) absorption and atmospheric conditions (air temperature, humidity, wind)
vi) barriers or screening
vii) vegetation

Each of these could potentially be used to decrease the amount of sound energy reaching the outer surface of the building envelope, thus reducing the sound insulation requirement of the façade. If the outdoor noise can be sufficiently decreased, the concern regarding sound transmission through open windows can be eliminated.

These outdoor attenuation factors have a combined effect on sound attenuation, which can be calculated. ISO 9613 (1996) provides the following formula for the calculation of sound attenuation outdoors (International Organization for Standardization, 1996):

$$A = A_{div} + A_{atm} + A_{gr} + A_{screen} + A_{misc} \quad [2\text{-}1]$$

Where:

A is overall attenuation

A_{div} is attenuation due to geometric divergence

A_{atm} is αd/100 (α = atmospheric attenuation coefficient in dB per km for each octave)

A_{gr} is attenuation due to ground effect

A_{screen} is attenuation due to screening

A_{misc} is attenuation due to other effects, such as vegetation, buildings, etc.

This simple calculation does not reflect the full complexity of modelling outdoor sound propagation in urban environments (Kamrath, Jean, Maillard, Picaut & Langrenne, 2018). However, it is commonly accepted and used in the prediction of community noise levels because its generality lends itself to a wide variety of applications (International Organization for Standardization, 1996). By virtue of the factors that are included in this calculation, it is informative as to the most pertinent aspects of outdoor sound propagation, which are discussed in the following sub-sections.

2.3.3.2.1 Geometric divergence

Geometric divergence refers to the effect of distance between the source noise and the receiver. The acoustic energy decreases as it diverges from the source; thus the further a receiver is from a source, the lower the sound pressure level will be at the receiver. In a theoretical free field scenario, a decrease of 6 dB for every doubling of distance occurs if the source is a point source. For a line source (such as a busy road), a decrease of 3 dB per doubling of distance occurs. This is due to the spherical (or cylindrical for a line source) divergence of the sound – the ‘spreading out’ of sound as the pressure wave moves away from the source (Lawrence, 1970).

In reality, these attenuation values will be different due to the effect of reflective or absorbent surfaces. The actual attenuation effect of distance, depending on the surrounding landscape, is approximately 1 dB per 30 m for mid-frequencies and less for lower frequencies (Lawrence, 1970, p. 61).

2.3.3.2.2 Building orientation

Orientation can also have an influence on sound transmission and propagation. While some sources recommend orienting windows away from the noise source (CIBSE, 2005), in some cases sound transmitted through windows on facades perpendicular to the source is experienced as more annoying than sound transmitted through the parallel façade that faces the sound source more directly. It is hypothesised that this is because the noise is more sporadic, coming and going as a moving source (vehicle) approaches and then passes in the acoustic shadow zone. By comparison, a façade parallel to the direction of traffic flow experiences a more gradual and consistent approach and fading away (Federal Highway Administration, 2017), although it is more directly exposed.

2.3.3.2.3 Ground absorption

The propagation of acoustic energy over the ground is influenced by the characteristics of the ground surface. This is referred to as the ground effect. If the ground is smooth and hard, acoustic energy will reflect off the ground, essentially making the ground itself a secondary source of noise. On the other hand, rough, porous ground can absorb acoustic energy, impairing the transmission over the ground surface.

SANS 10210:2004, *Calculating and predicting road traffic noise*, defines absorbent ground as “ground covered with thick, dense green grass, or intensively cultivated fields or plantations”, also referred to as “acoustically soft ground” (SABS Standards Division, 2004). Examples of non-absorbent or reflective ground surfaces given in SANS 10210 include paved surfaces, asphalt, packed earth, dry grass or bushes, and water. Sound absorption is frequency-dependent, with higher frequencies generally being more easily absorbed than lower frequencies. Acoustically soft ground may be considered effective for trafficnoise attenuation if it has a peak effect of around 1 kHz (Bashir, Taherzadeh, Shin & Attenborough, 2015).

According to ISO 9613-2, there are three regions of ground attenuation between the source and the receiver (International Organization for Standardization, 1996). The part of the path starting at the source for a distance of 30 times the height of the source (30 h_s) is the source region. The receiver region is similarly the distance at the receiver end of the path that is 30 times the height of the receiver (30 h_r). While the ground conditions in these two regions have an effect on the overall attenuation, the section in between has very little effect. So, for example, if the source height (h_s) for road-traffic noise is considered to be 0.5 m, the source region (30 x h_s) is 15 m; if the receiver height (h_r) is 1.5 m (assumed to be at mid-height of a typical single-storey window) the receiver region (30 x h_r) is 45 m. Adding h_s and h_r, it can be established that, if the distance is greater than 60 m, the ground absorption between the two regions is negligible.

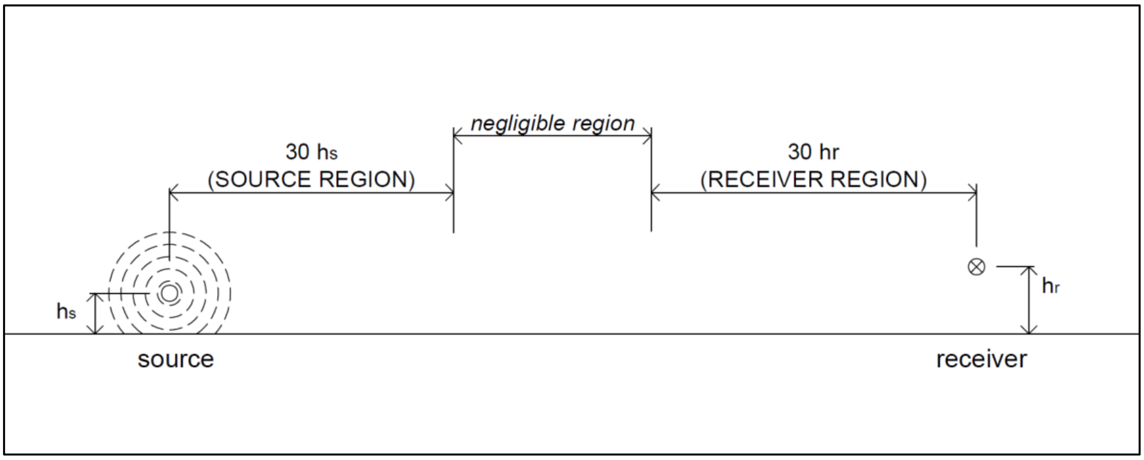


Figure 2-5: Diagrammatic illustration of source and receiver regions for ground absorption

2.3.3.2.4 Topography

Topography refers to the profile of the ground, which can affect the way sound is propagated over a distance. For a site higher than the road a barrier does not make a difference but for a site lower than the road a significant difference can be achieved with a barrier (Klingner, Mcnerney & Busch-Vishniac, 2003). A site that is raised above the level of the source produces a similar effect to that of a barrier, in that the path that the sound travels is increased.

2.3.3.2.5 Atmospheric absorption

Atmospheric absorption refers to the reduction of acoustic energy as a sound wave passes through the atmosphere. The effect of air as an absorber is almost negligible at short distances, particularly for low frequencies (Lawrence, 1970). Atmospheric absorption is defined by the atmospheric absorption coefficient, which is a factor of the frequency of sound as well as temperature, humidity and air pressure. Although air pressure has an effect on the speed of sound, the ambient air pressure has a very weak association with the attenuation of sound through the atmosphere (International Organization for Standardization, 1996).

Temperature and wind have an effect on the propagation of sound in that these factors occur on a vertical gradient. This vertical gradient causes the ‘bending’ of sound waves towards or away from the ground, thus creating the effect of increase or decrease in sound level at a receiver on the ground (Lawrence, 1970).

According to ISO 9613-2, the atmospheric attenuation coefficient should be based on average values for the range of weather conditions for a particular location.

According to SANS 10210, meteorological conditions may be ignored, provided that the measurements were not taken during gusts of wind, while Probst (2010) argues that the effect of meteorology is negligible.

2.3.3.2.6 Screening

The attenuation provided by a screen (or barrier) refers to the insertion of a barrier – whether a wall or an earth berm – which disrupts the path of sound transmission. The effective principle of a noise barrier is the increased path length between the source and receiver, as the sound is diffracted over or around the barrier, as illustrated in Figure 2-6.

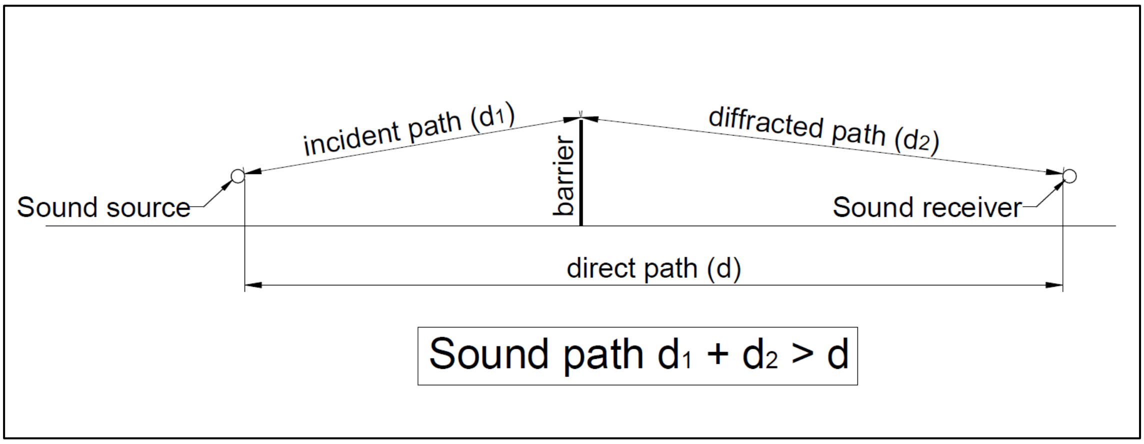


Figure 2-6: Path difference over a noise barrier (author's illustration)

As sound diffracts over the barrier, the path length between the source and the receiver is effectively increased. Because high-frequency sound waves tend to diffract less than lower frequencies, attenuation by screening is more effective for high frequencies (Knauer, Pedersen, Lee & Fleming, 2000). The efficacy is dependent on the difference in path length between the source and the receiver and the wavelength, and is indicated by the Fresnel Number (N_0), a dimensionless value calculated by the following formula:

$$N_0 = \pm 2\left(\frac{\delta_0}{\lambda}\right) \quad [2\text{-}2]$$

Where:

δ is path length difference between ($d_1 + d_2$) and d

$\pm$ is positive where the line of sight between the source and the receiver is below the top of the barrier

λ is wavelength = speed of sound (c) / frequency (f)

(Knauer *et al.*, 2000)

When considering the effectiveness of screening, one refers to the insertion loss (IL) which is equal to the difference between the sound pressure level (SPL) at the receiver if there were no barrier, and SPL when there is a barrier (i.e. the decrease in SPL due to the insertion of a barrier). With reference to road noise, it can generally be said that there is a 5 dB drop in SPL if the barrier only just intercepts the direct line of sight between the source and the receiver, and that 1.5 dB can be added for every additional metre of height of the barrier (Knauer *et al.*, 2000).

Earth berms, in general, provide slightly better screening than walls. This is attributed to the fact that the berm itself is often covered with soft ground, adding to the ground effect. Furthermore, the top surface of the berm is typically wider than the top surface of a wall resulting in an additional surface for diffraction, increasing the path length and Fresnel number. A berm typically increases the insertion loss by 1 to 3 dB compared to a screen wall. However, considering that a difference of 3 dB is barely perceptible and that a berm requires more physical land space, it is not necessarily preferable to a screen wall (Knauer *et al.*, 2000).

The effect of a barrier depends on its height and length and is limited by the fact that sound can propagate around or over it. For a barrier to be effective it must extend sufficiently either side of the receiver point to avoid the effect of diffraction (Lawrence, 1970). To be effective, a barrier should extend either side of the receiver for a distance at least four times the distance between the receiver and the barrier, measured normal to the source, as illustrated in Figure 2-7 (Knauer *et al.*, 2000). Diffraction occurs when sound waves bend around an obstacle; thus the wavelength is a factor to consider in the design of a sound barrier. The length of the barrier, measured perpendicular to the source-receiver path line, should at least be greater than the wavelength of the sound wave at the relevant frequency of interest (International Organization for Standardization, 1996).

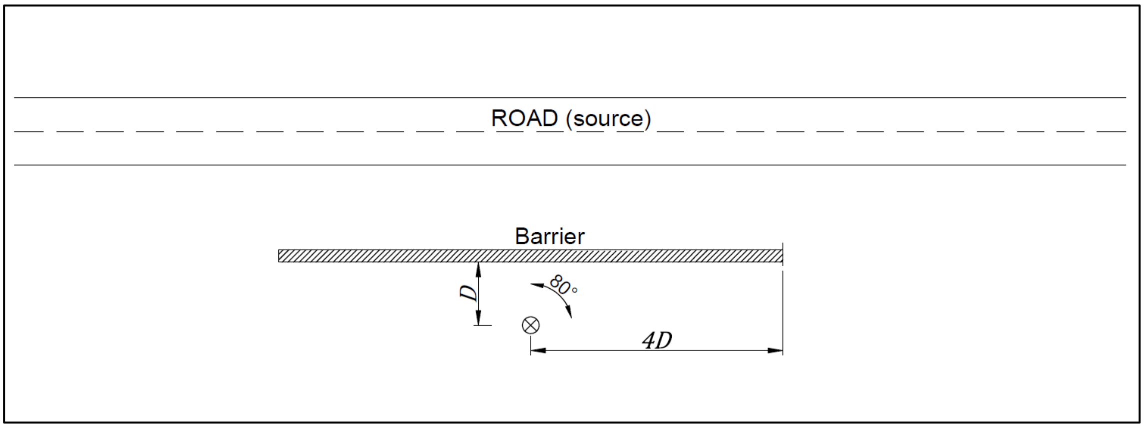


Figure 2-7: Illustration of barrier width requirement (author's illustration)

Ideally, a screen wall should be of a dense material (at least 10 kg/m^2) with an impervious surface so that little sound penetrates directly through it (International Organization for Standardization, 1996). The BB 93 recommends a close-boarded wooden fence offering density of at least 16kg/m^2, arguing that increasing density beyond this will have little effect as most noise will travel over the barrier (Institute of Acoustics & Acoustics & Noise Consultants, 2015).

The position of the screen wall relative to the noise source and the receiver is relevant. According to the guidelines of the Colorado Department of Transportation, a screen wall should be close to either the source or the receiver but not mid-way, as this will be less effective (Colorado Department of Transportation, 2017).

The shape or dimension of the top of a barrier can also influence the efficacy of the barrier. A barrier with a wide, flat top (crown) can produce the same effect as a narrow barrier that is higher (Department of Transport Welsh Office, 1988, p. 80). Similarly, a barrier with a T-shaped or Y-shaped crown can make a significant difference in the insertion loss achieved by a barrier (Karimi & Younesian, 2014).

Absorption on a barrier does not make a significant difference (Klingner *et al.*, 2003).

2.3.3.2.7 Vegetation

Contrary to popular belief, trees and shrubs do not provide significant sound attenuation, especially for lower frequency sounds (Lawrence, 1970; Halim, Abdullah, Ali & Nor, 2015). In order for vegetation to be an effective attenuator, a broad, dense vegetation belt is needed, preferably planted with large-leaf plants (Peng, Bullen & Kean, 2014; Bashir *et al.*, 2015). Ground covers, grasses and crops offer some attenuation effect at high frequencies due to viscous and thermal loss (Bashir *et al.*, 2015). Although vegetation does have some effect on noise propagation, most standard traffic-noise prediction calculation methods ignore the effect of vegetation due to the non-permanent nature of vegetation (Department of Transport Welsh Office, 1988; Peng *et al.*, 2014).

2.3.3.3 Other attenuation possibilities

There are other attenuation opportunities that are not typically included in the calculation of outdoor noise propagation.

Volume absorbers (also known as Helmholtz absorbers or resonators) have sometimes been used to increase ground absorption. Unlike absorption that occurs as a result of acoustic energy passing over rough ground, volume absorbers are hollow spaces of calculated dimension that ‘trap’ sound. Experiments using volume absorbers adjacent to roads have been carried out to establish the efficacy of this form of absorption in attenuating traffic noise. Results showed a limited effect of 2 to 4 dB (Forssén & Van der Aa, 2013). This is not a significant difference. The advantage – and also disadvantage – of volume absorbers is that they can be specifically designed to target certain frequencies. While this is very useful if the target noise is in a narrow frequency band, it is not very useful for broader spectrum noise. Although traffic noise falls within a certain area of the frequency spectrum, it is still a fairly broad spectrum. Thus, a number of different volume absorber designs would be required to target the full spectrum of traffic noise.

There is a possibility, in theory, to apply an innovative material such as the metamaterial developed by Tang, Ren, Meng, Xin, Huang, Chen, Zhang & Lu (2017), with a micro-perforated honeycomb corrugated core structure providing broadband low-frequency sound absorption. The structure provides good mechanical properties (strength and stiffness) while being light-weight, and shows promising sound absorption abilities even at low frequencies (a 60 mm panel provides 0.5 absorption at 290 Hz – i.e. 1 m wavelength).

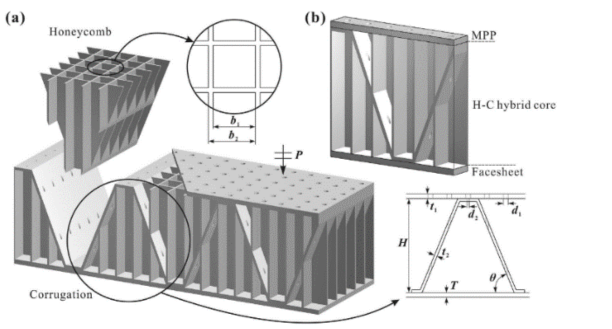


Figure 1. (**a**) Schematic of perforated honeycomb-corrugation hybrid (PHCH) metamaterial, which is composed of a micro-perforated panel as top facesheet, a honeycomb-corrugation hybrid as core and a panel as bottom facesheet. The corrugation is also perforated, just beneath the hole in top facesheet, but can have different perforation sizes. (**b**) One periodic unit cell. The front and right honeycomb walls are cut off to see details inside. Sound absorption of the metamaterial is investigated for a plane acoustic wave normally incident on top facesheet.

Figure 2-8: Illustration of metamaterial by Tang et al. (2017)

Such an innovative material, being both strong and absorbent, could be useful as a screen wall or possibly even as a horizontal surface material. However, this particular material has only been tested mathematically and theoretically and is unlikely to be a feasible option for environmental noise control around South African schools in the near future.

A detailed study by Krimm (2018) on the effect of geometric façade treatments to absorb and deflect environmental noise provides an interesting concept. However, the effect is only useful for decreasing unpleasant sound reflections experienced between buildings in urban areas. The paper does not discuss the effect on sound transmitted into the building.

Kang, Moon and Lim (2014) discuss the concept of using active noise cancellation to mitigate the effect of traffic noise. Active noise cancelling is a technique whereby an opposing signal is applied to cancel the sound pressure wave. It has been shown to be effective in industries such as aircraft and automotive design to mute engine noise. A US patent has been registered for a noise-cancelling system for buildings (Goldman, Krock, Rauscher & Runyon, 2009).

Controlled wave interference by physical wave guides has been explored as an alternative to active noise cancelling technology that does not require equipment and energy (Arjunan, 2019). Controlled wave interference relies on the geometry of cavities in a material that passively interferes with wave transmission, as illustrated in Figure 2-9. This innovation targets specific frequencies and requires further development to be accurately tuned.

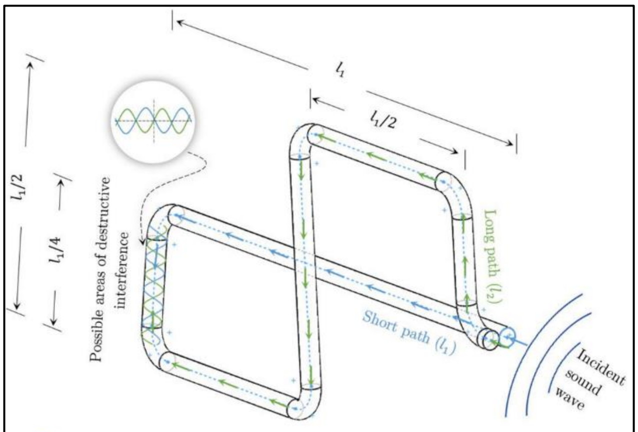


Fig. 2. Herschel–Quincke-Arjunan (HQA) single channel waveguide to create geometry-based destructive interference.

Figure 2-9: Illustration of controlled wave guided principle as per Arjunan (2019)

Noise transformation has also been proposed as an alternative to sound attenuation (Lacey, Pink, Harvey & Moore, 2019). This concept introduces sound into the environment with the intention of changing the listeners' perception of sound. This concept may be comparable in some ways to sound masking in that it involves the purposeful introduction of sound as a means of decreasing the level of annoyance in response to environmental noise, such as traffic noise. While noise transformation may be considered as a means of addressing annoyance, it actually increases the overall ambient sound level which negatively impacts the signal-to-noise ratio and speech intelligibility. This would be an unsuitable method of addressing break-in noise in a classroom situation.

Another alternative noise treatment is the introduction of vegetation. As discussed, while the vegetation does not necessarily have a significant effect on the actual noise level, the negative perception of sound seems to decrease when the source is blocked from vision by vegetation (Van Renterghem, 2018). Again, this technique is better suited to deal with annoyance and is not applicable when considering the signal-to-noise ratio.

These methods, though interesting, are not relevant to consider for this study. The scope of this study is limited to the factors that are included in the ISO 9613 calculation.

2.3.4 Acoustic requirements for classrooms

In the context of a classroom, there are two key aspects of acoustics that are important to consider. Firstly, the clarity and audibility of the teacher's voice for all learners and, secondly, the level of distraction caused by interfering noises. In some instances, these two issues are related since interfering noises can cause distraction as well as affect speech intelligibility. At other times, such as during a written assessment, speech clarity is not required but minimal distraction is important.

Speech clarity and audibility can be quantified by the speech transmission index (STI), which is defined in SANS 3382-3 as the "physical quantity representing the transmission quality of speech with respect to intelligibility" (SABS Standards Division, 2014). It is influenced by reverberation and background noise (Bistafa & Bradley, 2000; Ljung, Israelsson & Hygge, 2013). Though this will not be explored in this study, it is acknowledged that factors such as the reverberation time, the distance between the teacher and the learner, the room geometry, furniture and occupant placement are important considerations when designing a classroom (Crandell & Smaldino, 2000; Hodgson & Nosal, 2002; Pelegrín-García, Brunskog & Rasmussen, 2014). Since sound decays with distance, it is important to ensure that all learners are positioned suitably to enable speech audibility. Even in a classroom that is favourably designed, audibility of the teacher's voice has been demonstrated to decrease by as much as 6 dB from the front of the class (3 m from the teacher) to the back (9 m from the teacher) (Klatte *et al.*, 2010). Reverberation time, which refers to the time it takes for a sound signal to decay by 60 dB within a space, is influenced by the acoustic reflectivity of surfaces and room dimensions. A high reverberation time results in speech that is unclear.

The speech transmission index is compromised in the presence of high background noise, which is the focus of this study. Background noise affects the signal-to-noise ratio (SNR), which is the difference between the signal (such as the teacher's voice) and the background noise. The SNR has been shown to have an effect on the performance of children in class (Jamieson, Kranjc, Yu & Hodgetts, 2004), emphasising the importance of maintaining a low ambient noise level. A study on speech intelligibility in actual classrooms in three schools in Italy demonstrates that traffic noise in particular results in poor speech intelligibility (Astolfi, Bottalico & Barbato, 2012). This is attributed to the persistence of the noise along with the deep fluctuations.

Apart from the learners in the class suffering from being unable to hear clearly in the presence of high background noise, teachers also suffer, having to raise their voices and modify their speech in order to be heard above the ambient noise (Garnier & Henrich, 2014). It is argued that the vocal strain experienced by teachers makes teaching a high-risk occupation (Roy, Merrill, Thibeault, Parsa, Gray & Smith, 2004).

A number of studies have been conducted to establish the ideal listening environment for classrooms. For normal hearing children, a good SNR has been proven to be at least 10 dB if there is no reverberation (Crandell & Smaldino, 2000; Neuman, Wroblewski, Hajicek & Rubinstein, 2010) and should be even greater – at least 15 dB – for children with hearing or learning impairments or even children who are being taught in a second language (van Reenen & Karusseit, 2017; Gheller, Lovo, Arsie & Bovo, 2019). Bistafa and Bradley (2000) argue that the background noise level should be 25 dB below the signal (voice) level when measured 1 m from the speaker if the reverberation time is 0.4 – 0.5 seconds, which equates to an 'ideal' background noise level of 38 dBA or an 'acceptable' background noise level of 43 dBA. There is a general consensus in the literature that an ideal listening environment has an ambient (background) noise level of 30 – 35 dB (Crandell & Smaldino, 2000; Technical Committee on Architectural Acoustics, 2000; Nelson, Soli & Seltz, 2002), which is a very low noise level.

Many countries have developed standards and guidelines regarding noise control and suitable levels in classrooms (Mealings, 2016; Pelegrín-García *et al.*, 2014). Noise control in some guidelines is provided in terms of the isolation requirement, while ambient noise levels in the classroom are given in terms of the equivalent continuous sound pressure level and sometimes in terms of the reverberation time. Examples are listed in Table 2-2.

Table 2-2: List of some international regulations relating to classroom acoustics

Guideline/Standard	Ambient noise level in core learning space (dBA)	Isolation requirement	Reverberation time in core learning space (seconds)
United Kingdom BB93 (Department for Education, 2015)	35	Not specific	≤0.6
United States of America ANSI/ASA S12.60-2010 (Accredited Standards Committee S12, 2010)	35	Yes (Table 3) (Outdoor-Indoor Transmission Class, OITC)	0.6
WHO Guideline for community noise (Berglund, Lindvall & Schwela, 1999)	35	-	0.6
Association of Australasian Acoustical Consultants Guideline for Education Facilities Acoustics (Association of Australasian Acoustical Consultants, 2010)	35	Yes (Tables) (Weighted standardised level difference, $D_{nT,w}$)	0.4 - 0.5
AS/NZS 2107:2000 (Joint Standards Committee AV-004, 2000)	35	-	0.4 - 0.5

The WHO *Guideline for Community Noise* expresses that the critical effects of noise in school environments is "speech interference, disturbance of information extraction (e.g. comprehension and reading acquisition), message communication and annoyance" and recommends that background noise in classrooms should not exceed 35 dBA for normal-hearing children (Berglund, Lindvall & Schwela, 1999). Although this is a relatively old guideline, the ambient noise level requirement is confirmed in the most recent fact sheet on occupational and community noise (World Health Organization, 2001). The main health effect cited is disturbance of communication. The period for which this limit is applicable is for the relevant occupied period during class.

The design of school buildings in the United Kingdom and New Zealand is approached holistically. Performance requirements are provided as well as detailed discussion and design guidance, without being prescriptive in terms of the means of achieving the performance (i.e. no deemed-to-satisfy design solutions). Acoustic design requirements (BB 93) are referenced in the UK building regulations, as well as the *School premises regulations* and the *Independent schools standards,* and are accompanied by a separate detailed design guide. The New Zealand Ministry of Education has developed a comprehensive suite of design guides for schools covering acoustics, lighting and air quality and thermal comfort. The ambient sound level for cellular classrooms prescribed in the New Zealand design guide is 35 – 45 dB in terms of the equivalent continuous A-weighted sound pressure level (L_{Aeq}). However, it must be noted that this is only applicable for mechanically ventilated spaces with closed windows and that no specific time period for the measurement of L_{eq} is mentioned (Ministry of Education, 2016). In contrast, the BB 93 provides ambient limits for both mechanically and naturally ventilated classrooms, which are 35 dB and 40 dB respectively. The ambient noise level is specified in terms of $L_{Aeq,30min}$ during normal teaching hours, leaving no room for ambiguity (Institute of Acoustics & Acoustics & Noise Consultants, 2015; Department for Education, 2015). It is interesting to note that the required ambient sound level for naturally ventilated classrooms is relaxed by 5 dB. This seems to acknowledge the challenge of achieving a low ambient sound level under open-window conditions.

The American National Standard for the acoustical performance criteria for schools (ANSI/ASA S12.60-2010/Part 1) sets a target indoor ambient noise level for classrooms of 35 dBA. This standard differentiates between ambient (background) noise generated by outdoor sources (such as traffic) and indoor sources (such as building services); but, in either case, the required ambient level is 35 dB in terms of the A-weighted equivalent continuous sound pressure level over the noisiest continuous one-hour period during the normal school day (Acoustical Society of America, 2010). This standard provides performance criteria but no design guidance. It is noteworthy that the measurement period is specified as being the noisiest one-hour period, ensuring that suitable acoustic conditions are met even in the worst-case scenario. In addition to providing ambient noise level limits, the ANS/ASA S12.60 also considers the sound transmission through the building envelope, stipulating an Outdoor-Indoor Transmission Class (OITC) for walls. The OITC takes window and door openings into account, as well as the expected outdoor noise level. It is noted that the required OITC for walls with windows is approximately 6 dB lower than for a wall without windows, acknowledging that window openings compromise the sound isolation efficacy of the wall.

The Australasian Association of Acoustical Consultants has developed a comprehensive guideline that recommends an ambient noise level of 30 – 40 dBA in classrooms. This is in agreement with the Australian/New Zealand Standard AS/NZS 2107:2000. Although the ambient noise level is not explicitly defined in the guideline, based on the definition given for measured sound level, it can be assumed that the ambient noise level is the A-weighted equivalent continuous sound pressure level over a representative time period. The representative period is not defined and is left up to the designer to determine (Association of Australasian Acoustical Consultants, 2010). The Australian guideline does not provide a requirement for façade insulation; only guidance for the acceptable sound transmission between interior spaces in terms of weighted standardised level difference ($D_{nT,w}$) is provided.

In contrast, the standards and guidelines for school design in Rwanda provide very weak acoustic guidelines. The acoustic requirement is merely notional, requiring that acoustics be considered, yet no performance criteria are provided.

2.3.5 Acoustic requirements for classrooms in South Africa

In South Africa, the acoustic guidelines pertaining to schools specifically are relatively weak. General noise-control regulations are developed provincially, and provincial regulations are often not explicit but provide for local authorities to create their own by-laws for noise control.

The National Building Regulations (NBR), applied through SANS 10400, make no mention of noise control measures except briefly in terms of noise control during site operations. A number of South African National Standards pertaining to building acoustics and environmental noise are available, although not all are applicable to this study. Those that are relevant to building insulation, indoor noise levels and traffic noise are tabulated in Appendix D. Some provide performance requirements, which act as targets to achieve, while others are helpful in guiding methodology for taking measurements relating to acoustics.

The national standards that come into play for noise control in schools in South Africa are SANS 10103:2008 and SANS 10218-1:2004. These are not mandatory standards for designing classrooms. SANS 10103:2008 provides standardised methods and criteria for the measurement and rating of environmental noise with respect to annoyance and to speech communication in living and working environments, while SANS 10218-1:2004 specifies the means by which buildings can be graded based on the sound insulation value.

According to SANS 10103:2008, the design ambient noise level for a primary school classroom should not exceed 35 dBA or at most 40 dBA – this is the equivalent continuous sound pressure level in the space measured over the time period of occupation while the building is under normal operation conditions (with building services running) but is not occupied. The exact time period is not specified, although a normal school day of approximately five hours can be assumed. SANS 10218-1:2004 refers to higher grade (HG) buildings and standard grade (SG) buildings, which refer respectively to buildings that are acoustically designed to provide a minimal effect of intruding noise, and a tolerable effect of intruding noise (due to economic constraints). According to this standard, it is not advisable for education buildings to be erected where the outdoor ambient noise level exceeds 55 dBA.

The airborne sound insulation value of a classroom façade should be between 25 dB and 40 dB, depending on the building grade and the outdoor ambient level.

The *Regulations relating to minimum uniform norms and standards for public school infrastructure* (Department of Basic Education, 2013) provide little detail pertaining to acoustic requirements for classrooms, requiring only that “as far as reasonably practicable” acoustic condition should be suitable for clear communication of speech between teacher and learner, and among learners, and should not impede teaching and learning activities. The Regulations recognise that reverberation should be kept to a minimum, but no performance requirements are set.

The *Minimum uniform norms and standards for school infrastructure* (Department of Education, 2009), upon which the Regulations are based, provide a little more detail regarding the acoustic requirements for schools, although these are not enforceable by law. Herein it is stated that the classroom should be designed to achieve a background noise of 40-50 dB[A] (Department of Education, 2009); however, there is no reference to the L_{eq} or relevant time period for measurement and no guidance as to how to achieve the target.

Other local regulations also offer little guidance regarding acoustics. For example, the KwaZulu-Natal Department of Education’s *Space planning norms and standards for public schools* merely mentions that noise between classrooms should not be disruptive for general teaching spaces and, for upgrading of existing schools, soundproofing should be applied to classrooms adjacent to noise sources such as a motorway (KwaZulu-Natal Department of Education, 2011). These aspects are not quantified and thus have little real meaning. This provincial regulation also mentions that schools should preferably not be located next to roads with high traffic volumes.

2.3.6 Traffic noise

In the context of schools, the required ambient sound pressure level is well defined in research literature and regulations. The challenge is in achieving the prescribed levels in an environment that contains outdoor noise, particularly (in the context of this study) road-traffic noise.

In order to address the effect of traffic noise on the indoor ambient noise level, the nature of traffic noise must be understood. This section briefly discusses the factors to consider in establishing the parameters to apply in the current research.

When it comes to traffic noise, there are numerous ways of measuring or otherwise determining traffic noise. Some methods involve actual sound level readings, while others make use of calculations based on traffic volumes and characteristics or other means of determining or predicting road-traffic noise.

The character of traffic noise varies depending on many factors, such as traffic volume, speed, acceleration and road surface, to name a few. Traffic noise can be described in terms of traffic flow (vehicles per hour), noise emission (L_w), sound propagation (L_p), or other noise indicators, such as frequency spectrum, noise rating curve (equal loudness to a noise at 1 kHz), noise rating value (the noisiest octave bandwidth) and the spectrum gravity centre (SGC) (average of sound power frequency spectra) (Can, Leclerocq, Lerong & Botteldooren *et al.*, 2010).

The traffic noise study by Can *et al.* (2010) explores traffic noise characteristics with specific reference to the sound-frequency spectrum and the variability of traffic noise as vehicles slow down and accelerate. The findings highlight the variability of traffic noise at different points along a road in terms of noise emissions, as well as frequency (Hz).

The frequency range for traffic noise has been described as being 250 – 2 500 Hz, with an average broadband traffic noise level in urban areas of 70 – 80 dBA (De Salis, Oldham & Sharples, 2002). However, it is also noted that high-speed traffic generates middle frequency noise, while low-speed traffic generates low frequency noise (Buratti & Moretti, 2010).

A recent study carried out in Italy examined the effect of traffic noise in schools with a specific focus on the maximum noise levels and statistical noise levels. These factors are proposed to provide a more accurate indication of the effect of traffic noise than the equivalent continuous sound level usually referenced in guidelines and standards (Secchi, Brambilla, Casini & Cellai, 2018). In particular, the statistical measure L_{A1} gives an accurate indication of the level of annoyance and disturbance caused by short periods of loud noise.

Most standards, guidelines or regulations, including the South African National Standard 10210:2004, consider traffic noise simply in terms of the equivalent continuous sound pressure level (L_{eq} or L_{Aeq}).

The nature of traffic influences the characteristics of traffic noise. Research on traffic noise predictions by Kim, Barber and Srebric (2017) explores methods of modelling and measuring traffic noise. It is noted in this study that the frequency spectra significantly influences sound quality and therefore must be taken into consideration. According to Kim *et al.*, most models for predicting and assessing traffic noise only make reference to the various measures of equivalent continuous sound level (L_{10}, L_A, L_m) across a broad spectrum, highlighting the concern that without considering the full frequency spectrum, an accurate prediction of the propagation of sound is not possible. Another study discussed the comparison of static modelling and dynamic modelling of traffic noise compared to actual measurements (Can *et al.*, 2010), concluding that dynamic modelling is preferable since it includes the effect of the variable characteristics (speed change) of traffic noise. From these, it can be concluded that the characteristics of traffic noise are important to consider. Although a benchmark value, or series of frequency-related values, against which to assess traffic noise level is not provided, it can be concluded that when measuring traffic noise, the full spectrum should be measured and traffic flow and character should be noted at the measurement location.

A study in Belgrade by Paunovic, Belojevic and Jakovljevic (2013) explored the relationship between traffic density, noise levels and the presence of public transport on particular routes. It was concluded that public transport may serve as a proxy, or indicator, of noise exposure. However, the study was conducted in the context of establishing the potential health-related effects of noise exposure and is not suitable for establishing actual noise levels. In order to establish the efficacy of façade insulation, relatively accurate sound pressure levels are required.

Many European countries have developed standards for calculating and predicting road-traffic noise, such as the United Kingdom (CoRTN)[6], France (NMPB-Routes-2008)[7] and Germany (RLS-90)[8]. These standards provide calculation methods which are also employed in acoustic software to calculate and simulate noise.

The South African National Standard, *Calculating and predicting road traffic noise* (SANS 10210), is useful for determining the environmental sound pressure level emitted by a number of vehicles on a single road. This standard is in part derived from the publication by the Welsh Department of Transport, Calculation of road traffic noise (1988). The scope is to set out procedures to follow for the calculation and prediction of road-traffic noise under typical South African traffic conditions, using one-hour equivalent continuous A-weighted sound pressure levels ($L_{Aeq\ 1\ hour}$). According to this, the $L_{A,eq}$ for any one-hour period should be calculated at a reference distance of 10 m from the source line. This method assumes a noise source line that is 0.5 m above the road surface at the mid-point of the cross-section of the travelled way (lane). According to SANS 10210, traffic flow is defined in terms of hourly flow. The predicted

[6] Calculation of Road Traffic Noise

[7] Nouvelle Méthode de Prévision du Bruit des Routes

[8] Richtlinien für den Lärmschutz an Straβen

noise is calculated by a basic formula with primary corrections applied for gradient, speed, percentage of heavy vehicles and road texture (SABS Standards Division, 2004).

This standard is applicable to both uninterrupted traffic flow conditions and start-stop conditions and thus provides a useful means of calculating the ambient sound pressure level resulting from traffic in the environment of a school. It is therefore relevant for this study.

2.3.7 Studies on traffic noise at schools

Studies across the globe demonstrate how common it is to find traffic noise is a disturbance in a classroom.

In Portugal a case study showed that classrooms that are exposed to traffic on average have an unoccupied classroom noise level above 55 dBA; while it was established that a significant source of noise in occupied classrooms is contributed by the occupants themselves, traffic and schoolyard noise were also established as significant sources (Silva *et al.*, 2016). This study discovered that most students (38%) were affected by disturbing background noise during a test or exercise, while slightly fewer (34%) found noise disturbing during lessons when they needed to listen to the teacher. This finding illustrated the importance of low background noise, even when listening is not the main activity (i.e. SNR is not the issue but background noise is still disturbing). Although traffic noise was present, noise generated inside the classroom was identified as a greater source of noise. However, it is noted that the study by Silva *et al.* discusses occupied noise levels, whereas the current study is concerned with unoccupied noise levels. The main focus of the study by Silva *et al.* was establishing the perceived and actual noise and the effect. No recommendations or remedial actions to attenuate noise were discussed. Perceived and measured noise was generally in agreement.

A study was conducted considering indoor-outdoor noise and the related effects on occupants in schools in Nigeria, where most schools are located on major traffic routes (Ana *et al.*, 2009). Tiredness, lack of concentration and irritability were the highest reported noise-related conditions. Outdoor noise levels of 68.3 – 84.7 dBA and indoor (occupied) noise levels of 69.5 – 76.1 dBA were recorded at schools. Although the indoor levels were compared to the WHO limit of 35 dBA for schools, this is not entirely accurate because the WHO limit refers to an unoccupied classroom. While it can be argued that the unoccupied noise level is irrelevant, it is the only thing that a designer can use as a benchmark, since occupant-generated noise cannot be controlled or predicted by the designer in advance. This study highlights the existence of traffic noise in schools, even in less-developed countries, but does not discuss mitigation.

A case study in Florence, Italy, applying a methodology for determining the exposure of students in schools to road-traffic noise, shows that almost 60% of municipal primary and lower secondary schools in that city are subjected to noise levels in excess of 55 dBA (Secchi *et al.*, 2018). A method for predicting noise levels is offered, but no mitigation techniques are discussed.

Another study in Italy (2017) investigated more than 100 Italian schools considering façade insulation, outdoor (mainly traffic) noise and indoor speech intelligibility. This study measured indoor unoccupied noise levels in classrooms prior to façade interventions, and then compared them to levels measured after façade interventions. The interventions were in the form of replacing the window glazing with double-laminated panes. The average noise level in unoccupied classrooms dropped from 35.7 dBA to 27.4 dBA after the intervention. Though the results show a significant improvement, it is noted that the windows were closed for measurements.

A study considering the roadside, schoolyard and classroom noise levels in 21 schools in Greece reported a mean roadside noise level of 65.5 dBA. The unoccupied noise level in classrooms facing the road was in all cases above the WHO limit of 35 dBA (Sarantopoulos *et al.*, 2014), with a mean of 47.1 dBA. The mean occupied level was 69 dBA. The average SNR measured in the classrooms was 12 dB, with a range of 6.8 to 21.6 dB. This study also showed a correlation between the number of occupants and the occupied noise level, again indicating the occupants contribute significantly to the occupied noise level. Although in many of the studies referenced the occupant noise is more significant than traffic or other noise, the background noise (e.g. traffic) contributes to the Lombard effect, by which the voice is naturally raised above background noise, contributing to occupant noise and occupied background noise, leading to one raising one's voice and so on. This study measured traffic noise and occupied as well as unoccupied classroom noise simultaneously and showed that traffic noise has a significant effect on background noise in the classroom; however, again, no mitigation is discussed.

A study in Turkey demonstrated that it is possible to achieve improved noise levels in schools adjacent to roads by inserting concrete walls of suitable dimensions, embankments with vegetation and a combination of noise barriers such as vegetation, absorptive ground and walls (Avsar & Gonullu, 2005). The authors set out to establish standard distances between a school and a road, considering different types of attenuation interventions and traffic speed and volumes. Assuming 55 dBA to be the acceptable environmental (outdoor) noise level, they calculated that a road with one lane of traffic in each direction and a vehicle speed of 50 km/h would require a school building to be located 55 m away; for a 2-lane road 111 m away and for a 3-lane road 175 m away. The insertion of porous road surfaces, tall and dense trees in a 30 m band, a 2 m high concrete wall, bushes on an embankment up to 4 m high, and combinations of these were shown to result in lowered outdoor noise levels at the school building. This study provided recommended distances between the road and the school building under these various interventions.

This study by Avsar and Gonullu (2005) is one of the few examples of research resulting in practical and quantified recommendations for traffic noise attenuation at schools. It is noted, however, that the recommendations favour natural means, such as trees, bushes and embankments. In the context of Gauteng, these are not necessarily good mechanisms because vegetation requires watering and maintenance (which are not necessarily guaranteed resources), vegetation and embankments require space (which is not always available, especially in existing schools), vegetation is not necessarily permanent and may be removed at a later stage to accommodate other site facilities such as parking, and the recommendation for porous asphalt is not practical in the context of an existing school and possibly also not for a new school. Avsar and Gonullu only considered the noise level at the outside the buildings and did not consider the envelope design or indoor air quality or acoustic conditions.

2.3.8 Acoustics: pertinent issues within the context of the current study

There is general consensus internationally that the target ambient noise level inside classrooms is 35 dBA, although ranges of 30 – 40 dBA are found. In the context of SANS 10218-1, 35 dBA corresponds to a higher grade interior environment. For a standard grade environment which, it may be argued, is more representative of a typical South African classroom, a limit of 40 dBA is set. The South African *Minimum uniform norms and standards for public school infrastructure* (which preceded the Regulations) are less stringent, calling for an ambient noise level of 40 – 50 dB[A] inside classrooms (Department of Education, 2009). All regulations, standards and guidelines considered refer to the ambient level in an unoccupied classroom, except for the Regulations, which are not specific in this regard. Although there is general agreement regarding the ambient sound level, there are differences regarding the definition of ambient noise limit in terms of the measurement period, as summarised in Table 2-3.

Table 2-3: Summary of ambient sound level metrics in various countries

Guideline/Standard	Ambient noise level inside classroom measured as:
United Kingdom BB93 (Department for Education, 2015)	Equivalent continuous A-weighted sound pressure level over 30 minutes ($L_{Aeq,30min}$)
United States of America ANSI/ASA S12.60-2010 (Accredited Standards Committee S12, 2010)	Greatest one-hour average equivalent continuous A-weighted sound level of exterior source background noise
WHO Guideline for community noise (Berglund *et al.*, 1999)	No specific measurement period; only "during teaching sessions"
Association of Australasian Acoustical Consultants Guideline for Education Facilities Acoustics (Association of Australasian Acoustical Consultants, 2010)	Equivalent continuous A-weighted sound pressure level over representative period.
SANS 10103	No specific measurement period; but "during time periods when the areas are used for their intended purposes"

In reviewing a number of regulations, standards and useful guidelines that are currently in use, deemed-to-satisfy design solutions were not found. Performance criteria are set and in some cases guidance is provided, such as in the accompanying publication for BB 93. The American standard is the only one considered that specifies a sound insulation requirement for the building envelope to achieve a certain indoor ambient noise level, although the concept is discussed in principle in the BB 93.

The literature regarding traffic noise demonstrates that there are a number of aspects of traffic that need to be considered when assessing traffic noise, for example, traffic speed and fluctuation (stop-start nature). The accuracy of noise measurements and metrics used – whether statistical or continuous equivalent sound levels – is relevant and should be considered in light of the generally accepted norms and standards that are to be used in this study, particularly with reference to the standards applied in the selected software to be used.

2.4 Summary of literature review

The review of theory and literature clarifies that the basic theories of ventilation and acoustics are well-developed in science and literature. The requirements for ventilation and acoustic conditions in a classroom environment can be clearly established through evidence-based research and applicable norms and standards.

There is a strong body of evidence regarding the negative effects of poor ventilation and acoustic conditions in schools. There is a body of research regarding predicted traffic noise in open-window urban buildings, and the effect that traffic noise has on the ambient sound level in a classroom with open windows as opposed to closed windows, highlighting that open windows provide an acoustic disadvantage while at the same time having a positive effect on the fresh air supply in the classroom. This is not only evident in case study research but is scientifically sound, based on the theory of sound transmission through materials.

There is a growing body of research considering attenuation of noise through ventilation openings in the façade. Some of this research has been conducted in laboratory situations. Many of the studies were done in the context of residential apartments or offices (especially high-rise buildings) in urban areas that are subject to traffic noise. In many cases, hybrid systems, plenum windows or trickle ventilation utilising very small openings is suggested.

Window design (opening type) has been shown to influence both ventilation efficacy and noise transmission (CIBSE, 2005; The Building Performance Centre, 2007). The type of façade material (including glazing and construction material) evidently makes a difference but little research to quantify the effect of various façade composition scenarios was found. This is relevant to explore in the South African context, considering the promotion of the use of innovative building technologies (IBTs). The performance of IBTs in terms of sound transmission has not been proved in practice by evidence. In light of the fact that the use of IBTs in schools is actually promoted by the government, the need to establish its performance compared to traditional masonry construction is identified.

Trickle ventilation, which allows less sound transmission than open windows, is not suitable for South African classrooms, which typically have a high occupancy rate. Hybrid systems may not be suitable ventilation systems because of the potential cost and noise generated by the mechanical components. The climate in South Africa, and particularly in Gauteng, is hot, with some very cold winter months. However, the number of heating degree hours is relatively low (Conradie *et al.*, 2018) making it a suitable climate for natural ventilation, even in winter.

Evidence regarding noise levels or noise control in and around schools in South Africa in general, or Gauteng in particular, is extremely limited.

Chapter 3: Research methods

3.1 Introduction

This chapter elaborates on the research design and methods used to gather data. The purpose is to explain how information was gathered and used to answer the main research question, and why certain instruments were chosen.

The problem stated in Chapter 1 is that there is a lack of quantitative guidance for basic acoustic design in the context of urban schools exposed to road-traffic noise. Architects are poorly equipped to make good scenario-specific decisions regarding outdoor sound attenuation interventions and envelope sound insulation solutions to achieve suitable ambient sound levels in naturally ventilated classrooms that are subject to road-traffic noise.

Thus, the aim of this study is to provide quantitative heuristics for effective noise attenuation interventions to achieve a suitable ambient sound level in naturally ventilated classrooms that are exposed to road-traffic noise. The modelled evidence will provide a reference for designers to use in choosing design solutions in the early stages of planning, or for improvements to existing schools.

3.2 Research questions

As discussed in Chapter 1, the main research question is:

What interventions are appropriate and effective to attenuate road-traffic noise that is transmitted into a typical naturally ventilated classroom in Gauteng in order to achieve a suitable indoor ambient sound level?

There are four key elements in this question (underlined in the text box below), which require further definition before the main question can be answered.

> What <u>interventions</u> are appropriate and effective to attenuate road <u>traffic noise</u> that is transmitted into a <u>typical naturally ventilated classroom</u> in Gauteng in order to achieve a <u>suitable ambient noise</u> level?

These four sub-questions are listed below:

- What constitutes a typical naturally ventilated classroom design in Gauteng?
- What is a suitable ambient sound level in a classroom?
- What is the nature or definition of the problem noise (traffic) in the context of this study?
- What are the noise attenuation interventions that can be employed?

3.3 Objectives

The main objective of this study is to quantify the efficacy of outdoor-indoor noise attenuation interventions in specific scenarios by measuring and comparing the effect of various attenuation interventions against a target noise level in the presence of traffic noise.

Sub-objectives, required to establish the variables for investigating the main objective and corresponding to each research question, are listed below:

- Determine the design and natural ventilation condition in a typical South African classroom.
- Determine the target ambient noise level in a classroom.
- Identify and characterise the traffic noise problem.
- Determine what attenuation interventions are possible options to employ.

3.4 Research instruments

The following four research instruments were used to meet the objectives:

1. Literature review
2. Surveys
3. Site measurements
4. Modelling (computer simulation)

These are discussed in detail in the following sections.

3.5 Research design

This section explains the research design, motivating the selection of certain research techniques to meet the objectives of this study.

The research questions, objectives and research instruments, which constitute the research design, are illustrated in Figure 3-1. The sub-questions and corresponding objectives serve the purpose of determining the variables applied in meeting the main objective.

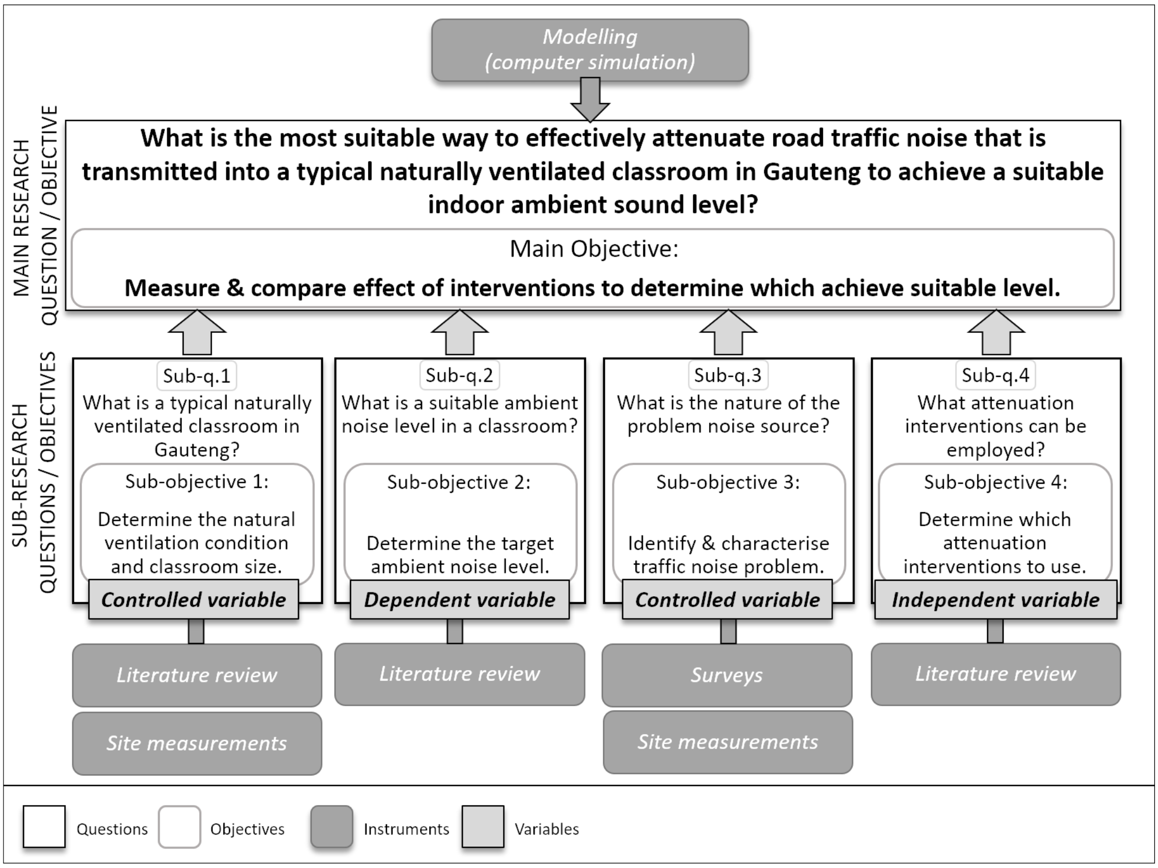


Figure 3-1: Research design illustrated

The research was investigative and experimental, making use of both qualitative and quantitative data in a number of research activities.

The main research methodology adopted in achieving the main objective is experimental. Experimental research involves an intervention (independent variable) that is expected to have an influence on a dependent variable. The influence that the intervention has on the dependent variable is determined experimentally by comparing the premeasurement and post-measurement (Welman, Kruger & Mitchel, 2005) (i.e. the dependent variable with and without the intervention).

In this research design, the dependent variable is the sound pressure level (SPL) inside a classroom. The independent variables are the sound attenuating interventions. The road-traffic noise and the classroom and façade design with window openings are controlled variables. Uncontrolled or confounding variables (such as meteorology) are eliminated by performing the experiment in a controlled virtual environment using modelling software.

The premeasurement of the dependent variable was the sound pressure level inside the modelled classroom when there were no sound attenuation interventions. The post-measurements were compared to the premeasurement, as well as a target sound level to determine the intervention condition(s) with the greatest effect and which met the target.

The details of the experimental design are discussed in a later section (3.6.5).

Other research activities, in achieving the sub-objectives that support the main objective, are investigative in nature. These activities make use of quantitative on-site measurements, qualitative surveys and literature reviews as instruments to establish and describe the independent variables and controlled variables to be used in the experimental research activity.

3.5.1 Establishing controlled variables

3.5.1.1 The typical classroom definition

Since the subject of the research is noise transmission through open windows in a typical Gauteng classroom, the size of a typical classroom and the typical façade and window design needed to be established. The aim of this study was to achieve a target indoor sound pressure level. This is influenced by the reverberation in the classroom, which is dependent on the size and material characteristics of the classroom. In addition, the construction material of the façade needed to be established and it needed to be determined whether this influences the sound transmission into the classroom when the windows are opened.

Although minimum window and classroom sizes can be determined according to regulatory requirements, as discussed in the literature review, in order to ensure that the modelled classroom is a fair representation of classrooms found in urban schools in Gauteng, a number of actual classrooms were selected and measured. The results were averaged to obtain a typical classroom size and window area. The classroom environment thus established was a controlled variable. As such, it was kept constant while other influencing factors were varied.

Although the façade component composition (in terms of the percentage of the façade area that was constituted by the closed and open windows) was thus established as a controlled variable, the material construction of the wall was treated as an independent variable to test the effect of two different construction materials. As a point of comparison, the façade was also tested under the minimum design requirements as per the National Building Regulations.

3.5.1.2 Traffic noise definition

The traffic noise to be entered as the noise source in the model needed to be established as a controlled variable that is a realistic representation of traffic noise occurring at actual urban school sites in Gauteng. Standard methods of determining traffic noise are built into the modelling software used. The required parameters in the software include traffic volume, road gradient and road surface. This information was gathered at one of the selected sites. It is noted as a limitation that this information was only gathered at one site and it is assumed that this is representative of the type of traffic present at the other sites.

In order to ensure that the modelled environment is a good reflection of an actual school environment, on-site traffic noise was measured at a selection of four urban school sites in Gauteng. Measured noise levels were used to validate the noise source generated in the model based on recorded traffic volumes.

The traffic noise was additionally described through qualitative survey data. An electronic survey for all schools in Gauteng was designed to determine the dominant source of disturbing outdoor noise (if any) in schools. In addition, a questionnaire was administered for teachers at the selected schools to verify whether traffic noise is perceived as problematic. Although this is a qualitative research component and is not used in the modelling, it is necessary due to the subjective nature of noise perception. Subjective noise perception refers to the phenomenon that some people will not be disturbed by noise levels above the recommended comfort levels, while others will find even low noise levels disturbing. Thus, the survey and questionnaire are designed to validate the problem as opposed to the traffic noise measurements, which are designed to validate the modelled data.

3.5.2 Establishing the dependent variable target value

The sound level inside the typical classroom was considered to be the dependent variable. Since the main objective was to determine how to achieve a suitable ambient sound level in a classroom, the definition of 'suitable' needed to be established. This became the target noise level. The target noise level to be achieved inside the classroom was established through a review of literature and regulations. Local regulations pertaining to classroom ambient noise levels were reviewed alongside international regulations and other research literature to confirm the target sound pressure level inside the classroom.

3.5.3 Establishing independent variables

The independent variables, which are the noise attenuating interventions, were determined through a review of the literature. Although there are numerous factors that can influence sound propagation and transmission, not all are applicable or appropriate for this study. Through a review of acoustic theory and literature, the relevant interventions to be modelled were identified, including both building envelope interventions and outdoor attenuation interventions.

3.5.4 Modelling the experimental environment

Lastly, based on the established variables, the virtual environment was modelled in acoustic simulation software and the effect of interventions was measured. A modelled experiment was chosen as a suitable research technique since it is possible to control all confounding variables that could influence the dependent variable in a physical environment. Furthermore, by using a modelled environment, the number of potential scenarios is almost infinite and unconstrained.

The independent variables identified each provide component research questions which query how each variable affects the dependent variable.

The model was validated against actual sound level measurements taken at three locations on selected school sites.

3.6 Methods for applying the research instruments

In this section, the instruments used in the research design are discussed with reference to their purpose, implementation and reliability.

The instruments employed include a review of literature; two types of survey instruments – a province-wide school survey and a selected teacher questionnaire; on-site measurements of sound pressure levels and physical environment; and acoustic modelling.

3.6.1 Literature review

A literature review was used to help determine the ventilation condition, which is a controlled variable; the target ambient noise level, which is the dependent variable; and the attenuation interventions, which are the independent variables.

A literature review was deemed useful because the knowledge is existing, but the application of the knowledge in the context of this particular study needed to be established. The literature reviewed included published reports on prior research, theory resources and standards, regulations or guidelines that are used in various countries.

For determining the natural ventilation parameters to be modelled, standards, regulations or guidelines were the main sources used. A number of sources were reviewed and compared to seek a common parameter for determining the ventilation design.

To determine the target ambient noise level (dependent variable) in the classroom, standards, regulations or guidelines from various countries were used as well as supporting literature. A common recommendation was sought by comparing these sources and considering the local context.

For determining the noise attenuation interventions to be used in the experiment, acoustic theory was reviewed, establishing the basic principles to consider. Standards, regulations or guidelines were referenced, as well as published research findings. The information thus gathered was assessed for applicability to this study based on the expected effect of the interventions. Interventions that emerged as having negligible or unreliable effects on sound attenuation were excluded from the group of independent variables.

3.6.2 Province-wide school survey

A province-wide survey was designed to investigate the prevalence and source of outdoor noise disturbance in classrooms in Gauteng schools. The purpose of determining the prevalence and source of noise was to validate the problem and to qualitatively characterise the noise source.

The findings can also provide a baseline and can be used to determine the potential reach of the impact of recommendations stemming from this study. The survey was in the form of an electronic survey distributed to all schools in Gauteng.

The survey was designed to find out how many schools in Gauteng are subject to outdoor noise disturbance in classrooms, and what the main source of such noise is. A full copy of the survey can be found in Appendix A.

The first page collected the email address and name of the school. This was necessary to ensure that there was no duplication of responses from any schools – only one response per school was required to find out how many schools in Gauteng are affected by outdoor noise disturbance in the classroom.

The first question was essentially an opinion poll as follows: “In your opinion, is your school located close to an external noise source (e.g. busy road, railway or industry) that regularly affects the background noise level in any of the classrooms during the school day?” The answers offered were multiple-choice radio buttons for “Yes”, “No” or “Not sure; unable to answer”. Only one answer could be checked.

If the respondent answered “No” or “Not sure; unable to answer” the survey ended. If the respondent answered “Yes”, they proceeded to the next section. The next section was designed to determine what the source of outdoor noise was, asking the question, “What is the main source of the disturbing noise?” The answer choices were “road traffic”, “rail traffic”, “air traffic”, “industry” or “other”. Lastly, respondents were given an opportunity to provide further comments regarding noise disturbance by typing in a long-answer text box.

The limitation of such a survey lies in the fact that it is an opinion survey and one person’s opinion may differ from another’s in answering the same question in the same context. The survey introduction requested that only one representative from the school respond. The survey was emailed to either the principal or the general administration contact. It was assumed that the respondent would have knowledge of complaints from classroom users and that this knowledge, combined with personal perception of sound, formed the basis for answering the questions. Personal perception of noise is variable and it is expected and accepted that opinions were given and that the data does not reflect actual (measured) noise disturbance. If the person who answered the survey did not represent the general opinion of the particular school, it would be a limitation on the study.

The survey was emailed to all addresses provided on the comprehensive list of Gauteng schools provided by the GDE, and a reminder was sent out a few weeks after the initial email. However, there was no further way of following up or ensuring participation.

Ideally, the prevalence of traffic noise disturbance would be determined by measuring traffic noise and indoor noise at every school in Gauteng – but that would not be reasonable given resource constraints.

3.6.3 Teacher questionnaire

Teachers in selected schools were asked to complete a questionnaire (see Appendix B). Schools selected were known (or strongly suspected) to be subject to traffic noise throughout the school day. The selection criteria and process are discussed in detail in a later section.

The questionnaire was designed to learn how the regular occupants of classrooms perceive outdoor noise disturbance, and what actions they take to counter the effect of noise in the classroom. The purpose was to compare perceptions of noise to actual noise measurements which were taken at the same schools. This comparison is done because it is known that noise perception is subjective. Although the findings are qualitative and do not contribute directly to determining the noise source input in the model, it provides additional noise characterisation information to validate the source.

The questionnaire was administered in a paper format. Participation was voluntary. The purpose of the study was explained to participants in person and in writing, and consent to participate was given in writing on the cover sheet of the questionnaire. No personal or private information was requested.

The first section of the questionnaire focused on noise and its source. Questions could be answered by means of checking boxes for “Yes”, “No”, “Sometimes” or “Not applicable”. The following four questions were posed:

1. Do you experience noise disturbance from adjacent classrooms?
2. Do you experience noise disturbance from classrooms above?
3. Do you experience noise disturbance from outdoor activities within the school grounds? (e.g. lawn-mower, generator)
4. Do you experience noise disturbance from outdoor activities outside the school grounds? (e.g. traffic, industry)

The second section was designed to investigate the effect of noise in the classroom and the actions taken by the teacher when the classroom is noisy. This section was required to be answered only if the response to any of the first section of questions was “Yes” or “Sometimes”. The same set of possible answers was offered for the following questions:

5. Do you notice a difference in learner performance when there is noise disturbance from any of the sources mentioned above?
6. As a teacher, do you feel a difference in your voice strain when there is noise disturbance from any of the above-mentioned sources?
7. As a teacher, do you feel a difference in your teaching style when there is noise disturbance from any of the above-mentioned sources?
8. If there is noise disturbance from outdoor noise, do you close the windows?
9. If you close the windows to block outside noise, is it quiet enough for normal classroom activities to continue as if there was no outside noise?

The questions were based on principles of concern established through literature.

The answers are subjective, based purely on the teacher's perception. The findings from the first set of questions contribute to the qualitative characterisation of traffic noise and are useful in establishing a baseline against which potential future interventions can be measured. The teachers' perception of noise, when viewed alongside actual sound pressure level measurements, will give an indication of the level of disturbance due to traffic noise that is experienced at urban schools in Gauteng. The second set of questions does not directly inform the research objectives of this study, but provide useful insight into the impact of noise in classrooms on the behaviour of the occupants. This contributes to the general body of evidence on the subject of classroom noise in Gauteng.

The number of participants for this questionnaire is very small (the sample size was five teachers) and the findings cannot be generalised.

3.6.4 On-site measurements

A small number of schools were selected as measurement sites to establish controlled variables for the model and to validate the simulation. The controlled variables that needed to be established were the physical design of a typical classroom, including room size and natural ventilation design, and the noise source. The simulation was validated by comparing actual sound level measurements on sites to corresponding resultant measurements in the model.

3.6.4.1 Selection of sites

Schools were selected from the list of schools provided by the Gauteng Department of Education (GDE) and may include both public and independent schools that were registered with the GDE in 2018. Because the site measurements are not intended to be used to draw generalised conclusions, a large sample of sites was not necessary. In order to calibrate the simulation, it was decided that at least three school sites would be selected. In each of these selected schools, one classroom was selected for the study.

The main selection criterion was that the school is exposed to traffic noise throughout the teaching period of the day and that classrooms are located adjacent to the noise source (peak traffic is not relevant because it is generally outside of school hours).

A number of schools were identified by the GDE as sites that are subject to high environmental noise. Other sites were identified by virtue of their location on a road map, being situated adjacent to busy roads.

Twenty-two schools were identified and contacted via email requesting permission to conduct on-site measurements and teacher questionnaires at the school. Five schools responded positively. One responded negatively, in that it reported that it was not subject to outdoor noise disturbance. The remainder did not respond to the email. One of the five schools did not have a classroom that met the criteria and the results were not included in this study.

The following criteria were used in selecting the classrooms for the study:

- The classroom must be a normal classroom (not an art, drama or other special classroom) with a floor area that at least meets the minimum requirements of the regulations and has a ceiling height of not more than 3 m.
- The classroom is the one most exposed to the identified source of environmental noise (i.e. close to the boundary).
- The classroom has functioning openable windows (if air conditioners or fans are present, they are to be switched off during measurements).
- Single-storey classrooms were selected where possible to eliminate the potential influence of noise from rooms above. Where this was not possible, every effort was made to prevent noise transfer from floors above during the measurement period.

Thus, four schools were selected – two in Johannesburg and two in Pretoria. These schools are referred to as Schools A, B, C and D.

3.6.4.2 Physical measurements

Although minimum standard classroom sizes can be determined through the guidance of the Regulations, in order to ensure that the modelled classroom is a fair representation of classrooms found in urban schools in Gauteng, a number of actual classrooms were measured.

Physical dimensions of the classroom length, width and height were measured using a laser measure and recorded on paper. Materials used in the classroom were also noted since these have an effect on reverberation time and sound level.

The window design and dimensions were also recorded, using a laser measure, photographs for reference and hand drawings. The number and size of opening sections of the windows was recorded. The openable window area shall be expressed as a percentage of the floor area of the classroom.

The distance from the noise source to the receiving envelope of the classroom was measured using a laser measure.

3.6.4.3 Sound level measurements

The purpose of the on-site sound level measurements was two-fold. Firstly, to establish a baseline regarding the status of noise levels and traffic noise transmission in classrooms and secondly, to establish actual noise levels at certain locations in the selected schools for comparison with corresponding measurements in the model in order to validate the model and to establish the traffic noise as a controlled variable in the model. Sound pressure level measurements were taken at three locations at each site: at the site boundary that is closest to the noise source (road), at the outer façade of the classroom closest to the source, and inside the classroom closest to the source (with windows open).

The measurement at the boundary was used to verify the noise source that was calculated by the modelling software based on standardised methods of calculating road-traffic noise. The noise measurements at the classroom façade and inside the classroom were used to validate the sound level at those locations in the model when the noise source was applied.

The sound pressure level at the identified locations was measured using a calibrated Class 1 integrating sound level meter. The methodology for taking these measurements was derived from an evaluation of local and international standards, together with precedents set by other studies and adapted to suit the requirements and context of this study.

Because there are several factors that can potentially influence the measurement of sound, it is important to follow a clear methodology that accounts for these factors in a consistent manner. Examples of factors that could influence sound level readings include reflections off nearby objects (which could amplify readings), deflection of sound by surrounding objects, and the influence of other sound sources that are not under investigation. The purpose and context of sound measurements also influence decisions pertaining to the positioning of the sound level meter relative to the sound source.

When taking measurements that are to be compared to each other (for example, comparing the sound level of two different roads) it is important that the methodology is consistent to enable a useful comparison. When evaluating a measurement against certain criteria, such as a prescribed noise level limit in a particular standard, it is important to take the measurement in a manner that is consistent with the method given in that standard, to enable a useful comparison. In this study, the method followed at each school needed to be consistent.

Many of the acoustics standards that exist refer to laboratory measurements of noise – whether vehicle noise or sound transmission through a particular element. These standards will not be discussed here since laboratory measurements are not relevant for this study.

The factors that need to be determined by reviewing the literature are:

- Time period for measurement
- Time of day
- Frequency (Hz)
- Location of meter from source and surrounding surfaces

3.6.4.3.1 Standards used as reference

Standard methods for measuring outdoor and indoor noise levels in three different countries were assessed for relevance to this study – namely, the South African standards, SANS 140-5:1998 and SANS 10103:2008, the American standard, ANSI/ASA S12.6-2010, and the British standard, BB 93. Each of these is explained in the following paragraphs and summarised with reference to this study.

SANS 140-5:1998

The International Organization for Standardization (ISO) has a prescribed method for measuring the effective sound insulation value of a façade in the field (International Organization for Standardization, 1998). This standard has been adopted in South Africa as SANS 140-5:1998 and provides methods for measuring sound pressure level outside a façade and inside a receiving room. Although the purpose of the method is to establish the sound insulation value of a separating element – whereas the purpose of the measurements in this study is to validate the model – the methodology is informative for this study.

Two methods are described – the element method and global method – for determining the airborne sound insulation value of façade elements and whole façades, respectively. The element method aims to estimate the sound reduction index of a façade element, such as a window, while the global method applies to the entire façade, which is more applicable for this study. The global method is used to determine the outdoor-indoor sound level difference under actual traffic conditions. Because traffic noise is not steady and constant in intensity, the sound level difference across the façade is calculated using the equivalent sound pressure levels (L_{eq}) on either side of the façade, measured as a function of frequency (Clause 6.2).

A specific measurement period is not given, but rather this standard specifies that the measurement time is to include at least 50 passing vehicles, and that measurement must be done on either side of the wall simultaneously. It further recommends avoiding measurements during quiet periods when traffic noise is less than 10 dB above background noise. The recommended frequency range for measurements is one-third-octave bands of at least 100 Hz to 3 150 Hz, but preferably 50 to 5 000 Hz.

The microphone position for the source side measurement should be in the middle of the façade at 2 m (+/- 0.2 m) from the face of the façade, at a height to be 1.5 m above floor level in the receiving room. Measurement in the receiving room should be done using an array of microphones, or a single moving microphone maintaining a distance of at least 0.7 m between microphone positions and between the microphone and any boundary or other surface.

The methodology of SANS 140-5:1998 is suitable to apply for this study, although the number and position of microphones required presents a limitation.

SANS 10103

The South African National Standard for the measurement of environmental noise (SANS 10103:2008) provides guidelines for the positioning of microphones for measuring ambient noise, which would be applicable for measuring traffic noise. These can be summarised as follows:

- Equipment to be calibrated according to applicable standards
- Measure outdoor levels: microphone to be 1.2 m to 1.5 m high
- At least 3.5 m away from walls, buildings or other large flat vertical surfaces
- Measure indoor levels: microphone height between 1.2 m and 1.4 m; at least 1.2 m away from a wall or other large reflecting surface
- Measurement time intervals must be representative of the time period that is regarded as typical for sound exposure.

ANSI/ASA S12.60-2010 Part 1

The ANSI/ASA S12.60-2010 Part 1 is an American standard for acoustic design requirements for schools. This standard uses the one-hour average A-weighted sound pressure, which is the time-mean-square sound pressure averaged over one hour (in dB). The one-hour period used is the noisiest continuous one-hour period during normal school (Accredited Standards Committee S12, 2010, sec. 5.4.1.1), which represents the worst-case scenario. This one-hour period is to be measured in accordance with ANSI/ASA S12.9 Part 2 & 3 (Accredited Standards Committee S12, 2013).

For the indoor (classroom) measurements, the sound level meter receiver should be more than 1 m from the exterior wall at a height of 1 m above floor level. When measuring indoor noise, the space should be furnished and unoccupied; including building services and outdoor noises, but excluding noise generated by people or instructional equipment. Outdoor background noise includes noise from any outdoor sources but excludes specific unusual events, such as sirens.

According to ANSI/ASA S12.9 Part 2, for measuring ambient sound level in built-up areas the horizontal distance between the microphone and the centre line of a traffic lane should be 15 m and should be at a height of approximately 1.2 m above ground level.

For façade measurements, the outdoor measurement position should be as per ASTM E966 for indoor-outdoor measurement method. Accordingly, the outdoor microphone position should be 2 m from the façade (as per Table 1 of ASTM E966). The position for indoor measurements should be more than 1 m from the exterior wall at a height of 1 m above floor level. According to ASTM E966, a set of fixed microphones or a moving microphone should be used for measuring indoor sound levels; however, for outdoor-indoor level reduction (OILR) a single microphone indoors may be used at a height of 1.2 – 1.5 m above floor level. The microphone should not be closer than 1 m from a room boundary surface.

Building Bulletin 93

This British Building Bulletin 93 calls for the calculation of internal noise levels to be done in accordance with BS EN 12354-310. This allows a designer to estimate the resultant internal noise level, depending on façade construction, and thus it can be useful in aiding decisions regarding façade composition. BS EN 12354 (which is synonymous with ISO 15712) considers the effect of flanking and direct sound paths, although BB 93 suggests that in many cases it is appropriate to consider only the direct sound transmission. Methods for measuring outdoor noise are not discussed in BB 93.

Table 3-1: Summary of standards reviewed relating to microphone positions for measuring indoor and outdoor noise

Standard	Microphone position: source side		Microphone position: receiving room		Time period
	distance from façade	height	distance from wall	height	
ISO/SANS 140-5 (façade transmission)	2 m	1.5 m	fixed array or sweeping (min 0.7 m)		50 passing vehicles
SANS 10103 (environmental)	min 3.5 m from any vertical surface	1.2 – 1.5 m	min 1.2 m	1.2 – 1.4 m	representative
ANSI/ASA S12.6 Part 1 (façade transmission)	2 m	1.2 - 1.5 m	fixed array or sweeping (min 1 m from wall)	1 m	Noisiest hour
ANSI/ASA S12.9 Part 2 (outdoor/traffic)	15 m from CL traffic	1.2 m	-	-	Noisiest hour
ASTM E966 (façade transmission)	2 m		min 1 m	1.2 - 1.5 m	-
BB 93 (façade transmission)	Comment/note: flanking path can be ignored.				

The measurement methods of the above standards (as summarised in Table 3-1) provide a useful guide.

3.6.4.3.2 Precedent studies

In spite of the standards, some researchers have deviated from these methods. For example, Torija and Flindell (2014), in their study on the effect of low height roadside noise barriers, took measurements at 3.5 m from the roadside.

A number of research studies that consider sound transmission across a façade were reviewed in terms of the measurement methodology used.

A case study to investigate the effect of sound insulation interventions to reduce the noise transmission at a school near Manchester Airport (Ehrlich & Gurovich, 2004) conducted pre- and post-intervention sound level measurements indoors and outdoors. The researchers used hourly average levels (L_{eq1h}) and took both indoor and outdoor measurements by moving the microphone in sweeping movements, rather than locating it in a static position. The sound source was generated using multi-directional pink noise, rather than measuring the actual environmental noise. The benefit of this method is that the source noise is controlled and repeatable, providing reliable results. However, this method is not suitable for the current study because the intention is to establish the actual traffic noise as a source. The methodology used was not referenced against a specific standard, although what is more important in such a case is the consistency of method for pre- and post-intervention measurements, rather than standardised measurements.

A study conducted by Napier University quantified the sound insulation effectiveness of a variety of window types and opening areas (The Building Performance Centre, 2007) in a laboratory situation. This study used methodology provided in BS ISO EN 140 Part 5 (which is equivalent to SANS 140-5:1998), using the element method. The sound level on both the source and receiver side of the separating element (containing the window) was measured at a number of static positions between 1 m and 3.3 m from the window.

A study in Greece regarding the indoor and outdoor noise levels at city schools provides an example of measurement methodology (Sarantopoulos *et al.*, 2014). A-weighted, fast-mode measurements were taken in five-minute intervals. Noise measurements were taken during the school day between 08h30 and 13h10. For traffic noise measurements, the meter was placed adjacent to the busiest road on the school perimeter at a height of 1.6 m. Indoor measurements were taken from a location in the centre of the classroom at a height of 1.6 m. The indoor measurements were taken with windows and doors closed and the classroom was occupied. In contrast, another study in Greek schools took sound level measurements in both occupied and unoccupied classrooms with windows open and outdoor measurements were taken at the side of the school building that was most exposed to environmental noise (Kapetanaki *et al.*, 2018).

These precedent studies provide additional points of reference for developing the measurement methodology for this study.

Table 3-2: Summary of methods used to measure indoor and outdoor noise across a façade in precedent studies

Precedent	**Microphone position: source side**		**Microphone position: receiving room**		**Time period**
	distance from façade	**height**	**distance from wall**	**height**	
Ehrlich & Gurovich (façade transmission)	sweeping	-	sweeping	-	1 hour (L_{eq1h})
Torija & Flindell (traffic)	3.5 m from road	-	-	-	-
The Building Performance Centre (window transmission)	1 – 3.3 m	-	1 – 3.3 m	-	-
Sarantopoulos, Lykoudis & Kassomenos (façade transmission)	Adjacent to road	1.6 m	centred	1.6 m	08h30-13h10 (school day)
	Comment/note: Occupied measurements, windows closed				
Kapetanaki, Konstantopoulou & Linos (façade transmission)	Comment/note: Occupied and unoccupied measurements, windows open				

3.6.4.3.3 Selected method

The methodologies discussed above were considered in conjunction with the purpose and the practical constraints of this study. The purpose was to measure the SPL either side of the façade as an indication of the amount of sound transmitted through the façade. A major constraint was that only one Class 1 sound level meter was available for the study.

For the time period for the measurements either side of the façade, the noisiest one-hour period was selected as the most appropriate. Out of the standards reviewed, this parameter from the American standards was the only finite period given, making it easier to coordinate and arrange with the school. Out of the precedents reviewed that specified the measurement period, the Manchester school case study also applied a one-hour period (Ehrlich & Gurovich, 2004). In the study by Sarantopoulos *et al.* (2014), measurements were taken throughout the school day, which is not necessary for this study. The others did not specify a measurement period.

A limiting factor in the current study was that only one Class 1 sound level meter was available for use. This made simultaneous measurements on either side of the façade during the noisiest hour impossible. Thus, instead of taking simultaneous measurements over the noisiest one-hour period, separate measurements over 30 minutes each were taken either side of the façade within the noisiest one-hour period.

The noisiest hour was determined by measuring the traffic noise at the boundary of the site for a full school morning (5 hours) on a normal school day, analysing the results to determine the noisiest hour, and then returning the following day to perform the façade measurement during that hour. Both measurement days were normal weekdays during the school term and thus it was assumed the traffic patterns would be similar on both days.

The sound level meter was set to take measurements in five-minute intervals. The noisiest hour was determined by calculating the continuous equivalent sound pressure level for the hour following each five-minute interval, and the highest level thus determined was used to define the noisiest hour.

The ambient indoor sound level over a 30-minute period was measured when the classroom was unoccupied (as required by SANS 10103) and while the normal outdoor environment activities that would be occurring during the school period are operating. The precedents and standards for the microphone position were considered. All used a microphone height of between 1 m and 1.6 m and a position between a centred position in the room to a minimum of 0.7 m from the wall. It was decided to position the microphone 1.2 m away from the façade inside the classroom, centred along the length of the classroom and at a height of 1.2 m, meeting the requirements of the local standard SANS 10103.

Similarly, for the external façade measurement, the microphone was located 1.2 m from the external wall of the classroom at a height of 1.2 m above ground level. It was noted that the outdoor ground level was not more than 0.2 m lower than the indoor floor level.

The following protocol was followed for on-site measurements:

The equivalent continuous sound pressure level (in dBA) was measured across the frequency range of 16 Hz to 20 kHz using a Class 1 integrating sound level meter mounted on a tripod at three locations described here and illustrated in Figure 3-2:

- Location A: a position at the school boundary that is most exposed to traffic noise; the microphone was at a height of 1.2 m above natural ground level and 15 m from the centre line of the road.
- Location B: a position outside the selected classroom, 1.2 m away from the external wall facing the identified noise source, and centred on the length of the classroom wall and at a height of 1.2 m above the finished floor level of the classroom. Ideally, this measurement should be done while the classroom is unoccupied; however, this was not possible as the classrooms could not be vacated at the time. In this study,

this measurement is referred to as the receiving envelope level and represents the amount of sound energy lost between the source and the building.

- Location C: a position inside the classroom 1.2 m away from the exposed wall and centred on the wall, and 1.2 m above the finished floor level of the classroom. For this measurement period, the classroom was to be unoccupied and normal building services were to be operational. The windows of the classroom were to be open as if to provide maximum ventilation. No mechanical ventilation was to be running during measurements. The difference between the receiving envelope level and the classroom receiver level indicates the amount of sound energy that is transmitted through the receiving envelope with windows open.

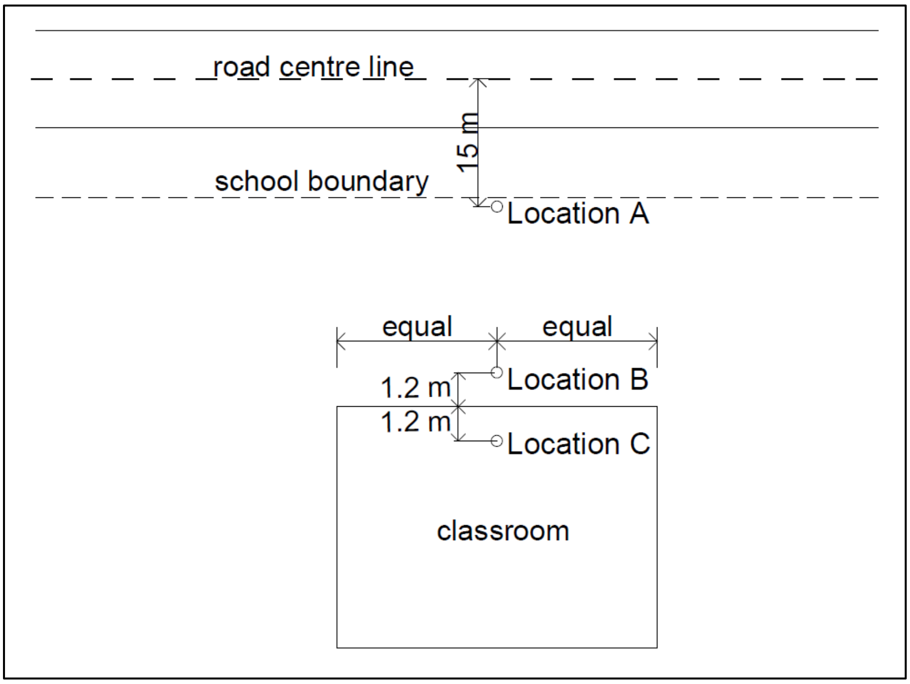


Figure 3-2: Illustration showing measurement locations A, B and C (not to scale)

The measurements were taken over two days for the periods as follows:

i. Location A: This measurement was taken over at least a five-hour period during the normal school day in order to determine the noisiest one-hour period. This was done on Measurement Day 1.

ii. Location B: This measurement was taken on Measurement Day 2 over a 30-minute period within the noisiest one-hour period determined on Measurement Day 1.

iii. Location C: This measurement was to be taken on Measurement Day 2 over a 30-minute period within the noisiest one-hour period determined on Measurement Day 1.

Other information collected on site for consideration in modelling included:

- The distance from the noise source (road) to the outer envelope of the classroom (receiving envelope), measured in metres.
- The site features between the noise source and the receiving envelope were observed, measured and documented since each feature potentially has an attenuating effect which must be accounted for (for example, paving or grass as ground surface and solid wall or fencing as boundary element).
- The classroom envelope material and the window design in terms of size and opening area were recorded on drawings and with the aid of photographs.

3.6.5 Acoustic modelling

Acoustic modelling software was used to create a virtual experimental environment. Computer modelling has a number of advantages over actual physical modelling. The independent variables can be changed an infinite number of times in a model, while it would be practically impossible, costly, time-consuming and disruptive to school activities to construct, move, and re-construct interventions and receiver positions (the classroom) in an actual school. All other variables, such as atmospheric conditions, which cannot be controlled for in a physical setting, can be kept constant in a model. The simulated results are repeatable and eliminate the need for sound generating, receiving and measuring equipment, which is costly and sensitive (requiring regular calibration).

Simulation is a method used in other similar studies where actual experimentation is costly and impractical. Examples are the studies done by Lee, Mohamed and Chang (2016), in which sound transmission through a double façade was determined using *SoundFlow* software, and by Batungbakal *et al.* (2013), regarding double-skin glass facades using both site measurements and *INSUL* software. Both of these studies were considering façade sound transmission in urban environments. Although there were limitations stated regarding the use of software, it is suitable for a comparative study in which certain variables are altered and the difference in effect is under investigation.

A number of acoustic standards and acoustic simulation software have emerged in recent years. This has been a response to the EU noise directive (Directive 2002/49/EC) which relates to noise exposure in urban environments and creates a requirement for noise mapping of cities in order to assess and manage environmental noise (European Parliament, 2015).

Most acoustic software packages, such as *Insul*, *SoundPlan* and *CadnaA*, make use of local or international standards to calculate traffic noise. The software applied for outdoor noise in this study was *CadnaA*, which can calculate and simulate the effects of road noise based on traffic volumes, with default weather conditions (Barber, Burdett, Reed, Warner, Formichella, Crooks, Theobald & Fristrup, 2011). Inputs required for the calculation of road noise in this software include traffic count, vehicle mix, gradient, and road geometry. However, this software does not take foliage into account so the possible effect of roadside vegetation absorption cannot be determined. The calculation of traffic noise in the software (using the German standard RSL 90 as a default, although other standard methods can be used) applies a standardised ground absorption factor and does not allow ground absorption in the model to be changed. For this reason, the effect of ground absorption on outdoor noise attenuation could not be included as a variable. The general ground absorption was on a default setting of 1, meaning that it was reflective, representing a worst-case scenario.

The criteria for selecting software were:

- Cost and availability;
- General acceptance within the acoustic engineering industry and reference to standards;
- Ability to manipulate and include in the noise calculation the necessary aspects such as screening, distance, envelope isolation, ground absorption, source type and power;
- Ability to model outdoor-indoor sound transmission.

CadnaA, along with the related software, *Bastian* (for indoor noise), met all these criteria.

The method of calculating noise using *CadnaA* employs both ray tracing and angle scanning. Most types of software use ray tracing, which calculates noise levels in straight line paths between a noise source and the receiver, correcting for diffraction around interfering objects. Angle scanning makes use of a summation of sound levels received by a point from a number of angles around 360 degrees (Probst, 2007). *CadnaA* makes use of both these approaches in combination. *CadnaA* integrates the approaches for determining sound levels contained in ISO 9613-21, NMPB 20082 and Harmonoise (Probst & Probst, 2011), which are models for predicting environmental noise.

CadnaA is only designed to calculate outdoor noise. For indoor sound level predictions and transmission through a façade, a related software program, *Bastian*, was used. *Bastian* bases calculations on EN 12354 (part 1 to 3) for the estimation of the acoustic performance of buildings from the performance of elements and has the ability to create complex facades. A model created in *Bastian* can be set up to account for reverberation time and flanking noise from junctions of all separating elements. Separating elements can be created using standard materials built into the software or customised materials using actual transmission values and multiple materials can be assigned to each separating element as a percentage of the area. A signal level can be set and the receiver level in the receiving room then gives an indication of the transmission through the separating element. Outdoor noise levels calculated in *CadnaA* can be directly linked as an input signal level in *Bastian*.

3.6.5.1 Model validation

Each of the four actual sites was re-created in a model to confirm that the sound levels that were achieved in the model were the same or similar to those measured on the sites. This was in order to validate the accuracy of the model.

CadnaA is designed to calculate traffic noise based on traffic count data according to standard methods. A traffic count was done at only one of the school sites. This was used as input into the software and the calculated result was compared to the measured sound level to verify accuracy. The actual traffic volume that was input was slightly adjusted (2% variation from the actual count) to produce a receiver level in the validation model that was the same as the measured level at the same location (Location A) on the site. Thus, the sound power level of the noise source in the model was set.

Using this source power level, the sound pressure level at a receiver at the receiving envelope (Location B) was determined in the model. This level was then compared to the measured receiving envelope level to validate the model.

The classrooms were modelled in *Bastian* with façade materials matching the actual classrooms. Using Location B, sound levels imported from the *CadnaA* validation models, the receiver level inside the modelled classroom was compared to the actual level measured in classrooms to validate the software.

The criterion for validating the software was that the difference between actual and simulated measurements should be less than 3 dB. This decision was based on the fact that a sound level difference of less than 3 dB is not perceptible to the human ear.

Once the software was thus validated, a base-case model was established, which served as a virtual experimental site for the implementation of various interventions.

3.6.5.2 Experimental set-up

In *CadnaA* a road was inserted to represent the typical road scenario according to the validation models. A classroom building, representing a block of four typical classrooms, was inserted with a receiver in front of the building façade corresponding to Location B on the actual sites.

The model was developed to represent a generic case and thus was simplified to contain a single road extending infinitely in either direction with no surrounding buildings. While this does not necessarily represent a realistic situation, it is used as a baseline scenario.

The independent variables were changed, creating a number of different scenarios. The resulting sound pressure level at the facade receiver (in *CadnaA*) and inside the classroom (in *Bastian*) was recorded. The resulting sound levels were compared to the target level and against a reference case, which was considered to be the building positioned closest to the noise source (road) without any interventions.

The independent variables tested were:

1. Building façade composition
2. Building (receiving façade) distance from source (road)
3. Building (receiving façade) orientation relative to source (road)
4. Building floor level (ground floor or first floor).
5. Barrier length
6. Barrier height
7. Barrier position relative to source and receiver
8. Alternative barrier arrangements

3.6.5.2.1 Façade composition

The classroom was modelled in *Bastian* with the façade components in ratios according to the typical classroom design established through the literature review and the survey of schools.

The material of the wall was set as either masonry or a light-weight panel system with the established typical window and opening sizes as a percentage of the façade area. As a reference for comparison, an alternative façade design was also created in which the wall construction was masonry and the window area was according to the National Building Regulations.

The façade receiver level recorded for each scenario was imported from *CadnaA* as the external source noise in *Bastian*, and the resulting indoor sound level recorded.

3.6.5.2.2 Distance from source

Four major building positions are used, between 17 m and 136 m from the source, each double the distance from the source of the previous. This was based on the theory that a doubling of the distance between two reference points will result in a 3 dB decrease in the SPL, which is considered to be a noticeable change. Interim positions were created between the major positions to provide a finer resolution.

3.6.5.2.3 Building orientation

At each building position, the building is oriented with the windows (receiving façade) either parallel to the road or perpendicular to the road.

3.6.5.2.4 Building floor level (receiver height)

Two building heights are used – single- and double-storey – to determine whether there is a difference in sound received in a ground-floor or first-floor classroom. The ground-floor level was assumed to be the same as the outdoor ground level, and the first-floor level was assumed to be 3 m above ground level. Façade receivers were set at mid-height of each floor, assuming this to be the mid-height of the windows.

3.6.5.2.5 Barrier length

A barrier (solid screen wall) was inserted between the noise source (road) and the receiver at the building façade. The length of the barrier was varied to establish whether the barrier length recommended in literature was valid. Once validated, the barrier length (as a ratio relative to the distance to the receiver) was deemed a controlled variable, being fixed for further experiments regarding the barrier height and position.

Because the barrier length is recommended as a ratio relative to the distance between the barrier and the receiver, the length of the barrier varied depending on its position relative to the receiver.

3.6.5.2.6 Barrier height

The height of the barrier is known to affect the SPL at the receiver. The height of the barrier was varied from 1.5 m up to 7 m in increments of 0.5 m, and the effect on the SPL recorded and analysed. Although a 7 m high barrier is not a practical height, it was applied for the sake of theoretically establishing the effect of a barrier up to 1 m above the roof height of a double-story building.

3.6.5.2.7 Position of barrier

The position of the barrier relative to the receiver is recognised as a potential factor influencing the sound level at the receiver. To determine the effect, the barrier was inserted close to the noise source at first, at a fixed position relative to the noise source and then at a fixed position close to the receiver (building). The height of the barrier at each position was varied incrementally, and its length as a ratio of the distance to the receiver.

3.6.5.2.8 Alternative barriers

In addition to the above-mentioned variables, the effect of wrapping the barrier around the site or the building was tested, as well as the effect of crowning the barrier and the addition of a topographical barrier, which was done by changing the ground level of the site relative to the level of the source (road).

3.6.5.2.9 Data collection and analysis

For each building position and orientation and height the other independent variables were toggled on and off, one at a time, creating a number of possible scenarios. Thus, numerous scenarios were created for each combination of barrier length, height and position, and the building position, orientation and floor level. The resulting sound level for each scenario was recorded in tables and evaluated against the target sound level.

3.7 Data analysis

The qualitative data collected via the survey and questionnaires provide a background against which recommendations stemming from the quantitative data analysis was illustrated. This was analysed and reported using simple statistics.

The data set collected from the experimental study was collated in tables for further analysis. This data consists of resultant sound levels recorded at the modelled receiver points.

In spite of potential differences between modelled/calculated data and actual measured data, the variables tested are comparable with one another, enabling the assessment of relative effectiveness of various possible interventions.

The target indoor sound pressure level was 40 dBA.

The sound transmission values of the two envelope scenarios (i.e. masonry wall and light-weight panel wall) were determined by the model. This transmission loss, when added to the indoor target SPL, provided a target SPL for the receiving envelope. This new target eliminated the need to import the *CadnaA* receiving envelope level into *Bastian* for every iteration of the experiment, thus simplifying the process.

The receiving envelope SPL data set was sorted to find the scenarios that achieved the target level for masonry walls and light-weight walls. This then indicated the efficacy of the various intervention scenarios.

The data collected from the simulation were used to quantify and rank the efficacy of each outdoor noise attenuation intervention in terms of the amount of noise that is transmitted from the source to the receiving envelope.

3.8 Limitations

It was originally intended to conduct this study countrywide. However, this was not practically feasible within the resources available. It was decided that since sound behaviour is the same, regardless of physical location, the measurement of sound in a large sample of schools was not necessary. Although no sound modelling software is flawless (Probst & Huber, 2010), most commercially available software is based on standard methods of calculation and, while not perfectly accurate due to the many factors that can potentially influence sound propagation, the results are consistent. Thus, it is possible to conduct the sound measurements using simulations of different environmental and building conditions, rather than seek such differing conditions in actual situations. Furthermore, the advantage of using software is that variables (such as traffic volume) can be controlled.

The survey response rate was low (5% out of 3 065 schools), which can be viewed as a limitation in that the results cannot be confidently generalised, although they are informative. Similarly, only five teachers participated in the teacher questionnaire and only four schools were selected for the on-site measurements. This means that the results cannot be generalised. However, the intention was not to generalise findings but rather inform the establishment of the model.

Although the modelled scenarios are not reflective of actual cases, since it was assumed that the noise source was singular and infinitely long, the traffic noise level was based on only one of the school sites and there were no surrounding buildings, the results are useful to compare the efficacy of one intervention to another under controlled conditions.

Chapter 4: Research results: Sub-objectives

This chapter records the findings of the sub-objective activities. As discussed in the previous chapter, the main objective of this research was achieved through experimentation. This experimentation is performed through a simulated model. The variables used in the experiment were established by means of a number of research instruments described earlier.

This chapter establishes the controlled variables, then the dependent variable and then the independent variables. These are then used to answer the main research question in Chapter 5.

4.1 Establishing controlled variable: The typical classroom design

This study seeks to investigate noise control solutions in the case where outdoor noise is transmitted through the classroom envelope via natural ventilation openings. A typical classroom was modelled in acoustic--simulation software to determine the resultant sound-pressure level inside the classroom. The natural ventilation design of the classroom and the classroom size were controlled variables intended to represent a typical Gauteng classroom. To define the typical classroom, regulatory requirements, as well as observations of existing Gauteng classrooms, were considered. The ‘average’ design of existing classrooms was determined (as explained in section 4.1.2) and evaluated against the criteria of the regulations reviewed.

4.1.1 Literature review findings: Natural ventilation condition

A literature review was conducted to determine whether there is a recommended window design to achieve adequate natural ventilation for a classroom. The findings showed that there is very little literature about the actual window design for a classroom. However, regulations pertaining to classroom ventilation design were explored. The summary of regulations in Table 4-1 shows that, of those explored, only the South African, Rwandan and American regulations speak directly to the window design through deemed-to-satisfy solutions, while the others refer to performance requirements.

Table 4-1: Summary of ventilation design requirements for classrooms in regulations

Reference	Recommended ventilation design
South African National Building Regulations (SANS 10400 Part O)	Window opening area of at least 5% of the floor area
United Kingdom (British Building Bulleting BB 101)	No recommended design; performance requirement of at least 5 L/p/s on average (or 1 500 ppm CO_2)
World Health Organization	No recommended design; performance requirement of at 12 ACH (approximately 1 000 ppm CO_2)
USA (ASHRAE 62.1)	Window opening area of at least 2.5- 4% of the usable floor area
New Zealand (Designing Quality Learning Spaces)	No recommended design; performance requirement of at least 1 500 ppm CO_2
Rwanda (Child Friendly Schools Infrastructure and Guidelines)	Minimum openable area of 5 m^2

The deemed-to-satisfy solutions offered refer to the window size as a percentage of the floor area or a minimum opening area. For a classroom in South Africa, the required floor area can be calculated based from the minimum area per person of allocation of 1 m^2 per learner and 7 m^2 for the teacher (Department of Basic Education, 2013). Assuming the maximum allowable class size of 40 learners (Department of Basic Education, 2013), this calculates to a floor area of 47 m^2.

When the South African and American solutions (5% and 4% of usable floor area, respectively) are applied to a minimum-sized South African classroom of 47 m^2, the resultant openable window area (including door as an openable area) is 2.35 m^2 and 1.88 m^2 respectively. This is significantly less than the Rwandan recommendation of 5 m^2, which is probably based on the hot climate in Rwanda.

Considering the solution based on the South African National Building Regulations (NBR), the minimum openable window area of 2.35 m^2 can be translated into a standard door area (0.8 x 2.1 = 1.68m^2) plus a window of approximately 1 m by 0.6 m. This is a very small opening area and is not in line with what is generally observed in schools in Gauteng, an example of which is shown in Figure 4-1, where the entire window area (for daylighting) as well as the openable area (for ventilation) is more than strictly required by the NBR.

Figure 4-1: Photo showing the large window areas commonly found in Gauteng classrooms

4.1.2 On-site measurements findings: Physical classroom design

The regulations cited above refer to minimum requirements for ventilation design. In order to determine what is more typical in an actual classroom in Gauteng, a number of schools were surveyed and on-site measurements of the physical design of the classrooms were recorded and analysed to come up with a reasonable description of a typical Gauteng classroom.

Four classrooms, each from a different school, were selected – two in Johannesburg and two in Pretoria.

The sizes of the classrooms and the window areas and openable areas (including doors) are recorded in Table 4-2. The classrooms were all cross-ventilated. The figures recorded in the table show the total glazed and open section window areas relative to the floor area, and the glazed and open section window areas of the receiving façade only relative to the floor area.

Table 4-2: Floor and window areas in selected classrooms

School identifier	Classroom floor area (m^2)	Total window area (on all facades) as percentage of floor area		Receiving façade window area as percentage of floor area	
		Full window area (fixed + open sections)	Openable window area	Glazed window area (fixed + open sections)	Openable window area
A	66.4	16.2%	13.9%	9.3%	9.3%
B	59	43.9%	32.7%	21.7%	15.7%
C	64.8	32.4%	21.8%	14.5%	14.5%
D	55	33.4%	17.8%	13.5%	7.3%
Averages:	61.3	31.4%	21.6%	14.7%	11.7%

It is evident that the opening areas as a percentage of the floor area are much greater than the recommended minimum found in the South African and American regulations – on average the openable area is 21.6% compared to the requirements of 5% or 4%, respectively. In terms of actual size, the average is approximately 13 m^2, which is also much larger than the Rwandan required minimum open area.

The typical floor area is also greater than the minimum norms prescribed by the South African regulations. The minimum size of a classroom according to the regulations calculates to 47 m^2, assuming a maximum class size of 40 learners, while the average floor area of a typical classroom as determined by on-site measurements is 61.3 m^2.

It can thus be concluded that the typical classroom in urban schools in Gauteng exceeds the minimum requirements, offering a better-ventilated and more spacious classroom.

4.1.3 Conclusion: The typical classroom

The classroom for the model was defined based on the established typical classroom, which is confirmed to comply with norms and standards.

For the purpose of modelling a typical classroom, dimensions that represent the typical classrooms measured were applied, conservatively rounding down the figures to whole numbers. Thus, the modelled classroom was 7 m by 8 m (56 m^2). The receiving façade was made on the longer side (8 m). The height of the ceiling was 2.7 m; thus the total receiving façade area was 21.6 m^2. The total window area on the receiving facade was 14% of the floor area (rounded down average from Table 4-2), equalling 7.8 m^2 (1.2 m high x 6.5 m wide in total). The openable area on the receiving façade was 11% of the floor area, equalling 6.1 m^2 (1.2 m high x 5.1 m wide) or 28% of the façade area. Subtracting the openable area from the total window area of the façade, the remaining (fixed) window area was 1.64 m^2 (1.2 m x 1.36 m) or about 7.5% of the façade area.

The modelled classroom is illustrated in Figure 4-2, showing only the windows and openings in the receiving façade. There are three materials that were applied to the façade: the wall material, the glass of the fixed window sections and the open windows. The exact configuration (positioning) of the various surfaces is inconsequential to the amount of sound transferred through the façade, since the modelling software only applies each material as a percentage of the façade area. It is also assumed that the opening sections are horizontal pivot windows, which provide minimal influence on air and sound transmission (The Building Performance Centre, 2007).

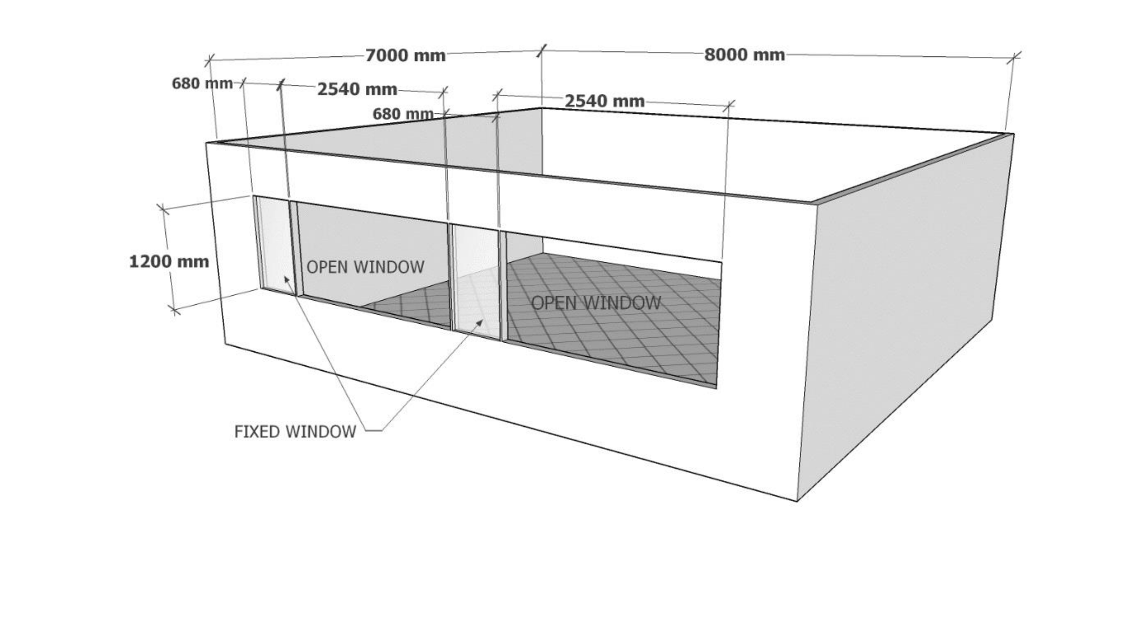


Figure 4-2: Modelled typical classroom showing receiving facade composition

The window glazing material applied was 4 mm thick clear float glass, which is the most common glazing material used in South Africa. The effect of the window framing is negligible (The Building Performance Centre, 2007) and was not specified.

Two different wall construction materials were applied in separate scenarios. The first was a masonry wall with a density of 200 kg/m^3, 240 mm thick with a plaster render on one side. This represents a common construction found in three out of the four schools selected as study sites (Schools B, C and D). The second construction was a light-weight construction, using two panels of 9 mm fibre-cement board with a 58 mm fill of 16 kg/m^3 expanded polystyrene (EPS). This represents a common alternative building material similar to the material used in the construction of classrooms at School A.

The interior finishes of the classroom are not specified but are such that the reverberation inside the classroom was is 0.5 seconds, as stated in section 1.10.

4.2 Establishing controlled variable: Traffic noise condition

To establish what a realistic 'typical' value for traffic noise around urban schools is, surveys, questionnaires and on-site measurements were conducted.

4.2.1 Province-wide survey findings: Traffic noise condition

A list of all schools registered with the Gauteng Department of Education (GDE) was obtained from the GDE. With permission, all 3 065 (N) schools were sent a survey. The survey asked the following questions:

- In your opinion, is your school located close to an external noise source (e.g. busy road, railway or industry) that regularly affects the background noise level in any of the classrooms during the school day? (Yes/No)
- What is the main source of disturbing external noise?
- Do you have any further comments regarding noise disturbance at your school?

The survey was an electronic survey sent to the contact email address of each school. Only one response per school was requested. Many of the email addresses could not be reached (353). Thus the effective number of schools reached was 2 712. Out of this number (over a period of 5 months, with reminders sent), 124 schools responded, which is a response rate of 5%.

Out of these 124 responses, 36% (n=45) responded “Yes”, 61% (n=76) responded “No”, and 2% (n=3) responded “Not sure” to the first question regarding exposure to external noise sources in general. These responses are graphically represented in Figure 4-3.

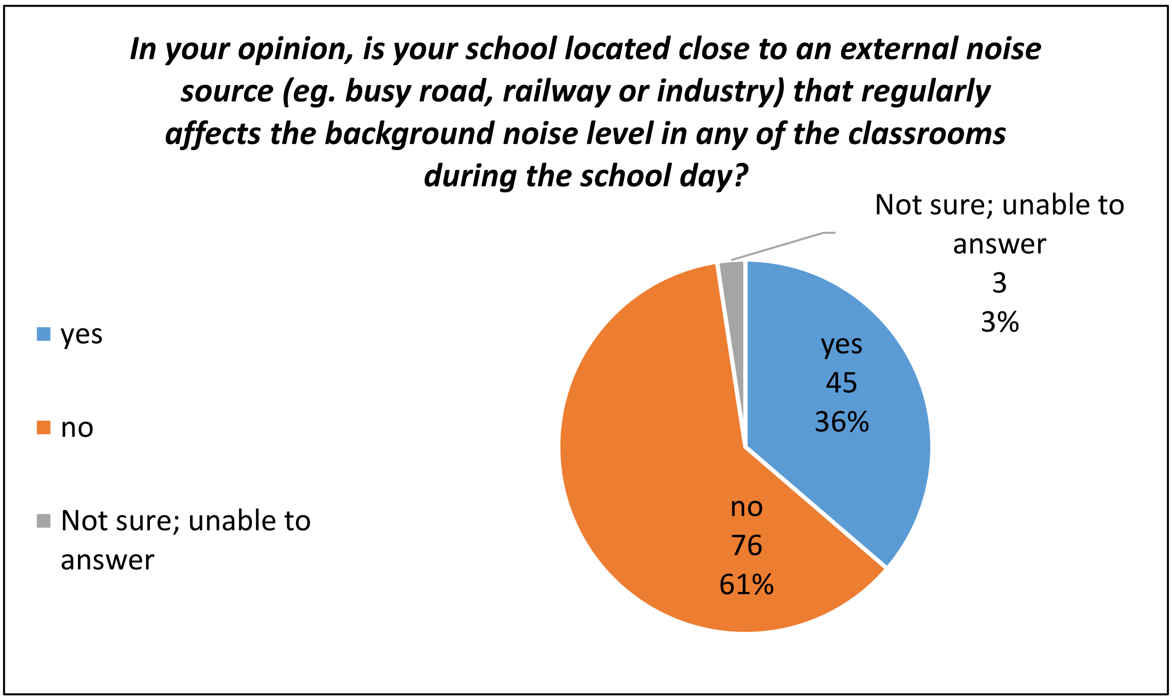


Figure 4-3: Distribution of responses to province-wide school noise survey

Of those that responded “Yes”, 73 % (n=32) reported the main source of noise to be road traffic, 5% (n=2) reported the main problem to be air traffic, 7% (n=3) reported the main source to be rail traffic, and the remainder of the reported sources of noise were industry, business or entertainment related sources. Of those that responded “Yes”, 22% (n=10) specifically mentioned noise caused by taxis in the optional comments section of the survey. The comments refer to loud music and activity emanating from taxis, rather than taxi traffic noise.

Out of the total number of responses (n=124), 26% of the schools reported being exposed to road-traffic noise.

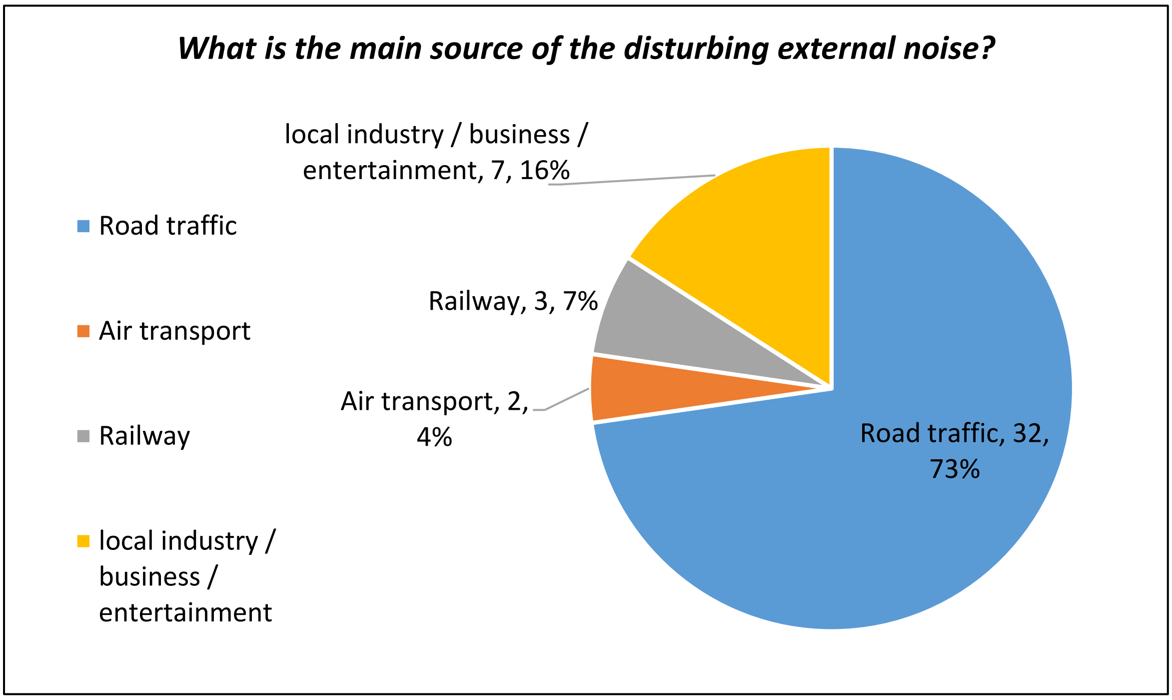


Figure 4-4: Sources of noise around schools as per province-wide survey

Although the response rate was low, it is evident that the dominant source of noise is road traffic, as opposed to other outdoor sources. It could be argued that the schools located in quiet areas (and therefore not concerned with noise) did not take note of the survey, accounting for the low response rate.

The schools that responded were each identified on a map to determine what type of environment they are exposed to. The schools that answered that it is noisy due to road noise, were not necessarily located next to a highway or in business districts, where high traffic volumes are expected. It seems that even in some apparently quiet residential areas, traffic can be a noise problem.

The results of this survey confirm road traffic as a dominant source of disturbing outdoor noise in classrooms in Gauteng and that it is a general problem in the province, even in peri-urban areas.

4.2.2 Teacher questionnaire findings: Traffic noise condition

At the four schools selected, a classroom in each was selected for the indoor measurement location. The teachers who regularly occupied the selected classrooms were asked to complete a questionnaire regarding noise in and around the classroom. At School A the teacher using an adjacent similar classroom was also approached to participate. Altogether, five questionnaires were administered in four schools.

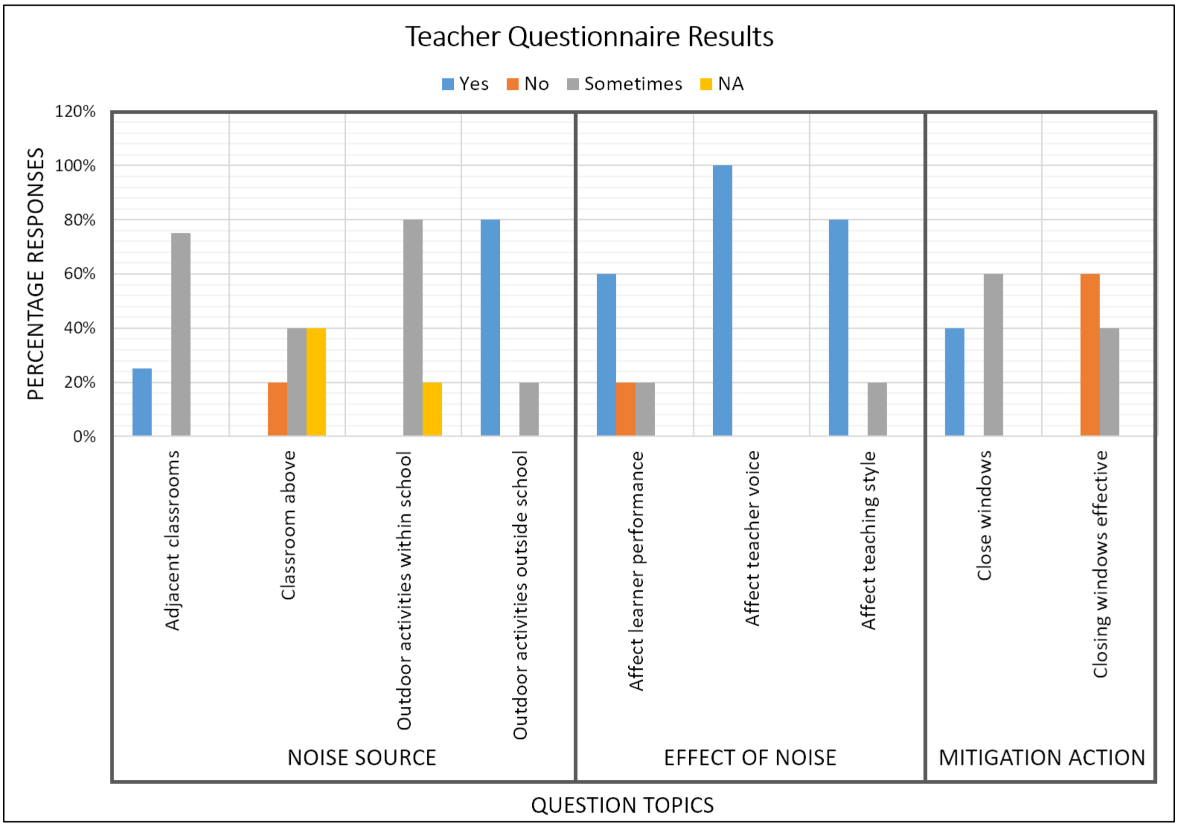


Figure 4-5: Results of Teacher questionnaire

The results indicate that noise disturbance is seldom experienced due to noise in classrooms adjacent to or above the selected classroom or from outdoor noise sources within the school, such as a lawn-mower or other activities on the grounds. In comparison, 80% (n=4) reported to experience noise disturbance from sources outside the school (such as traffic) and 20% (n=1) reported that such external noise was sometimes experienced. While these results cannot be generalised with confidence due to the small sample size, as a case study they do confirm that at the selected schools, classroom noise due to external noise sources are a cause for concern.

Regarding the effects of noise, the results show that 60% (n=3) find that noise affects the learners' performance, 20% (n=1) find that noise sometimes affects learner performance and 20% (n=1) find that noise does not affect learner performance. It is noted that at the school that reported that noise does not affect learner performance, the classroom was the furthest away from the noise source (School B). All teachers reported that they experience voice strain in the presence of noise, 80% (n=4) reported that noise disturbance affects their teaching style, and 20% (n=1) reported that it sometimes affects their teaching style.

With respect to actions taken to prevent noise disturbance, 40% (n=2) reported that they close the windows (these respondents were both from the same school) and that it sometimes helps reduce noise ingress. Sixty percent (n=3) reported that they sometimes close the windows and that it does not help reduce noise ingress.

Although this is a small sample, these results confirm again that noise from outdoor sources external to the schools, such as road traffic, is a concern and that it has a negative effect on teaching and learning. The results also confirm that closing the windows against disturbing outdoor noise is not very effective. The teachers' perception of noise is verified by the actual sound pressure level measurements taken on site, as discussed in the following section.

4.2.3 On-site measurements findings: Traffic noise condition

The road-traffic sound pressure level (SPL) was measured at each selected site at Location A, according to the method described in Section 3.6.4.3.3 at a distance of approximately 15 m from the centre of the road. The position of Location A at each site is shown in Figure 4-6.

It was noted that the boundary element at all the sites consisted of a palisade fence or diamond mesh fence that offered no resistance to sound transmission.

Figure 4-6: Aerial photos showing Location A at each school site and distance to centre of road[9]

The sound level meter recorded the equivalent continuous SPL (L_{eq}) in periods of five minutes over a five-hour period at Location A. The minimum and maximum $L_{eq\ 5min}$ (predominantly traffic noise) at each site, as well as the noisiest hour L_{eq}, the five-hour L_{eq} and the levels recorded at Locations B and C over 30 minutes during the noisiest hour are as recorded in Table 4-3.

The average traffic noise over the 5-hour measurement period ($L_{eq\ 5hrs}$), characterising urban road traffic, was calculated to be 64.7 dBA.

[9] https://www.google.co.za/maps [accessed 5 August 2019]

Table 4-3: Record of sound level measurements (ambient including traffic) taken at sites over a 5-hour period

School Identifier	Location A						Location B Noisiest hour	Location C Noisiest hour
	Minimum $L_{eq\ 5min}$ (dBA)	Maximum $L_{eq\ 5min}$ (dBA)	L_{10} (dBA)	L_{90} (dBA)	$L_{eq\ 5hours}$ (dBA)	L_{eq} Noisiest hour (dBA) (time)	$L_{eq\ 30min}$ (dBA) (distance from centre of road)	$L_{eq\ 30min}$ (dBA)
A	60.1	66.1	65.6	55.3	63.0	64.4 (08h15-09h15)	61.9 (25 m)	62.1
B	57	64.5	65	52.9	61.4	63.7 (08h10-09h10)	58.0 (51 m)	51.6
C	66.3	75.1	72.3	52.8	68.8	70.8 (11h45-12h45)	70.8 (15 m)	57.0
D	61.9	69.9	68.8	58	65.7	67.2 (11h35-12h35)	62.7 (30 m)	65.0

The measured noise levels were ranked and viewed in relation to the teacher questionnaires regarding traffic noise. School B has the lowest measured SPL at each measurement location; School B was also the only school at which the participating teacher reported that traffic noise is ‘sometimes’ disturbing. At Schools A, C and D, the SPL was higher than at School B and the participating teachers at these schools reported that traffic noise was a disturbance in the classroom. Though this is a case study using a small sample, these findings indicate a correlation between measured and perceived noise levels. It is also observed that as School B the distance between the noise source and the classroom is the greatest, indicating correlation between noise level and distance from noise source.

Traffic flow was only recorded at School B. It was calculated that on average over the 5-hour measurement period, the hourly traffic count was 1 104 vehicles, 2% of which were heavy vehicles. During the noisiest hour (between 08h05 and 09h05) the traffic volume was calculated to be 1 120 vehicles per hour, 3% of which were heavy vehicles. Traffic speed was not measured but was assumed to be at the speed limit of 60 km/h.

Each hour within the total period was analysed to determine the $L_{eq\ 1hr}$ for every hour period within the total period. The noisiest hour of the school day for each school was thus determined. The highest one-hour period recorded at any of the schools was 70.8 dBA. The average was 66.5 dBA.

An analysis of the dominant frequencies in the outdoor traffic noise (by sorting according to first, second and third highest) revealed that in all cases the highest energy occurred in the 1 kHz frequency band. The adjacent bands (between 630 Hz and 1.6 kHz) also contained high energy. This is expected for the traffic speeds of approximately 60 km/h when compared to the urban traffic noise studies by Kim, et al. (2017) and Buratti and Moretti (2010).

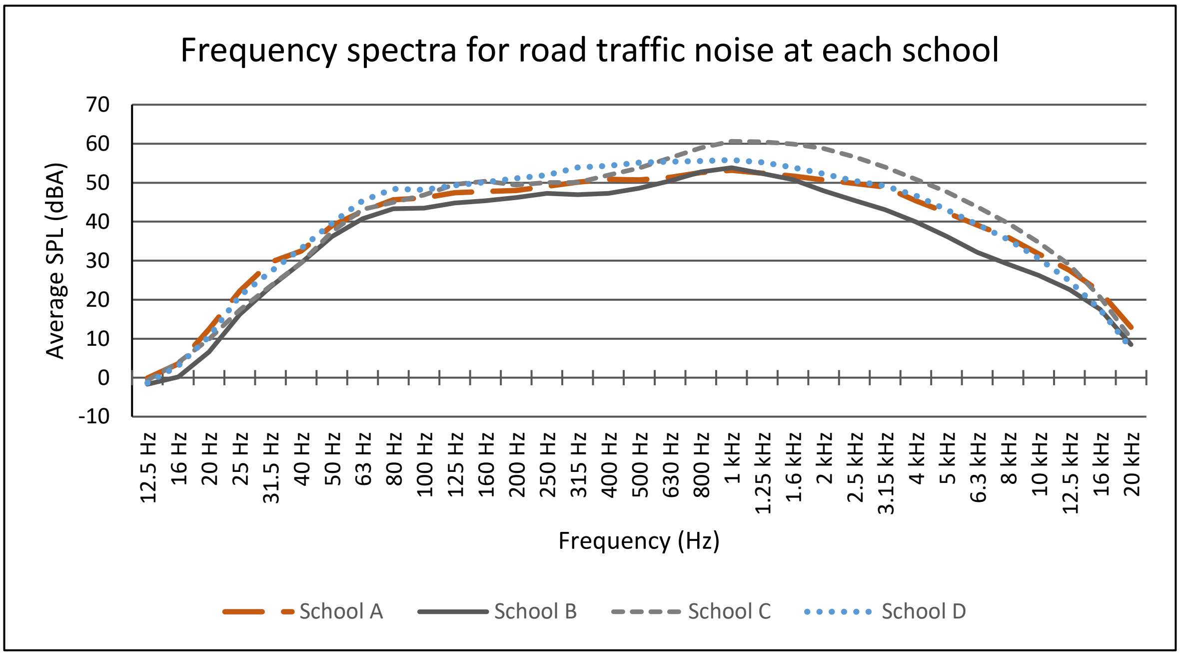


Figure 4-7: Spectrum for road traffic noise measured at each school site (at Location A)

4.2.4 Conclusion: Typical traffic noise

The above findings confirm that noise disturbance in classrooms from outdoor sources is often attributed to road-traffic noise.

The L_{eq} for the noisiest hour measured at each site is intended to be used to determine the 'typical' noise generated by road traffic. However, in the modelling software traffic volume is used as an input to determine the power of the noise source, rather than the sound level being input directly. This method is used by a number of European standards used in *CadnaA*, such as RSL-90, Nordic Prediction Method, Nouvelle Méthode de Prévision du Bruit and others, and accounts for the frequency spectrum, road surface, gradient and the ratio of heavy and light vehicles.

For the configuration settings selected in*CadnaA*, road-traffic noise was be modelled based on method of RLS-90 by default. This method has been shown to be able to accurately predict road-traffic noise levels (Murillo-Gómez, Gil-Carvajal, Zapata-Rodriguez & Téllez-Garcia, 2015; Lin, Peng, Tsai, Chang & Chen, 2018) and is a well-established and accepted standard (Quartieri, Mastorakis, Iannone, Guarnaccia, D'Ambrosio, Troisi & Lenza, 2009).

Traffic volume was recorded at only one of the school sites, School B. This data was input into a model of the site of School B. The road was modelled to be 14 m wide (representing a double lane road); the speed was set to 60 km/h; the road surface was set as 'smooth mastic asphalt' with a 0% gradient; reflections were set to 0 dBA. The resulting sound pressure level at a receiver positioned at Location A in the model was 64.4 dBA (see Figure 4-8). The corresponding actual measured SPL at the site was 63.7 dBA (L_{eq} for the noisiest hour). The traffic input data was adjusted (changing the vehicles per hour from 1 120 to 1 000 and the percentage of heavy vehicles from 3% to 2.5%) until the resulting SPL in the model matched the measured SPL. This traffic data (see table in Figure 4-9) was taken to be the input data for the virtual research site. This is conservative data, representing the site at which the SPL was the lowest in the noisiest hour. However, it can be considered representative of typical traffic noise as the SPL it is within the 3 dB range of perceptible difference from the average $L_{eq\ 5hours}$ at all four schools (64.7 dBA).

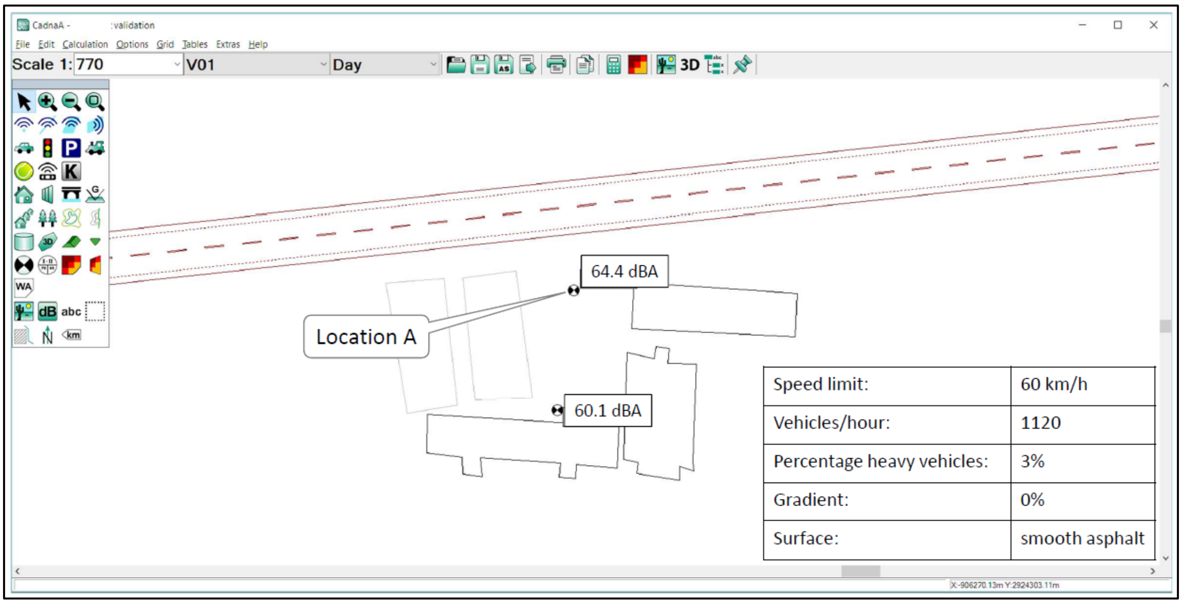


Figure 4-8: Resulting SPL at Location A of School B based on actual traffic input (screenshot from CadnaA simulation)

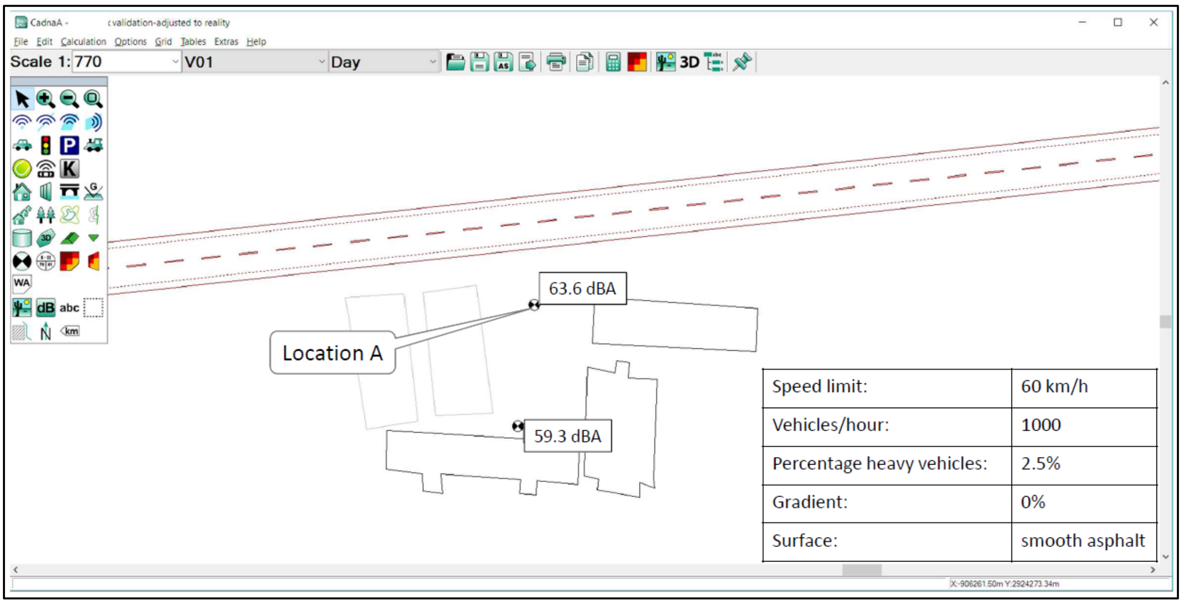


Figure 4-9: Resulting SPL at Location A of School B using adjusted traffic input to achieve the SPL measured on site (screenshot from CadnaA simulation)

4.3 Establishing the dependent variable: Target ambient noise level

The dependent variable was considered to be the ambient sound pressure level in the modelled classroom, which varied depending on the condition of the independent variables. The ideal ambient sound level in a classroom was viewed as the target to be achieved by implementing various interventions. This target was established through the literature review.

4.3.1 Literature review findings: Target ambient noise level

The literature reviewed in Chapter 2 included both regulations and research findings regarding classroom ambient noise levels. A summary of international standards (see Table 2-2) reveals strong agreement that the target level should be 35 dBA. This is further supported in local standards (SANS 10103:2008) and the research findings of others.

An ambient level of 35 dBA is very low and difficult to achieve in reality. This is demonstrated in research by Ramma (2007) in which the noise level in a number of Gauteng schools was measured. The results revealed that no unoccupied classrooms met the requirement of 35 dBA, with the lowest (which was in a suburban area) being 39.9 dBA, and the highest (close to an outdoor noise source) being 62.5 dBA.

It is noted that in the SANS 10103:2008 a maximum ambient level of 40 dBA is allowable for classrooms, although not ideal. This was considered in conjunction with SANS 10218-1 and the general context of South African public schools.

According to SANS 10218-1:2004, outdoor ambient noise is categorised as E1 (L_{eq} ≤ 65 dBA), E2 (65 dBA < L_{eq} ≤ 75 dBA) or E3 (75 dBA < L_{eq} ≤ 85 dBA). The traffic noise level established in section 4.2 was 63.7 dBA and the average traffic noise measured over 5 hours at each school was 64.7 dBA. Both these values are close to the transition between category E1 and E2, but strictly are in category E1 (≤ 65 dBA). Thus, with reference to Table 5 of SANS 10218-1:2004, the minimum airborne insulation of a classroom façade should be 30 dBA or 25 dBA for a higher grade or standard grade building, respectively. From a reference outdoor level that is less than 65 dBA for a category E1 building, it can be calculated that the allowable indoor level should be less than 35 dBA (for HG) or less than 40 dBA (for SG), which correlates with the ideal and allowable levels provided in SANS 10103:2008.

Considering that higher grade buildings are designed with every effort to minimise sound transmission through the façade, and that the sound insulation value of a façade is significantly compromised by open windows, it stands to reason that a typical classroom in South Africa would be considered a standard grade building. As such, an indoor ambient noise level of 40 dBA is considered acceptable.

The literature reviewed further established that a good listening environment should enable a signal-to-noise ratio (SNR) of at least 10 dB, although preferably 15 dBA. For a signal (voice) level of 65 dBA dB (Breitsprecher, 2011; Sarantopoulos *et al.*, 2014), the ambient noise level could be as high as 50 dBA to achieve a 15 dB SNR. However, this is only the case at the distance from the signal at which the signal level was measured (usually 1 m). It is noted that the SNR value should be achieved at a normal listening distance from the speaker. Considering the classroom of 8 m in length and a teacher standing 1 m away from the front wall, the furthest that a listener could be from the signal (teacher) in a typical classroom is 7 m (6 m from the point of measurement of the signal level). If the SNR decreases by 6 dB over 6 m, as demonstrated by Klatte *et al* (2010), it can be calculated that in order to maintain an SNR of 15 dB, the ambient level at the back of the classroom should be 44 dBA (50 dB – 6 dB).

Differences were found amongst the literature reviewed regarding the time period over which indoor measurements should be taken. However, since the dependent variable will be measured in a simulated and thus highly controlled environment, this is not a relevant consideration.

4.3.2 Conclusion of findings: Target ambient noise level

Based on the literature and considering the purpose and context of establishing a target ambient noise level for the modelled classroom, it was concluded that the acceptable target is 40 dBA, acknowledging that the ideal target is 35 dBA.

A secondary target is a signal-to-noise ratio of 15 dB, which corresponds to an ambient level of 44 dBA. This is a slightly more relaxed target than 40 dBA and is only just perceptible.

Since speech clarity is dependent on the SNR as well as reverberation time, and the ambient noise level indoors is also affected by reverberation time, the reverberation time in the model (in *Bastian*) was set at 0.5 seconds.

4.4 Establishing the independent variables

There are a number of different ways to attenuate noise and prevent or minimise sound transmission through a building envelope. Interventions can either be in the form of façade interventions, which entails changing building envelope composition and materials to increase the sound insulation, or outdoor interventions that reduce the incident sound pressure level at the outer face of the building envelope. It is noted that these interventions act in combination. For each independent variable tested, the others need to be controlled. The result is a vast number of scenarios of various combinations.

These were discussed in the literature review in Chapter 2 and are considered here in the context of the experimental model.

4.4.1 Literature review findings: Attenuation interventions

As discussed in the literature review in Chapter 2, means of reducing sound transmission through the façade of a building include interventions such as the installation of double glazing or changing the wall construction material. Double glazing is not commonly used in South African schools, particularly public schools, due to the cost. Furthermore, in the context of this study, in which open windows are considered, double glazing would be of little value.

The typical classroom façade design, established in section 4.1.3, consists of a high percentage of glazing and openings. However, the wall construction could consist of any number of building materials. Much of the literature concludes that any glazed or open element decreases the sound reduction of a separating element significantly, rendering the strength of the remainder of the façade almost negligible. In spite of this, the effect of walling material was tested to confirm this.

In South Africa – particularly in urban settings like Gauteng – most schools are built using masonry construction. A small portion of schools are constructed using light-weight building systems. Out of the four schools selected for on-site measurements, one was a light-weight construction. The cabinet resolution of 2013, requiring that at least 60% of public buildings should be constructed from innovative building technologies (IBTs), many of which are light-weight panel systems, means that it was relevant in this study to consider the effect of such construction types on sound transmission.

Thus, as mentioned in section 4.1.3, two wall construction materials were tested as possible interventions – a high density masonry wall and a light-weight insulated panel construction. These each constituted an independent variable.

Outdoor attenuation interventions were also discussed in the literature review. The options considered included geometric divergence, building orientation, ground absorption, atmospheric absorption, screening and vegetation.

Ground absorption was eliminated as an independent variable (making it a controlled variable) because the software uses a default ground absorption factor of 1, which represents a reflective surface (assuming a hard, non-porous surface) (Datakustic, 2017, sec. 3.5). This is a potential limitation and results in a worst-case scenario model in which the sound can be amplified rather than attenuated. The advantage of a worst-case scenario model is that it produces conservative results – in practice the resulting SPL at the building façade is likely to be more favourable if ground absorption is present. Modelling a worst-case scenario also provides a future-proof solution so that the acoustic performance of the classroom will not be negatively affected if the ground surface absorption changes (e.g. if grass is replaced by paving).

Similarly, vegetation was eliminated as an independent variable. Vegetation has been shown to have a limited effect over a short distance (Halim, *et al*., 2015). Furthermore, the disadvantage of relying on vegetation (or landscaping) is that it is not guaranteed to be maintained and thus the efficacy of a solution that relies on it cannot be guaranteed. Thus, vegetation was established as a controlled variable by assuming no vegetation, removing the risk of future changes negatively affecting the classroom ambient noise.

Atmospheric and meteorological conditions do not have a significant effect on noise in this context and were also eliminated as independent variables. In practice, these factors are not constant and would be considered confounding variables. Since this study focuses on the comparison of one scenario to the next, their effect can be eliminated in the modelled environment so that the results will be comparable.

The literature and theory indicate a strong correlation between sound propagation and the distance between the source and receiver, with a theoretical decrease in SPL of 3 dB for every doubling of distance for a line source in a free field. This is a relevant factor to consider in the experiment. It is noted that sound waves travel in all directions, not only horizontally. Thus, the height of the receiving façade relative to the noise source is also necessary to consider. This was applied by considering the SPL inside a modelled classroom on both ground-floor and first-floor levels.

The orientation of the receiving façade is mentioned as a factor affecting the transmission of traffic noise into a building by the Federal Highway Administration (Knauer *et al.*, 2000). This is relevant to the design of a classroom building on a site and is possible to model and was thus included as an independent variable.

The literature reviewed also supported screening as an effective means of mitigating traffic noise propagation outdoors. The height, position, length and shape of a screen wall can influence the amount of sound that can be blocked by it. The insertion of screens (or barriers) is a design-related matter and the software used was able to model screen walls of any dimension. Thus, it was deemed relevant to include barriers as an independent variable, changing parameters such as the length, height and position of the barrier relative to the noise source and receiver. The effects of adding a cantilevered crown and changing the shape of the barrier to wrap around the site or the building were also investigated as alternative barrier designs.

The effect of topography was included as an alternative barrier arrangement, rather than an independent variable of its own. In order to present a generic case, topography was generally excluded and the site assumed to be level. However, it was recognised that an elevated site can improve sound attenuation, having a similar effect as a barrier. Thus, the effect of a site raised by 2 m with a barrier at the boundary of the site was included as an alternative barrier design.

4.4.2 Conclusion of findings: Attenuation interventions

The findings regarding sound attenuating interventions are summarised in Table 4-4.

Table 4-4: Summary of attenuation interventions

Intervention	Comments
Façade material and design	R-value of materials and percentage of materials used in a facade has an effect; can be modelled (in *Bastian*)
Geometric divergence (distance between source and receiver)	Effective; can be modelled
Building (façade) orientation	Possibly effective; can be modelled
Ground absorption or reflection	Effective up to 60 m; can be modelled but not when using RLS-90 method for traffic noise calculation.
Topography	Possibly effective; can be modelled but not representative of a 'generic' case
Atmospheric (air) absorption and atmospheric conditions (air temperature, humidity, wind)	Minimal effect
Barriers or screening	Effective; can be modelled
Vegetation	Limited effect; not easily modelled and not a permanent solution.

Based on these findings, the following interventions were chosen as independent variables:

- Building façade (material and composition)
- Geometric divergence / Building location (distance from source)
- Building orientation relative to source
- Building floor level (ground or first floor)
- Barrier length
- Barrier height
- Barrier position relative to source and receiver
- Barrier alternatives (crowning, shape, double barriers, topographical barrier)

The following chapter will elaborate on the experimental research that was conducted to evaluate the efficacy of each of these interventions under various sets of conditions to determine which are suitable and effective for achieving suitable ambient noise levels in classrooms that are exposed to traffic noise, thus answering the main research question.

4.5 Conclusion

The purpose of this chapter was to establish the controlled, dependent and independent variables to be applied in the experimental research.

The findings are summarised as follows:

The typical South African classroom (controlled variable) that was modelled was established as being 7 m wide by 8 m long and 2.7 m high. This provides a receiving façade (the façade through which traffic noise would be expected to be transmitted) of 21.6 m^2, constructed from either masonry or light-weight panels with open windows constituting 28% of this façade area and fixed glazed windows constituting 7.5%.

Traffic noise (controlled variable) was modelled based on a traffic flow of 1 000 vehicles per hour, 2.5% of which are heavy vehicles, with a traffic speed of 60 km/h. This is assumed representative of a typical main road during the day in urban areas in Gauteng. The spectral characteristic of the traffic noise is not required as input data as it is automatically calculated by the software based the other inputs required (speed, gradient, road surface).

The target indoor ambient SPL in a classroom (dependent variable) was established to be 40 dBA for naturally ventilated classrooms, although 35 dBA is ideal, with a signal-to-noise ratio of at least 15 dB at all seating positions in the classroom and a reverberation time of 0.5 seconds (controlled variable).

The modelled environment eliminated the effects of ground absorption, landscaping and atmospheric conditions on sound propagation (controlled variables). The modelled environment was used to experiment regarding the effect of the independent variables listed in the previous section. The results of the experiment are discussed in the following chapter.

Chapter 5: Research results: Main objective

The variables established in Chapter 4 were used in modelling a virtual school site. This virtual environment was used to create various scenarios of different building facade designs and positions and different barrier designs and positions to test which scenarios produce the target sound pressure level (SPL) inside the modelled classroom.

This part of the research sets out to answer the following component questions:

- Does the wall construction material influence the sound transmission if there are open windows of an area equal to 11% of the interior floor area?
- If the open window area is changed to 2.5% of the floor area (in line with the National Building Regulations), does the sound transmission decrease significantly?
- Can the target SPL be met under any of these façade conditions for a building at different distances from the road?
- At what distance (less than or equal to 136 m from the road) can the target SPL be met, if any at all?
- Does the orientation of the receiving façade change the amount of sound transmitted through the window (receiving) façade and can the target level be met in either a parallel or perpendicular orientation relative to the road?
- Does it make a difference to the classroom SPL if the classroom is on the ground floor or the first floor?
- How long should a barrier be (relative to the distance from the receiver) to minimise the effect of sound travelling around the barrier rather than over it?
- How high does a barrier need to be (up to 7 m) to result in the target SPL in a classroom that is at various distances from the road?
- Does it make a difference if the barrier is positioned closer to the source or closer to the receiver and is the target SPL in the classroom achieved under either condition?
- Can the target SPL be achieved by alternative barrier arrangements, such as raising the ground level of the school relative to the road, or changing the shape of the barrier?

5.1 Modelling

The software selected was *CadnaA* for outdoor sound modelling and *Bastian* for indoor sound modelling, which is specifically intended for measuring sound transmission through a separating element.

CadnaA has the ability to model and define a sound source as a road or as a line source, amongst other source types. It has been established as having accuracy in predicting traffic noise and the effect of barriers (Radoi, 2015). Road noise is calculated using the methodology of the German standard for road-traffic noise prediction, RLS-90, which is native to the software and has been found to be accurate (Murillo-Gómez *et al.*, 2015). When modelling a road source, the traffic count is used as a parameter and includes assumptions regarding the character of the noise, such as frequency. As discussed earlier, the traffic flow was established and validated against the model for School B. These parameters were then deemed representative of the scenario and used going forward in setting up the experimental site in *CadnaA*.

Two receiver points were used in the modelling to measure the dependent variable. The first, referred to as the *façade receiver* (corresponding to Location B of the on-site measurements), was located outside the classroom building at 1.5 m above ground level, 1.2 m away from the façade and centred along the façade of the building. This was constructed in *CadnaA*. The sound pressure level of the façade receiver was imported into *Bastian* as a sound source 1.5 m high and 1.2 m from the outside of the façade. The second receiver was inserted in the classroom (in *Bastian*) at the centre of the room at a height of 1.2 m, referred to as the *classroom receiver* (corresponding to Location A of the on-site measurements). The sound pressure level measured at this point was assessed against the target indoor ambient sound level of 40 dBA.

5.1.1 Model validation

Each of the four school sites was modelled in *CadnaA* and *Bastian* and the simulated results were compared to the measured results at each receiver point. The table below lists the actual and modelled sound levels at Locations A, B and C for each site.

Table 5-1: Table of validation results

School	Location A			Location B			Location C		
	Actual	Modelled	Deviation	Actual	Modelled	Deviation	Actual	Modelled	Deviation
A	64.4	66.9	*2.5*	61.9	62.1	*0.2*	62.1	52.3	*9.8*
B	63.7	63.6	*0.1*	58	58.3	*0.3*	51.6	50.4	*1.2*
C	70.8	68	*2.8*	70.8	68	*2.8*	57	58.3	*1.3*
D	67.2	66.8	*0.4*	62.7	62.6	*0.1*	65	52.8	*12.2*

At Location A and B there was not a significant deviation between the simulated and actual measurements at all the schools. The indoor measurements (Location C) showed low deviation at Schools B and C but high deviation at Schools A and D, where the actual levels were much higher than the modelled levels.

It is speculated that the deviation at School A could be due to the low-pitched sheet metal roof, which would offer low resistance to sound transmission, and which is not represented in the model. At School D, the high indoor sound level could be due to the high reverberation time which was observed on site and which is not accounted for in the model, which had a set reverberation time of 0.5 seconds. Thus, School A and D were disregarded as validation benchmarks.

School B, on which the traffic noise controlled variable was based, shows a low level of deviation at Locations A, B and C, and School C shows insignificant deviations (less than 3 dB). Based on this, and the literature confirming the accuracy of the software, the modelled environment was considered suitably accurate for the experiment.

5.1.2 Setting up the model for outdoor noise

The model in *CadnaA* was constructed to determine the SPL at the façade receiver.

The road was modelled according to the parameters determined in Section 4.2. A classroom building was constructed with the façade receiver positioned 1.2 m in front of the receiving façade. The receiving façade is the outer envelope wall of the modelled classroom that is assumed to include window elements and thus would be the façade of concern regarding outdoor sound transmission. The classroom building was modelled at different distances and orientations relative to the noise source. Barriers of different positions, dimensions and shapes were inserted and the ground level of the school site was raised relative to the road level in certain scenarios.

The various scenarios were modelled by activating or deactivating objects in *CadnaA* via the Object Tree (where barrier conditions/heights were grouped, the parent group was made to “do nothing” while each child group was activated one by one).

The model was a simple model with one source (the road), which was activated for all scenarios, and one receiver point per scenario. The aim was to determine which conditions are suitable to meet the target indoor ambient sound level (40 dBA).

The following modelling assumptions and configuration settings were used in the *CadnaA* model:

- The surrounding area is free of obstructions, such as neighbouring buildings, which would cause reflections and influence the resulting SPL.
- A road front extending infinitely either side of the receiver point was constructed using the parameters established in Section 4.2. This road was assumed to be the only source of noise and side roads were excluded from the model.
- The road was modelled strictly according to RLS-90 with the additional option included to calculate one reflection order.
- The classroom building was 32 m long (representing four adjacent classrooms of 8 m long), 7 m wide and 3 m high for a single-storey and 6 m high for a double-storey (includes slab thickness).
- The building inserted was assumed to have a reflection of 0.5. This was established through the validation modelling of School B (0.5 returned the closest SPL to the actual when compared to applying a building absorption of 0.25 or 0.75).
- The single-storey receiver is 1.2 m away from the façade at a height of 1.5 m. This corresponds to the assumed mid-height of the ground-floor windows.
- The double-storey receiver is 1.2 m away from the façade at a height of 4.5 m. This corresponds to the assumed mid-height of the first-floor windows.
- The ground is assumed to be reflective, representing the worst-case scenario (ground absorption set to zero).
- The road level, ground level outside the building and indoor finished floor level were assumed to be equal.
- The effect of meteorology was excluded.
- One order of reflection was assumed (the road calculation cannot accommodate more than this).
- The country configuration setting was set to “international” (this refers to the standards used for calculations).
- General settings were set to defaults.
- The barriers inserted were assumed to have no reflection.

Four basic building positions were constructed at different distances from the noise source. These basic building positions were identified as Position A, B, C and D, with Position A being closest to the road and Position D being the furthest.

The distance from the centre of the road to the buildings was determined by the following logic. A four-lane road (two lanes of traffic in either direction) with a width of 14 m from curb to curb was assumed, based on the precedent of on-site observations. A road reserve of at least 5 m and a minimum building line of 5 m were assumed, which is a reasonable representation of the typical conditions in Gauteng urban areas. Thus, the closest to the centre of the road that a building could be constructed was 17 m (5 m building line + 5 m road reserve + 7 m to centre of road) as illustrated in Figure 5-1. This was the building position for Position A (measured from the receiving façade).

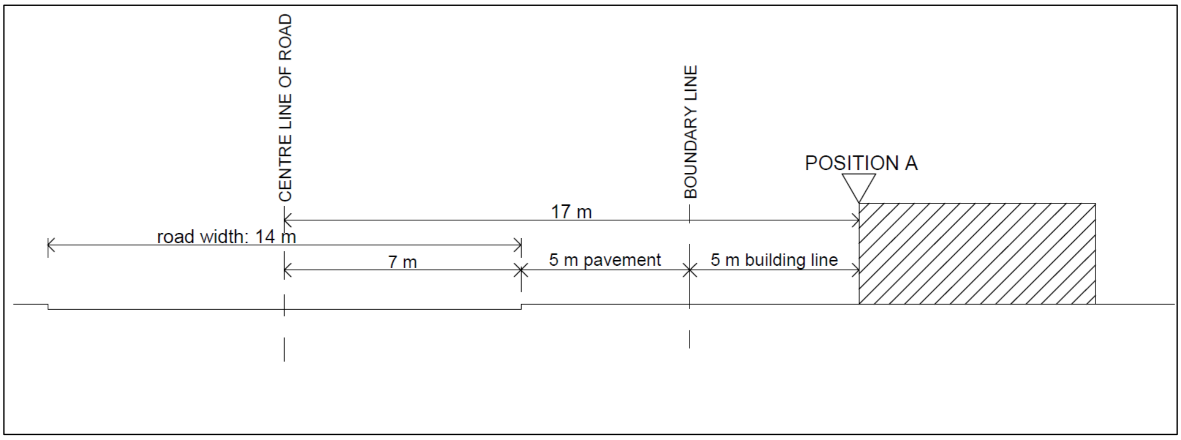


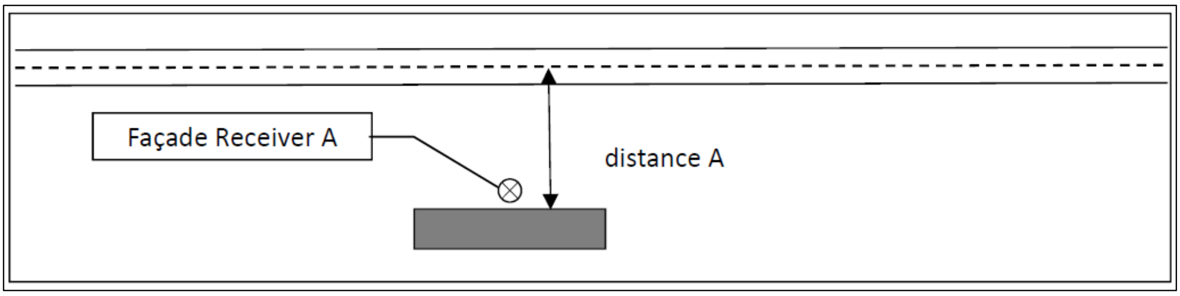
Figure 5-1: Basic set up of virtual experimental site, showing distance from noise source (centre of road) to building Position A

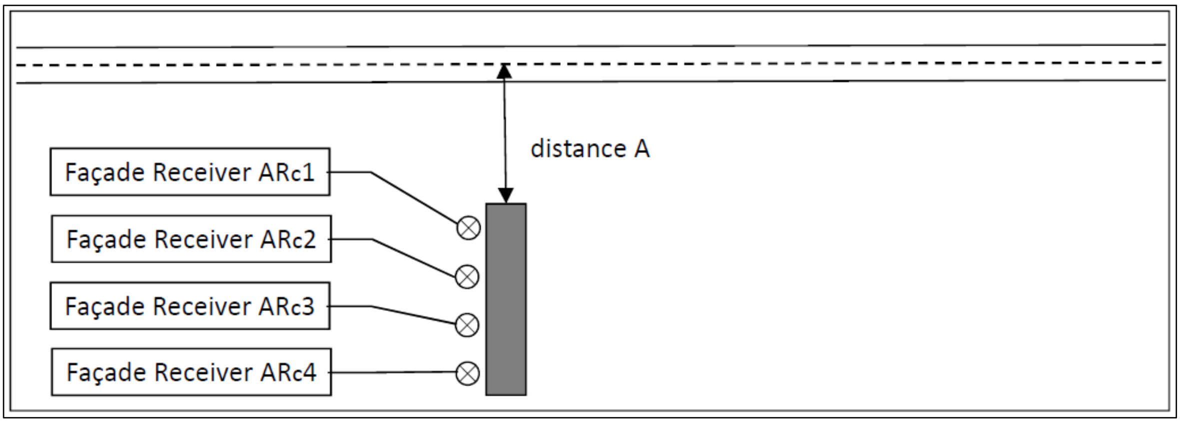
Position B was double the distance (34 m) since a doubling of distance should theoretically (for a line source in a free field) reduce the sound pressure level by 3 dB, which is a perceivable difference. Position C was double this distance again (68 m) and Position D double that again (136 m).

Incremental distances of half the distance of Position A (8.5 m) were used in between each major building position to enable a higher resolution of results. These incremental distances are labelled using numbers indicating the number of increments away from the previous position (e.g. Position B1 is 8.5 m further than Position B: 34 + 8.5 = 42.5 m). Thus, fifteen building and receiver positions were created.

The building at each position was tested in two different orientations. First, the building was orientated parallel to the road, as in Figure 5-2, with the receiver was located 1.2 m in front of the receiving façade at each of the 15 positions. Then the building was turned 90° so that the receiving façade was perpendicular to the road, as shown in Figure 5-3. In this scenario, only the four major building positions (A, B, C and D) were used since the building in this orientation overlapped the interim positions. In the perpendicular orientation, receivers were positioned at the window façade of each of the four classrooms to enable the evaluation of SPL at each as the classroom position recedes from the road. The receiver positions were labelled using the Position ID (A, B, C, D) with the suffix Rc and the number of the receiver. Thus, the four receivers along the façade of the building in Position A were numbered ARc1, ARc2, ARc3, etc. This created sixteen receiver positions. Altogether there were 31 receivers.

Figure 5-2: Illustration of source and receiver with building orientation





parallel to the road

Figure 5-3: Source and receiver positions with building in perpendicular orientation

Table 5-2 below lists the position references (Position ID) and corresponding distances between the centre line of the road and the building façade and receiver at each building position.

Table 5-2: Naming of positions of buildings and receivers relative to the centre line of the road

	Position ID	Distance from centre of road to road-facing façade (m)	Distance from centre of road to façade receiver (m)
Building parallel to the road	**A**	**17**	15.8
	A1	25.5	24.3
	B	**34**	32.8
	B1	42.5	41.3
	B2	51	49.8
	B3	59.5	58.3
	C	**68**	66.8
	C1	76.5	75.3
	C2	85	83.8
	C3	93.5	92.3
	C4	102	100.8
	C5	110.5	109.3
	C6	119	117.8
	C7	127.5	126.3
	D	**136**	134.8
Building perpendicular to the road	**A**	**17**	
	ARc1		21
	ARc2		29
	ARc3		37
	ARc4		45
	B	**34**	
	BRc1		38
	BRc2		46
	BRc3		54
	BRc4		62
	C	**68**	
	CRc1		72
	CRc2		80
	CRc3		88
	CRc4		96
	D	**136**	
	DRc1		140
	DRc2		148
	DRc3		156
	DRc4		164

At each position, a single-storey building and a double-storey building was modelled. Thus, 15 single-storey parallel building receivers, 15 double-storey parallel building receivers, 16 single-storey perpendicular building receivers and 16 double-storey perpendicular building receivers were created, making 62 receivers altogether.

5.1.3 Setting up the model for indoor noise

In *Bastian*, a typical classroom was modelled as determined in Section 4.1 and the resulting SPL at the classroom receiver was determined by the software. The model was set to represent transmission through an external separating element, using the façade receiver levels established in the *CadnaA* model as an external noise source for each scenario.

Three different scenarios were modelled. In two scenarios the façade composition was as established in Section 4.1 with the open area equal to 11% of the floor area. In these two scenarios, the model was exactly the same except for the construction material of the separating element (exterior façade). In one scenario the separating element was a heavy monolithic construction with glazed and open window sections of areas previously determined. In the other scenario the separating element was constructed from a light-weight panel with the same glazed and open window areas. This enabled the comparison of the effect of the two different wall constructions.

The third scenario assumed a monolithic masonry wall with glazed and open areas as per the minimum deemed-to-satisfy requirements of the National Building Regulations (NBR). The NBR requires that the window area in a room be equal to at least 10% of the floor area and the open area be equal to at least 5% of the floor area. Assuming the classroom is cross-ventilated with equal window areas on two opposite walls, these areas were halved to calculate the window and open areas on the receiving façade. Thus the total window area (glazed and open sections) was equal to 5% of the floor area (2.8 m^2) and the open area was equal to 2.5% of the floor area (1.4 m^2).

The model was set up in *Bastian* using the following configurations and assumptions:

- The model was set to evaluate sound transmission through an exterior wall.
- The room dimensions were 8 m long, 7 m wide and 2.7 m high.
- A reference reverberation time of 0.5 seconds was used.
- A detailed calculation model in 1/3 octave bands was used with structural reverberation time according to EN 12354-1.
- An exterior source was imported from *CadnaA*.
- Standard available materials were used for heavy masonry elements.
- New construction materials were created for the light-weight wall construction, single-pane 4 mm float glass and open window sections, using data available from manufacturers. For the open section, an assumed R-value of 0 dB was assigned to all octave bands.
- The performance parameter for outdoor sound transmission was specified as the weighted standardised level difference ($D_{2m,n,Tw}$) with spectrum adaptation for traffic noise (C_{tr}).

In this study, the weighted standardised level difference ($D_{2m,nT,w}$) was used to describe the sound reduction across the façade, with the spectrum adaptation term C_{tr} for traffic. In spite of a concern as to the accuracy of the various descriptors for sound transmission in practice (Scamoni & Scrosati, 2014), the descriptors currently accepted and used in local and international standards were used. These terms were used in the software, *Bastian*, and are in accordance with standards (International Organization for Standardization, 1998; Sobreira-Seoane, Rodriguez-Molares, Martin-Herrero & Rodriguez-Fernandez, 2010) and have been used by others (Urbán *et al.*, 2016) in the calculation of sound transmission through a façade.

Because reverberation time has an effect on the ambient noise level in the receiving room, it is necessary to account for this. The standardised level difference ($D_{2m,nT}$) takes reverberation time into account as opposed to the level difference (D_{2m}), which is the difference, in decibels, between the outdoor sound pressure level 2 m in front of the façade ($L_{1.2m}$) and the space- and time-averaged sound pressure level (L_2) in the receiving room. This is accounted for in ISO/SANS 140-5 by assuming a reverberation time of 0.5 seconds.

5.2 The effect of building design on sound transmission

In this section, the effect of aspects of the building on the classroom sound pressure level is reported. This includes the façade design, building distance from the source, building orientation and floor level.

A series of simulations was run to determine the sound pressure level (SPL) at the receiver for each of the parallel and perpendicular scenarios. The resulting SPL at each façade receiver for each scenario was applied as an external noise source in *Bastian* to determine the corresponding indoor SPL.

The indoor SPL was determined for each scenario under two façade conditions (masonry or light-weight). The results are recorded in Table 5-3, showing the building Position ID, the distance from the centre of the road to the façade, and the corresponding sound level results.

Table 5-3: SPL at single- and double-storey façade receivers and indoor receivers for masonry and light-weight construction with reflective ground surface

Building position ID		Distance from centre of road to road-facing façade	Distance from centre of road to receiver (receiver 1.2 m away from façade)	single-storey			Double-storey			Difference in SPL at single- and double-storey façade receiver	Transmission loss across façade for single-storey (for either construction)	Transmission loss across façade for double-storey (for either construction)
				SPL at façade receiver (1.5 m)	Classroom receiver (indoor):		SPL at façade receiver (4.5 m)	Classroom receiver (indoor):				
					masonry	light-weight		masonry	light-weight			
		m	m	dBA	dBA	dBA	dBA	dBA	dBA	dB	dB	dB
Building parallel to the road	**A**	**17**	**15.8**	**68.1**	**58.4**	**58.4**	**68.9**	**59.2**	**59.2**	**0.8**	**9.7**	**9.7**
	A1	25.5	24.3	64.4	54.6	54.7	66.2	56.5	56.5	1.8	9.8	9.7
	B	**34**	**32.8**	**62.1**	**52.4**	**52.4**	**64.0**	**54.3**	**54.3**	**1.9**	**9.7**	**9.7**
	B1	42.5	41.3	60.7	50.9	50.9	62.1	52.4	52.4	1.4	9.8	9.7
	B2	51	49.8	59.4	49.7	49.7	60.7	51.0	51.0	1.3	9.7	9.7
	B3	59.5	58.3	58.4	48.6	48.6	59.6	49.9	49.9	1.2	9.8	9.7
	C	**68**	**66.8**	**57.5**	**47.8**	**47.8**	**58.8**	**49**	**49.1**	**1.3**	**9.7**	**9.8**
	C1	76.5	75.3	56.8	47.1	47.1	58.0	48.3	48.3	1.2	9.7	9.7
	C2	85	83.8	56.0	46.2	46.2	57.3	47.6	47.6	1.3	9.8	9.7
	C3	93.5	92.3	54.9	45.2	45.2	56.7	47	47	1.8	9.7	9.7
	C4	102	100.8	54.4	44.6	44.6	56.2	46.4	46.4	1.8	9.8	9.8
	C5	110.5	109.3	53.6	43.9	43.9	55.6	45.9	45.9	2.0	9.7	9.7
	C6	119	117.8	53.1	43.4	43.4	55.2	45.5	45.5	2.1	9.7	9.7
	C7	127.5	126.3	52.7	43.0	43.0	54.7	45.0	45.0	2.0	9.7	9.7
	D	**136**	**134.8**	**52.3**	**42.6**	**42.6**	**54.3**	**44.6**	**44.6**	**2.0**	**9.7**	**9.7**
Building perpendicular to the road	**A**	**17**										
	ARc1		21	63.7	53.9	53.9	64.9	55.2	55.2	1.2	9.8	9.7
	ARc2		29	60.6	50.8	50.8	62.5	52.7	52.7	1.9	9.8	9.8
	ARc3		37	58.8	49.1	49.1	60.4	50.7	50.7	1.6	9.7	9.7
	ARc4		45	57.5	47.7	47.7	58.8	49.1	49.1	1.3	9.8	9.7
	B	**34**										
	BRc1		38	58.8	49.1	49.1	60.4	50.7	50.7	1.6	9.7	9.7
	BRc2		46	57.4	47.7	47.7	58.7	49.0	49.0	1.3	9.7	9.7
	BRc3		54	56.2	46.5	46.5	57.5	47.8	47.8	1.3	9.7	9.7
	BRc4		62	55.4	45.6	45.6	56.6	46.8	46.8	1.2	9.8	9.8
	C	**68**										
	CRc1		72	54.6	44.9	44.9	55.8	46.1	46.1	1.2	9.7	9.7
	CRc2		80	53.8	44.0	44.0	55	45.2	45.2	1.2	9.8	9.8
	CRc3		88	53.1	43.4	43.4	54.4	44.6	44.6	1.3	9.8	9.8
	CRc4		96	52.4	42.6	42.6	53.8	44.0	44.0	1.4	9.8	9.8
	D	**136**										
	DRc1		140	50.2	40.4	40.4	52.5	42.7	42.7	2.3	9.8	9.8
	DRc2		148	49.4	39.7	39.7	52.1	42.4	42.4	2.7	9.7	9.7
	DRc3		156	49	39.3	39.3	51.8	42.0	42.0	2.8	9.8	9.8
	DRc4		164	48.7	38.9	38.9	51.4	41.7	41.7	2.7	9.7	9.7

Note: values meeting target (40 dBA) are underlined

5.2.1 Façade design

5.2.1.1 Typical façade design

The indoor SPL for a classroom that has a masonry façade and one with a light-weight façade is shown in the table corresponding to each outdoor façade receiver. It is noted that the target indoor SPL of 40 dBA was only achieved at Position D for a building perpendicular to the road (the ideal level of 35 dBA was not achieved in any of the scenarios).

There is no difference in the indoor SPL measured in the classrooms whether the façade construction was masonry or light-weight. To test whether this phenomenon is related to the façade material or the glazed and open sections, a short series of simulations were run in which there were no glazed or open sections. The results for the masonry and light-weight constructions differed, demonstrating that the façade construction material does have an effect on the indoor SPL if there are no windows.

Thus, it could be concluded that the presence of the glazed and open sections in the façade, as per the specific façade design for this study, influences the sound transmission to such an extent that the façade material becomes negligible. In other words, for the naturally ventilated classroom considered in this study, in which the open window area on the receiving façade is 11% of the floor area, the wall construction material is acoustically irrelevant. The wall construction was treated as a controlled variable (set as a masonry wall) for further experiments.

The sound transmission loss across the façade is given for each scenario in Table 5-3. This was calculated by subtracting the façade receiver SPL from the classroom receiver SPL. The sound transmission loss due to the façade in all cases is 9.7 dB or 9.8 dB. This demonstrates that neither distance nor height nor orientation affects the façade transmission.

If the façade transmission is accepted to be 10 dB (rounding up from 9.8 dB) in all cases, and the indoor target SPL is 40 dBA, then the target façade receiver level should be 50 dBA. Thus, the target was changed to 50 dBA at the façade receiver to eliminate the need to import *CadnaA* data into *Bastian* for every scenario.

5.2.1.2 Deemed-to-satisfy façade design

The façade design was changed to reflect the deemed-to-satisfy ventilation requirements of the National Building Regulations, with glazed and open window areas each equal to 2.5% of the floor area. Thus, for the pre-determined floor area of 56 m^2, the fixed pane window area on the receiving façade was 1.4 m^2 and the open window area was 1.4 m^2 within a masonry wall. This was only modelled for the major building positions (A, B, C and D) and one interim position (A1). The resulting indoor receiver levels are shown in Table 5-4.

Table 5-4: SPL inside classroom with deemed-to-satisfy window sizes

Building Position ID (parallel to road)	Distance from centre of road to receiving façade (m)	SPL at façade receiver (dBA)	SPL at classroom receiver (dBA)	Sound transmission loss (dB)
A	**17**	**68.1**	52.0	16.1
A1	25.5	64.4	48.2	16.2
B	**34**	**62.1**	46.0	16.1
C	**68**	**57.5**	41.4	16.1
D	**136**	**52.3**	<u>36.2</u>	16.1

Note: values meeting target (40 dBA) are underlined

The sound transmission loss calculated in each scenario represented is 16.1 – 16.2 dB. With the smaller windows and window openings, the target indoor ambient SPL of 40 dBA inside the classroom was only achieved at Position D.

With the insertion of a barrier at the site boundary (barrier arrangement 1 as discussed in section 5.3.4) the target classroom level could be achieved at building positions closer to the road. Table 5-5 shows the barrier height at which the target classroom SPL is achieved for each major building position. The 40 dBA target was achieved in classrooms with the minimum window sizes at Position A1 and in those further from the road, while the ideal target of 35 dBA was at a further distance from the road and with higher barriers.

Table 5-5: Summary of scenarios in which the classroom target SPL was achieved for a single-storey classroom with deemed-to-satisfy window design with barrier arrangement 1

Position ID	Distance from centre of road to facade (m)	Minimum barrier height at which 40 dBA achieved(m)	Minimum barrier height at which 35 dBA achieved(m)
A	**17**	Not achieved	Not achieved
A1	**25.5**	3.5	Not achieved
B	**34**	2.5	6.5
C	**68**	1.5	3
D	136	0	2

However, it must be noted that the deemed-to-satisfy window design is not likely to provide suitable ventilation for a fully occupied classroom. The deemed-to-satisfy façade design is not considered in further experimentation.

5.2.2 Distance

Considering the SPL at the façade receiver recorded in Table 5-3, it is evident that, as the receiver position recedes from the noise source, the measured SPL decreases. This is clearly illustrated by the shading in the table, where the darker colour indicates a higher SPL. The lowest receiving façade SPL recorded (48.7 dBA) was at the single-storey receiver Position DRc4, 164 m from the road, which meets the façade target of 50 dBA (40 dBA + 10 dB for the R-value of the façade). The highest façade SPL (68.9 dBA) was recorded at double-storey Position A, 15.8 m from the road.

This is expected due to geometric divergence and indicates the magnitude of sound attenuation due to distance only. While the theoretical expectation is a reduction of 3 dB per doubling of distance for a line source (Lawrence, 1970, p. 62), in reality interaction with surfaces influences the attenuation effect of distance. The reduction from Position A to B is 6 dB, the reduction from Position B to C is 4.6 dB and the reduction from Position C to D is 5.2 dB.

Based on this model, **an attenuation of approximately 5.3 dB per doubling of distance can be expected** (for receivers between 17 m and 136 m from the source).

5.2.3 Orientation

Considering the perpendicular buildings, the results show that the difference between Receiver 1 (Rc1, at the classroom closest to the road) and Receiver 4 (Rc4, at the classroom furthest from the road) decreases as the building recedes from the noise source.

Table 5-6 shows the difference in SPL from one classroom to the next is in all cases less than 3 dB, except between ARc1 and ARc2. Because an SPL difference of less than 3 dB is barely noticeable, **it might be concluded that these differences are insignificant and that the position of the classroom along the building doesn't matter**. This conclusion, however, is limited to comparing immediately adjacent classrooms. When comparing classroom 1 at Position A to classroom 4 at Position A, there is a difference of 6.2 dB, which would be noticeable. This deviation between classroom 1 and classroom 4 decreases as the building position recedes from the source and becomes negligible at Position C and Position D. It was decided that further experimental scenarios would not consider the results of Receivers Rc2, Rc3 and Rc4 and would deem Rc1 as a worst-case scenario, arguing that if the target can be achieved for classroom 1, it follows that it will be achieved at the other classrooms.

Table 5-6: SPL at receivers along the length of buildings perpendicular to the road and deviation

Building and Receiver position (m from source)	SPL at Single-storey façade receiver (dBA)	SPL at Double-storey façade receiver (dBA)
A		
ARc1 (21 m)	63.7	64.9
ARc2 (29 m)	60.6 (-3.1)	62.5 (-2.4)
ARc3 (37 m)	58.8 (-1.8)	60.4 (-2.1)
ARc4 (45 m)	57.5 (-1.3)	58.8 (-1.6)
Maximum deviation (Rc1-Rc4)	*6.2*	*6.1*
Average deviation	*2.0*	*2.1*
B		
BRc1 (38 m)	58.8	60.4
BRc2 (46 m)	57.4 (-1.4)	58.7 (-1.7)
BRc3 (54 m)	56.2 (-1.2)	57.5 (-1.2)
BRc4 (62 m)	55.4 (-0.8)	56.6 (-0.9)
Maximum deviation (Rc1-Rc4)	*3.4*	*3.8*
Average deviation	*1.2*	*1.3*
C		
CRc1 (72 m)	54.6	55.8
CRc2 (80 m)	53.8 (-0.8)	55 (-0.8)
CRc3 (88 m)	53.1 (-0.7)	54.4 (-0.6)
CRc4 (96 m)	52.4 (-0.7)	53.8 (-0.6)
Maximum deviation (Rc1-Rc4)	*2.2*	*2.0*
Average deviation	*0.7*	*0.7*
D		
DRc1 (140 m)	50.2	52.5
DRc2 (148 m)	49.4 (-0.8)	52.1 (-0.4)
DRc3 (156 m)	49.0 (-0.4)	51.8 (-0.3)
DRc4 (136 m)	48.7 (-0.3)	51.4 (-0.4)
Maximum deviation (Rc1-Rc4)	*1.5*	*1.1*
Average deviation	*0.5*	*0.4*

A comparison of the façade receiver SPL for parallel and perpendicular buildings recorded in Table 5-3 shows that the SPL at receivers adjacent to perpendicular buildings is generally lower than that of receivers adjacent to parallel buildings of the same distance from the noise source. This seems to demonstrate that the receiving facade orientation influences the SPL measured at the façade receivers.

However, the comparison is not direct because the building positions were determined based on the distance from the road-facing façade to the noise source, whereas the façade receivers are 1.2 m away from the relevant façade and centred along the length of the classroom. This means that while the road-facing façade of the parallel and perpendicular buildings are the same distance from the source, the receiver for the parallel building is 1.2 m closer to the source and for a perpendicular building, the receiver is set 4 m further away from the source (centred on the side of the 8 m long classroom). This is illustrated in Figure 5-2 and Figure 5-3.

The results at this stage show that for a building that is a certain distance away from a noise source, it is better to orientate the receiving façade of the classrooms perpendicular to the road. However, whether this effect is due to distance or orientation needs to be established.

Thus, a separate scenario was set up to determine the effect of building orientation with a fixed receiver point. The position of the perpendicular buildings and receivers was maintained as in the previous experiment, while the position of the parallel building was adjusted relative to the façade receiver of the first classroom (ARc1, BRc1, etc.), as shown in Figure 5-4. The results are tabulated in Table 5-7.

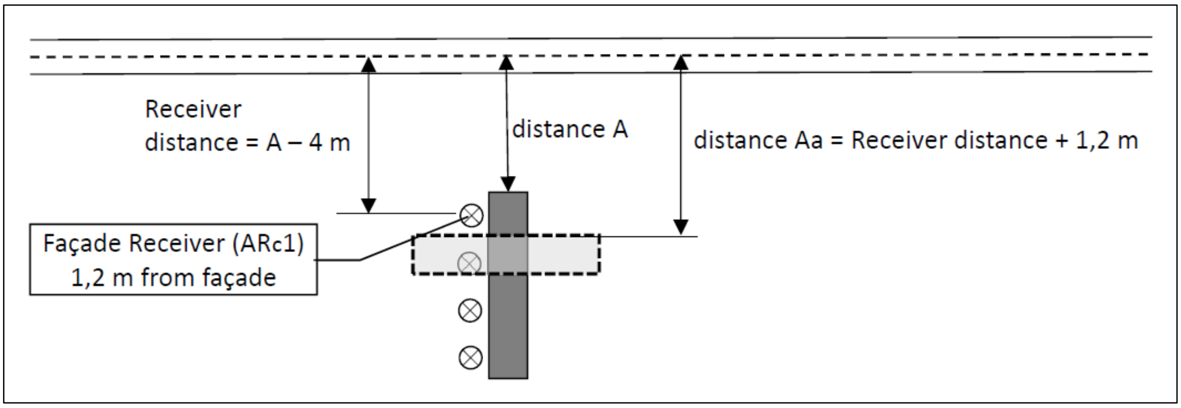


Figure 5-4: Position of perpendicular and parallel buildings relative to receiver at fixed distance from noise source (road)

Table 5-7: SPL at fixed façade receiver position when adjacent to a building parallel or perpendicular to the road

Receiver ID	Distance from centre of road to receiver (m)	SPL at single-storey receiver (dBA)		SPL at double-storey receiver (dBA)	
		perpendicular to road	parallel to road	perpendicular to road	parallel to road
ARc1	21	63.7	65.9	64.9	67.3
BRc1	38	58.8	62.1	60.4	62.8
CRc1	72	54.6	57.1	55.8	58.3
DRc1	140	50.2	52.2	52.5	54.1

The results are recorded in Table 5-7, showing that the SPL at a receiver 1.2 m from a façade that is perpendicular to the road is lower by an average of 2.5 dB than when the same receiver is 1.2 m from a façade parallel to the road. This was found at both the single-storey and double-storey heights. It is likely that this is due to the sound shadow created by the perpendicular building, shielding the receiver from a portion of the noise. This difference is illustrated by the sound contours shown in Figure 5-5.

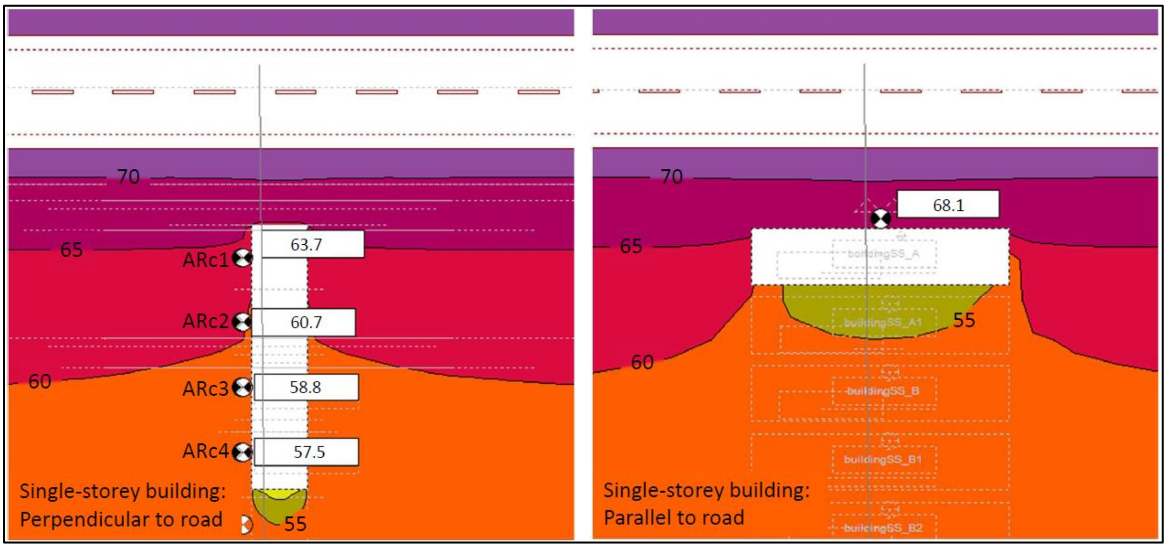


Figure 5-5: Comparison of SPL at receiver and sound contours for buildings parallel or perpendicular to road

It can be concluded from this that for a similar classroom position (in terms of the distance of its closest facade from the road) **it would be preferable to orientate the building so that the windows are on the façade perpendicular to the road**.

5.2.4 Receiver height

The difference in the SPL at the single- and double-storey façade receivers is also tabulated in Table 5-3. It is noted that there is minimal difference in the SPL measured at single- and double-storey height – on average 1.6 dB and at most 2.8 dB (at DRc3), which would be barely noticeable. This can be easily seen in the graph in Figure 5-6, which depicts the modelled façade receiver levels for a building parallel to the road and includes the theoretical receiver level under the inverse square law and the inverse law for purposes of comparison. The difference in SPL between the single- and double-storey receivers is the least at position A and increases as the distance from the source increases.

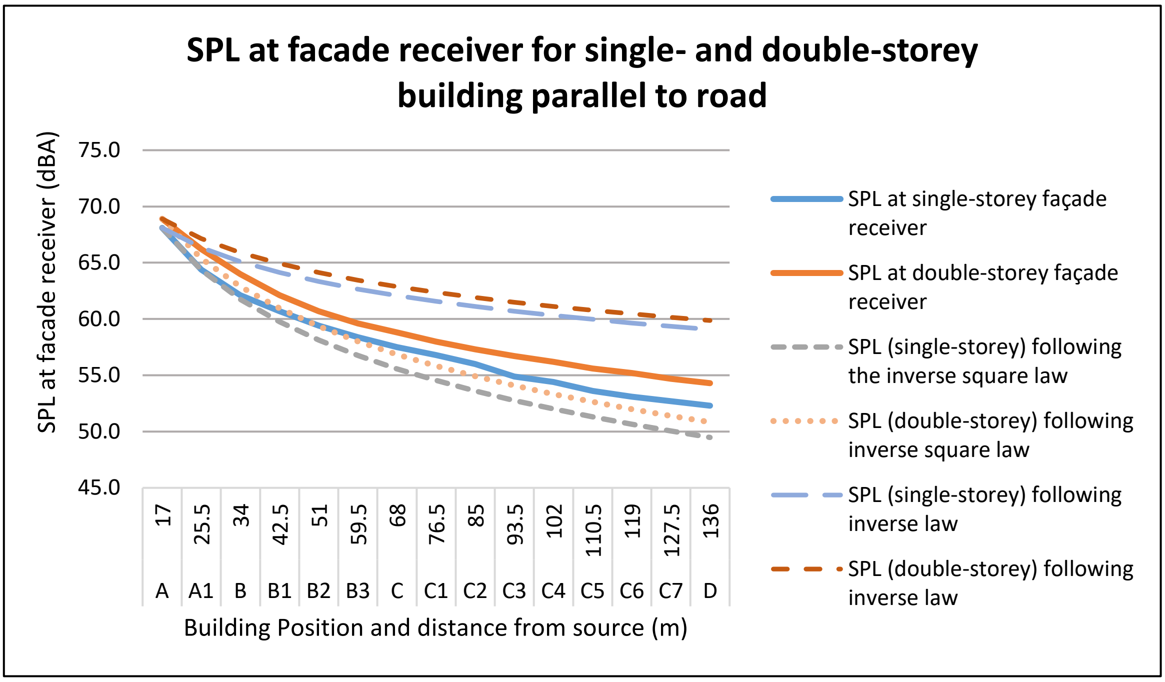


Figure 5-6: Line graph comparing SPL at single- and double-storey facade receivers at different building positions parallel to the noise source (road).

It is noted that **the façade receivers at the double-storey height generally measure a higher SPL than those at the single-storey height of the same position**, demonstrating that sound is attenuated more at ground level. This phenomenon is illustrated by the sound contours in the vertical cross-section in Figure 5-7, where the double-storey façade receiver is in a different colour zone (representing a higher SPL) than the single-storey façade receiver. It should be noted that in an actual situation with an absorbent ground surface, the difference at the single-storey and double-storey receivers will be smaller than that modelled here.

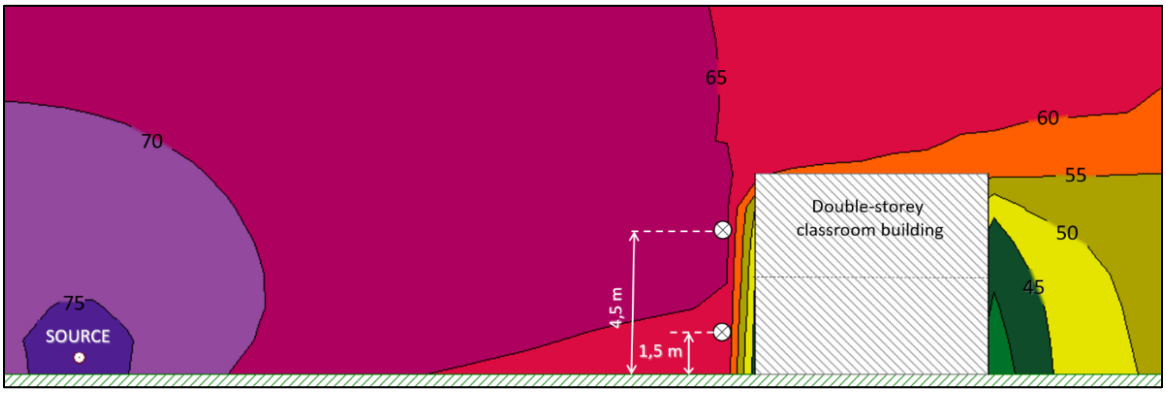


Figure 5-7: Cross-section of sound contours illustrating higher SPL at double-storey receiver compared to single-storey receiver at same horizontal distance from source.

To test whether the height of the building affects the SPL measured at the single-storey level, an additional series of simulations was performed. The SPL of a single-storey façade receiver adjacent to a double-storey building was compared to the SPL of the same receiver adjacent to a single-storey building. The results, tabulated in Table 5-8 and graphically illustrated in Figure 5-8, show that the SPL is higher by an average of 1.1 dB if the receiver is adjacent to a double-storey building. This could be due to reflections off the higher building, as illustrated by the vertical sound contours in Figure 5-9.

It is important to consider this effect when making decisions regarding the height of a classroom block.

Table 5-8: Comparison of SPL at facade receiver 1.5 m high in front of single- or double-storey building

Building position		Distance from centre of road to road-facing façade (m)	Distance from centre of road to façade receiver (m)	SPL at ground-floor façade receiver at single-storey (dBA)	SPL at ground-floor façade receiver at double-storey (dBA)	Difference (dB)
Building parallel to the road	**A**	**17**	**15.8**	**68.1**	**69.2**	**1.1**
	A1	25.5	24.3	64.4	65.5	1.1
	B	**34**	**32.8**	**62.1**	**63.4**	**1.3**
	B1	42.5	41.3	60.7	61.9	1.2
	B2	51	49.8	59.4	60.7	1.3
	B3	59.5	58.3	58.4	59.7	1.3
	C	**68**	**66.8**	**57.5**	**58.9**	**1.4**
	C1	76.5	75.3	56.8	58.2	1.4
	C2	85	83.8	56.0	57.4	1.4
	C3	93.5	92.3	54.9	56.5	1.6
	C4	102	100.8	54.4	55.9	1.5
	C5	110.5	109.3	53.6	55.3	1.7
	C6	119	117.8	53.1	54.8	1.7
	C7	127.5	126.3	52.7	54.4	1.7
	D	**136**	**134.8**	**52.3**	**54.0**	**1.7**
Building perpendicular	A	17				
	ARc1		21	63.7	64.5	0.8
	B	34				
	BRc1		38	58.8	59.7	0.9
	C	68				
	CRc1		72	54.6	55.6	1.0
	D	136				
	DRc1		140	50.2	51.1	0.9

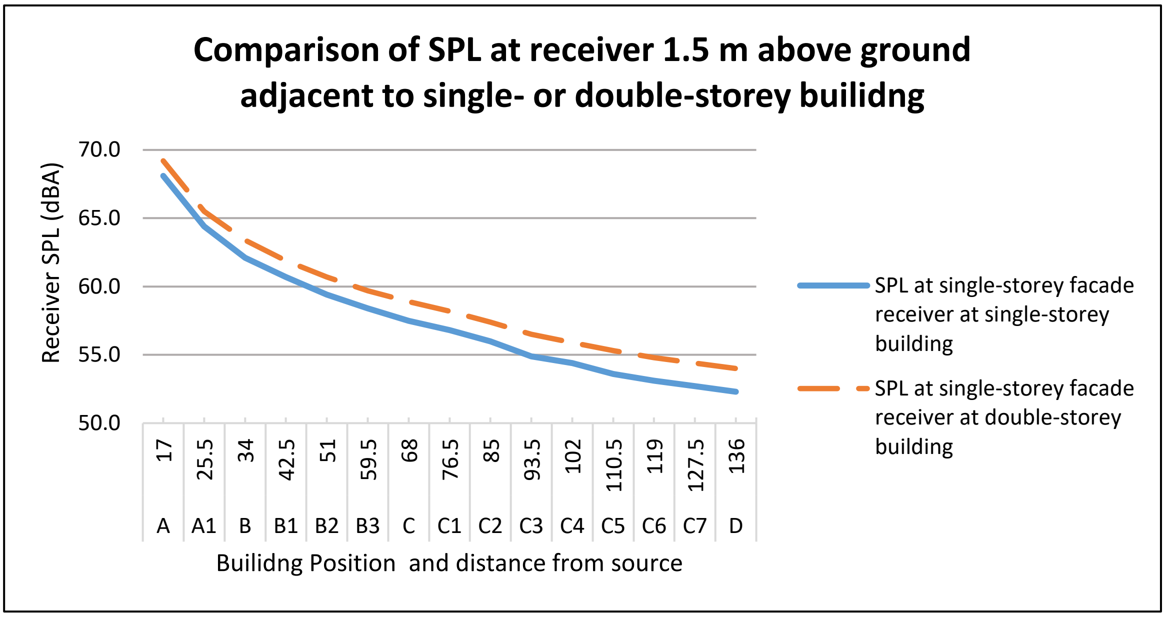


Figure 5-8: Comparison of SPL at equal height facade receivers when placed adjacent to single- or double-storey buildings

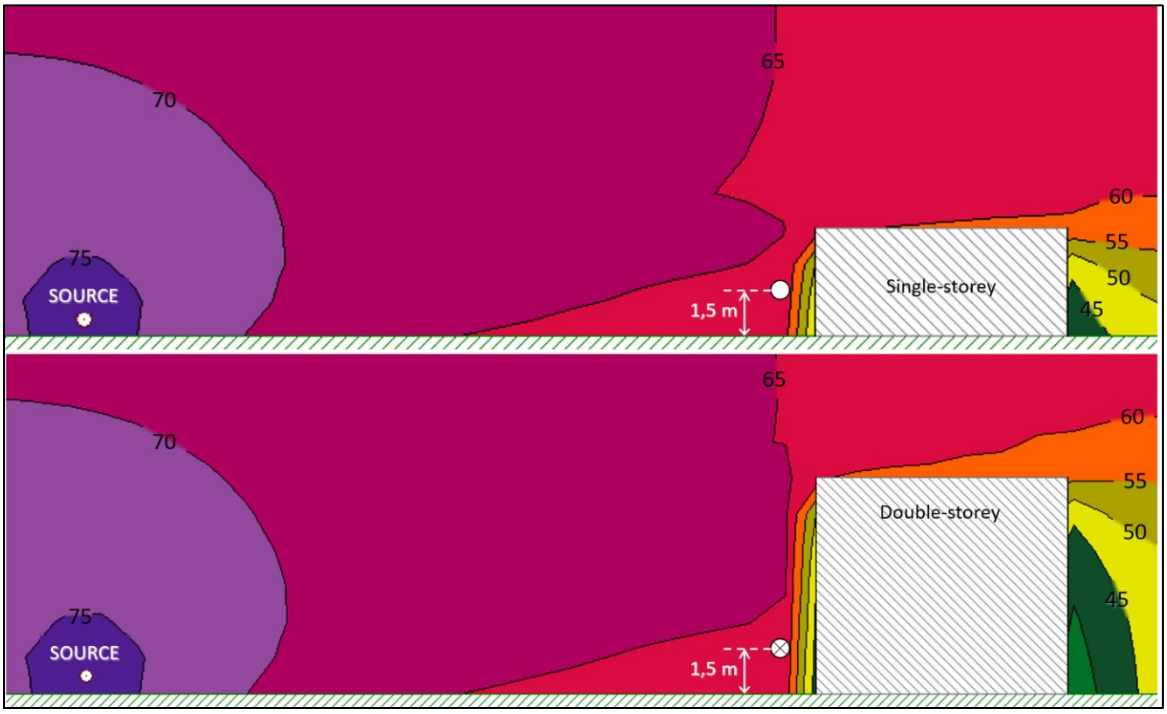


Figure 5-9: Comparison of sound contours in front of single- or double-storey facade for receiver of equal height

5.2.5 Sub-section conclusion: building design

This stage of the experiment sets the basic case for each building position. The results of this experiment show that the target classroom SPL of 40 dBA is only achieved at Position D perpendicular to the road for ground-floor classrooms (40.4 – 38.9 dBA for classrooms 1 – 4), at receiver positions that are 140 m to 164 m from the centre line of the noise source.

Furthermore, it was found that:

- for a façade with an open window area of 11% of the floor area and a fixed window area of 3% of the floor area, the type of wall construction is inconsequential to the sound transmission;
- decreasing the window area makes a significant (6 dB) difference to the sound transmission; however, even with this difference, the classroom target SPL was not achieved at buildings positioned close to the road and sufficient ventilation is unlikely to be achieved;
- the sound transmission through the façade is the same at all building positions, thus demonstrating that sound transmission through a separating element is not dependent on the distance from the noise source;
- the SPL at the façade receiver (and consequently inside the classroom) is dependent on the distance from the noise source, decreasing as the distance increases (on average 5.3 dB for every doubling of distance);
- the SPL in ground level classrooms is lower than the SPL in upper level classrooms for the same horizontal distance from the noise source and this difference increases with distance away from the sound source. Thus, it would be preferable to design classrooms on the ground floor to minimise noise.
- the SPL in ground level classrooms in a single-storey building is lower than the SPL in a ground level classroom in a double-storey building for the same horizontal distance from the noise source, and this difference increases with distance away from the sound source. Thus it would be preferable to design single-storey classrooms to minimise noise.

Additional interventions would be necessary to achieve the target SPL.

The additional intervention of a barrier or screen wall was introduced in the next experiment to determine the effect of a barrier.

5.3 The effect of barrier insertion

The effect of a barrier or screen wall for sound attenuation largely depends on the change in path length that the sound needs to travel between the source and the receiver. This is illustrated in Figure 5-10. The height of the barrier (H_b), relative to the height of the source (H_s) and the height of the receiver (H_r), influences the path length. The path length also depends on the distance between the source, the barrier and the receiver, as well as the length of the barrier. The material of the barrier is not as significant as the height of the barrier, provided that it is solid with sufficient surface density. Most of the sound will travel over or around the barrier. It is assumed that transmission of noise through a barrier is negligible and it is not considered in calculations (Datakustic, 2017, sec. 3.2.3).

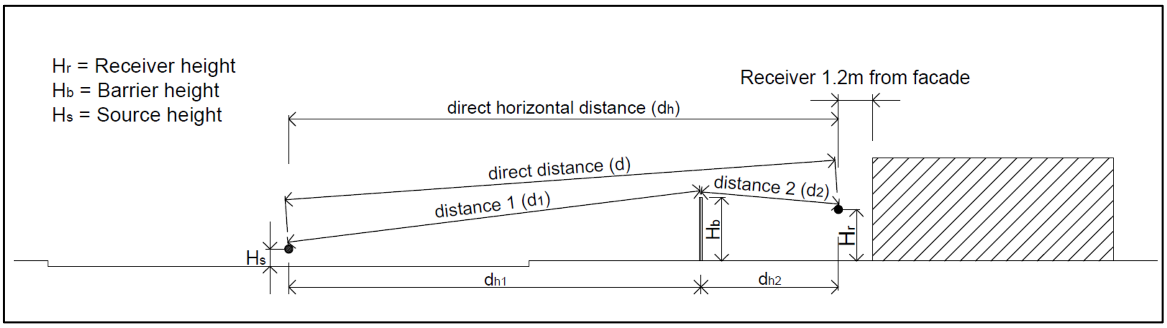


Figure 5-10: Cross-section diagram illustrating dimensional factors that influence the effect of a barrier

A series of scenarios was modelled to test which barrier position (relative to the source and receiver) and barrier dimensions provided more effective sound attenuation (the lowest SPL measured at the receiver), answering the questions:

- How high must a barrier be to provide a façade receiver level of 50 dBA or less for each building position?
- How long must the barrier be to be effective?
- Is it better to have a barrier close to the façade (receiver) or at the boundary (source)?

5.3.1 Setting up barrier heights

The lowest barrier height tested was 1.5 m high. This was determined according to the following logic:

The lowest barrier height that is theoretically likely to have an effect should be just over the direct line of sight between the source and the receiver. The source height for traffic noise is considered to be 0.5 m and the receiver level is considered to be mid-height of a window (1.5 m for a single-storey building). Assuming a completely flat site, the direct line of sight was used to determine the lowest barrier height for Position A. As illustrated in Figure 5-11, the barrier, if inserted at the boundary, should be greater than 1.2 m. If inserted at a distance of 3 m from the façade, the minimum barrier height should be greater than 1.35 m.

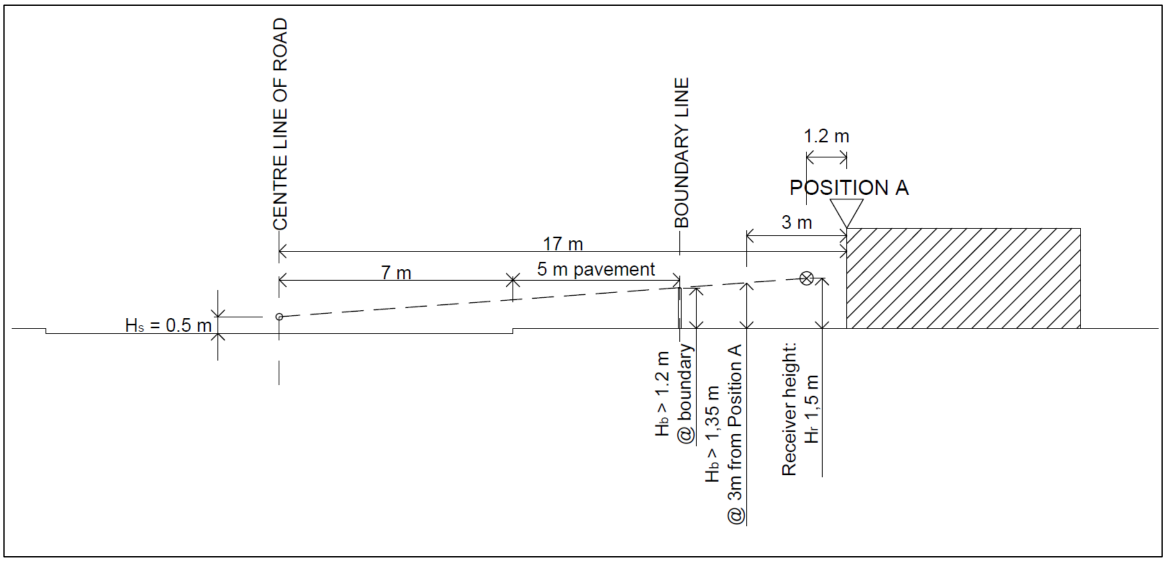


Figure 5-11: Minimum barrier height

As the building position recedes from the noise source, the angle of the line of sight will become smaller and thus the minimum barrier height would decrease. However, since a very low boundary wall is unlikely to be practical for its purpose (safety and privacy), it was not deemed suitable to set a barrier height lower than the minimum height determined for Position A. Rather, the minimum barrier height was set to be 1.5 m, slightly above the minimum determined for Position A, rounding up to the nearest half metre for practicality and simplicity.

The screen height was increased in 0.5 m increments up to a height of 1 m above the roof level for each storey. A single-storey building is assumed to be 3 m high and a double-storey building is assumed to be 6 m high. Thus the barrier heights tested range from 1.5 m high to 7 m high. It is noted that a barrier wall of more than 3.5 m high is likely to be considered excessively high for a school setting. However, for the sake of the exercise, this was allowed.

5.3.2 Setting the barrier positions

To determine whether the position of the barrier matters, the effect of the height and length of the barrier was tested under two basic arrangements. In the first arrangement (referred to as 'barrier arrangement 1'), the barrier was at a fixed position close to the noise source; in the second ('barrier arrangement 2'), the barrier was in a fixed position close to the receiver, as illustrated in Figure 5-12.

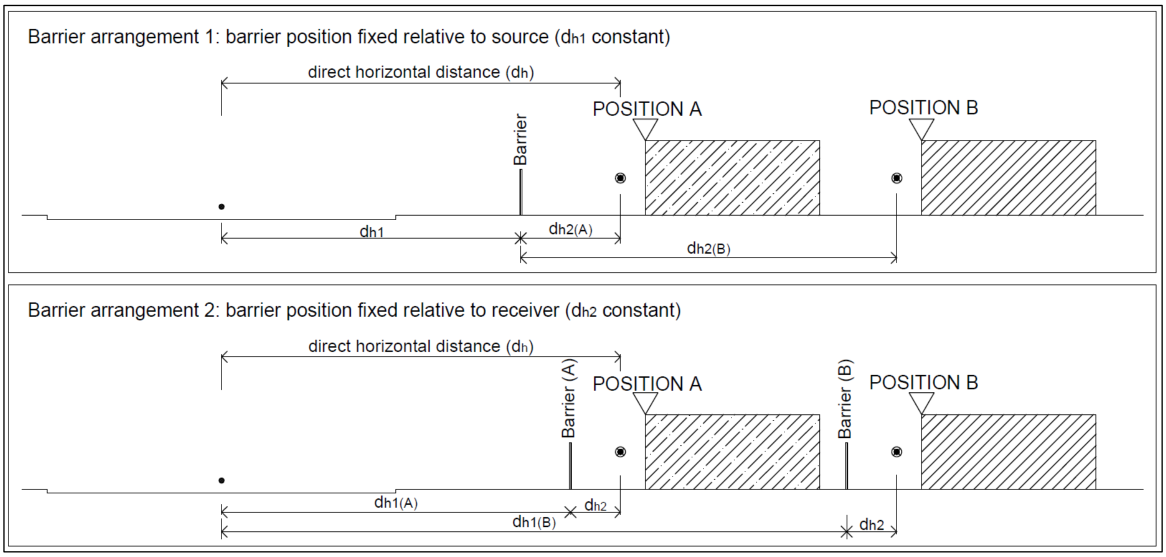


Figure 5-12: Illustration of barrier position relative to source and receiver.

For the first barrier arrangement, the barrier was positioned at the boundary of the site, assumed to be 12 m from the centre of the road. Thus, the distance d_{h1} (Figure 5-12) remained constant.

For the second barrier arrangement, the barrier was in a fixed position relative to the building. Thus, d_{h2} (Figure 5-12) remained constant. Two different distances for this arrangement were tested – one with the barrier 3 m from the façade, the other with the barrier 2 m from the façade.

The effect of barrier height for each arrangement was tested by inserting barriers of different heights and measuring the resultant SPL at the façade receivers.

5.3.3 Setting the barrier length

The effect of a barrier is related to the change in path length that the sound in travels. The path length is increased as the sound travels over and around a barrier. At a certain barrier length, the dominant pathway for sound is over the barrier, making the barrier height the significant factor to consider.

The effect of a barrier is described in terms of the insertion loss (IL), calculated as the difference between the SPL at the receiver with and without the barrier. When comparing barriers of differing lengths but the same height, a low difference in IL shows that most of the sound is travelling over the barrier, regardless of barrier length. This is expected at low barrier heights. As the barrier height increases, it can be expected that less sound will travel over the barrier and that sound travelling around the barrier will play a greater role.

The barrier length recommended in the *FHWA Highway noise barrier design handbook* was used as a reference. This provides a rule of thumb that a barrier should extend either side of the receiver for a distance of at least four times the distance between the receiver and the barrier, measured normal to the source, or that the barrier should extend up to the length determined by an angle of at least 80° to the normal, as illustrated in Figure 5-13 (Knauer *et al.*, 2000). Although it is noted that this is considered rather arbitrary by some (Transportation Research Board, 1981), a study by the New Hampshire Department of Transportation validates this 1:4 ratio rule of thumb (Ross, Arnoldy & Evans, 2018) while noting that at certain barrier heights, the length of the barrier contributes more to the insertion loss (IL) than the height.

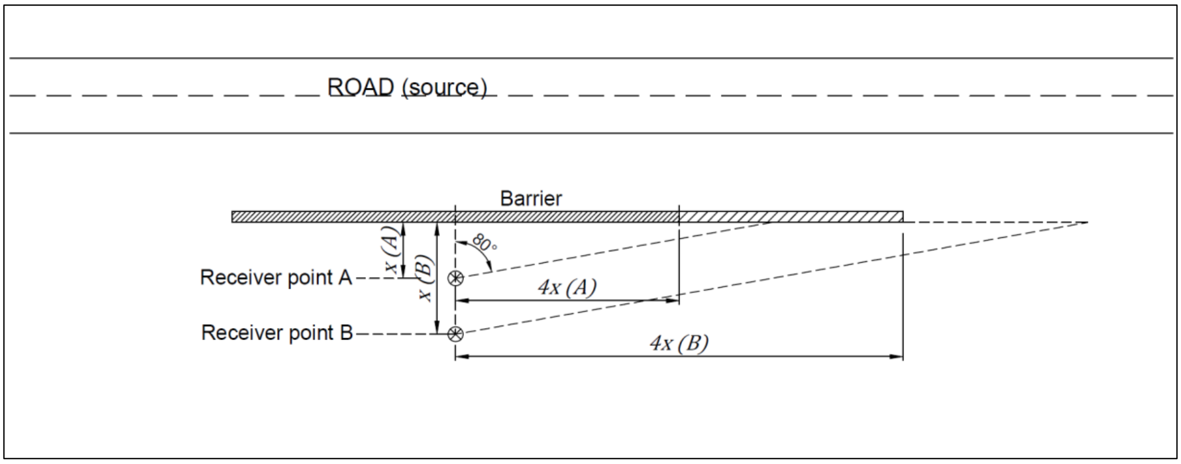


Figure 5-13: Illustration of barrier length calculation relative to receiver position

To confirm whether this rule of thumb using a 1:4 ratio is reasonable to apply in this study, it was tested by inserting barriers of different lengths and comparing the results.

The insertion loss achieved for different barrier heights and façade-receiver positions using the length calculated according to the 1:4 ratio rule was compared to the insertion loss achieved using the length calculated using ratios smaller and greater (1:3 and 1:5) and the extreme ratio 1:8 (doubling the rule of thumb). The comparison was performed for the main building positions (A, B, C and D).

The resulting insertion losses are tabulated in Table 5-9. The difference in insertion loss between barriers of differing length (rows in Table 5-9) but of the same heights (columns in Table 5-9) was less than 2 dB, indicating little noticeable effect from one barrier length to the next.

When comparing the effect of a 1:3 barrier length to a 1:4 barrier length for Position A, the difference in insertion loss ranges from 0.1 dB (for a 1.5 m high barrier) to 1.5 dB (for a 7 m high barrier). Comparing the 1:4 barrier to a 1:5 barrier, the difference ranges from 0.1 dB to 1.3 dB. Similar results are found for the other building positions. These differences are not significant (being less than 3 dB) and indicate that the proposed barrier length based on a 1:4 ratio is reasonable to assume.

When comparing a 1:4 ratio length to the extreme 1:8 ratio length, the range in difference in IL is from 0.2 dB (at 1.5 m) to 4 dB (at 7 m) for Position A. It is noted that the difference in IL for a 7 m high barrier is significant (being greater than 3 dB). The range in the difference in IL reduces at Positions B, C and D to less than 3 dB, demonstrating a reduction in the effect of barrier length as the distance between the source and the receiver increases.

These results are also graphically represented in Figure 5-14. Each line on the graphs represents a particular barrier height, thus illustrating the change in insertion loss (vertical axis) due to barrier length (horizontal axis).

The results show that, regardless of the barrier length, the IL for low barriers is relatively steady.

Table 5-9: Insertion loss recorded at Positions A, B, C and D for different barrier heights and lengths

Barrier height (m)		1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Position ID	**Length Ratio** (m)	**Insertion loss (dB)** *(difference in IL due to barrier length for barrier height compared to 1:4 ratio length)*											
A	**1:3** (22.8 m)	4.2 *(-0.1)*	6.2 *(-0.5)*	7.4 *(-0.8)*	8.1 *(-1.1)*	8.4 *(-1.3)*	8.6 *(-1.3)*	8.7 *(-1.4)*	8.8 *(-1.4)*	8.9 *(-1.4)*	8.9 *(-1.5)*	8.9 *(-1.5)*	9 *(-1.5)*
	1:4 (30.4 m)	**4.3**	**6.7**	**8.2**	**9.2**	**9.7**	**9.9**	**10.1**	**10.2**	**10.3**	**10.4**	**10.4**	**10.5**
	1:5 (38 m)	4.4 *(+0.1)*	6.9 *(+0.2)*	8.8 *(+0.6)*	9.9 *(+0.7)*	10.5 *(+0.8)*	11 *(+1.1)*	11.2 *(+1.1)*	11.4 *(+1.2)*	11.6 *(+1.3)*	11.7 *(+1.3)*	11.7 *(+1.3)*	11.8 *(+1.3)*
	1:8 (60.8 m)	4.5 *(+0.2)*	7.2 *(+0.5)*	9.4 *(+1.2)*	11 *(+1.8)*	12 *(+2.3)*	12.8 *(+2.9)*	13.3 *(+3.2)*	13.7 *(+3.5)*	14 *(+3.7)*	14.2 *(+3.8)*	14.4 *(+4)*	14.5 *(+4)*
B	**1:3** (124.8 m)	2.6 *(-0.1)*	4.4 *(-0.2)*	5.8 *(-0.4)*	6.8 *(-0.7)*	7.6 *(-0.8)*	8.1 *(-1.1)*	8.5 *(-1.2)*	8.7 *(-1.5)*	9 *(-1.5)*	9.1 *(-1.7)*	9.2 *(-1.8)*	9.3 *(-1.8)*
	1:4 (166.4 m)	**2.7**	**4.6**	**6.2**	**7.5**	**8.4**	**9.2**	**9.7**	**10.2**	**10.5**	**10.8**	**11**	**11.1**
	1:5 (208 m)	2.8 *(+0.1)*	4.7 *(+0.1)*	6.4 *(+0.2)*	7.7 *(+0.2)*	8.8 *(+0.4)*	9.7 *(+0.5)*	10.4 *(+0.7)*	10.9 *(+0.7)*	11.3 *(+0.8)*	11.7 *(+0.9)*	11.9 *(+0.9)*	12.2 *(+1.1)*
	1:8 (332.8 m)	2.7 *(+0)*	4.6 *(+0)*	6.4 *(+0.2)*	7.8 *(+0.3)*	9.1 *(+0.7)*	10.1 *(+0.9)*	11 *(+1.3)*	11.8 *(+1.6)*	12.5 *(+2)*	13 *(+2.2)*	13.5 *(+2.5)*	13.9 *(+2.8)*
C	**1:3** (328.8 m)	2 *(+0)*	3.7 *(+0)*	1.2 *(-0.4)*	2.2 *(-0.7)*	7.2 *(-0.4)*	7.9 *(-0.6)*	8.5 *(-0.7)*	8.6 *(-1.3)*	9.2 *(-1.2)*	9.5 *(-1.3)*	9.7 *(-1.4)*	9.9 *(-1.5)*
	1:4 (438.4 m)	**2**	**3.7**	**1.6**	**2.9**	**7.6**	**8.5**	**9.2**	**9.9**	**10.4**	**10.8**	**11.1**	**11.4**
	1:5 (548 m)	2 *(+0)*	3.6 *(-0.1)*	1.8 *(+0.2)*	3.1 *(+0.2)*	7.8 *(+0.2)*	8.7 *(+0.2)*	9.6 *(+0.4)*	10.3 *(+0.4)*	10.9 *(+0.5)*	11.5 *(+0.7)*	12 *(+0.9)*	12.4 *(+1)*
	1:8 (876.8 m)	2 *(+0)*	3.7 *(+0)*	1.8 *(+0.2)*	3.2 *(+0.3)*	7.8 *(+0.2)*	8.9 *(+0.4)*	9.9 *(+0.7)*	10.8 *(+0.9)*	11.4 *(+1)*	12.1 *(+1.3)*	12.7 *(+1.6)*	13.3 *(+1.9)*
D	**1:3** (736.8 m)	1.4 *(-0)*	2.7 *(-0)*	4.1 *(-0)*	5.4 *(-0.1)*	6.5 *(-0.2)*	7.4 *(-0.4)*	8.3 *(-0.5)*	9 *(-0.7)*	9.6 *(-0.5)*	10.1 *(-0.6)*	10.5 *(-0.8)*	10.9 *(-0.9)*
	1:4 (982.4 m)	**1.4**	**2.7**	**4.1**	**5.5**	**6.7**	**7.8**	**8.8**	**9.7**	**10.1**	**10.7**	**11.3**	**11.8**
	1:5 (1228 m)	1.4 *(+0)*	2.8 *(+0.1)*	4.2 *(+0.1)*	5.5 *(+0)*	6.7 *(+0)*	7.8 *(+0)*	8.7 *(+0.1)*	9.6 *(-0.1)*	10.3 *(+0.2)*	11 *(+0.3)*	11.6 *(+0.3)*	12.2 *(+0.4)*
	1:8 (1964.8 m)	1.4 *(+0)*	2.8 *(+0.1)*	4.2 *(+0.1)*	5.5 *(+0)*	6.7 *(+0)*	7.8 *(+0)*	8.7 *(-0.1)*	9.6 *(-0.1)*	10.3 *(+0.2)*	11 *(+0.3)*	11.6 *(+0.3)*	12.2 *(+0.4)*

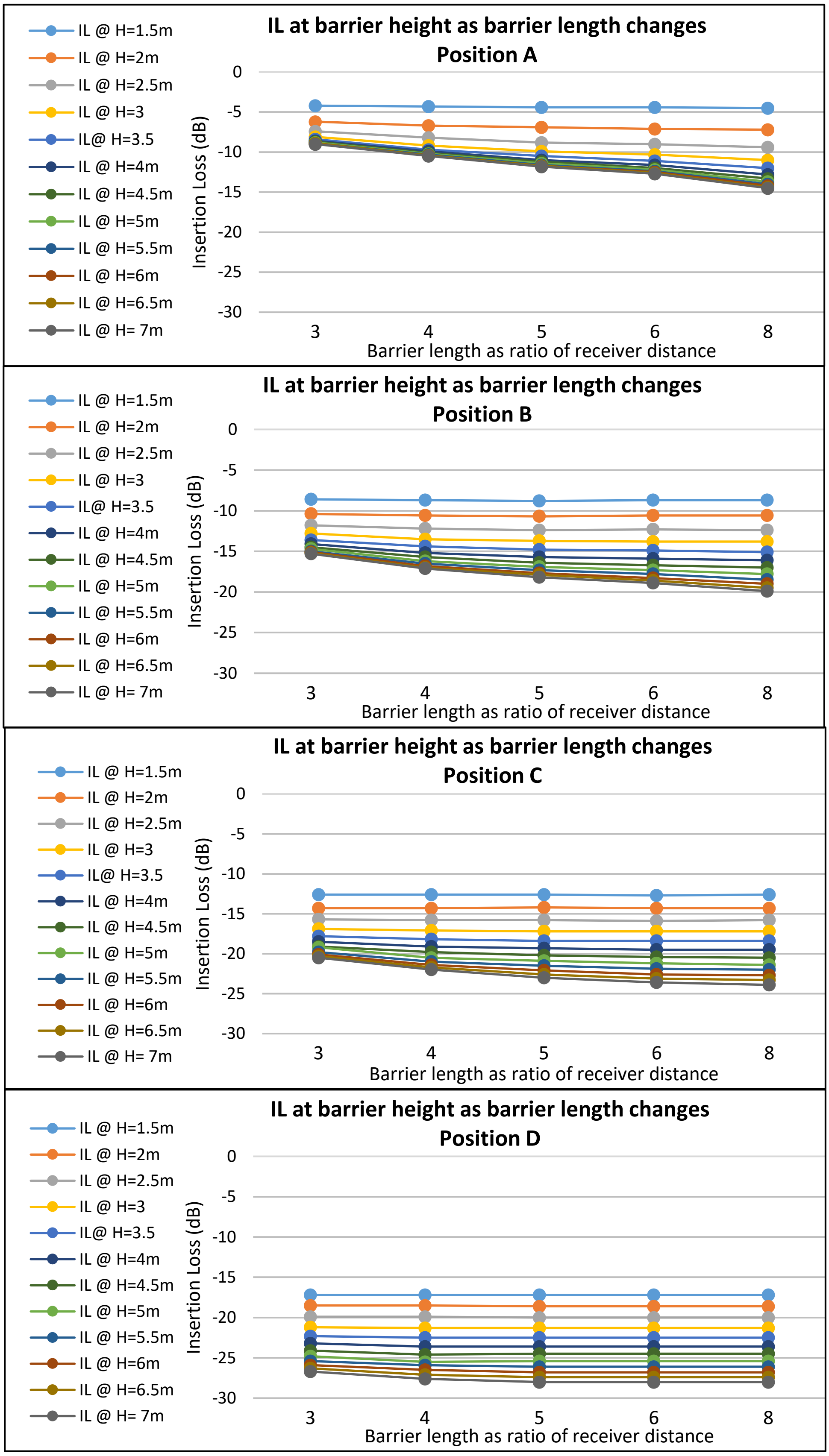


Figure 5-14: Comparison of insertion loss (IL) at facade receiver at building Positions A, B, C and D when barrier height and length vary

Based on the finding that the variance due to barrier length per barrier height is not significant, it was determined that a barrier length calculated by an extension in either direction of four times the distance between the barrier and the receiver is a reasonable length to use in the context of this study. Furthermore, at larger ratios, such as 1:5 or 1:8, the length of the wall becomes excessive for a school site, being up to 982 m either side of the barrier (a total length of almost 2 km).

The resulting barrier lengths (using the 1:4 ratio rule) for each position are indicated in Table 5-10. For the scenarios in which the building is orientated perpendicular to the road, the distance from the receiver to the barrier (d_{h2}) was taken to be the distance from the receiver point closest to the road (Rc1), thus representing the worst-case scenario.

Table 5-10: Length of barrier for each building position when barrier is at 12 m from centre of road

Building position		**Distance from centre of road to road-facing façade**	**Distance from centre of road to receiver**	**Distance from receiver to barrier (12 m from centre of road)**	**Barrier extension either side of receiver by 1:4 ratio**	**Total barrier length**
		(m)	**d (m)**	**D_{h2} (m)**	**(m)**	**L (m)**
Building parallel to road	**A**	**17**	**15.8**	**3.8**	**15.2**	**30.4**
	A1	25.5	24.3	12.3	49.2	98.4
	B	**34**	**32.8**	**20.8**	**83.2**	**166.4**
	B1	42.5	41.3	29.3	117.2	234.4
	B2	51	49.8	37.8	151.2	302.4
	B3	59.5	58.3	46.3	185.2	370.4
	C	**68**	**66.8**	**54.8**	**219.2**	**438.4**
	C1	76.5	75.3	63.3	253.2	506.4
	C2	85	83.8	71.8	287.2	574.4
	C3	93.5	92.3	80.3	321.2	642.4
	C4	102	100.8	88.8	355.2	710.4
	C5	110.5	109.3	97.3	389.2	778.4
	C6	119	117.8	105.8	423.2	846.4
	C7	127.5	126.3	114.3	457.2	914.4
	D	**136**	**134.8**	**122.8**	**491.2**	**982.4**
Building perpendicular	**A (ARc1)**	**17**	21	9	36	72
	B (BRc1)	**34**	38	26	104	208
	C (CRc1)	**68**	72	60	240	480
	D (DRc1)	**136**	140	128	512	1 024

The barrier length relative to the building length was also evaluated to determine whether reflections between the barrier and the building influence the SPL at the façade receiver. When a barrier is placed in front of a building façade, it is possible that reflections occurring between the parallel faces of the barrier and the building could affect the SPL measured at a receiver in front of the façade. Such an effect could influence the attenuation efficacy of a barrier. The amount of reflection that occurs will depend on the length of the parallel overlap of the barrier and the building (illustrated in Figure 5-15).

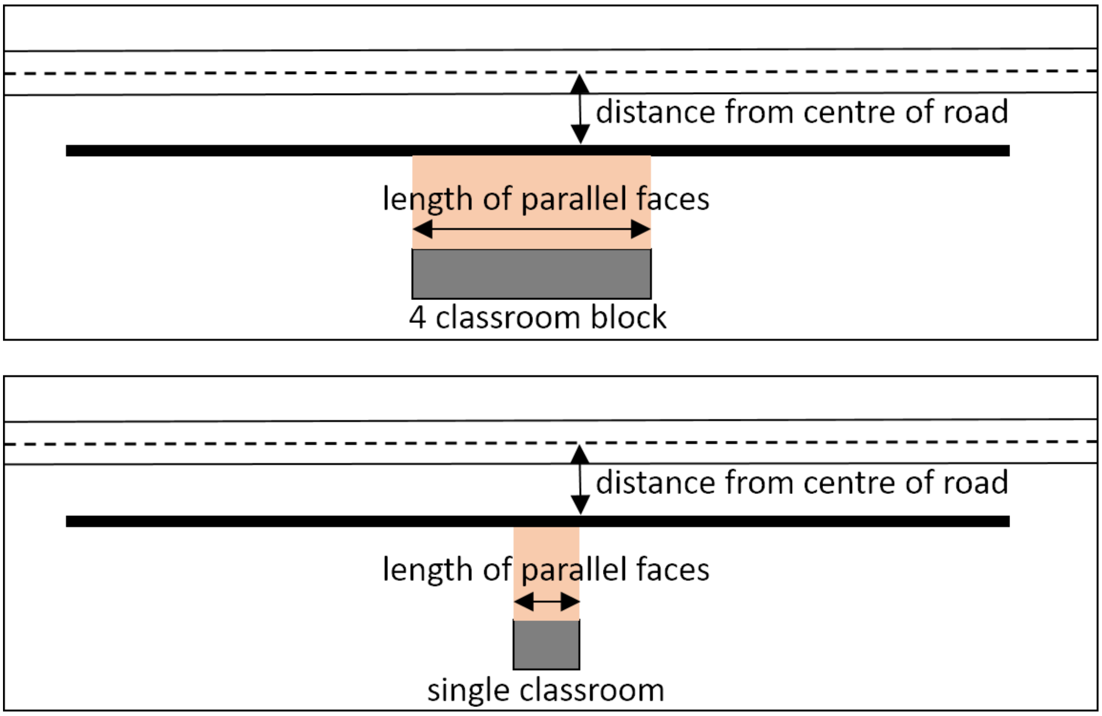


Figure 5-15: Illustration of differing length of parallel faces in single- or four-classroom block

To quantify this effect and determine whether it is necessary to consider, a number of simulations were performed comparing the SPL at the receiver at the façade of a short building (single classroom of 8 m length) and a long building (four classrooms of 32 m length), using different barrier heights and positions. For the purpose of this sensitivity test, a small sample of scenarios was used as an indicator. Thus, only the receivers at single-storey buildings at the major building positions were measured.

A barrier length four times the distance between the barrier and the receiver (d_{h2}) was used. Applying a barrier in a position fixed relative to the noise source, the barrier length was different for each building position scenario. The SPL at the façade receiver positioned along the centre of the four-classroom façade and the single-classroom façade was measured for each barrier height at building Positions A, B, C and D, and the difference calculated. The results are tabulated in Table 5-11.

Table 5-11: Resultant SPL at facade of multiple-classroom block or single-classroom block with different barrier heights (1:4 ratio receiver distance to barrier length; screen fixed at 12m from source)

Building Position:	A			B			C			D		
Barrier height (m)	**4-class building (dBA)**	**1-class building (dBA)**	***difference in SPL (dB)***	**4-class block (dBA)**	**1-class building (dBA)**	***difference in SPL (dB)***	**4-class block (dBA)**	**1-class building (dBA)**	***difference in SPL (dB)***	**4-class block (dBA)**	**1-class building (dBA)**	***difference in SPL (dB)***
1.5	63.8	63.6	*0.2*	55.5	55.4	*0.1*	50.9	50.9	*0*	50.9	50.9	*0*
2	61.4	61.2	*0.2*	53.8	53.7	*0.1*	49.6	49.6	*0*	49.6	49.6	*0*
2.5	59.9	59.5	*0.4*	52.3	52.2	*0.1*	48.2	48.2	*0*	48.2	48.2	*0*
3	58.9	58.5	*0.4*	51.0	50.9	*0.1*	46.8	46.8	*0*	46.8	46.8	*0*
3.5	58.5	57.9	*0.6*	49.9	49.8	*0.1*	45.6	45.6	*0*	45.6	45.6	*0*
4	58.1	57.6	*0.5*	49.0	49.0	*0*	44.5	44.5	*0*	44.5	44.5	*0*
4.5	58.0	57.3	*0.7*	48.3	48.2	*0.1*	43.5	43.5	*0*	43.5	43.5	*0*
5	57.9	57.2	*0.7*	47.6	47.6	*0*	42.6	42.6	*0*	42.6	42.6	*0*
5.5	57.8	57.1	*0.7*	47.1	47.1	*0*	42.2	42.2	*0*	42.2	42.2	*0*
6	57.7	57.0	*0.7*	46.7	46.7	*0*	41.6	41.6	*0*	41.6	41.6	*0*
6.5	57.7	57.0	*0.7*	46.4	46.4	*0*	41.0	41.0	*0*	41.0	41.0	*0*
7	57.6	56.9	*0.7*	46.1	46.1	*0*	40.5	40.5	*0*	40.5	40.5	*0*

Generally, the SPL measured in front of the four-classroom building is higher than it is in front of the single-classroom building. This indicates that reflections off parallel faces can result in an increased SPL at the façade receiver. However, the increase due to sound reflecting off the longer façade is at most only 0.7 dB. The greatest differences (ranging from 0.2 dB to 0.7 dB), are recorded for building Position A, where the distance between the barrier and the building is the least (5 m). The reflection effect is reduced to 0 dB or 0.1 dB at the buildings B, C and D. Because a difference in SPL of less than 3 dB is not noticeable, it can be concluded that the effect of reflections related to the length of the building parallel to the barrier is negligible.

The results for Position A also show that the effect of reflection increases as the barrier height increases, but becomes stable beyond a barrier height of 4.5 m.

These results demonstrate that the greater the length and height (area) of parallel faces, the greater the effect of reflection. However, the effect is negligible. Thus, for the next iterations of this part of the experiment, only the four-classroom building (which is more representative of actual cases) will be used.

The effect of reflectivity of the barrier was also tested. By default, barriers inserted in *CadnaA* have no reflection. When the barrier reflectivity was changed to a reflective barrier with the pre-set reflection loss of 1 dB a negligible difference (at most 0.7 dB) was observed and so the default setting of 'No Reflection' was maintained.

5.3.4 Barrier height in barrier arrangement 1

The effect of the height of the barrier for each building position was tested with the barrier at a fixed position close to the noise source (12 m from the centre of the road). This position is considered to be at the boundary of the school premises, calculated assuming a 14 m wide road and a 5 m wide pavement. The barrier length was four times the distance between the barrier and the receiver (d_{h2}). Since the barrier position remained fixed relative to the source and the receiver position changed for each building position, the distance d_{h2} was different for each façade receiver position. Thus the barrier length changed for each building position scenario.

Barriers of differing heights, ranging from 1.5 m to 7 m in 0.5 m increments, were inserted one at a time. The resulting SPL at each façade receiver position was recorded and evaluated against the criteria of achieving a receiving façade SPL of 50 dBA. The results are recorded in Table 5-12 (for single-storey buildings) and Table 5-13 (for double-storey buildings).

The effectiveness of a barrier is normally described in terms of the insertion loss (IL), which is the difference between the measured SPL with and without the barrier. However, in this exercise, the effectiveness is determined with respect to the target SPL of 50 dBA. Thus, the façade receiver SPL rather than the IL is recorded.

The tables are coloured as heat maps with red indicating high SPL measurements (i.e. poor effect of inserted barrier or low IL) and green indicating low SPL measurements (i.e. good effect of the inserted barrier or high IL). Where the target SPL of 50 dBA was achieved, the reading is underlined in the tables (the criteria of SPL ≤ 50.5 dB was used). The ideal target of 45 dBA (≤45.5 dBA), where an indoor SPL of 35 dBA is expected, is double underlined.

The colour-coding of the tables makes it very clear that the higher the barrier (towards the right of the table) and the further the distance from the source (towards the bottom of the table), the lower the SPL. It should be noted the values would be lower if the ground surface was non-reflective, which would absorb some of the sound energy, particularly at high frequencies.

Table 5-12: Resultant SPL at facade receiver 1.5 m above ground level in front of single-storey building at various positions with barrier of varying height at fixed position 12 m from road

Barrier height (m):		0	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Building position:		SPL at façade receiver (dBA)												
Building parallel to the road	A	**68.1**	**63.8**	**61.4**	**59.9**	**58.9**	**58.5**	**58.1**	**58.0**	**57.9**	**57.8**	**57.7**	**57.7**	**57.6**
	A1	64.4	61.0	59.0	57.4	56.2	55.3	54.7	54.3	53.9	53.6	53.5	53.3	53.2
	B	**62.1**	**59.4**	**57.5**	**55.9**	**54.6**	**53.7**	**52.9**	**52.4**	**51.9**	**51.6**	**51.3**	**51.1**	**51.0**
	B1	60.7	58.1	56.4	54.8	53.5	52.5	51.7	51.1	50.6	50.2	49.9	49.7	49.5
	B2	59.4	57.1	55.3	53.8	52.5	51.5	50.6	50.0	49.5	49.0	48.7	48.4	48.2
	B3	58.4	56.2	54.5	53.0	51.7	50.6	49.8	49.1	48.5	48.0	47.7	47.4	47.1
	C	**57.5**	**55.5**	**53.8**	**52.3**	**51.0**	**49.9**	**49.0**	**48.3**	**47.6**	**47.1**	**46.7**	**46.4**	**46.1**
	C1	56.8	54.7	53.1	51.6	50.3	49.2	48.3	47.5	46.9	46.3	45.9	45.5	45.2
	C2	56.0	54.1	52.5	51.0	49.7	48.6	47.6	46.8	46.1	45.5	45.1	44.6	44.3
	C3	54.9	53.1	51.6	50.2	48.9	47.8	46.8	46.0	45.3	44.6	44.1	43.5	43.1
	C4	54.4	52.6	51.1	49.7	48.4	47.3	46.3	45.4	44.7	44.0	43.4	42.9	42.5
	C5	53.6	52.0	50.6	49.2	47.9	46.8	45.8	44.9	44.1	43.4	42.8	42.2	41.7
	C6	53.1	51.6	50.2	48.8	47.5	46.4	45.3	44.4	43.6	43.4	42.8	42.4	42.0
	C7	52.7	51.3	49.9	48.5	47.2	46.0	44.9	43.9	43.1	42.8	42.2	41.7	41.3
	D	**52.3**	**50.9**	**49.6**	**48.2**	**46.8**	**45.6**	**44.5**	**43.5**	**42.6**	**42.2**	**41.6**	**41.0**	**40.5**
Building perpendicular	ARc1	63.7	59.6	57.5	55.9	54.7	54.0	53.4	53.1	52.8	52.5	52.4	52.2	52.1
	BRc1	58.8	56.1	54.4	52.8	51.6	50.6	49.9	49.3	48.9	48.5	48.2	48.0	47.8
	CRc1	54.6	52.5	50.9	49.8	48.3	47.3	46.4	45.7	45.0	44.5	44.1	43.7	43.4
	DRc1	50.2	48.6	47.2	45.9	44.6	43.4	42.3	41.4	40.5	40.6	40.1	39.6	39.2

Table 5-13: Resultant SPL at facade receiver 4.5 m above ground level in front of double-storey building at various positions with barrier of varying height at fixed position 12m from road

Barrier height (m):		0	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Building position:		SPL at facade receiver (dBA)												
Building parallel to road	A	**68.9**	**68.9**	**68.9**	**68.4**	**66.3**	**65.0**	**62.2**	**60.8**	**59.9**	**59.5**	**59.2**	**59.1**	**59.0**
	A1	66.2	66.2	63.9	63.2	60.5	59.1	57.8	56.9	56.2	55.7	55.4	55.1	55.0
	B	**64.0**	**62.2**	**61.5**	**59.4**	**58.1**	**56.8**	**55.6**	**54.8**	**54.1**	**53.7**	**53.3**	**53.1**	**52.9**
	B1	62.1	60.7	58.9	57.8	56.5	55.2	54.1	53.3	52.7	52.2	51.8	51.5	51.3
	B2	60.7	59.5	57.8	56.6	55.2	54.0	52.9	52.1	51.4	50.9	50.5	50.2	49.9
	B3	59.6	58.5	56.8	55.6	54.2	53.0	52.0	51.1	50.4	49.9	49.4	49.0	48.8
	C	**58.8**	**57.1**	**56.0**	**54.7**	**53.4**	**52.1**	**51.1**	**50.2**	**49.5**	**48.9**	**48.4**	**48.0**	**47.7**
	C1	58.0	56.4	55.3	53.9	52.6	51.3	50.2	49.3	48.5	47.8	47.2	46.6	46.2
	C2	57.3	55.8	54.7	53.3	52.0	50.7	49.7	48.7	47.9	47.2	46.6	46.1	45.7
	C3	56.7	55.2	54.1	52.7	51.3	50.1	49.0	48.0	47.1	46.3	45.7	44.9	44.4
	C4	56.2	54.7	53.6	52.2	50.8	49.6	48.5	47.5	46.6	45.8	45.1	44.5	43.9
	C5	55.6	54.2	53.1	51.7	50.3	49.1	47.9	46.9	45.9	45.1	44.4	43.7	43.1
	C6	55.2	53.8	52.6	51.2	49.8	48.6	47.4	46.4	45.7	44.9	44.3	43.7	43.2
	C7	54.7	53.4	52.2	50.8	49.5	48.2	47.0	45.9	45.2	44.1	43.2	42.5	41.8
	D	**54.3**	**53.0**	**51.8**	**50.5**	**49.1**	**47.8**	**46.6**	**45.5**	**44.5**	**43.9**	**43.2**	**42.5**	**41.9**
Building perpendicular	ARc1	64.9	64.9	64.9	62.3	61.6	58.4	56.9	55.7	55.0	54.5	54.2	53.9	53.7
	BRc1	60.4	58.8	58.1	56.0	54.7	53.4	52.3	51.5	50.8	50.3	49.9	49.6	49.4
	CRc1	55.8	54.1	53.1	52.0	50.4	49.3	48.3	47.4	46.7	46.1	45.6	45.2	44.8
	DRc1	52.5	51.1	50.0	48.7	47.4	46.1	44.9	43.9	43.3	42.5	41.8	41.2	40.6

For a single-storey building parallel to the road, the position closest to the noise source at which the target SPL is achieved reached is Position B1 (42.5 m from the road) with a barrier height of at least 5.5 m. It is noted that this is a very high barrier.

As the receiver position recedes from the noise source, the barrier height at which the target SPL is achieved is lower. However, for single-storey buildings closer than 68 m (Position C) from the road, excessively high barriers (> 3.5 m) are required. Considering the double-underlined values in the tables, one can clearly see how challenging it is to achieve the ideal target of 35 dBA inside a classroom.

It is noted that, for a building perpendicular to the noise source, the target level is achievable with a lower barrier or a shorter distance between the source and receiver than for the parallel building scenarios. For a perpendicular single-storey building the target SPL is achieved at Position B (façade 34 m from noise source) with a barrier height of 4 m, at Position C (68 m from the source) with a barrier of only 2.5 m and at Position D (136 m from source) no barrier is required to achieve a façade receiver level of 50 dBA.

Positions at which the target SPL is achieved, and the corresponding barrier heights, are summarised in Table 5-14. By referring to this summary, one can determine the minimum building distance and barrier height required to achieve the target.

Table 5-14: Summary of scenarios in which the target SPL is achieved for a single-storey building

Position ID	Distance from centre of road to facade (m)	Minimum barrier height at which target is achieved (m)	Minimum barrier height at which ideal target is achieved (m)
B1	42.5	5.5	Not achieved
B2	51	4.5	Not achieved
B3	59.5	4	Not achieved
C	68	3.5	Not achieved
C1	76.5	3	6 .5
C2	85	3	5.5
C3	93.5	2.5	5
C4	102	2.5	4.5
C5	110.5	2.5	4 .5
C6	119	2	4
C7	127.5	2	4
D	136	2	4
B (perpendicular)	34	4	Not achieved
C (perpendicular)	68	2.5	5
D (perpendicular)	136	0	3

For a classroom on the second storey of a building parallel to the road, suitable façade levels are achieved at Position B2 (51 m) with a barrier height of at 6 m. The lowest barrier height at which the target SPL is achieved is at building Position D with a barrier height of 2.5 m.

When considering a double-storey building that is perpendicular to the noise source, a suitable SPL is achieved at Position B (face 34 m from source) with a barrier of at least 5.5 m high, at Position C with a barrier of 3 m high and at Position D with a barrier height of 2 m.

Positions at which the target SPL for second-storey classrooms is achieved, and the corresponding barrier heights, are summarised in Table 5-15.

Table 5-15: Summary of scenarios in which the target SPL is achieved for a double-storey building

Position ID	Distance from centre of road to façade (m)	Minimum barrier height at which target is achieved (m)	Minimum barrier height at which ideal target is achieved (m)
B2	51	6	Not achieved
B3	59.5	5	Not achieved
C	68	4.5	Not achieved
C1	76.5	4	Not achieved
C2	85	4	7
C3	93.5	3.5	6 .5
C4	102	3.5	6
C5	110.5	3	5.5
C6	119	3	5.5
C7	127.5	3	5
D	136	2.5	4.5
B (perpendicular)	38	5.5	Not achieved
C (perpendicular)	68	3	6.5
D (perpendicular)	136	2	4

It is noted that a higher barrier is required to achieve the target SPL for first-floor (double-storey) classrooms than for ground-floor classrooms. The difference in SPL at a double-storey façade receiver (4.5 m high) and a single-storey façade receiver (1.5 m high) is recorded in Table 5-16 (double-storey SPL minus single-storey SPL) and illustrated by the sound contours in Figure 5-16. As in the scenario with no barriers, it is evident here that the SPL at the higher receiver (first floor) is consistently higher than that at the lower level (ground floor).

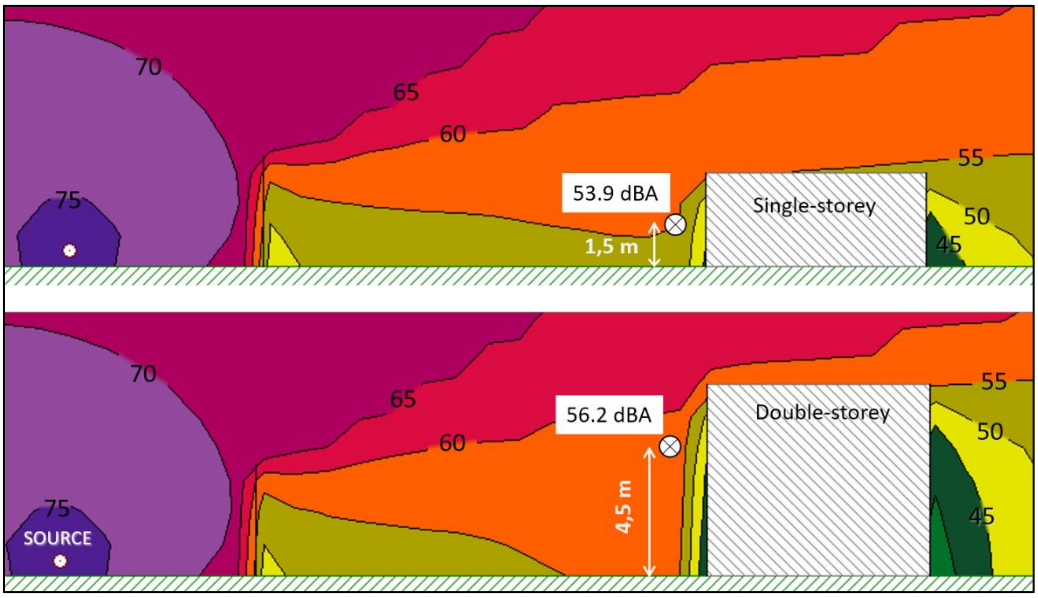


Figure 5-16: Illustrated example of receiver position for single-storey classroom and double-storey classroom with barrier arrangement 1

Table 5-16: Difference between facade receiver level at single- or double-storey building for different building positions and barrier heights

	Barrier height (m):	0	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Building position:		Difference in SPL (double-storey SPL – single-storey SPL)												
Building parallel to road	**A**	0.8	5.1	7.5	8.5	7.4	6.5	4.1	2.8	2	1.7	1.5	1.4	1.4
	A1	1.8	5.2	4.9	5.8	4.3	3.8	3.1	3.1	2.3	2.1	1.9	1.8	1.8
	B	1.9	2.8	4	3.5	3.5	3.1	2.7	2.4	2.2	2.1	2	2	1.9
	B1	1.4	2.6	2.5	3	3	2.7	2.4	2.2	2.1	2	1.9	1.8	1.8
	B2	1.3	2.4	2.5	2.8	2.7	2.5	2.3	2.1	1.9	1.9	1.8	1.8	1.7
	B3	1.2	2.3	2.3	2.6	2.5	2.4	2.2	2	1.9	1.9	1.7	1.6	1.7
	C	1.3	1.6	2.2	2.4	2.4	2.2	2.1	1.9	1.9	1.8	1.7	1.6	1.6
	C1	1.2	1.7	2.2	2.3	2.3	2.1	1.9	1.8	1.6	1.5	1.3	1.1	1
	C2	1.3	1.7	2.2	2.3	2.3	2.1	2.1	1.9	1.8	1.7	1.5	1.5	1.4
	C3	1.8	2.1	2.5	2.5	2.4	2.3	2.2	2	1.8	1.7	1.6	1.4	1.3
	C4	1.8	2.1	2.5	2.5	2.4	2.3	2.2	2.1	1.9	1.8	1.7	1.6	1.4
	C5	2	2.2	2.5	2.5	2.4	2.3	2.1	2	1.8	1.7	1.6	1.5	1.4
	C6	2.1	2.2	2.4	2.4	2.3	2.2	2.1	2	2.1	1.5	1.5	1.3	1.2
	C7	2	2.1	2.3	2.3	2.3	2.2	2.1	2	2.1	1.3	1	0.8	0.5
	D	2	2.1	2.2	2.3	2.3	2.2	2.1	2	1.9	1.7	1.6	1.5	1.4
Building perpendicular	ARc1	1.2	5.3	7.4	6.4	6.9	4.4	3.5	2.6	2.2	2	1.8	1.7	1.6
	BRc1	1.6	2.7	3.7	3.2	3.1	2.8	2.4	2.2	1.9	1.8	1.7	1.6	1.6
	CRc1	1.2	1.6	2.2	2.2	2.1	2	1.9	1.7	1.7	1.6	1.5	1.5	1.4
	DRc1	2.3	2.5	2.8	2.8	2.8	2.7	2.6	2.5	2.8	1.9	1.7	1.6	1.4

It can be seen from Table 5-16 that the closer a classroom building is to the source (road), the more benefit can be gained from designing classrooms at the ground level only. With no barrier, there is not a significant difference between single-storey and double-storey classrooms; but, with the insertion of a barrier, the use of a single-storey building would be beneficial, especially for buildings positioned closer to the noise source.

It is evident that the SPL at the single-storey façade receiver is lower than that of the double-storey receiver for a building at the same position and with the same barrier height.

The resulting SPL in front of a single-storey building with receiver height at 1.5 m above floor level was consistently lower than the SPL at the same receiver, but in front of a double-storey building. A visual analysis of the sound contours in cross-section in Figure 5-16 shows that this is likely due to greater reflections off the taller building and ground attenuation at the lower level. This is found to be true both for buildings that are parallel to the road and perpendicular buildings.

5.3.5 Barrier height in barrier arrangement 2

In this arrangement, a barrier of varying heights was inserted at a fixed distance from the façade of the building in each position. Thus the distance from the source to the barrier (d_{h1}) varied for each building position, while this distance from the barrier to the receiver (d_{h2}) remained constant. This means that the length of the barrier, which is a factor of d_{h2}, remained the same for all building positions.

At first, the distance of the barrier from the façade was set at 3 m from the building façade. This distance was a somewhat arbitrary starting point, determined by practical and aesthetic criteria, allowing sufficient comfortable circulation space between the building and the barrier wall.

Again, the barrier extended four times the distance between the receiver and the barrier. For a building parallel to the road, with the receiver 1.2 m from the façade, the distance from the receiver to the barrier is 1.8 m and thus the barrier is extended 7.2 m (4 x 1.8) in either direction, making it 14.4 m long (see Figure 5-17).

For a building perpendicular to the road, the receiver is positioned 1.2 m away from the window façade and half the length of a classroom (4 m) from the road-facing façade. Thus the distance from a barrier 3 m in front of the road-facing façade is 7 m away from the receiver point, making the extension of the barrier either side of the receiver 28 m, and the total barrier length 56 m (see Figure 5-18). The receivers for perpendicular buildings are positioned to the side of the building, making the barrier asymmetrical to the building (being symmetrical to the receiver position). This asymmetry is considered to be of no consequence for the purpose of this exercise.

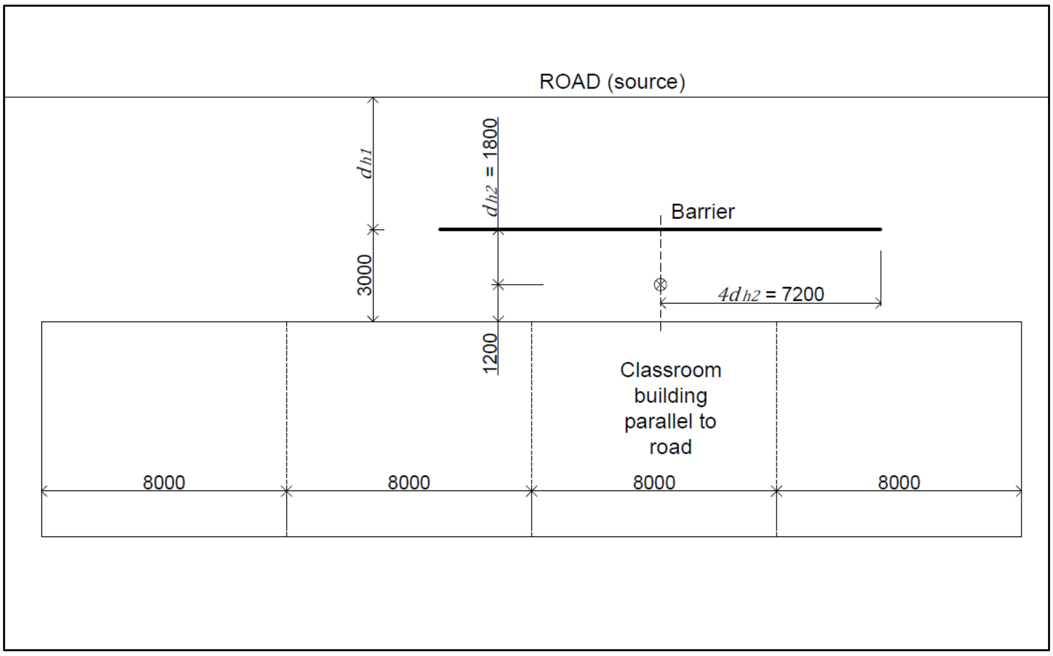


Figure 5-17: Illustration of determination of barrier length for building prallel to road

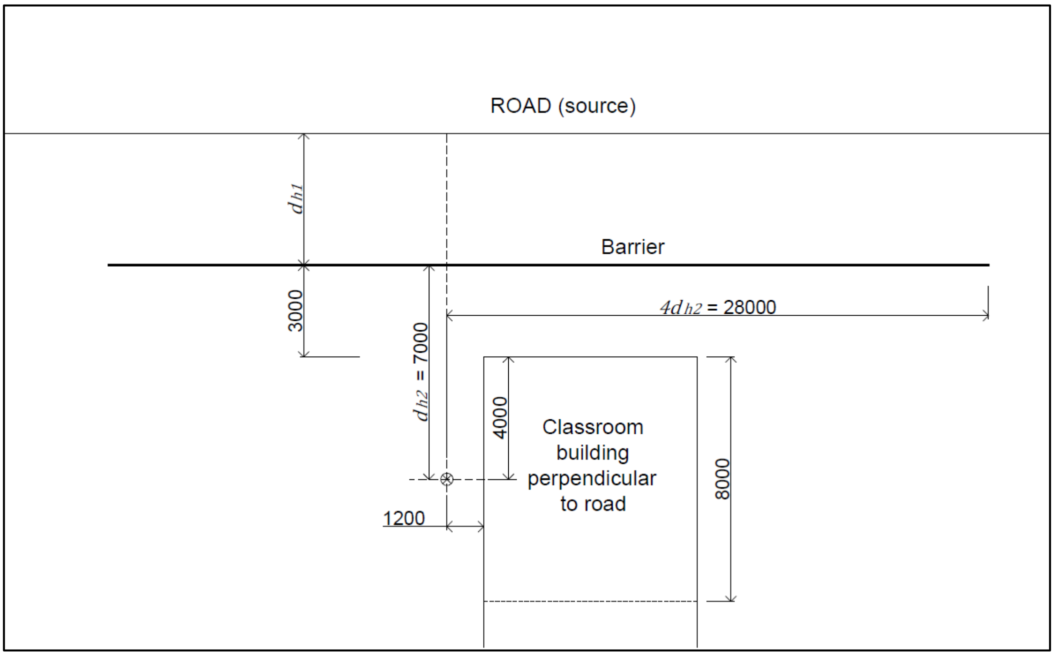


Figure 5-18: Illustration of determination of barrier length for building parallel to road

As in the previous arrangement, the SPL at each position was measured. The results at each position with varying barrier heights are shown in Table 5-17 (for single-storey buildings) and Table 5-18 (for double-storey buildings).

Table 5-17: Resultant SPL at facade receiver 1.5 m above ground level in front of single-storey building at various positions with barrier of varying height at fixed position 3 m from the façade

Barrier height (m):		0	1.5	2	2.5	3	3.5	4		4.5	5	5.5	6	6.5	7
Building position			SPL at façade receiver (dBA)												
Building parallel to the road	A	**68.1**	**64.5**	**61.5**	**59.7**	**58.8**	**58.4**	**58.2**		**58.1**	**58**	**57.9**	**57.9**	**57.9**	**57.7**
	A1	64.4	62.5	59.5	57.3	56.1	55.5	55.2		55	54.9	54.8	54.7	54.6	54.5
	B	**62.1**	**61**	**58.1**	**55.5**	**54.1**	**53.4**	**52.9**		**52.7**	**52.5**	**52.4**	**52.3**	**52.2**	**52**
	B1	60.7	59.9	57	54.3	52.8	51.9	51.4		51.1	50.9	50.7	50.6	50.5	50.4
	B2	59.4	58.8	56	53.1	51.3	50.3	49.7		49.3	49	48.8	48.7	48.5	48.3
	B3	58.4	57.9	55.1	52	50	48.8	48		47.6	47.2	47	46.5	46.7	46.4
	C	**57.5**	**57.1**	**54.4**	**51.2**	**49.1**	**47.8**	**47.1**		**46.5**	**46.2**	**45.9**	**45.7**	**45.6**	**45.3**
	C1	56.8	56.4	53.7	50.4	48.2	46.9	46.1		45.5	45.1	44.9	44.7	44.5	44.2
	C2	56.0	55.6	52.9	49.6	47.4	46	45.1		44.5	44.1	43.8	43.6	43.5	43.1
	C3	54.9	54.6	51.9	48.5	46.3	44.9	44		43.5	43	42.8	42.5	42.4	42.2
	C4	54.4	54.2	51.5	48	45.7	44.2	43.3		42.6	42.2	41.8	41.6	41.4	41.2
	C5	53.6	53.4	50.7	47.2	44.8	43.2	42.2		41.5	41.1	40.7	40.5	40.3	40.1
	C6	53.1	52.9	50.3	46.7	44.2	42.6	41.5		40.7	40.2	39.8	39.5	39.3	39.1
	C7	52.7	52.5	49.9	46.3	43.7	42	40.9		40.1	39.5	39.1	38.8	38.5	38.3
	D	**52.3**	**52.2**	**49.6**	**45.9**	**43.2**	**41.5**	**40.3**		**39.4**	**38.8**	**38.4**	**38**	**37.7**	**37.5**
Building perpendicular															
	ARc1	63.7	60.1	57.8	56	54.7	53.8	53.2		52.7	52.3	52.1	51.9	51.7	51.5
	BRc1	58.8	57.7	56	53.9	52.3	51	50.1		49.4	48.9	48.4	48.1	47.8	47.5
	CRc1	54.6	54.2	53.1	51.1	49.3	47.9	46.7		45.8	45.1	44.5	44	43.6	43.1
	DRc1	50.2	49.9	49.4	47.6	45.8	44.2	42.8		41.6	40.4	39.4	38.4	37.6	36.9

Table 5-18: Resultant SPL at facade receiver 4.5 m above ground level in front of double-storey building at various positions with barrier of varying height at fixed position 3 m from the façade

	Barrier height (m):	0	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Building position		SPL at façade receiver (dBA)												
Building parallel to the road	A	**68.9**	**68.9**	**68.9**	**68.9**	**68.9**	**68.4**	**65.8**	**62.4**	**60.7**	**60.1**	**59.7**	**59.7**	**59.5**
	A1	66.2	66.2	66.2	66.2	66.2	66.2	65.5	61.2	58.7	57.5	56.9	56.6	56.4
	B	**64.0**	**64**	**64**	**64**	**64**	**64**	**63.6**	**60.4**	**57.5**	**55.9**	**55.2**	**54.7**	**54.5**
	B1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	59.6	56.6	54.8	53.8	53.3	53.1
	B2	60.7	60.7	60.7	60.7	60.7	60.7	60.7	58.9	55.9	53.8	52.7	52.2	51.8
	B3	59.6	59.7	59.7	59.7	59.7	59.7	59.7	58.2	55.2	53	51.8	51.2	50.8
	C	**58.8**	**58.8**	**58.8**	**58.8**	**58.8**	**58.8**	**58.8**	**57.5**	**54.6**	**52.2**	**50.9**	**50.2**	**49.7**
	C1	58.0	58	58	58	58	58	58	57	54.1	51.6	50.2	49.4	48.9
	C2	57.3	57.3	57.3	57.3	57.3	57.3	57.3	56.4	53.6	51	49.4	48.5	48
	C3	56.7	56.7	56.7	56.7	56.7	56.7	56.7	55.9	53.2	50.5	48.8	47.8	47.2
	C4	56.2	56.1	56.1	56.1	56.1	56.1	56.1	55.5	52.8	50	48.2	47.1	46.5
	C5	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55	52.4	49.5	47.6	46.5	45.8
	C6	55.2	55.2	55.2	55.2	55.2	55.2	55.2	54.6	52.1	49.1	47.1	45.9	45.1
	C7	54.7	54.7	54.7	54.7	54.7	54.7	54.7	54.2	51.7	48.7	46.6	45.3	44.4
	D	**54.3**	**54.3**	**54.3**	**54.3**	**54.3**	**54.3**	**54.3**	**53.8**	**51.4**	**48.3**	**46.1**	**44.7**	**43.9**
Building perpendicular	ARc1	64.9	64.9	64.9	64.9	62.4	59.4	57.8	56.2	55.1	54.4	53.9	53.9	53.3
	BRc1	60.4	60.4	60.4	60.4	60.4	60.4	57.7	56	54.1	52.6	51.6	50.8	50.2
	CRc1	55.8	55.8	55.8	55.8	55.8	55.8	55.8	54.4	52.7	50.8	49.3	48.1	47
	DRc1	52.5	52.4	52.4	52.4	52.4	52.4	52.4	51.9	51	49.2	47.3	45.6	44

For a single-storey building parallel to the road, the position closest to the noise source at which the target façade SPL is achieved is at Position B1 (42.5 m from the centre of the road), with a barrier height of at least 6.5 m (50.5 dBA). Compared to the results under barrier arrangement 1, the target at B1 is achieved here, requiring a barrier 1 m higher. However, between Positions B2 and C2, the target is achieved with a lower barrier with barrier arrangement 2 than with barrier arrangement 1. This indicates that it is preferable to insert a barrier closer to the receiver than closer to the source at these building positions. Beyond Position C3 there is little difference between the scenarios with barrier arrangement 1 and 2.

As the receiver position recedes from the noise source, the barrier height at which the target SPL is achieved is lower. However, for buildings to the road closer than 51 m, the target is not achievable without excessively high barriers, if at all.

For a building perpendicular to the noise source, a lower barrier or a shorter distance is required than for a building parallel to the source. The target was not achieved at Position A but could be achieved at Position B with a barrier of 4 m high (compared to not at all for a parallel building) and at Position C with a barrier height of 3 m (same as for parallel building); at Position D no barrier was required (compared to requiring a 2 m high barrier for a parallel building).

Positions at which the target SPL is achieved, and the corresponding barrier heights, are summarised in Table 5-19.

Table 5-19: Summary of scenarios in which the target SPL is achieved for a single-storey building with barrier 3 m from facade

Position ID	Distance from centre of road to facade (m)	Minimum barrier height at which target is achieved (m)	Minimum barrier height at which ideal target is achieved (m)
B1	42.5	6.5	Not achieved
B2	51	3.5	Not achieved
B3	59.5	3	Not achieved
C	68	3	6
C1	76.5	2.5	4.5
C2	85	2.5	4
C3	93.5	2.5	3.5
C4	102	2.5	3.5
C5	110.5	2.5	3
C6	119	2	3
C7	127.5	2	3
D	136	2	3
B (perpendicular)	34	4	Not achieved
C (perpendicular)	68	3	5
D (perpendicular)	136	0	3.5

For a classroom on the second storey of a building parallel to the road, suitable façade levels are only achieved at Position C (68 m) with a barrier height of at 6.5 m, which is very high. The lowest barrier height at which the target SPL is achieved is at building Position D with a barrier height of 5.5 m. **For a double-storey receiver level, the performance of a barrier close to the receiver is less effective than when the barrier is closer to the source**.

When considering a double-storey building that is perpendicular to the noise source, a suitable SPL is achieved at Position B (face 134 m from source) with a barrier of at least 6.5 m high and at Positions C and D with 5.5 m high barriers, making this an unrealistic option.

Positions at which the target SPL for second-storey classrooms is achieved, and the corresponding barrier heights, are summarised in Table 5-20.

Table 5-20: Summary of scenarios in which the target SPL is achieved for a double-storey building with barrier 3 m from façade

Position ID	Distance from centre of road to façade (m)	Minimum barrier height at which target is achieved (m)	Minimum barrier height at which ideal target is achieved (m)
C	68	6	Not achieved
C1	76.5	6	Not achieved
C2	85	6	Not achieved
C3	93.5	5.5	Not achieved
C4	102	5.5	Not achieved
C5	110.5	5.5	7
C6	119	5.5	6.5
C7	127.5	5.5	6.5
D	136	5.5	6.5
B (perpendicular)	34	6.5	Not achieved
C (perpendicular)	68	5.5	Not achieved
D (perpendicular)	136	5.5	6.5

It is evident that large distances and excessively high barriers are required to achieve the target SPL for classrooms on the first floor.

5.3.6 Effect of barrier distance from façade

Since the distance between the barrier and the building was somewhat arbitrary, loosely based on circulation space, the effect of changing this distance was tested by decreasing the distance between the barrier and the façade from 3 m to 2 m. The barrier extension (length) was adjusted accordingly to 6.4 m (using the 1:4 ratio rule) for the buildings parallel to the road, and 24 m for the buildings perpendicular to the road. Only the major building positions were tested to gain an indication of the effect. The results are shown in Table 5-21.

Table 5-21: Resultant SPL at façade receiver 1.5 m above ground level in front of single-storey building at various positions with barrier of varying height at fixed position 2 m from the façade

	Barrier height (m):	0	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Building position		SPL at façade receiver (dBA)												
Building parallel	A	**68.1**	**64.9**	**61.5**	**60.2**	**59.8**	**59.6**	**59.5**	**59.4**	**59.4**	**59.3**	**59.3**	**59.3**	**59.3**
	B	**62.1**	**61.1**	**57.5**	**55.7**	**54.9**	**54.6**	**54.4**	**54.3**	**54.2**	**54.1**	**54.1**	**54.1**	**54.1**
	C	**57.5**	**57.2**	**52.9**	**50.1**	**48.9**	**48.3**	**47.9**	**47.7**	**47.6**	**47.3**	**47.3**	**47.2**	**47.2**
	D	**52.3**	**52.5**	**47.7**	**44.7**	**43.4**	**43.3**	**42.5**	**42.3**	**42.2**	**42.1**	**42**	**41.9**	**41.9**
Building perpendicular	ARc1	63.7	60.3	57.9	56	54.7	53.8	53.1	52.7	52.3	52	51.8	51.6	51.6
	BRc1	58.8	57.7	55.9	53.7	52.1	50.8	49.9	49.2	48.7	48.3	47.9	47.6	47.4
	CRc1	54.6	54.2	52.9	50.8	48.9	47.5	46.4	45.5	44.8	44.2	43.7	43.2	42.9
	DRc1	50.2	49.9	49.2	47.3	45.4	43.7	42.3	41	39.8	38.8	37.9	37.1	36.3

The resulting SPL values were compared at each of the major building positions when the barrier is inserted 3 m from the façade, 2 m from the façade and 12 m from the source. The comparison is graphically represented for each major building position in Figure 5-19 (for single-storey) and Figure 5-20 (for double-storey). The vertical axis scale is kept the same for ease of comparison.

In almost all scenarios the barrier at 2 m from the façade results in a higher façade receiver sound level, or a very similar level to that achieved with a barrier at 3 m from the façade. The maximum difference between a barrier at 2 m or 3 m from the façade is 4.6 dB.

The maximum difference between the façade receiver levels with a barrier at the source (barrier arrangement 1) or at 3 m from the façade, is 4.2 dB (this is at a barrier height of 4 m). With a 3.5 m high barrier, which it may be argued is the maximum realistic barrier height, it is better to insert a barrier at 3 m from the façade than at the source.

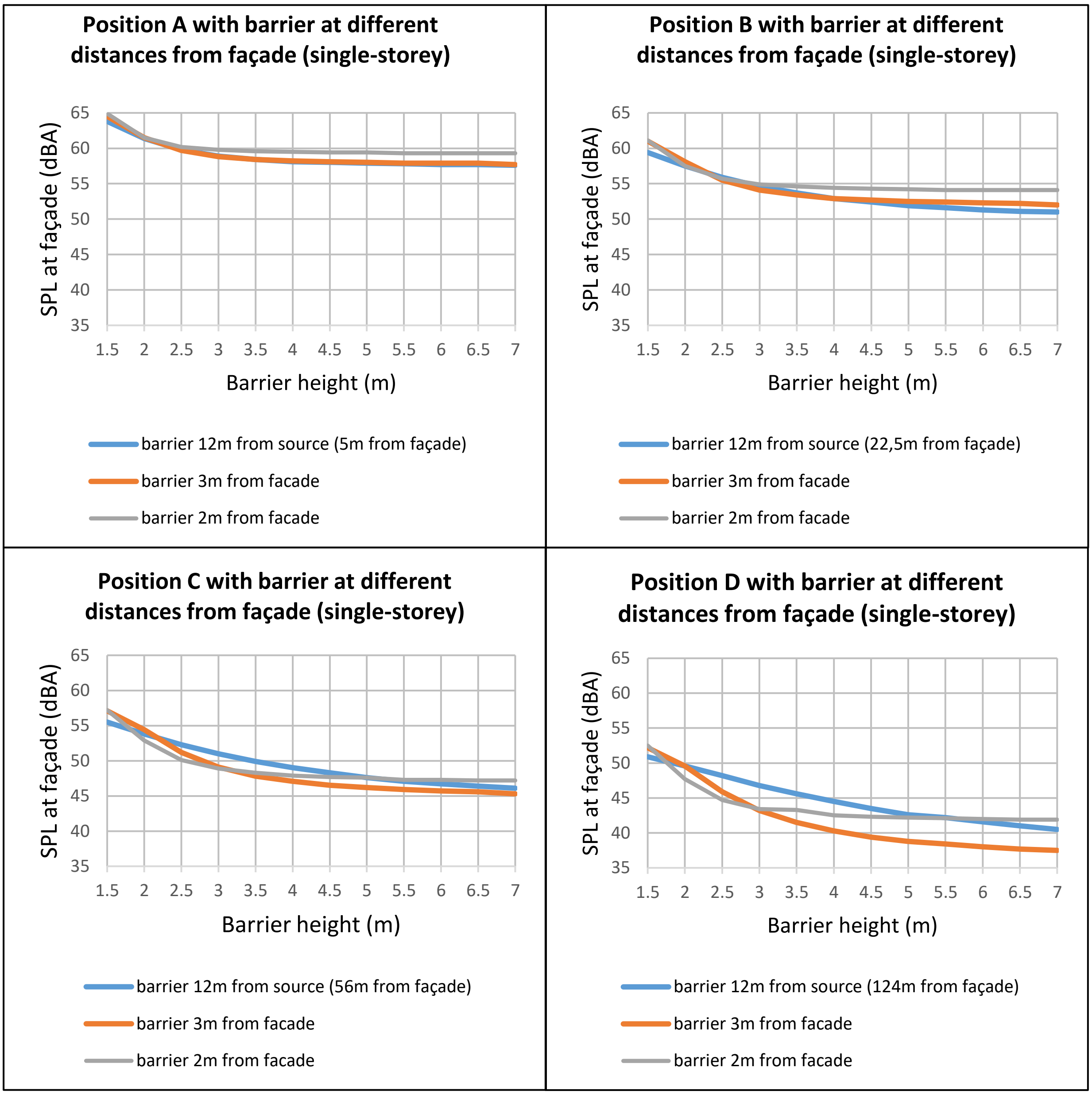


Figure 5-19: Graphic comparison of SPL at single-storey facade receiver when barrier distance relative to receiver differs

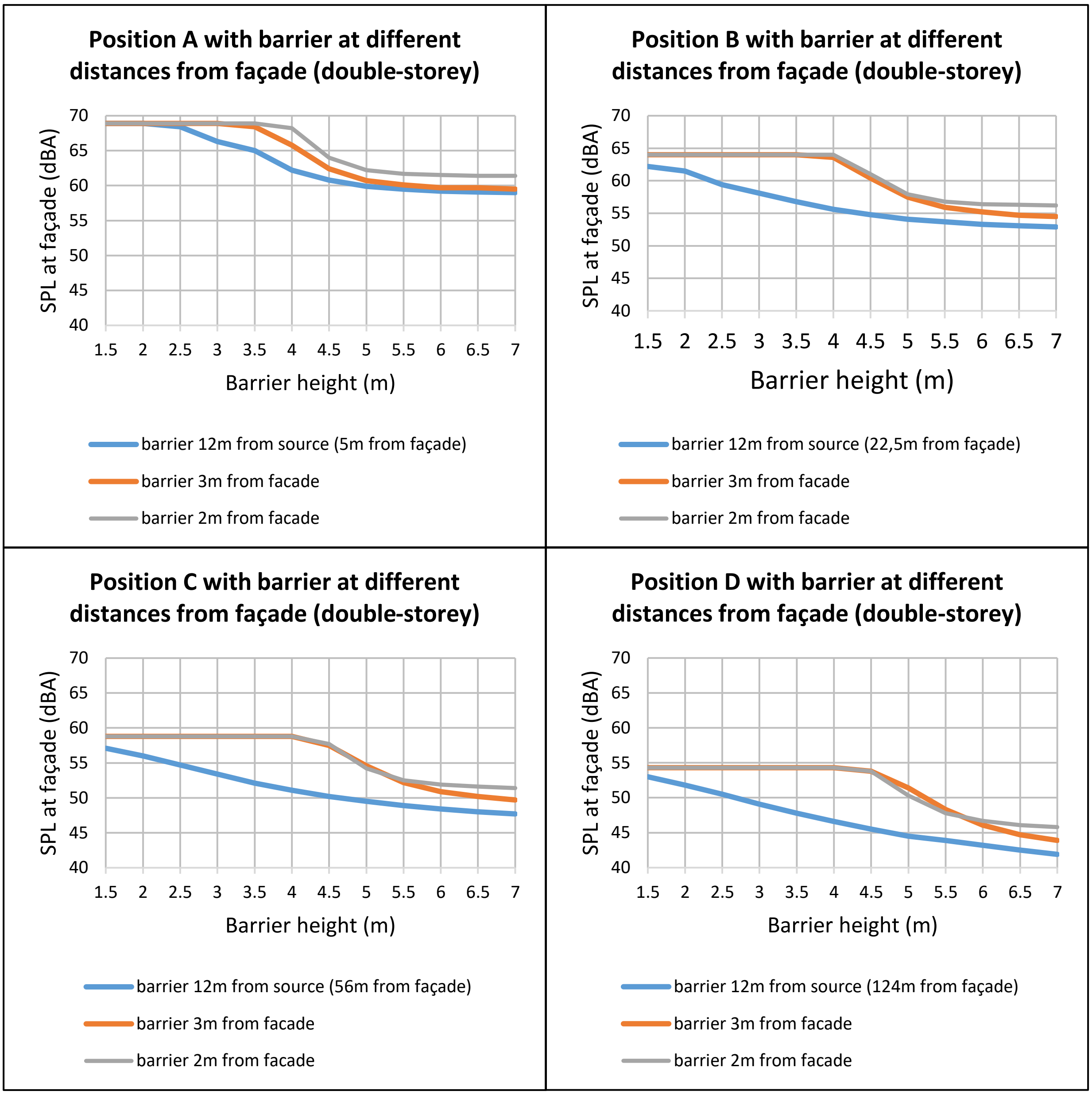


Figure 5-20: Graphic comparison of SPL at double-storey facade receiver when barrier distance relative to receiver differs

The following is observed from the results at a single-storey building:

At Position A (close to the source noise) there was very little difference in the effect of the barrier at the source (5 m from the façade) and the barrier 3 m from the façade. A slight difference occurs when the barrier is inserted 2 m from the façade, as opposed to 3 m or 5 m. This only occurs only beyond the barrier height of 2.5 m, where the barrier height begins to become excessively high. When the barrier is positioned 2 m from the façade the measured SPL is generally higher. Although the difference is noticeable on the graph, the maximum measured difference is only 1.6 dB, which is practically negligible. Thus it can be concluded that for a building close to the noise source, such as Position A, the distance of the barrier from the receiver has little effect.

Similarly, at Positions B and C, the maximum difference in SPL measured when the barrier is inserted at 3 m and at 2 m from the façade is negligible at 2.1 dB and 1.9 dB respectively. However, when the barrier is inserted close to the source and further from the receiver, the results are similar at Position B, but noticeably different at Position C, where the barrier further from the receiver generally results in a higher SPL and is thus less effective.

At Position D, there is a significant (> 3 dB) increase in the SPL measured with the barrier at 2 m from the facade when the barrier is more than 4.5 m high.

It can be concluded that at reasonable barrier heights (below 3.5 m high) there is a slight but insignificant benefit to inserting a barrier at 3 m from the façade rather than 2 m. It is also noted that at reasonable barrier heights (less than 3.5 m high) the barrier at the source (further from the receiver) results in higher SPL than with a barrier of 3 m or 2 m high. Thus, **for a single-storey building, it is generally more beneficial to insert a barrier at 3 m from the façade than at a distance closer (2 m from façade) or further (12 m from source)**.

The following is observed from the results at a double-storey building:

For the double-storey receiver, there is generally no noticeable difference in the measured SPL when a barrier is inserted 3 m or 2 m from the façade, up to a barrier height of about 4 m. This makes sense because the top of the barriers at these heights is well below the receiver level, allowing a direct line of sight between the source and receiver. With higher barriers, the measured SPL behind a barrier 2 m from the façade is slightly higher (less favourable) but insignificant (maximum 1.9 dB).

Comparing the effect of a barrier at the boundary, which is further away from the façade, to the effect of the two closer barriers, it is evident that the measured SPL is consistently lower than when the barrier is at 3 m or 2 m from the façade receiver. This seems to indicate that **for a double-storey building there is greater benefit in inserting a barrier closer to the source of the noise than closer to the receiver**, even at low barrier heights.

5.4 Alternative barrier arrangements

To try and achieve the target level at building positions closer to the road and with lower barrier heights, alternative barrier options were considered.

Only the buildings parallel to the road in the major building positions were tested to see if there was a significant result and benefit in testing at a finer resolution. Barriers in excess of 3.5 m were excluded from the exercise since these are considered to be impractical and unappealing.

5.4.1 Double barriers

Considering that the barrier further away from the receiver was more effective for double-storey receivers, but a barrier closer to the façade was more effective for single-storey receivers, it was decided to evaluate the benefit of adding barriers in both positions.

A barrier at the boundary, as in barrier arrangement 1, was inserted as well as a barrier 3 m from the façade, as in barrier arrangement 2. The results obtained for both single- and double-storey buildings are shown in Table 5-22. Comparing the range of values in the columns for each position shows the increasing benefit of inserting a barrier at the façade per source barrier height. Where the target level is achieved, the value is underlined (the ideal target is double underlined).

Even using double barriers, the target is only achieved at a distance of at least 68 m from the source (Position C). Since only the major positions were tested, and considering that with a single barrier the target was achieved at Position B2 (within the constraint of a 3.5 m high barrier), it can be assumed that the target would be reached at a building position between Positions B and C. However, the data in Table 5-22 shows that the target is still not achieved at Positions B or A.

It can be seen that the target façade SPL for a single-storey building with a barrier only at the boundary is achieved at Position C with a barrier height of 3.5 m (49.9 dBA). However, when a façade barrier is added, the target can be achieved with two lower barriers of various combinations. For example, a 2 m high boundary barrier with a 2.5 m high façade barrier achieves a façade SPL of 50.2 dBA, compared to a 2.5 m high barrier only at the façade, which would yield a façade SPL of 51.2 dBA. At the first-floor classroom, the addition of these two barriers would yield a double-storey façade SPL of 56 dBA compared to 58.8 dBA if there was only a barrier at the façade.

While such a scenario may not prove economical, it is useful to apply in situations where an existing barrier is in a constrained position with a constrained height, and an additional barrier can help improve the IL.

It is noted that the ideal target remains a challenge to achieve for any building position other than Position D.

Table 5-22: SPL recorded at facade positions with two barriers

Barrier height at boundary (m) →		**0**	**1.5**	**2**	**2.5**	**3**	**3.5**	**0**	**1.5**	**2**	**2.5**	**3**	**3.5**
Position	Barrier height at 3m from façade (m) ↓	SPL measured at single-storey façade receiver (dBA)						SPL measured at double-storey façade receiver (dBA)					
A	0	**68.1**	63.8	61.4	59.9	58.9	58.5	68.9	68.9	68.9	68.4	66.3	65
	1.5	**64.5**	63.7	61.4	59.8	58.8	58.3	68.9	68.9	68.9	68.4	66.3	65
	2	**61.5**	61.3	60.8	59.6	58.7	58.2	68.9	68.9	68.9	68.4	66.3	65
	2.5	**59.7**	59.5	59.3	59.1	58.6	58.1	68.9	68.9	68.9	68.4	66.3	65
	3	**58.8**	58.6	58.4	58.3	58.2	57.9	68.9	68.9	68.9	68.4	66.3	65
	3.5	**58.4**	58.1	58	57.9	57.8	57.7	68.4	68.4	68.4	68.3	66.3	65
B	0	**62.1**	59.4	57.5	55.9	54.6	53.7	64.0	62.2	61.5	59.4	58.1	56.8
	1.5	**61**	59.4	57.5	55.9	54.6	53.6	64	62.2	61.5	59.4	58.1	56.8
	2	**58.1**	57.5	56.4	55.8	54.2	53.3	64	62.2	61.5	59.4	58.1	56.8
	2.5	**55.5**	55.3	54.7	55.6	53.4	52.9	64	62.2	61.5	59.4	58.1	56.8
	3	**54.1**	53.9	53.6	55.4	52.7	52.3	64	62.2	61.5	59.4	58.1	56.8
	3.5	**53.4**	53.2	52.8	55.3	52.1	51.9	64	62.2	61.5	59.4	58.1	56.8
C	0	**57.5**	55.5	53.8	52.3	51	49.9	58.8	57.1	56	54.7	53.4	52.1
	1.5	**57.1**	55.4	53.8	52.2	51	49.9	58.8	57.1	56	54.7	53.4	52.2
	2	**54.4**	53.3	52.1	51	50	49.1	58.8	57.1	56	54.7	53.4	52.2
	2.5	**51.2**	50.8	50.2	49.5	48.9	48.2	58.8	57.1	56	54.7	53.4	52.2
	3	**49.1**	48.9	48.6	48.2	47.8	47.4	58.8	57.1	56	54.7	53.4	52.2
	3.5	**47.8**	47.7	47.6	47.3	47	46.7	58.8	57.1	56	54.7	53.4	52.2
D	0	**52.3**	50.9	49.6	48.2	46.8	45.6	54.3	53	51.8	50.5	49.1	47.8
	1.5	**52.2**	50.9	49.5	48.2	46.8	45.6	54.3	53	51.8	50.5	49.1	47.8
	2	**49.6**	48.4	47.3	46	44.9	43.8	54.3	53	51.8	50.5	49.1	47.8
	2.5	**45.9**	45.4	44.8	44.1	43.3	42.5	54.3	53	51.8	50.5	49.1	47.8
	3	**43.2**	43	42.7	42.2	41.7	41.2	54.3	53	51.8	50.5	49.1	47.8
	3.5	**41.5**	41.4	41.2	40.9	40.5	40	54.3	53	51.8	50.5	49.1	47.8

5.4.2 Barrier with crown

The shape of the barrier was changed by adding a crown cantilevered at 45° by 0.5 m on the roadward side of the barrier. The crown dimensions were limited by reasonable construction constraints, a cantilever of greater than 0.5 m being difficult to stabilise and construct.

The crowned barrier was inserted at the site boundary, as in barrier arrangement 1. The results are shown in Table 5-23.

Table 5-23: SPL at façade receivers resulting when crowned barrier inserted at 12 m from the source

		Single-storey						Double-storey					
Barrier height (m):		0	1.5	2	2.5	3	3.5	0	1.5	2	2.5	3	3.5
Building position		SPL at façade receiver (dBA)											
Building parallel	A	68.1	63.6	61.3	59.8	58.9	58.4	68.9	68.9	68.9	68.3	66.0	64.8
	B	62.1	59.3	57.4	55.8	54.6	53.6	64.0	62.2	61.4	59.2	57.9	56.6
	C	57.5	55.4	53.7	52.2	<u>50.9</u>	<u>49.8</u>	58.8	57.0	55.9	54.5	53.2	52.0
	D	52.3	50.8	<u>49.4</u>	<u>48.0</u>	<u>46.7</u>	<u>45.5</u>	54.3	52.9	51.7	<u>50.3</u>	<u>49.0</u>	<u>47.7</u>

The target SPL was only achieved at Position C with a barrier of at least 3.5 m high and at Position D with a barrier of at least 2 m high. When compared to the insertion loss achieved with the insertion of non-crowned barriers of the same total height, the difference was negligible (less than 0.5 dB). This minimal effect can be seen in the sound contour illustration in Figure 5-21.

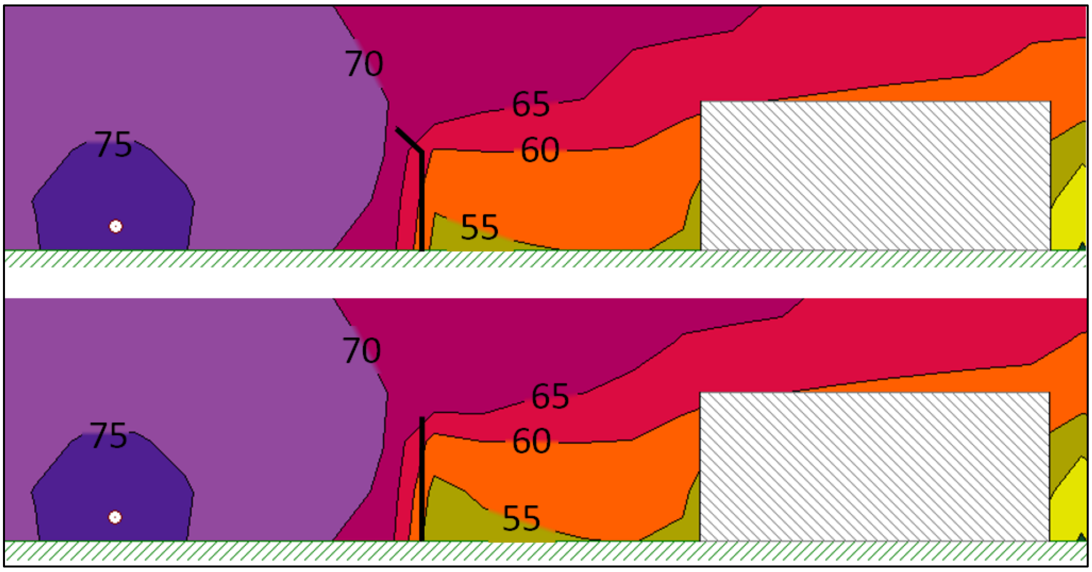


Figure 5-21: Illustration of effect of crowned barrier on sound contours

This exercise was repeated with the barrier inserted at a fixed distance of 3 m from the building façade, as in barrier arrangement 2.

Table 5-24: SPL at facade receivers resulting when crowned barrier inserted at 3 m from the façade

		Single-storey						Double-storey					
Barrier height (m):		0	1.5	2	2.5	3	3.5	0	1.5	2	2.5	3	3.5
Building position		SPL at façade receiver (dBA)											
Building parallel	A	68.1	64.4	61.6	59.8	59	58.5	68.9	68.9	68.9	68.9	68.9	68.3
	B	62.1	61	58.4	55.9	54.5	53.6	64.0	64	64	64	64	64
	C	57.5	57.1	54.8	51.8	49.7	48.4	58.8	58.8	58.8	58.8	58.8	58.8
	D	52.3	52.2	50.1	46.8	44.3	42.6	54.3	54.3	54.3	54.3	54.3	54.3

The target SPL was again only achieved at a distance of at least 68 m from the road (Position C) with at least a 3 m high barrier, and at Position D with at least a 2 m high barrier. When compared to the insertion loss achieved with the insertion of non-crowned barriers of the same total height, the difference was negligible (less than 3 dB, on average 0.7 dB).

It can be concluded that the addition of crowning as described has no noticeable effect.

5.4.3 Wrapped barrier

The barrier arrangements tested so far were parallel to the road. This is not necessarily representative of an actual school site, where a boundary wall would be wrapped around the sides of the site and not only in front of the road.

A series of scenarios was created in which the barrier was partially wrapped around the building or site to gauge the effect of the length, position and height.

The first wrapped barrier design assumed a barrier of 62 m long (twice the length of the building), parallel to the road, and turned back towards the inside of the site by a length of 16 m, as illustrated in Figure 5-22. This was inserted as in barrier arrangement 1 (barrier close to source).

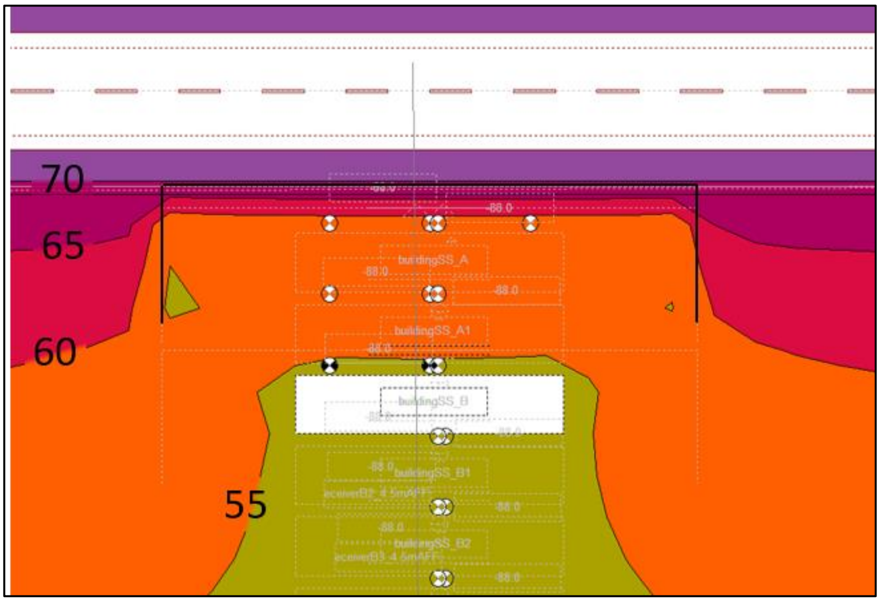


Figure 5-22: Illustration of sound contours with barrier at source and turned back at sides

The resulting façade SPL for this barrier scenario at various heights for each of the major building positions and for single- and double-storey buildings is recorded in Table 5-25.

Table 5-25: SPL at façade receivers when barrier at source is turned back at sides

		Single-storey						Double-storey					
Barrier height (m):		0	1.5	2	2.5	3	3.5	0	1.5	2	2.5	3	3.5
Building position		SPL at façade receiver (dBA)											
Building parallel	A	68.1	63.6	60.8	58.4	56.4	54.8	68.9	68.9	68.9	69.3	66.1	64.6
	B	62.1	59.5	57.8	56.1	54.7	53.4	64.0	62.4	61.7	59.9	58.8	57.6
	C	57.5	57.1	53.8	50.3	48.1	46.6	58.8	57.8	57.2	56.7	56.3	56
	D	52.3	51.9	51.6	51.4	51.3	51.2	54.3	53.9	53.6	53.4	53.3	53.2

The results show that the target SPL is achieved at Position C when the barrier is at least 2.5 m high. These results were compared to the respective resulting SPL with a parallel barrier and the following observations were made:

- Position A: It is found that the wrapped barrier provides a better insertion loss for a single-storey building, and equivalent performance for a double-storey building at Position A. However, the difference was insignificant (less than 3 dB), except at the maximum reasonable barrier height of 3.5 m.
- Position B: There was hardly any difference in performance for both types of barriers for single- and double-storey buildings.

- Position C: For a single-storey building the wrapped barrier performs better than the parallel barrier if the barrier is more than 2 m high; at a barrier height of 2 m the performance is equivalent, and at lower than 2 m the parallel barrier is more effective. However, the difference in performance is only significant (> 3 dB) if the barrier is more than 3 m high. For a double-storey building, the wrapped barrier is less effective than the parallel barrier, with the difference only being significant when the barrier is at least 3 m high.
- Position D: For a single- and double-storey building the parallel barrier provides a more favourable insertion loss than the wrapped barrier, although the difference is only significant if the barrier is at least 2.5 m high. This could be expected due to the short length of the wrapped barrier in this scenario relative to the distance to the receiver, allowing sound to travel around the barrier.

An alternate of this barrier scenario was modelled in which a wrapped barrier of the same design was positioned at 3 m from the building façade, as illustrated in Figure 5-23.

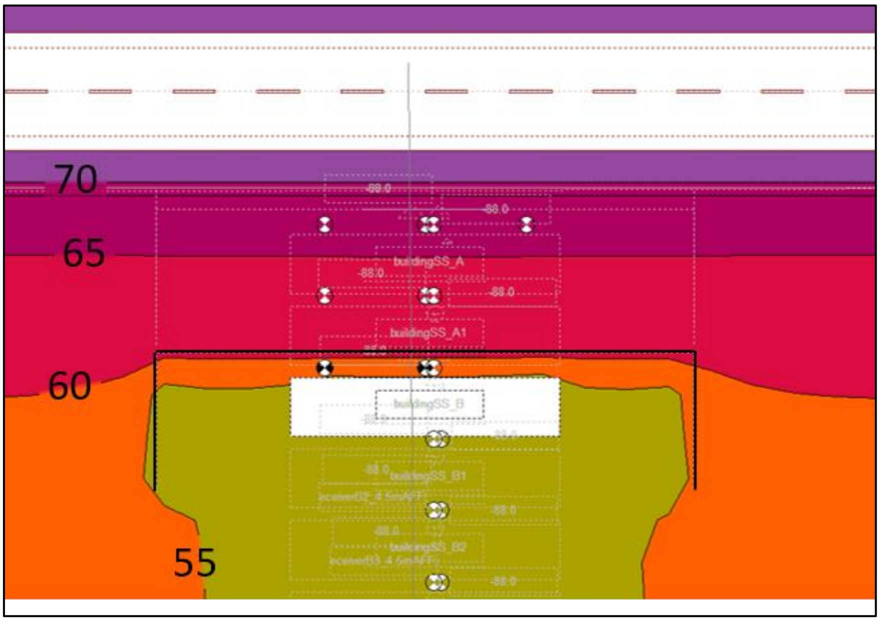


Figure 5-23: Illustration of sound contours with barrier at façade and turned back at sides

The results in Table 5-26 show that this type of barrier arrangement is effective in achieving the target SPL at Positions B, C and D with barriers of at least 3.5 m, 3 m and 2 m high respectively. At Positions A and C, the SPL values are similar for the previous scenario. However, the results are significantly improved for Positions B and D.

Table 5-26: SPL at façade receivers when barrier at facade is turned back at sides

		Single-storey						Double-storey					
Barrier height (m):		0	1.5	2	2.5	3	3.5	0	1.5	2	2.5	3	3.5
Building position		SPL at façade receiver (dBA)											
Building parallel	A	68.1	64.3	60.7	57.7	55.4	53.6	68.9	68.9	68.9	68.9	68.9	68.2
	B	62.1	61	57.9	54.7	52.2	<u>50.3</u>	64.0	64	64	64	64	64
	C	57.5	57.1	54.3	50.8	<u>48.1</u>	<u>46</u>	58.8	58.8	58.8	58.8	58.8	58.8
	D	52.3	52.2	<u>49.6</u>	<u>45.8</u>	<u>42.8</u>	<u>40.5</u>	54.3	54.3	54.3	54.3	54.3	54.3

The following was observed when these results are compared to previous results:

- Position A: The wrapped barrier positioned at the façade performs similarly to the wrapped barrier at the source for a single-storey building, yielding a higher IL for higher barriers than a parallel barrier at the source or at the façade. For a double-storey building, the performance is the same as for a parallel barrier in the same position.
- Position B: The wrapped barrier close to the façade of a single-storey building results in lower façade SPL levels if the barrier is more than 2 m high; however, the difference is only significant where the barrier is at least 3.5 m high. For a double-storey building, the performance is the same as that of a parallel barrier at the façade and significantly poorer than the performance of the parallel or wrapped barriers at the source.
- Position C: For a single-storey building, the IL achieved by inserting a wrapped barrier close to the façade is almost exactly the same as that achieved by the wrapped barrier at the source. For a double-storey building, the performance of a wrapped barrier at the façade is the same as for a parallel barrier at the façade and poorer than the insertion of barriers at the source.
- Position D: For a single-storey building at this distance from the source the wrapped and parallel barriers at the façade perform equally to each other and generally better than the parallel or wrapped barrier at the source. However, if the building is double-storey, the wrapped barrier at the façade provides a significantly better insertion loss than any of the alternate barrier scenarios if the barrier is at least 2.5 m high.

Lastly, the wrapped barrier design was changed, greatly increasing the length to represent a wall wrapped around a larger school area. A barrier of 200 m long parallel to the road and turned back at the sides by 50 m yielded the results in Table 5-27.

Table 5-27: SPL at façade receivers when barrier wrapped around site

		Single-storey						Double-storey					
Barrier height (m):		0	1.5	2	2.5	3	3.5	0	1.5	2	2.5	3	3.5
Building position		SPL at façade receiver (dBA)											
Building parallel	A	68.1	63.6	60.8	58.4	56.5	54.9	68.9	68.9	68.9	68.3	66.1	64.6
	B	62.1	59.4	57.6	55.8	54.3	53.1	64.0	62.2	61.6	59.3	58	56.5
	C	57.5	55	54	52.7	51.6	50.7	58.8	57.1	56.2	55	53.9	53
	D	52.3	51.3	50.6	50	49.4	48.8	54.3	53.2	52.4	51.5	50.9	50.5

The target SPL in this scenario was only achieved at Position D with a barrier of at least 2 m high. The following is observed when comparing these results to previous results:

- Position A: The insertion loss achieved by the perimeter barrier is similar to that of the wrapped barrier at the façade of either the single- or double-storey buildings and not significantly different from any other results.
- Position B: The resulting SPLs at the façade of the single- or double-storey buildings are the same as for those measured when a wrapped or parallel barrier is inserted at the source.
- Position C: The wrapped perimeter barrier performs equally to the parallel barrier at the source.
- Position D: Here the wrapped perimeter barrier performs slightly better than the wrapped barrier at the source for a single-storey building, and worse than either of the parallel barriers and the wrapped barrier at the façade. This could be attributed to the short length of the barrier relative to the distance to the receiver allowing sound to travel around the barrier. Better performance could probably have been achieved if the turned back sections of the barrier were extended by the distance from the source to the receiver. For a double-storey building, the results are similar.

The above comparisons are graphically represented in Figure 5-24, where it is visually clear that a wrapped barrier at the façade yields a lower façade SPL than other options for a single-storey building, and for double-storey buildings, a parallel barrier at the source is generally better. In all cases, there is only a significant difference between the worst-performing and best-performing scenarios if the barrier is at least 2.5 m high.

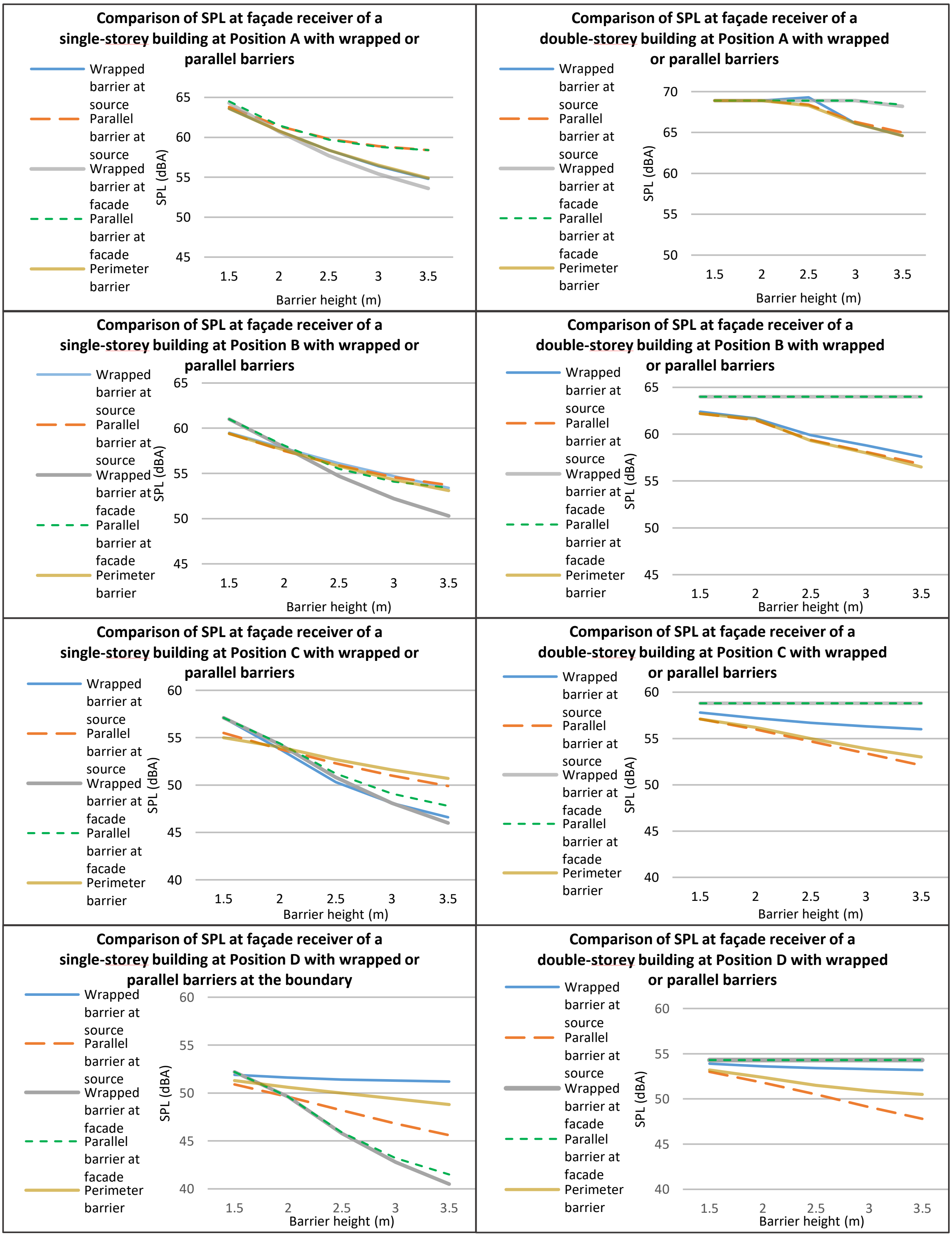


Figure 5-24: Graphic representation of different barrier scenarios for single- and double-storey buildings at each major position

5.4.4 Topographical barrier

Although the initial assumption was that the site is level with the road, the influence of topography was explored to a limited extent since it can be seen as a type of barrier, changing the sound path.

A site was created in the model that is raised 2 m above the road level by a steep embankment at the boundary, as shown in Figure 5-25.

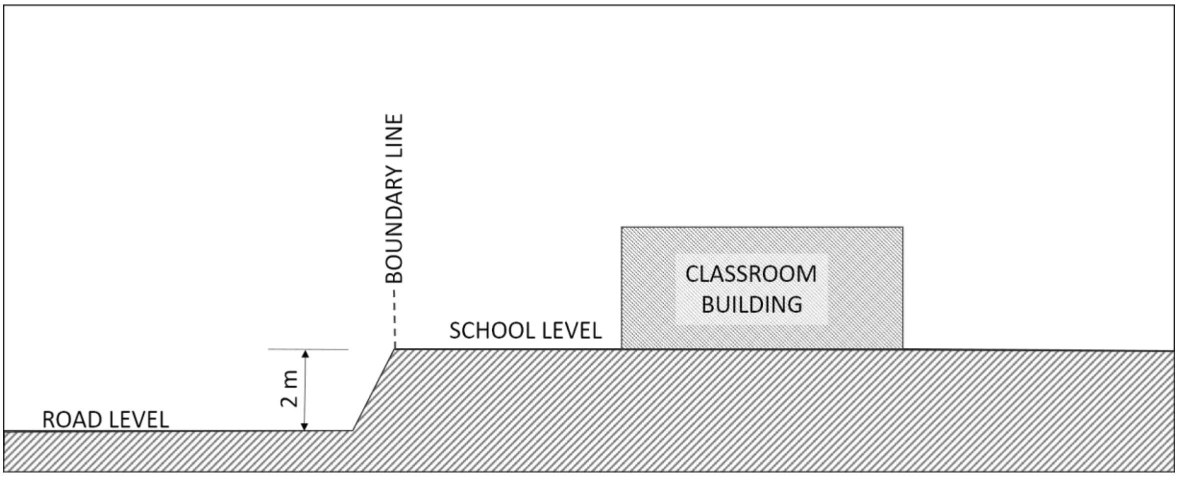


Figure 5-25: Illustration of change in ground level applied in model

The height of the barrier at the boundary was varied and the resultant façade SPLs at the major building positions are recorded as shown in Table 5-28 for a single-storey building and

Table 5-29 for a double-storey building.

The resultant SPL values are lower relative to barrier height for the façade receivers on the raised site compared to the level site, as graphically illustrated in Figure 5-26. This can be attributed to the fact that the barrier on the raised site is effectively 2 m higher than on the level site since the ground level is raised by 2 m above the noise source. The effective factor in attenuating sound that is at play is the path difference – the sound path is longer for the raised site.

Table 5-28: SPL at façade receivers of single-storey building when site level is raised 2 m above road level with barriers of different heights

Barrier height (m):		**0**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**
Building position		SPL at façade receiver (dBA)												
Parallel	A	59.4	55.7	55.3	55	54.8	54.7	54.6	54.5	54.5	54.5	54.4	54.3	54.3
	B	56.2	52.6	52	51.5	51.1	50.8	50.6	50.4	50.3	50.2	50.1	50	50
	C	52.9	49.3	48.5	47.7	47.2	46.7	46.3	46	45.7	45.5	45.3	45.2	45.1
	D	49.5	45.6	44.5	43.5	42.6	41.7	40.9	41	40.5	40.1	39.7	39.4	39.1
Perpendicular	ARc1	56.1	52.3	51.8	51.4	51.1	50.9	50.8	50.7	50.6	50.5	50.4	50.4	50.3
	BRc1	53.3	49.6	48.9	48.4	47.9	47.6	47.4	47.2	47	46.9	46.8	46.7	46.6
	CRc1	50.4	46.5	45.7	45.2	44.4	43.9	43.5	43.1	42.8	42.6	42.4	42.2	42.1
	DRc1	47.2	43	41.9	40.9	40	39.2	38.4	39.3	38.9	38.6	38.4	38.1	37.9

Table 5-29: SPL at façade receivers of double-storey building when site level is raised 2 m above road level with barriers of different heights

Barrier height (m):		**0**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**
Building position		SPL at façade receiver (dBA)												
Parallel	A	69.7	65.5	62.9	61.5	60.7	60.2	59.9	59.8	59.7	59.5	59.5	59.4	59.4
	B	62.0	57.4	56.1	55.2	54.4	53.8	53.3	53.1	52.8	52.6	52.5	52.3	52.2
	C	58.7	52.6	51.5	50.5	49.8	49.1	48.6	48.1	47.8	47.5	47.2	47	46.8
	D	51.8	47.8	46.6	45.5	44.5	43.6	43.2	42.5	41.9	41.4	40.9	40.5	40.2
Perpendicular	ARc1	65.4	59	57.4	56.2	55.3	54.7	54.3	54.1	53.8	53.7	53.6	53.5	53.4
	BRc1	58.5	53.7	52.5	51.5	50.8	50.2	49.8	49.4	49.2	49	48.8	48.6	48.5
	CRc1	53.5	49.3	48.2	47.7	46.6	45.9	45.4	45	44.6	44.3	44	43.8	43.6
	DRc1	49.1	44.9	43.8	42.7	41.7	40.8	40.9	40.3	39.9	39.5	39.2	38.9	38.6

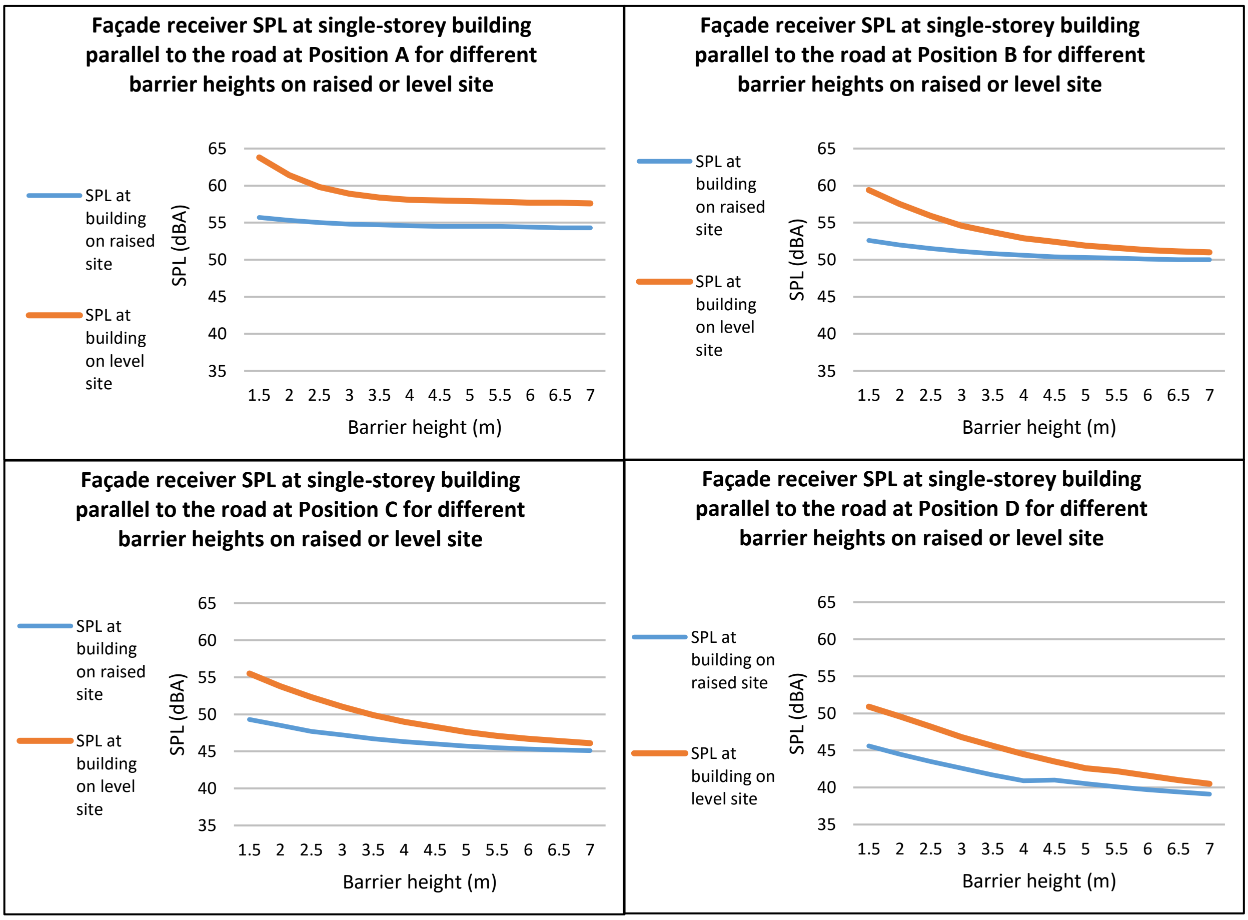


Figure 5-26: Comparison of SPL at façade receiver of buildings on raised and level sites with varying barrier heights

It can be concluded that raising the site by 2 m above the level of the noise source (road) increases the attenuation effect of barriers inserted at the boundary of the site.

5.5 Conclusion to experiment

Through the data generated by the modelled scenarios, a number of suitable options for effectively attenuating road-traffic noise and achieving an acceptable ambient noise level in a classroom were established.

It was established that the ideal target ambient SPL of 35 dBA in a typical naturally ventilated classroom could not be achieved for any building position 136 m or less from a typical source of traffic noise, and the accepted target of 40 dBA could only be achieved in a building at least 136 m from the road if the building was orientated perpendicular to the road. This is assuming that there are no physical barriers, that the site is level with the road and that the façade consists of a solid wall with 28% of its area open and 7.5% of its area glazed. In order to achieve the accepted target for any other building position or orientation considered in this experiment, barriers were required.

When a barrier, in the form of a dense, solid wall, was inserted between the noise source and the receiver position, the target SPL could not be achieved at any building positioned less than 42.5 m from the noise source, at which distance a barrier of at least 5.5 m high was required (see Table 5-19). The further the building is positioned from the noise source, the lower the barrier needs to be.

The findings are summarised and discussed in terms of their application in Chapters 6 and 7.

Chapter 6: Discussion and application

The findings in Chapter 5 were reported with reference to the target indoor ambient noise level, which was accepted to be 40 dBA, although ideally 35 dBA. However, the insertion of barriers is normally discussed in terms of the insertion loss (IL) and, although the target SPL was not achieved in all scenarios, an insertion loss was achieved.

The application of the findings with reference to the target SPL and with reference to the insertion losses achieved will be discussed in this chapter.

6.1 Insertion loss assessment

If one considers that a 3 dB change in SPL represents a noticeable difference in perceived sound level, and that a 6 dB change is a significant perceived difference (McShefferty *et al.*, 2015), it can be argued that a significant improvement in the signal-to-noise ratio (SNR) in a classroom can be achieved by an insertion loss (IL) of 6 dB.

An exercise was performed to determine under which of the barrier conditions an IL of at least 6 dB could be achieved relative to the SPL when there was no barrier for a classroom at the same distance from the road. A reduction in the ambient SPL in the classroom would result in the signal-to-noise ratio (SNR) increasing by 6 dB, making a significant difference to the intelligibility of the teacher's voice in a classroom.

The insertion losses achieved by inserting a barrier of differing heights at a fixed position relative to the centre of the road (barrier arrangement 1) are shown in Table 6-1 for a ground-floor classroom and Table 6-2 for a first-floor classroom. The insertion losses that are at least 6 dB, representing a significant reduction in perceived sound level and improvement in SNR, are underlined in the tables.

Table 6-1: Insertion loss achieved with barrier arrangement 1 (barrier 12 m from centre of road) for single-storey building (receiver height 1.5 m)

Position	**Barrier height (m):**											
	1.5	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**
A	**4.3**	**6.7**	**8.2**	**9.2**	**9.6**	**10**	**10.1**	**10.2**	**10.3**	**10.4**	**10.4**	**10.5**
A1	3.4	5.4	7	8.2	9.1	9.7	10.1	10.5	10.7	10.9	11	11.2
B	**2.7**	**4.6**	**6.2**	**7.5**	**8.4**	**9.2**	**9.7**	**10.2**	**10.5**	**10.8**	**11**	**11.1**
B1	2.6	4.3	5.9	7.2	8.2	9	9.6	10.1	10.5	10.8	11	11.2
B2	2.3	4.1	5.6	6.9	7.9	8.8	9.4	9.9	10.4	10.7	11	11.2
B3	2.2	3.9	5.4	6.7	7.8	8.6	9.3	9.9	10.4	10.7	11	11.3
C	**2**	**3.7**	**5.2**	**6.5**	**7.6**	**8.5**	**9.2**	**9.9**	**10.4**	**10.8**	**11.1**	**11.4**
C1	2.1	3.7	5.2	6.5	7.6	8.5	9.3	9.9	10.5	10.9	11.3	11.6
C2	1.9	3.5	5	6.3	7.4	8.4	9.2	9.9	10.5	10.9	11.4	11.7
C3	1.8	3.3	4.7	6	7.1	8.1	8.9	9.6	10.3	10.8	11.4	11.8
C4	1.8	3.3	4.7	6	7.1	8.1	9	9.7	10.4	11	11.5	11.9
C5	1.6	3	4.4	5.7	6.8	7.8	8.7	9.5	10.2	10.8	11.4	11.9
C6	1.5	2.9	4.3	5.6	6.7	7.8	8.7	9.5	9.7	10.3	10.7	11.1
C7	1.4	2.8	4.2	5.5	6.7	7.8	8.8	9.6	9.9	10.5	11	11.4
D	**1.4**	**2.7**	**4.1**	**5.5**	**6.7**	**7.8**	**8.8**	**9.7**	**10.1**	**10.7**	**11.3**	**11.8**
ARc1	4.1	6.2	7.8	9	9.7	10.3	10.6	10.9	11.2	11.3	11.5	11.6
BRc2	2.7	4.4	6	7.2	8.2	8.9	9.5	9.9	10.3	10.6	10.8	11
CRc1	2.1	3.7	4.8	6.3	7.3	8.2	8.9	9.6	10.1	10.5	10.9	11.2
DRc1	1.6	3	4.3	5.6	6.8	7.9	8.8	9.7	9.6	10.1	10.6	11

Note: underlined values indicate a significant IL (at least 6 dB with reference to no barrier)

Table 6-2: Insertion loss achieved with barrier arrangement 1 (barrier 12 m from centre of road) for double-storey building (receiver height 4.5 m)

Position	**Barrier height (m):**											
	1.5	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**
A	**0**	**0**	**0.5**	**2.6**	**3.9**	**<u>6.7</u>**	**<u>8.1</u>**	**<u>9</u>**	**<u>9.4</u>**	**<u>9.7</u>**	**<u>9.8</u>**	**<u>9.9</u>**
A1	0	2.3	3	5.7	<u>7.1</u>	<u>8.4</u>	<u>9.3</u>	<u>10</u>	<u>10.5</u>	<u>10.8</u>	<u>11.1</u>	<u>11.2</u>
B	**1.8**	**2.5**	**4.6**	**5.9**	**<u>7.2</u>**	**<u>8.4</u>**	**<u>9.2</u>**	**<u>9.9</u>**	**<u>10.3</u>**	**<u>10.7</u>**	**<u>10.9</u>**	**<u>11.1</u>**
B1	1.4	3.2	4.3	5.6	<u>6.9</u>	<u>8</u>	<u>8.8</u>	<u>9.4</u>	9.9	<u>10.3</u>	<u>10.6</u>	<u>10.8</u>
B2	1.2	2.9	4.1	5.5	<u>6.7</u>	<u>7.8</u>	<u>8.6</u>	<u>9.3</u>	9.8	<u>10.2</u>	<u>10.5</u>	<u>10.8</u>
B3	1.1	2.8	4	5.4	<u>6.6</u>	<u>7.6</u>	<u>8.5</u>	<u>9.2</u>	9.7	<u>10.2</u>	<u>10.6</u>	<u>10.8</u>
C	**1.7**	**2.8**	**4.1**	**5.4**	**<u>6.7</u>**	**<u>7.7</u>**	**<u>8.6</u>**	**<u>9.3</u>**	**9.9**	**<u>10.4</u>**	**<u>10.8</u>**	**<u>11.1</u>**
C1	1.6	2.7	4.1	5.4	<u>6.7</u>	<u>7.8</u>	<u>8.7</u>	<u>9.5</u>	<u>10.2</u>	<u>10.8</u>	<u>11.4</u>	<u>11.8</u>
C2	1.5	2.6	4	5.3	<u>6.6</u>	<u>7.6</u>	<u>8.6</u>	<u>9.4</u>	<u>10.1</u>	<u>10.7</u>	<u>11.2</u>	<u>11.6</u>
C3	1.5	2.6	4	5.4	<u>6.6</u>	<u>7.7</u>	<u>8.7</u>	<u>9.6</u>	<u>10.4</u>	<u>11</u>	<u>11.8</u>	<u>12.3</u>
C4	1.5	2.6	4	5.4	<u>6.6</u>	<u>7.7</u>	<u>8.7</u>	<u>9.6</u>	<u>10.4</u>	<u>11.1</u>	<u>11.7</u>	<u>12.3</u>
C5	1.4	2.5	3.9	5.3	<u>6.5</u>	<u>7.7</u>	<u>8.7</u>	<u>9.7</u>	<u>10.5</u>	<u>11.2</u>	<u>11.9</u>	<u>12.5</u>
C6	1.4	2.6	4	5.4	<u>6.6</u>	<u>7.8</u>	<u>8.8</u>	<u>9.5</u>	<u>10.3</u>	<u>10.9</u>	<u>11.5</u>	<u>12</u>
C7	1.3	2.5	3.9	5.2	<u>6.5</u>	<u>7.7</u>	<u>8.8</u>	<u>9.5</u>	<u>10.6</u>	<u>11.5</u>	<u>12.2</u>	<u>12.9</u>
D	**1.3**	**2.5**	**3.8**	**5.2**	**<u>6.5</u>**	**<u>7.7</u>**	**<u>8.8</u>**	**<u>9.8</u>**	**<u>10.4</u>**	**<u>11.1</u>**	**<u>11.8</u>**	**<u>12.4</u>**
ARc1	0	0	2.6	3.3	<u>6.5</u>	<u>8</u>	<u>9.2</u>	<u>9.9</u>	<u>10.4</u>	<u>10.7</u>	<u>11</u>	<u>11.2</u>
BRc1	1.6	2.3	4.4	5.7	<u>7</u>	<u>8.1</u>	<u>8.9</u>	<u>9.6</u>	<u>10.1</u>	<u>10.5</u>	<u>10.8</u>	<u>11</u>
CRc1	1.7	2.7	3.8	5.4	<u>6.5</u>	<u>7.5</u>	<u>8.4</u>	<u>9.1</u>	9.7	<u>10.2</u>	<u>10.6</u>	<u>11</u>
DRc1	1.4	2.5	3.8	5.1	<u>6.4</u>	<u>7.6</u>	<u>8.6</u>	<u>9.2</u>	<u>10</u>	<u>10.7</u>	<u>11.3</u>	<u>11.9</u>

Note: underlined values indicate a significant IL (at least 6 dB with reference to no barrier)

It is evident that a significant insertion loss, and consequent improvement in the SNR in the classroom, can be achieved at positions as close as 17 m (Position A) from the noise source with reasonable barrier heights (less than 3.5 m).

At Position A (the building closest to the noise source), the ambient sound pressure level in a ground-floor classroom without any interventions was predicted by the model to be 58.4 dBA (see Table 5-3). With the insertion of a 2 m high barrier at the site boundary, providing an insertion loss of 6.7 dB, an indoor level of 51.7 dBA can be achieved. While this does not provide a suitable SNR at all seat positions in the classroom and it will not correct other factors that influence speech intelligibility, such as reverberation time, it will still result in a significant improvement in the ability fo learners to hear the teacher.

This example demonstrates the potential for the interventions explored in this study to improve the acoustic conditions in classrooms, even when the target ambient SPL is not achieved.

At building positions where the target level is reached, the acceptable SNR is already achieved.

Similarly, the insertion losses for barrier arrangement 2 (fixed at 3 m from façade), with barriers of varying heights, are shown in Table 6-3 for a single-storey building and Table 6-4 for a double-storey building.

Under this barrier arrangement, a significant decrease in ambient sound pressure level in the classroom at Position A will be experienced. Here, the classroom SPL was predicted by the model to be 58.4 dBA, which is reduced to 51.8 dBA with a 2 m high barrier at 3 m from the façade. This is effectively the same as the previous scenario (under barrier arrangement 1) because in both cases the building is very close to the source and the barrier.

At Position B, the model predicted an indoor SPL of 52.4 dBA with no interventions. This can be reduced to 45.8 dBA with the insertion of a 2.5 m high barrier. The same building position, but under barrier arrangement 1, produces an indoor SPL of 46.2 dBA with the insertion of a 2.5 m high barrier, which is similar. At Position C a lower barrier (2.5 m) can be inserted to produce at least a 6 dB insertion loss compared to the same building position but under barrier arrangement 1 (where an insertion loss of at least 6 dB can only be achieved at a barrier height of 3.5 m).

It can be concluded from this that although the target SPL of 40 dBA indoors cannot be achieved with reasonable barrier heights, a significant insertion loss can be achieved at reasonable barrier heights for ground-floor classrooms but not for first-floor classrooms.

Table 6-3: IL for single-storey with barrier 3 m from façade

Position	Barrier height (m):											
	1.5	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**
A	**3.6**	**6.6**	**8.4**	**9.3**	**9.7**	**9.9**	**10.0**	**10.1**	**10.2**	**10.2**	**10.2**	**10.4**
A1	1.9	4.9	7.1	8.3	8.9	9.2	9.4	9.5	9.6	9.7	9.8	9.9
B	**1.1**	**4.0**	**6.6**	**8.0**	**8.7**	**9.2**	**9.4**	**9.6**	**9.7**	**9.8**	**9.9**	**10.1**
B1	0.8	3.7	6.4	7.9	8.8	9.3	9.6	9.8	10.0	10.1	10.2	10.3
B2	0.6	3.4	6.3	8.1	9.1	9.7	10.1	10.4	10.6	10.7	10.9	11.1
B3	0.5	3.3	6.4	8.4	9.6	10.4	10.8	11.2	11.4	11.9	11.7	12.0
C	**0.4**	**3.1**	**6.3**	**8.4**	**9.7**	**10.4**	**11.0**	**11.3**	**11.6**	**11.8**	**11.9**	**12.2**
C1	0.4	3.1	6.4	8.6	9.9	10.7	11.3	11.7	11.9	12.1	12.3	12.6
C2	0.4	3.1	6.4	8.6	10.0	10.9	11.5	11.9	12.2	12.4	12.5	12.9
C3	0.3	3.0	6.4	8.6	10.0	10.9	11.4	11.9	12.1	12.4	12.5	12.7
C4	0.2	2.9	6.4	8.7	10.2	11.1	11.8	12.2	12.6	12.8	13.0	13.2
C5	0.2	2.9	6.4	8.8	10.4	11.4	12.1	12.5	12.9	13.1	13.3	13.5
C6	0.2	2.8	6.4	8.9	10.5	11.6	12.4	12.9	13.3	13.6	13.8	14.0
C7	0.2	2.8	6.4	9.0	10.7	11.8	12.6	13.2	13.6	13.9	14.2	14.4
D	**0.1**	**2.7**	**6.4**	**9.1**	**10.8**	**12.0**	**12.9**	**13.5**	**13.9**	**14.3**	**14.6**	**14.8**
ARc1	3.6	5.9	7.7	9.0	9.9	10.5	11.0	11.4	11.6	11.8	12.0	12.2
BRc1	1.1	2.8	4.9	6.5	7.8	8.7	9.4	9.9	10.4	10.7	11.0	11.3
CRc1	0.4	1.5	3.5	5.3	6.7	7.9	8.8	9.5	10.1	10.6	11.0	11.5
DRc1	0.3	0.8	2.6	4.4	6.0	7.4	8.6	9.8	10.8	11.8	12.6	13.3

Table 6-4: IL for double-storey with barrier 3 m from façade

Position	Barrier height (m):											
	1.5	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**
A	**0.0**	**0.0**	**0.0**	**0.0**	**0.5**	**3.1**	**6.5**	**8.2**	**8.8**	**9.2**	**9.2**	**9.4**
A1	0.0	0.0	0.0	0.0	0.0	0.7	5.0	7.5	8.7	9.3	9.6	9.8
B	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.4**	**3.6**	**6.5**	**8.1**	**8.8**	**9.3**	**9.5**
B1	0.0	0.0	0.0	0.0	0.0	0.0	2.5	5.5	7.3	8.3	8.8	9.0
B2	0.0	0.0	0.0	0.0	0.0	0.0	1.8	4.8	6.9	8.0	8.5	8.9
B3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	1.4	4.4	6.6	7.8	8.4	8.8
C	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**1.3**	**4.2**	**6.6**	**7.9**	**8.6**	**9.1**
C1	0.0	0.0	0.0	0.0	0.0	0.0	1.0	3.9	6.4	7.8	8.6	9.1
C2	0.0	0.0	0.0	0.0	0.0	0.0	0.9	3.7	6.3	7.9	8.8	9.3
C3	0.0	0.0	0.0	0.0	0.0	0.0	0.8	3.5	6.2	7.9	8.9	9.5
C4	0.1	0.1	0.1	0.1	0.1	0.1	0.7	3.4	6.2	8.0	9.1	9.7
C5	0.0	0.0	0.0	0.0	0.0	0.0	0.6	3.2	6.1	8.0	9.1	9.8
C6	0.0	0.0	0.0	0.0	0.0	0.0	0.6	3.1	6.1	8.1	9.3	10.1
C7	0.0	0.0	0.0	0.0	0.0	0.0	0.5	3.0	6.0	8.1	9.4	10.3
D	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.5**	**2.9**	**6.0**	**8.2**	**9.6**	**10.4**
ARc1	0	0	0	2.5	5.5	7.1	8.7	9.8	10.5	11	11	11.6
BRc1	0	0	0	0	0	2.7	4.4	6.3	7.8	8.8	9.6	10.2
CRc1	0	0	0	0	0	0	1.4	3.1	5	6.5	7.7	8.8
DRc1	0.1	0.1	0.1	0.1	0.1	0.1	0.6	1.5	3.3	5.2	6.9	8.5

6.2 Achieving a suitable signal-to-noise ratio

The target ambient noise level was established to be 40 dBA, noting that 35 dBA is more ideal. However, the literature also established that a signal-to-noise ratio of 15 dB should be suitable for most learners to be able to hear the teacher's voice, even those with some hearing loss or learning disabilities, or learning in a second language (Van Reenen & Karusseit, 2017).

Thus, if it is assumed that the average teacher's voice is 65 dBA (Astolfi & Pellerey, 2008), then an ambient classroom sound level of 50 dBA should be acceptable. However, considering the attenuation of the signal noise (teacher's voice) over distance by 6 dB over 6 m (Klatte *et al*, 2010), it was established that for a suitable SNR at the back of a classroom, the ambient sound level should be 44 dBA (see section 4.3.1). This is assuming that there are no other negative acoustic factors present, such as a high reverberation time or other user-generated noises. It is noted that there is very little difference between this and the 40 dBA target in practice. The ideal SNR is included in the table as it is a slightly relaxed target, allowing a planner to select an option that will result in a significantly improved condition, even if the acceptable target cannot be achieved in a given scenario.

While the difference between the target level of 40 dBA and 44 dBA is not significant, an exercise was performed to determine the conditions under which this relaxed target was met. With reference to this adjusted target of 44 dBA, the modelled evidence established in this study shows that suitable SNR (≥15 dB at all positions within the classroom) can be achieved at the positions and barrier heights indicated in Table 6-5 and Table 6-6. For example, at Position B a suitable SNR can be achieved in the classroom with the insertion of a 3.5 m high barrier at the boundary, even though the 40 dBA target is not achieved.

This presents a more optimistic case, demonstrating that a significant difference can be achieved, even for classrooms that are very close to the source.

6.3 Application

The findings were applied theoretically to the sites that were used to establish the traffic noise conditions. For this exercise, the maximum barrier considered is 3.5 m.

6.3.1 School A

At School A, the façade of the classroom building was 25 m from the centre of the road. This roughly corresponds to Position A1 in the model.

For the sake of this exercise, it is assumed that the road generates traffic noise according to the modelled road and that the maximum practical barrier height is 3.5 m. At the actual site there is effectively no barrier because the boundary element is a palisade fence. According to the modelled data, if there is no barrier the SPL at the façade would be 64.4 dBA. Assuming a façade sound transmission loss of 10 dBA, the resulting classroom SPL would be 54.4 dBA, which is well above the target level of 40 dBA. This would result in an SNR of 10.6 dB at the front of the class, which is acceptable though not ideal, and 4.6 dB at the back of the class, which is not acceptable. It is thus predicted that learners in this class will struggle to hear the teacher's message clearly.

If a 3.5 m barrier were to be inserted at the boundary (12 m from the centre of the road), the SPL at the façade is predicted to be 55.3 dBA (Table 5-12) and the classroom SPL would be 45.3 dAB. Although this is still above the target level, the insertion loss would be 9.1 dB, which is significant. The improvement in SNR in the classroom will have changed to 19.7 dB at the front of the class and 13.7 dB at the back of the class, which will be experienced as a significant improvement.

However, a boundary barrier of 3.5 m is still quite high. Referring to Table 6-1, it is determined that a significant IL of at least 6 dB can be achieved by inserting a barrier of 2.5 m. This is a more reasonable barrier height and will result in a classroom SPL of 47.4 dBA and a change in SNR at the back of the class from 4.6 dB to 11.6 dB.

Similar results are found if a barrier is inserted closer to the building façade, at a distance of 3 m from the façade. At a barrier height of 3.5 m, the resulting SPL at the façade receiver would be 55.5 dBA, resulting in a classroom SPL of 45.5 dBA and an SNR of between 19 dB and 13 dB, yielding similar findings as for the barrier at the boundary. A minimum significant difference in SNR would be achievable with a barrier of 2.5 m high.

Using heuristics derived from the modelled data, it can be recommended that a barrier of at least 2.5 m be inserted at School A at either the boundary (length of barrier to extend 49.2 m either side of the centre of the classroom) or at 3 m from the façade (length of barrier to extend 7.2 m either side of the centre of the classroom).

6.3.2 School B

At School B the classroom façade is approximately 50 m from the centre of the road, which is represented by Position B2. Without any interventions, the SPL at the façade is predicted by the model to be 59.4 dBA. Applying a façade transmission loss of 10 dB, the resulting classroom SPL with no outdoor interventions would be 49.4 dBA and the SNR would be 15.6 dB to 9.6 dB, which may be considered acceptable.

The lowest barrier that can be inserted to achieve at least a 6 dB change in the classroom SPL is 3 m (Table 6-1). With a 3 m high barrier inserted at the boundary, the SPL at the façade is predicted to be 52.5 dBA, representing an insertion loss of 6.9 dB and an improvement in the SNR between 22.5 dB and 16.5 dB, which exceeds the ideal in spite of the ambient level being a little above the target of 40 dBA. Although the insertion loss at School B is less than at School A, distance plays a role and the resulting classroom noise level is lower at School B than at School A.

By comparison, if a barrier of the maximum reasonable height of 3 m was to be inserted 3 m from the façade of the classroom, the IL would be 8.1 dB (59.4 – 51.3 dB), resulting in a classroom SPL of 41.3 dBA and an improvement of the SNR of between 23.7 dB and 17.7 dB (depending on the seat position in the class). The minimum barrier height in this arrangement at which a significant change (at least 6 dB) in the classroom SPL can be achieved is 2.5 m (IL = 6.3 dB, Table 6-3).

It is noted that the classroom at this school was on the ground floor within a double-storey classroom block. Thus the predicted (modelled) SPL at the façade is slightly (though negligibly) higher at 60.7 dBA (see Table 5-8).

6.3.3 School C

At School C the distance from the centre of the road to the façade is 15 m, which is most closely represented by Position A. Here the façade SPL with no interventions is predicted to be 68.1 dBA and the resultant indoor SPL 58.1 dBA

With a maximum barrier height of 3.5 m, a façade SPL of 58.5 dBA can be achieved (Table 5-12), providing an insertion loss of almost 10 dB. Although this is a significant IL, the resulting SPL inside the classroom is 48.5 dBA; the predicted SNR ranges between 16.5 and 10.6 dB. At a more reasonable barrier height of 2.5 m, the resulting indoor SPL is predicted to be 49.9 dBA and the resulting SNR between 15.1 and 9.1 dB, which may be considered acceptable for normal hearing learners.

Since this classroom is very close to the boundary, changing the position of the barrier or inserting an additional barrier is neither practical nor very effective.

Although a reduction in the indoor classroom noise level of 10 dB would be favourably noticed by the occupants, the resulting indoor level is not likely to be conducive to good outcomes.

6.3.4 School D

School D is a double-storey school building with the classrooms on the first floor. The classroom façade is 30 m from the centre of the road, roughly corresponding to Position B.

At the double-storey façade, the predicted SPL is 64 dBA. A 3.5 m high barrier inserted at the boundary would result in a façade SPL of 56.8 dBA (Table 5-13), representing an insertion loss of 7.2 dB. While this would be a noticeable difference, the resulting indoor SPL will still be high, with a corresponding SNR of between 8.2 to 2.2 dB.

Inserting a 3.5 m high barrier closer to the façade, at a distance of 3 m, will produce no effective insertion loss because the receiver level is higher than the barrier.

6.3.5 New School

In the previous sections, the modelled data was applied to the existing schools that were used as reference sites for this research. This section discusses the application of the data to a new school that does not have the constraints of an existing site.

Ideally, a school should be located on a quiet street with low traffic volumes. However, assuming a school is located adjacent to a road generating traffic noise as established in the model, the following heuristic recommendations could be made from the modelled data.

To achieve an indoor SPL of 40 dBA, an outdoor façade level of 50 dBA is set as a target. According to the data gathered from the simulations, this level cannot be achieved without some kind of intervention, except if the classroom building is positioned 136 m away from the road and orientated so that the classroom window façade is perpendicular to the road.

A summary of the scenarios in which the target level will be met is provided in Table 6-5 and Table 6-6. Since ground-floor classrooms were shown to generally have lower indoor ambient noise levels, let us assume for the sake of this exercise that the school building will be a single-storey building.

By inserting a boundary wall of at least 3.5 m high, the target level can be achieved if the building is at least 68 m (Position C) from the road (building parallel to the road), noting that the length such a barrier would need to extend at least 219.2 m in either direction (438.4 m long). Alternatively, the building might be moved closer to the road (51 m) and a 3.5 m high barrier (14.4 m long) inserted at 3 m from its façade and achieve similar classroom noise levels. Although the height of the barrier in either case is the same, the length is significantly different, which would have financial implications.

Should the ideal classroom noise level of 35 dBA be required, while maintaining natural ventilation, the classroom could be located 136 m from the road with a 3.5 m high wall (980 m long) at the boundary or it could be 102 m from the boundary with a 3 m high (14.4 m long) barrier positioned 3 m from the building façade.

Numerous alternative scenarios can be derived from the tables provided through this study. Limiting factors, such as the size of the site (which can influence the length of the boundary barrier) and the location of other constraining elements on the site, should be considered when applying the heuristics in the tables.

6.4 Summary table

The following tables summarise the application of the evidence collected and analysed in this study. These tables indicate the interventions that can be applied to achieve the target classroom sound level of 40 dBA, the ideal target of 35 dBA, an SNR of at least 15 dB at the back of the class, and a change (decrease) in classroom sound level of at least 6 dB.

These tables can be used to determine which interventions (barrier design) can be effectively applied at existing school sites (in which case the building position is already established) or to determine which attenuation interventions (distance, orientation, barrier design, site elevation) can be effectively applied for new school designs.

The shaded blocks indicate where a change in barrier height will yield at least a 6 dB decrease in SPL for a particular building position, relative to no barrier for that building position. This was established by calculating the difference in the modelled result with no barrier and the modelled result for each barrier height. This is applicable when the building position is predetermined (as would be the case in an existing school or in a new school with constraints that determine the building position) and the planner needs to determine the minimum height that a barrier would need to be to achieve a significant difference (if any), even if the target cannot be met. No shading in a block is interpreted as meaning that there is no significant effect.

The relaxed target of 44 dBA, based on an SNR of at least 15 dB throughout the classroom, is indicated in the table with a dot (•). This was determined by selecting all scenarios in which the modelled SPL value at the façade receiver was less than or equal to 54.5 dBA (44 dBA + 10 dB for the insulation value of the façade, with a 0.5 dB tolerance).

The acceptable target SPL of 40 dBA is indicated in the tables with a tick (✓). This was determined by identifying the modelled values that are less than or equal to 50.5 dBA (40 dBA + 10 dB for the insulation value of the façade, with a 0.5 dB tolerance).

The ideal target SPL of 35 dBA is indicated in the tables with a tick in a box (☑). This was determined by identifying the modelled values that are less than or equal to 45.5 dBA (35 dBA + 10 dB for the insulation value of the façade, with a 0.5 dB tolerance).

Where data was not available, as in cases when only the major building positions were tested, the box contains a dash (-).

Regarding double barriers, the tables should be interpreted as follows:

In Table 6-5 and Table 6-6 the symbols indicate whether the denoted difference can be achieved for the respective source barrier height. Table 6-7 then elaborates on at which façade barrier height the denoted effect can be achieved for each source barrier height. The reference value for a significant difference (≥ 6 dB) is the SPL with the respective source barrier height and no façade barrier.

Table 6-5: Summary of possible design choices for single-storey building

If the building is at Position:	The various targets (relative to a classroom at building Position with no intervention) can be achieved by using one of the following marked options:																																				
	Distance from road centre (m)	No barrier	Parallel barrier @ source (12 m from road centre)					Parallel barrier @ façade (3 m from building)					Wrapped barrier @ source (12 m from road centre)					Wrapped barrier @ façade (3 m from building)					Perimeter barrier					Site raised 2 m					Double barrier (see Table 6-7 for corresponding second barrier height details) Barrier at source + other				
			1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5
A	17																					•															
A1	25.5												-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	34						•				•	•					•				•	✓				•	•	•	•	•	•	•	•	•		•	•
B1	42.5					•	•			•	•	•	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B2	51				•	•	•			•	•	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B3	59.8			•	•	•	•			•	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	68			•	•	•	✓		•	•	✓	✓		•	✓	✓	✓		•	•	✓	✓		•	•	•	•	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1	76.5			•	•	✓	✓		•	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C2	85		•	•	•	✓	✓		•	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C3	93.5		•	•	✓	✓	✓		•	✓	✓	☑	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C4	102.5	•	•	•	✓	✓	✓	•	•	✓	✓	☑	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C5	110.5	•	•	•	✓	✓	✓	•	•	✓	☑	☑	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C6	119	•	•	✓	✓	✓	✓	•	✓	✓	☑	☑	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C7	127.5	•	•	✓	✓	✓	✓	•	✓	✓	☑	☑	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D	136	•	•	✓	✓	✓	✓	•	✓	✓	☑	☑	•	•	•	•	•	•	✓	✓	☑	☑	•	•	✓	✓	✓	✓	☑	☑	☑	☑	☑	☑	☑	☑	☑
A⊥	17						•					•	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	•	•	•	•	•	-	-	-	-	-
B⊥	34			•	•	•	•			•	•	•	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	-	-	-	-	-
C⊥	68		•	•	✓	✓	✓	•	•	•	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	☑	☑	☑	-	-	-	-	-
D⊥	136	✓	✓	✓	✓	☑	☑	✓	✓	✓	✓	☑	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	☑	☑	☑	☑	☑	-	-	-	-	-

	Legend:
(grey shading)	Significant Insertion Loss (≥ 6 dB) achieved relative to SPL with no intervention at same building Position
☑	Ideal indoor SPL of 35 dBA predicted to be achieved
✓	Target indoor SPL of 40 dBA predicted to be achieved
•	Target SNR of at least 15 dB throughout the classroom predicted to be achieved (SPL ≤ 44 dBA)
-	No data

Table 6-6: Summary of possible design choices for double-storey building

If the building is at Position:	The various targets (relative to a classroom at building Position with no intervention) can be achieved by using one of the following marked options:																															
	Distance from road centre (m)	No barrier	Parallel barrier @ source (12 m from road centre)					Parallel barrier @ façade (3 m from building)					Wrapped barrier @ source (12 m from road centre)					Wrapped barrier @ façade (3 m from building)					Perimeter barrier					Site raised 2 m					Double barrier (see Table 6-7 for corresponding second barrier height details) Barrier at source + other				
			1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5
A	17																																				
A1	25.5												-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	34																														•	•					
B1	42.5												-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B2	51						•						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B3	59.8					•	•						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	68					•	•																			•	•	•	•	✓	✓	✓				•	•
C1	76.5				•	•	•						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C2	85				•	•	•						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C3	93.5			•	•	•	✓						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C4	102.5			•	•	•	✓						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C5	110.5		•	•	•	✓	✓						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C6	119		•	•	•	✓	✓						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C7	127.5		•	•	•	✓	✓						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D	136	•	•	•	•	✓	✓	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	✓	✓	✓	☑	☑	☑	•	•	•	✓	✓
A⊥	17												-	-	-	-	-	-	-	-	-	-	-	-	-	-	-						-	-	-	-	-
B⊥	34						•						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	•	•	•	•	✓	-	-	-	-	-
C⊥	68		•	•	•	✓	✓						-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	-	-	-	-	-
D⊥	136	•	✓	✓	✓	✓	☑	•	•	•	•	•	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	☑	☑	☑	☑	☑	-	-	-	-	-

	Legend:
(grey shading)	Significant Insertion Loss (≥ 6 dB) achieved relative to SPL with no intervention at same building Position
☑	Ideal indoor SPL of 35 dBA predicted to be achieved
✓	Target indoor SPL of 40 dBA predicted to be achieved
•	Target SNR of at least 15 dB throughout the classroom predicted to be achieved (SPL ≤ 44 dBA)
-	No data

Table 6-7: Summary of possible design choices for double barrier

If the building is at Position:	Then the target SPL can be achieved by inserting one of the following marked options:										
	Height of barrier at façade (m)	Height of barrier at source (m) (if single-storey)					Height of barrier at source (m) (if double-storey)				
		1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5
A	1.5										
	2										
	2.5										
	3										
	3.5										
B	1.5					•					
	2					•					
	2.5				•	•					
	3	•	•		•	•					
	3.5	•	•		•	•					
C	1.5	•	•	•	•	✓				•	•
	2	•	•	•	•	✓				•	•
	2.5	•	•	✓	✓	✓				•	•
	3	✓	✓	✓	✓	✓				•	•
	3.5	✓	✓	✓	✓	✓				•	•
D	1.5	•	•	✓	✓	✓	•	•	•	✓	✓
	2	✓	✓	✓	☑	☑	•	•	•	✓	✓
	2.5	✓	✓	☑	☑	☑	•	•	•	✓	✓
	3	☑	☑	☑	☑	☑	•	•	•	✓	✓
	3.5	☑	☑	☑	☑	☑	•	•	•	✓	✓

Legend:	
(shaded)	Significant Insertion Loss (≥ 6 dB) achieved relative to SPL with no intervention at same building Position*
☑	Ideal indoor SPL (35 dBA) predicted to be achieved
✓	Target indoor SPL of 40 dBA predicted to be achieved
•	Target SNR of at least 15 dB throughout the classroom predicted to be achieved (SNR)

*at least a 6 dB difference between only a barrier at source and barrier at source plus barrier at façade

Chapter 7: Conclusion and recommendations

This chapter summarises and concludes this study. The core purpose and processes are revisited and the findings are summarised. The answer to the main research question is discussed in terms of its application. Finally, recommendations for further research are given.

7.1 Background and purpose

This study set out to investigate means of mitigating outdoor noise disturbance in naturally ventilated classrooms of schools that are exposed to road-traffic noise and more specifically, to quantify the modelled effect of various noise barrier designs and building designs (positions and façade design) for a typical classroom under conditions of a typical traffic noise source with the aim to achieve a target classroom ambient sound level of 40 dBA.

The context for the study was the highly urbanised province of Gauteng, South Africa, where urban schools are exposed to the sounds of the city, particularly traffic. There is very little attention given to acoustic requirements and design solutions in the current guidelines for school design in South Africa, as set out in the *Regulations relating to minimum uniform norms and standards for public school infrastructure* (Department of Basic Education, 2013), or the relevant South African national standards.

While the issue of outdoor noise attenuation is addressed in some international guidelines and literature, the applicability in the context of schools in Gauteng, South Africa, has not been explored. Thus, a need was identified to investigate the type of outdoor noise to which Gauteng urban schools are exposed and to investigate and quantify the efficacy of available attenuation interventions.

There is a high demand for new schools in Gauteng. New schools present an opportunity to design the school in such a way that intrusive outdoor noise can be suitably (practically and feasibly) attenuated, while maintaining natural ventilation by means of open windows in accordance with the Regulations. Existing schools in urban areas that are exposed to traffic noise do not have as much opportunity to attenuate the noise due to existing space constraints.

Compounding the problem of outdoor noise interference in classrooms is the fact that most South African classrooms rely on natural ventilation via openable windows. Open windows compromise the sound insulating ability of the classroom envelope. Unlike mechanical ventilation, natural ventilation, depends on atmospheric temperature and pressure differentials which are not controllable. The implication is that where natural ventilation is employed, the required rate of fresh air delivery is much higher. For natural ventilation via windows, large openings in the envelope, preferably on opposite sides to allow cross-ventilation, are required.

Both acoustics and ventilation have been established through prior research as indoor environmental factors that can significantly impact the quality of classroom outcomes. Poor ventilation lowers alertness and performance of learners (Haverinen-Shaughnessy *et al.*, 2011; Twardella *et al.*, 2012) and bears health risks (Patterson *et al.*, 2017), while poor acoustic conditions result in low speech intelligibility and distraction. Research has shown that unfavourable acoustics can negatively influence both teachers' and learners' performance and well-being. Speech clarity depends on two factors – firstly, the reverberation time in a space and secondly, the ambient sound level. This study focused only on the ambient sound level which relates to the signal-to-noise ratio (SNR) in a classroom. The SNR is essentially the difference between the signal noise level (usually the teacher's voice) and the background noise level. The ideal SNR for a classroom environment is 15 dB or greater.

In order to avoid costly design changes late in the design process, or costly remedial work after construction, good decisions regarding acoustics and ventilation need to be made early on in the planning stages of school infrastructure. Outdoor noise attenuation guidelines are required to aid designers. However, quantitative guidelines are lacking and architects and planners are not suitably qualified or confident to make technical acoustic design decisions.

Robust heuristics that can be applied in a variety of situations are needed to provide practical guidance to planners and architects. Suitable design decisions made in the early stages of infrastructure planning can eliminate the need for specialist services, allowing such costly and rare resources to be reserved for particularly intractable cases and to minimise the number of corrective interventions in later phases of the design or construction.

A number of different interventions can be applied to control classroom noise. In this study, the mitigation of outdoor noise disturbance in the classroom, particularly from road traffic, was investigated through modelling. Possible outdoor attenuation interventions included the insertion of a solid dense barrier, distancing the receiver (in this case, the classroom) from the source (in this case, the road) and changing the orientation of the receiver relative to the source. Façade treatment in terms of the size of openings and construction materials were also considered. Outdoor interventions help decrease the amount of noise reaching the classroom façade, while the façade provides a transmission barrier.

The amount of sound that can be transmitted from the outside of the classroom to the interior through the façade depends on the composition of the envelope. Different materials have different sound transmission characteristics. Envelopes constituted from different materials, such as glazing and brickwork, will provide sound transmission resistance according to the size (area) and transmission characteristics of each material. Openings in the envelope, such as open windows, represent a material that provides no transmission resistance. Thus, naturally ventilated classrooms are vulnerable to outdoor noise exposure.

This study set out to quantify the efficacy of outdoor sound attenuation interventions and façade designs to achieve suitable ventilation and acoustic conditions in classrooms. The aim was to establish practical guidelines, enabling architects and planners who do not have extensive knowledge of acoustic design to make suitable design decisions.

The main research question was:

What interventions are appropriate and effective to attenuate road-traffic noise that is transmitted into a typical naturally ventilated classroom in Gauteng in order to achieve a suitable indoor ambient sound level?

Sub-questions in support of the main research were:

1) What is a typical naturally ventilated classroom design in Gauteng?
2) What is a suitable ambient sound level in a classroom?
3) What is the nature of problem noise (traffic) in the context of this study?
4) What are the noise attenuation interventions that can be employed?

The guidelines resulting from this study are limited in that they are based on models that eliminate confounding factors and site-specific factors. However, they provide a high level framework to guide better decision-making and avoid grave design mistakes.

The main objective was to establish which noise attenuation interventions are suitable and effective to reduce road-traffic noise in a classroom in order to achieve a suitable ambient noise level. The scope of the study included outdoor interventions (noise barriers and distance) and considered transmission through the façade. Interior treatment and attenuation (e.g. acoustic absorption inside the classroom) was excluded from the study.

The major portion of the research was performed using acoustic modelling software (*CadnaA* and *Bastian*). This enabled the insertion of numerous different interventions without the cost or practical limitations of real interventions. The simulated environment also enabled all potentially confounding variables to be controlled.

The model provided a virtual experimental environment in which controlled variables could be set, independent variables could be changed and the dependent variable could be measured.

The dependent variable was the sound pressure level (SPL) inside the classroom, which was evaluated against a target SPL of 40 dBA. The controlled variables were the road-traffic noise and the facade design (which was the design of windows and openings for ventilation in the façade). The independent variables were the interventions tested.

The controlled, dependent and independent variables were determined through answering the sub-research questions. These variables were then applied in the experimental research to answer the main research question.

A province-wide survey and teacher questionnaires confirmed that traffic noise is the dominant source of noise in urban schools in Gauteng. Although the sample size was limited by only one representative from each school responding to the survey and a response rate of 5%, the finding of the survey was that 36% of the schools were located close to noise sources and that traffic noise constitutes 73% of the noise sources. The teacher questionnaire revealed a correlation between measured and perceived noise levels in classrooms located close to a busy road. Although these findings do not directly relate to the main research objective, they do support the need for suitable outdoor noise attenuation interventions in Gauteng schools.

7.2 Summary of findings

A model based on the established controlled variables was created in *CadnaA* and *Bastian* acoustic software, and the effect of the independent variables on the dependent variable was tested to answer the main research question and determine which interventions are suitable and effective to achieve the target ambient sound level in the classroom.

The controlled variable in the experiment was the typical Gauteng school, which included a fixed classroom design and a fixed noise source (traffic).

Through on-site observations at four urban Gauteng schools a typical classroom was established to be 7 m wide, 8 m long and 2.7 m high (internal dimensions). Windows were placed on the long facade so that 1.64 m^2 of the façade area (28%) was constituted by glass and 6.1 m^2 (11%) was open. This design, satisfying the first sub-question, was used in all experimental scenarios, except in one alternative experiment in which the regulatory minimum areas were used.

The dependent variable was the resultant modelled noise level inside the classrooms. However, in order to evaluate whether the attenuation interventions were effective at achieving a suitable ambient noise level in the classroom, 'suitable' needed to be defined. A review of literature and local and international standards was performed to determine a suitable target ambient sound level in a classroom. In the context of Gauteng, South Africa, this was established to be 40 dBA (the target SPL), satisfying the second sub-question, although the international benchmark of 35 dBA was also considered in the discussion of the results. The efficacy of interventions in the model was measured against this target.

There are a number of possible attenuation interventions to reduce the effect of traffic noise on the indoor ambient noise level, such as sealing the building envelope, distancing the building from the source, inserting noise barriers (walls), or adding ground absorption, to name a few. However, not all these interventions were deemed suitable or applicable to this study – for example, sealing the building envelope is not applicable since this study specifically considers a naturally ventilated classroom. The following interventions were selected for consideration, satisfying the fourth sub-question:

1. Building façade (material and composition)
2. Building location (distance from source)
3. Building orientation relative to source
4. Building floor level (ground or first floor)
5. Barrier length
6. Barrier height
7. Barrier position relative to source and receiver
8. Barrier alternatives (crowning, shape, double barriers, topographical barrier)

These can broadly be categorised into the effect of distance, the effect of barriers and the effect of building design.

The effect of changing the metric of an intervention is dependent on the condition of the other interventions that are naturally part of the scenario. For example, the effect of changing the height of a barrier will depend on how far the receiver is from the noise source. Thus, each independent variable can also be a controlled variable, producing a number of alternative scenarios.

The result is that various combinations of interventions yielded the target SPL, which are best reported in the tables in Chapters 5 and 6. The effect of each intervention is summarised in the following sections:

7.2.1 Classroom building design

Interventions related to the design of the building included the façade design, the distance of the building from the road, the orientation of the building relative to the road, and whether the classroom is on the ground floor or first floor.

7.2.1.1 Building facade

Two different types of wall construction were tested: a light-weight wall panel system on the market was used and a typical 230 mm thick brick wall, plastered on one side.

It was found that the wall material does not influence the sound transmission when such a large percentage of the façade area is open. This finding is significant, considering the cabinet resolution of the government of South Africa to promote the use of alternative building materials for public buildings, including schools. Furthermore, it was found that the sound transmission was consistently just below 10 dB.

When the areas of the glazed windows and open sections were reduced to meet the deemed-to-satisfy requirements of the National Building Regulations (NBR), assuming a masonry wall construction as is assumed in the NBR, the transmission loss was 16 dB. While this is clearly an improved situation, the efficacy of the ventilation is uncertain.

The sound insulation of the typical façade was established to be 10 dB, which will only be suitable to achieve the target indoor SPL if the SPL at the outer façade is as low as 50 dBA.

7.2.1.2 Building distance

As the distance between the noise source and the building facade was increased in the model, the SPL at the façade receiver decreased. This was expected, due to geometric divergence. The sound level at the façade decreased by 4.4 – 6 dB per doubling of distance.

The target indoor level (40 dBA) was not achieved, even when the building is as far as 136 m from the road, except in the scenario in which the building is orientated perpendicular to the road. In this case, the target is achieved for a building at 136 m from the road (the furthest distance modelled).

While it was found that there is a difference in indoor SPL in adjacent classrooms in a block that is perpendicular to the road, the difference from one to the next as the classrooms receded from the road was negligible (less than 3 dB). Thus the position of the building itself (in terms of the distance of the closest façade from the noise source) is relevant above the positioning of classrooms within the block.

7.2.1.3 Building orientation

It was found that when the building was orientated so that the receiving façade (the façade with the windows) was perpendicular to the road, the façade receiver level decreased by approximately 2.5 dB, compared to that of a building of the same distance from the road but orientated parallel to the road. This indicates that the orientation of the classrooms has an effect on the noise transmitted into the classroom. However, even in the perpendicular orientation, the target level was only achieved at 136 m from the road.

7.2.1.4 Classroom floor level

The sound level at a receiver at a ground-floor classroom and a first-floor classroom were modelled and compared under each scenario. Ground-floor classrooms in a single- and double-storey classroom block were modelled as well as first-floor classrooms in a double-storey classroom block.

It was found that sound level at first-floor classrooms was on average 1.6 dB more than ground-floor classrooms and that the sound level at ground-floor classrooms in a double-storey building was on average 1.1 dB more than a ground-floor classroom in a single-storey building. In both cases, the difference is negligible (less than 3 dB).

It can be added that single-storey classrooms (as opposed to ground-floor classrooms with a floor above) have the benefit of not being subject to disturbing noise from activities on the floor above. At the same time, however, it can be argued that a concrete floor slab above will provide better sound insulation from outdoor noise than a light-weight roof construction.

The treatment of the upper envelope of a classroom is a suggested topic for subsequent research.

7.2.2 Noise barriers

The target SPL was not achieved using interventions of building design alone, except in one scenario. Barriers of different heights, positions and shapes were inserted in combination with the building design interventions.

7.2.2.1 Barrier length

A review of the literature uncovered a general rule of thumb that a barrier should extend either side of the receiver by a length of at least four times the distance between the barrier and the receiver. This rule of thumb was tested by inserting barriers of various lengths relative to the barrier-receiver distance. A shorter barrier (in a ratio of 1:3) showed a difference of more than 1 dB and a longer barrier (1:5) showed a difference of less than 1 dB indicating that a longer barrier makes little difference while a shorter barrier allows more sound to pass around it. Thus it was confirmed that a barrier length based on the 1:4 ratio is a valid barrier length.

7.2.2.2 Barrier height

Barriers of heights between 1.5 m and 7 m were inserted either close to the source, or close to the receiver, or both.

It was found that the ideal target level (35 dBA) was achieved in the model for a building that is at least 76.5 m from the source with a barrier near the source of at least 6.5 m high. As the building position receded from the source, the barrier height required to achieve the target level decreased. The nearest distance from the road at which the accepted target SPL (40 dBA) was achieved in a ground-floor classroom with the insertion of a barrier was 42.5 m, in which case the barrier needed to be 5.5 m high if the barrier was 12 m away from the centre of the road, or 6.5 m high if the barrier was 3 m away from the facade.

Arguing that a barrier more than 3.5 m high is excessively high, being unsightly, unfriendly and impractical, barriers above this height were disregarded. Thus, the minimum distance from the road at which the target level was achieved for a ground-floor classroom building parallel to the road was 59.5 m, if the barrier was 3 m away from the façade, or 68 m if the barrier was 12 m from the road. For a first-floor classroom, the target was not achieved at any distance modelled if the barrier was inserted 3 m away from the façade, and it was achieved at a minimum distance of 93.5 m from the road if the barrier was inserted 12 m from the road.

7.2.2.3 Barrier position

Scenarios were modelled with the barrier inserted close to the road and close to the receiver. This was repeated for buildings at different distances from the road and for different barrier heights.

It was found that for a ground-floor classroom, a lower façade SPL was achieved by inserting a barrier close to the receiver (at 3 m from the façade) rather than closer to the noise source. However, for a first-floor classroom, a better insertion loss is achieved by inserting the barrier close to the source, rather than close to the façade.

7.2.2.4 Double barriers

Barriers of varying heights were inserted simultaneously near the source and near the receiver. Although this resulted in a slightly improved insertion loss, the target level was still only achieved at the building positioned at least 68 m from the source.

7.2.2.5 Barrier with crown

Barriers with a cantilevered crown of 0.5 m were inserted for each barrier height and position, but the effect was negligible compared to a barrier without a crown.

7.2.2.6 Wrapped barrier

Barriers of varying heights were inserted wrapped around the building to some extent and positioned near the source, near the building itself, or partially around the perimeter of the site. It was found that if the barrier is close to the façade the insertion loss was improved compared to a straight parallel barrier that is the same distance from the façade, particularly at heights greater than 3 m. Yet the target level was only achieved at a distance of 68 m from the road with a barrier height of 2.5 m.

It is noted that there are limitations to this finding in that the length of the barrier was not adjusted relative to the distance between the barrier and the receiver. Had this been done, it is possible that the target would have been achieved at buildings closer to the road. Further research regarding this factor was not possible due to time constraints placed on the use of the modelling software, but it is identified as a potential area of future research and investigation.

7.2.3 Topographical barrier

By raising the site above the road level, the barrier height is essentially increased. The level of the site was raised 2 m above the road level. The sound level at the façade of each building position was generally lower, compared to similar scenarios on a level site. It was found that the target sound level was achieved at a building 68 m away from the road with a barrier of at least 1.5 m high.

7.3 Discussion

It is clear that the target level of 40 dBA inside the classroom is not easily achieved at buildings that are within 51 m of a busy road (with the barrier height limited to 3.5 m). If considering the ideal target level of 35 dBA, this distance increases to 110.5 m.

These findings are useful to apply when designing new schools when the site layout and positioning of classroom blocks on the site relative to the dominant source of road-traffic noise is being decided.

For an architect or infrastructure planner to be able to decide where to locate a school building with typical classrooms, the first matter to consider would be the target SPL required. As established in this study, 40 dBA is acceptable for a naturally ventilated classroom. Possible attenuation interventions will need to be considered in conjunction with the target and the constraints of the specific site, which will dictate the possible options for the distance of the building from the road and orientation relative to the road. The summary tables can then be consulted to determine the possible solution that will achieve the target SPL on the site in question. It is likely that there will be more than one solution, from which the one most desirable can be selected.

For existing schools exposed to traffic noise, it is obviously not possible to move the buildings away from the source and excessively high walls would be required to achieve the target classroom SPL. However, while it may not be possible to achieve the target, a significant improvement (> 6 dB) may be deemed acceptable.

A significant decrease in the classroom sound level can be achieved, even if the target level is not achieved. A significant sound level difference is considered to be a 6 dB decrease, which results in an improved signal-to-noise ratio (SNR) and will improve speech intelligibility. This was shown to be achieved with the insertion of barriers of at least 2 m for buildings closest to the source (17 m), or as low as 1.5 m if the classroom building is at least 25.5 m from the source.

It was established that for a classroom that is naturally ventilated by means of large opening window sections (equivalent to 11% of the floor area), the construction material of the wall plays no role in the sound transmission of the façade. This means that either light-weight alternative building technologies or heavy conventional masonry construction can be used for schools exposed to road-traffic noise. However, this cannot be applied to sound transmission between classrooms, which is a recommended topic for further research in the context of the South African cabinet resolution to encourage the use of IBTs in public infrastructure.

The findings of the survey and questionnaires provide a useful baseline against which to measure future changes. Although the results cannot be generalised, the sites that formed part of this study, both for qualitative and quantitative data, provide useful case studies. A future case study investigation is recommended whereby interventions recommended in this study are implemented and the resulting conditions compared to the existing and the modelled conditions.

The established guidelines are not intended to replace the knowledge and expertise of acoustic professionals but rather are intended to be used to guide planning decisions in the early phases of school infrastructure projects to avoid planning errors that would be costly and disruptive to correct. As such, it is acknowledged that there are some limitations to the guidelines established through the modelled findings.

These findings are limited to the selected barrier designs, particularly in terms of barrier length. In application, it will not necessarily be possible to insert a barrier that complies with the 1:4 length ratio used in this study. However, the modelled evidence established through this experiment provides a useful guide at least with respect to assessing which intervention is likely to be more effective compared to another. For example, even though the barrier to be inserted may not be of the length used in this study, the finding that a barrier closer to the façade of a ground-floor classroom is more effective than a barrier at the boundary will remain true.

Similarly, the modelled scenario represents an assumed situation with a single road and no surrounding reflective surfaces, thus it is not necessarily representative of a particular situation for application. The heuristic guidelines established are only useful as an indication of the general type of intervention to be applied.

Limitations in the model which were treated as controlled variables restrict the application of the findings. However, most controlled variables that can be seen as limitations (ground absorption, vegetation, meteorology) represent a worst-case scenario. In other words, actual site conditions are likely to achieve better results than the modelled results, particularly at high frequencies that are more easily absorbed by absorbent ground surfaces, and thus the implementation of the modelled results should lead to improved acoustic conditions.

This study was deliberately limited in the assessment of ventilation design. The typical design established can be assumed to be sufficient based on its compliance with regulations. However, an in-depth study of alternative suitable and effective natural ventilation design that decreases sound transmission and reduces the need for outdoor interventions is recommended. This study stemmed from the tension that exists between natural ventilation and acoustic requirements for classrooms. An assumption was made that the 'typical' classroom is adequately ventilated. However, there is a lack of local research regarding the actual ventilation efficacy in classrooms in South Africa. Research regarding ventilation rates in conjunction with noise levels is recommended in the South African context to establish an ideal natural ventilation design, which can then be applied to the methodology of the study to create a revised set of heuristics.

An area for future research is alternative or novel natural ventilation designs could be employed to simultaneously limit noise transmission and provide sufficient ventilation rates in classrooms.

Further research is also recommended regarding the feasibility and potential benefit of noise attenuation interventions that were excluded or limited in this study, such as ground absorption, vegetation and topography. Sound transmission reduction through the roof (for outdoor noise) and between classrooms (for inter-class noise) has not been well studied in the South African context and is recommended for future research as well as means to mitigate traffic noise, such as traffic control and road design.

7.4 Final statement

The results of this study provide a heuristic framework by which noise attenuation interventions can be selected based on their efficacy in various combinations. The intention of this research was to provide a quantitative means of supporting better design decisions to ensure that classrooms are acoustically suitable learning environments.

In the growing urban context of Gauteng, and indeed the world, traffic noise is increasingly present in everyday life. In Gauteng, where the climate lends itself to natural ventilation, attenuating outdoor noise is necessary to ensure that classrooms are suitable spaces for learning. Schools should provide sanctuary from the sensory overload of the city, rather than spaces where learners and teachers struggle to hear and be heard. If we are to design sustainable, habitable and healthy spaces, attention to noise control is crucial.

It was established that the *Regulations relating to minimum uniform norms and standards for public school infrastructure* do not provide adequate detail regarding the performance requirements for natural ventilation or acoustics. Nor are sufficient details or guidance provided to enable a designer to achieve suitable conditions.

It is hoped that this study will prove useful in aiding the design of classrooms that support the education ambitions of South Africa.

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Appendix A

School Noise Survey

This is a survey to establish the percentage of schools in Gauteng Province that experience noise disturbance due to proximity to EXTERNAL NOISE SOURCES. The information collected will also be used to map sources of external noise.

Your participation will enable further research to take place to improve the teaching and learning environment.

Participation is voluntary. You will not benefit from participation and will experience no disadvantage for lack of participation.

The survey should not take more than five minutes to complete. Please complete this survey before 14 September 2018.

Only one representative from each school should respond.

This survey is distributed with the permission of the Gauteng Department of Education and the CSIR Research Ethics Commitee. For any queries, please contact cvreenen@csir.co.za.

* Required

Email address *

Your email

Please state the name of the school that you are completing this form for. *

Your answer

In your opinion, is your school located close to an external noise source (eg. busy road, railway or industry) that regularly affects the background noise level in any of the classrooms during the school day? *

- ◯ Yes
- ◯ No
- ◯ Not sure; unable to answer

NEXT

Page 1 of 2

School Noise Survey

* Required

Noise characterisation

Please answer the following question to describe the noise disturbance.

What is the main source of the disturbing external noise? *

- ○ Road traffic
- ○ Rail traffic
- ○ Air traffic
- ○ Industry
- ○ Other: ____________

Do you have any further comments regarding noise disturbance at your school?

Your answer ____________

BACK SUBMIT Page 2 of 2

Never submit passwords through Google Forms.

Appendix B

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Engineering, Built Environment and Information Technology
Department of Architecture

Questionnaire

This questionnaire is to be completed after the Informed Consent form for this research study has been completed.

Project Title:
Establishing an evidence base for effective mitigation of outdoor noise in naturally ventilated school rooms in South Africa.

The purpose of this questionnaire is to collect opinions and perceptions from classroom users (teachers) regarding intrusive noise from outdoor sources.

Official use only: *(this information is for administrative reference only)*	
Questionnaire participant number:	
Date:	
School:	

Section 1

Please answer the following questions by making the applicable answer block with and X.				
Question:	YES	NO	SOMETIMES	NOT APPLICABLE
1. Do you experience noise disturbance from adjacent classrooms?				
2. Do you experience noise disturbance from classrooms above?				
3. Do you experience noise disturbance from outdoor activities within the school grounds? (eg. lawn-mower, generator)				
4. Do you experience noise disturbance from outdoor activities outside the school grounds? (eg. traffic, industry)				

Sponsor: CSIR

Section 2

Optional: Please answer the following questions if you answered YES or SOMETIMES to any of the above:				
Question:	YES	NO	SOMETIMES	NOT APPLICABLE
5. Do you notice a difference in learner performance when there is noise disturbance from any of the sources mentioned above?				
6. As a teacher, do you feel a difference in your voice strain when there is noise disturbance from any of the above-mentioned sources?				
7. As a teacher, do you feel a difference in your teaching style when there is noise disturbance from any of the above-mentioned sources?				
8. If there is noise disturbance from outdoor noise, do you close the windows?				
9. If you close the windows to block outside noise, is it quiet enough for normal classroom activities to continue as if there was no outside noise?				

End of questionnaire. Thank you for your participation.

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NOTE: The name of the school and participant will not be published in the final research output.

Appendix C

List of South African National Standards pertaining to building acoustics and environmental noise.

SANS number	Title	Scope
10181:2003	The measurement of noise emitted by road vehicles when stationary	Methodology for measuring.
10281:2003	Engine speed (S values), reference sound levels and permissible sound levels of stationary road vehicles	Gives stationary vehicle sound level limits (range 95 – 109 dBA, at distance of approx.. 500 mm from exhaust)
10205:2007	The measurement of noise emitted by motor vehicles in motion	Methodology for measuring.
10103:2008	The measurement and rating of environmental noise with respect to annoyance and to speech communication	Limit indoors for various occupancy types; limit outdoors (day/night) for type of district.
140-5:1998 (ISO 140:5)	Acoustics – Measurement of sound insulation in building and of building elements. Part 5: Field measurement of airborne sound insulation of façade elements and facades	Methodology for sound level difference across a façade.
3382-1:2014	Acoustics – Measurement of room acoustic parameter. Part 1: Performance spaces	N/A
3382-2:2014 (ISO 3382-2)	Acoustics – Measurement of room acoustic parameter. Part 2: Reverberation time in ordinary rooms	Methodology for reverberation time measurements
3382-3:2014	Acoustics – Measurement of room acoustic parameter. Part 3: Open plan offices	Methodology for STI and privacy/distraction distance
10117:2008	Calculation and prediction of aircraft noise around airports for land use purposes	N/A
10210:2004	Calculating and predicting road traffic noise	Methodology under typical SA conditions, one-hour-equivalent continuous A-weighted
10218-1:2004	Acoustical properties of buildings Part 1: Grading criteria for the airborne sound insulation properties of buildings	
10218-2:2004	Acoustical properties of buildings Part 2: The assessment of building plans and buildings with respect to their acoustical properties	

Response to examiners' comments

Examiner's comment	**Chapter/ Section/ Page** **(as per current revised version)**	**Candidate's response**
Examiner 1		
After a thorough study and analysis of abovementioned thesis I have the following comments and recommendations that should improve the general quality of the thesis. It is a thorough and interesting thesis based on extensive literature studies and a significant amount of parametric simulation and data analysis that lead to quantified results. It is good that actual measurements and simulated calculations were made, because software is sometimes not entirely accurate. The results are practical and can directly be applied. This begs the question if a doctoral thesis has just to be practical and if it could not also attempt to move beyond current state-of-the-art knowledge into experimental realms? The thesis is definitely breaking some new ground in the rather difficult subject of acoustics that is generally badly neglected in South Africa. This work should make appropriate noise mitigation measures more accessible to the general design community such as architects and engineers as well as regulatory authorities. However there is one major comment. In this case the student is confronted with a classic case of technical/	Chapter 1	The goal of this study was to ensure suitable acoustic and natural ventilation conditions, without compromising one for the other. This is stated in Section 1.4 (Aim), in Section 1.6 (Objectives) and in section 1.7 (Rationale and relevance of the study. Section 1.10 (Scope and delimitations) explicitly states that a typical naturally ventilated classroom is considered. The study goes on to define a typical classroom in terms of natural ventilation, based on the *Regulations Relating to Minimum Uniform Norms and Standards for Public School Infrastructure* and case study examples. The study does not focus on ventilation solutions but rather noise attenuation solutions under typical open-window ventilation conditions, thus alternative natural ventilation solutions, such as stack ventilation, are not explored. While natural daylighting and thermal comfort are also important aspects of classroom design, these are not discussed in this study as they do not conflict with acoustic requirements.

design contradictions. A façade should not be interrupted by openings such as windows to ensure an adequate *R-value* for the façade and suitable ambient sound pressure level (SPL) in the classrooms. However good natural ventilation and daylighting requires large openings to ensure adequate airflow and light penetration through the same façade. The solution in this thesis is to essentially make a compromise between these two contradictory requirements. If one looks at techniques such as TRIZ (The Russian Theory of Inventive Problem Solving) it is recommended that this type of problem should be solved by making an entirely new invention. This implies that the solution should ideally be such that it does not make a compromise. In this context this strongly points to indirect natural ventilation methods such as stack ventilation (buoyancy driven ventilation) solutions such as *solar towers*, *Trombe walls*, *wind towers* and *lined ducts* to improve the natural ventilation aspect of the problem. If a ventilation stack parallel to noise source (road) is used the uninterrupted façade would have a very high acoustical *R-value* especially if the hot air vent is at the top of the single or multi-storey structure is turned away 90° from the noise source. The stack also increases the length of the sound path and could even be lined with acoustic absorption material or use an array of Helmholtz resonators. This kind of solution could solve the rather problematic contradictory requirements without making a compromise. Natural daylight can be brought in through roof lights or non-openable windows of sufficient *R-value* on the facade. A good local example is the University of Fort Hare campus, East London and abroad the iconic Queens Building at the de Montfort University. In these buildings the stack ventilation was the primary concern, however much improved acoustics is a direct and useful		

spinoff of this approach. It is strongly suggested that at least one simple acoustic simulation is included to prove/ disprove this type of type of approach as an indication what the amount of sound attenuation would if cost wasn't the constraint and if a new building is designed, i.e. it is not a retrofit on an old building. 2 I am generally in agreement with the methodology and findings and conclusions of the work within the bounds and constraints (delimitations) of the thesis. However there are certain adjustments that could potentially significantly improve the thesis.		
General recommendations		
Façade design with stack ventilation As mentioned above it is strongly suggested that at least one simple acoustic simulation is included to prove/ disprove an indirect type of natural ventilation such as stack ventilation as an indication what the amount of sound attenuation would be if cost wasn't the constraint and if a new building is designed, i.e. it is not a retrofit.		Refer to Section 1.10 (Scope and delimitations), paragraph 2: *"The focus is on noise control rather than ventilation solutions. Thus, the exploration of ventilation solutions is limited to establishing a typical natural ventilation (window) design, and mechanical ventilation or alternative natural ventilation designs are not explored."*
List of technical terms It is strongly recommended that a comprehensive list of all technical terms (Definition of terms/ Glossary) and their definitions is added at the start of the thesis and not just a List of abbreviations. This should be combined with the sound insulating descriptors currently listed in Appendix C. Numerous technical acoustical terms are used throughout the work, however these are not always properly defined and if they are defined it is not	List of terms, page vii	A list of terms has been added at the beginning of the thesis.

conveniently in one location and before the attentive researcher/ reader starts to study the work.		
Size of figures and tables Some of the annotations in figures, especially graphs, are really very small (especially subscripts of symbols/ variables) making them difficult to read and understand. In many cases this was worsened by the use of grey scale characters. The text in tables is sufficiently legible. The quality (resolution) of some of the figures should never be less than at least 300 dpi.		All figures that apply to this comment have been revised.
Formulas It is recommended that all formulas are written with a proper formula writer such as Microsoft Equation (or similar). Avoid placing or imbedding the description of the formula terms inside the text and rather use the following more formal scientific style. Each formula should also have a unique formula number for reference purposes.	List of terms, page vii; Section 2.3.3.2, page 49; Section 2.2.2.2.6, page 52	All formulas have been formatted and numbered as suggested.
Language There are still some spelling mistakes. It is suggested that software names mentioned is also written in italics like foreign language terms.		All names of software have been italicised. Spelling errors have been corrected and checked by a professional editor.
Specific comments		
p. 1, para 2 Define “well-being”. It is rather vague. It should be defined in a glossary or at least stated in the paragraph. Does it mean physiological and/or psychological factors?	List of terms, page vii; Chapter 1, page 1	A short explanation added within paragraph 2 of the Introduction and a definition of the term has been included in the List of terms.

p. 1, para 4 In the sentence "These have several potential disadvantages. Firstly, these devices also contribute to the ambient noise level to some extent (Ehrlich & Gurovich, 2004)." Be more specific, e.g. is it a low frequency type of noise?	Chapter 1, page 2	Quantitative detail from the referenced study has been added within paragraph 4 of the Introduction: *"Firstly, these devices also contribute to the ambient noise level, as demonstrated in the study by Ehrlich and Gurovich (2004) where the ventilation system noise level limit of 35 dBA could not be achieved in all classrooms."*
p. 3, footnote 1 "*etc*." should never be used in the context of an academic writing unless it is deemed absolutely necessary to quote verbally from the NBRI information sheet mentioned.	Section 1.1.2, page 3	The footnote is informative and is not included in the text as it would make the paragraph unnecessarily wordy. This is a direct quote which efficiently communicates the reference to the 1970s description of evolving pedagogy and it is not necessary to paraphrase the content. No amendment was made to the text.
p. 4, para 2 ". . . design, the urban dynamics of the neighbourhood . . .". Define more precisely, i.e. change in morphology or typology? One definition is Urban Dynamics are the forces that shape and reshape cities over time. Urban dynamics can happen as gradual and natural processes or as coordinated government actions.	Section 1.1.2, page 4	The term 'urban dynamics' is explained through the discussion in the sentences that follow in the same paragraph, i.e. that residential neighbourhoods become commercial or industrial due to urbanisation. No amendment was made to the text.
p. 4, Figure 1-1 The source or origin (photographer) of the photographs should be stated. The quality should also be at least 300 dpi.	Section 1.1.2, page 5	New images inserted that are slightly larger to improve clarity. The image quality is limited to that which is available from the sources: https://www.google.co.za/maps/@-25.7504553,28.1961031,485m/data=!3m1!1e3 and https://repository.up.ac.za/bitstream/handle/2263/60293/Strip07-05%2893597%29.jpg?sequence=5&isAllowed=y which have been referenced in the footnotes to the caption.

6, para 1 Define "well-being". It is rather vague. It should be defined in a glossary or at least stated in the paragraph. Does it mean physiological and/or psychological factors?	(Section 1.1.3, page 7) List of terms, page vii	A definition of what is meant by this term in this thesis has been provided in the List of terms.
p. 7, para 1 Spelling mistake "fcan" in sentence " . . . different types of noise fcan result in different . . ."	Section 1.1.4, page 8	This has been corrected to "can" in paragraph 3 of Section 1.1.4
p. 9, para 4 In the sentence ". . . natural ventilation implies that certain portions of the building envelope are open . . .". This does not imply that it must be directly open and could also mean one of the indirect natural ventilation methods.	Section 1.2, page 11	Paragraph 9 of Section 1.2 has been amended to acknowledge the fact that openings are not necessarily directly open: *"However, natural ventilation implies that certain portions of the building envelope are open to the outside, whether directly or indirectly, which presents a problem when it comes to acoustic isolation from outdoor noise as any opening in the envelope will facilitate sound transmission."*
p. 10, para 2 I do not agree with this statement in the sentence "A potential problem exists that, in the case where a school is located close to an outdoor noise source and employs natural ventilation as the primary means of achieving suitable indoor air quality in classrooms, the ambient noise level in the classrooms will exceed the suitable level for speech intelligibility.". It depends on the type of facade design used. There is a rich design vocabulary available to overcome this type of problem.	Section 1.2, page 11	Paragraph 10 of Section 1.2 has been amended to qualify the type of natural ventilation intended to be referred to: *"A potential problem exists that, in the case where a school is located close to an outdoor noise source and employs natural ventilation in the form of openable windows as the primary means of achieving suitable air quality in classrooms, the ambient noise level in the classrooms will exceed the suitable level for speech intelligibility."*
p. 13, para 3 In the sentences "Additionally, the climate in South Africa, particularly in Gauteng, is conducive to natural ventilation. Thus, passive ventilation through the openable windows is a sensible solution and should be supported. However, open ventilation apertures make the classroom vulnerable to the effect of outdoor noise transmission.".	Section 1.7, page 15	Paragraph 2 of Section 1.7 has been amended to support the reference to natural ventilation through openable windows, which is the scope of this study (see Section 1.10) and is based on the Regulations: *"The Regulations stipulate that classrooms should be naturally ventilated by means of permanent wall vents and openable windows (Department of Basic Education, 2013). This is a good*

I do not think that one can assume *a priori* that passive ventilation with operable windows is necessarily the only natural ventilation solution.		*principle, particularly in South Africa. Mechanical ventilation and air-conditioning require financial resources for the installation and operation. These resources, as well as the required energy resources, are not always available or reliable in the South African context. Additionally, the climate in South Africa, particularly in Gauteng, is conducive to natural ventilation. Thus, passive ventilation through the openable windows, as suggested in the Regulations, is a sensible and economically feasible solution and should be supported."*
p. 18, para 3 The delimitation ". . . or alternative natural ventilation designs are not explored.". It is a pity that this has not been done a little bit as it might offer very good solutions in new single and multi-storey school designs. Natural ventilation, natural daylight and acoustics are intricately linked.	Section 1.10, page 20	The ventilation solution considered in this thesis is based on what is typically found currently in South African classrooms and based on the requirements of the Regulations. No change has been made in the text.
p. 19, para 4 ". . . and façade treatment. Façade treatment is limited to only two options, namely a 220 mm masonry wall or a light-weight panel construction.". Why was this limitation introduced before any simulations had been done? It appears a bit premature?	Section 1.10, page 21	An explanation has been added in this paragraph: *"Masonry walling is the most common construction method seen in urban schools, however, some are found constructed from light-weight prefabricated panels. Furthermore, the South African government promotes the use of alternative building methods that are quick to erect and cost-effective, which are often in the form of light-weight panels. Thus, façade treatment is limited to two options, namely a 220 mm masonry wall or a light-weight panel construction."*
p. 21, para 8 ". . . more specifically, acoustics and ventilation." . Why is natural daylight not mentioned? Lower down in the thesis the specific areas of openable and non-openable windows (glazing) is discussed in detail. The m² are required for natural ventilation is much less than what is required for sufficient natural daylight. The latter	(Section 1.13, page 24) Section 1.0, page 20	Refer to paragraph 3 of Section 1.10. *"…the natural daylight requirement for classrooms does not compromise acoustic insulation in the same way that natural ventilation through open windows does."*

requirement affects the **R-value** of the façade significantly and is therefore a significant constraint.		
p. 24, para 3 "The *Classroom 4.0* or smart learning environments require more space for flexibility." It is suggested that an illustration is included so that other readers can understand the crux of the new concept.	Section 2.1.1, page 27	Figures 2-1, 2-2 and 2-3 have been included to illustrate different learning environments relative to learning mode.
p. 27, para 6 Although stack ventilation is mentioned it has not been investigated at all. (refer introductory comments)	(Section 2.2.1, page 31) Section 1.0, page 20	Refer to Section 1.10 and comment above regarding the scope of the research with reference to the type of ventilation.
p. 30, para 1 What is the relationship between ACH and L/s/p Perhaps a formula should be included to explain the difference.	Section 2.2.2, page 33	The equivalent value of 8.6 L/s/p has been included in paragraph 6 of Section 2.2.2.
p. 32, para 2 A large portion of Rwanda has Tropical Savanah climate (Köppen-Geiger Aw) that necessitates very good natural ventilation.	Section 2.2.2, page 35	This is not relevant to discuss; the discussion is regarding the fact that some countries have deemed-to-satisfy regulations, while others are performance-based, rather than an analysis of the technical merit of each standard. The climate conditions of each country whose regulations have been assessed are not discussed. No changes were made.
p. 33, para 2 It sounds here that more is better. One should rather say not more than 1000 ppm otherwise people get very drowsy.	Section 2.2.3, page 36	Amended as suggested.
p. 35, para 3 Shouldn't formulas rather be provided?	(Section 2.3.1, page 38) List of terms, page vii	Formula for L_{eq} has been included with the definition in the List of terms.
p. 35, para 5 Give formulas of the various measures.	(Section 2.3.1, page 38) List of terms, page vii	Formula for $L_{Aeq,T}$ has been included with the definition in the List of terms.
p. 35, para 6 One should mention somewhere that sound is a longitudinal wave in air, water and solids which	Section 2.3.1, page 37	The following was introduced in Section 2.3.1, paragraph 2:

consists of compressions and rarefactions travelling through a medium. In solids the wave may also be a transverse wave.		*"Sound is transmitted as a longitudinal wave of compressions and rarefactions in gasses, liquids or solids, although it can be a transverse wave in solids."*
p. 36, para 2 Provide a formula.	(Section 2.3.2, page 39) List of terms, page vii	Formula and definition for sound reduction index has been included in the List of terms.
p. 37, para 1 The terms '*mass transmission*', '*co-incidence'* and '*resonance*' must be defined somewhere.	Section 2.3.2, page 40	A brief description has been added into the last paragraph of Section 2.3.2.
p. 37, para 3 If indirect natural ventilation is used in stack ventilation ducts then sound absorbing material can be applied in the duct (lined duct) and hence sound absorption of the envelope is also a possibility. It is recognized that this solution is not within the context set in the delimitations it is also a design solution that might be considered.	(Section 2.3.3, page 41) Section 1.0, page 20	Refer to Section 1.10 and comment above regarding the scope of the research with reference to the type of ventilation.
p. 40, para 5 Maybe a small illustration can be added to explain clearly what is meant.	Section 2.3.3.1, page 44	A lot of different options are discussed in this paragraph; illustrating them will be a diversion from the aim of the section, which is to give a brief account of what other researchers have found regarding the juxtaposition of sound transmission and air flow. Furthermore, suitable illustrations were not provided in the original article referenced. No amendment was made.
p. 41, para 1 This is an important statement and I am surprised that this has not been taken through or simulated!	(Section 2.3.3.1, page 44) Section 1.0, page 19	Refer to Section 1.10 and comment above regarding the scope of the research with reference to the type of ventilation.
p. 41, para 4 A small illustration will go a long way to explain what is written.	Section 2.3.3.1, page 45	Diagrammatic illustration included (Figure 2-4).
p. 44, para 1 Number formulas as suggested above.	Section 2.3.3.2, page 48	Formula has been numbered as suggested (Equation 2-1).

p. 45, para 4 Suggest a small diagram/ illustration to explain.	Section 2.3.3.2.3, page 50	Diagrammatic illustration included (Figure 2-5).
p. 47, para 2 Formulas should be numbered.	Section 2.3.3.2.6, page 51	Formula has been numbered as suggested. (Equation 2-2)
p. 50, para 1 Provide an illustration.	Section 2.3.3.3, page 54	An illustration has been included from the referenced article (Figure 2-8).
p. 50, para 5 Provide an illustration.	Section 2.3.3.3, page 55	An illustration has been included from the referenced article (Figure 2-9).
p. 51, para 4 In the sentence "Reverberation time, which refers to the time it takes for a sound signal to decay, . . .". Decay to which level? Author must be specific. I assume it is defined as the time it takes for the sound pressure level to reduce by 60 dB, measured after the generated test signal is abruptly ended.	Section 2.3.4, page 56; List of terms, page vii	Amended to include reference to 60 dB reduction in text and definition added in List of terms.
p. 55, para 3 In the sentence "General noise- control regulations". There is a spelling mistake.	Section 2.3.5, page 60	Corrected.
p. 57, para 3 Spelling mistake.	Section 2.3.6, page 62	Corrected.
p. 57, para 7 Define what the various terms (L10, LA and LM) means. Provide formulas or define in the glossary of terms.	(Section 2.3.6, page 62) List of terms, pave vii	Definitions added in the List of terms.
p. 58, footnote 6 Spelling mistake in the German word '*Straben*'. It is in fact the German '*doppelt s* ' and should be written either as '*Strassen*' or with the '*doppelt s* ' symbol '*Straßen* '. The latter looks a bit like a Greek beta symbol.	Section 2.3.6, page 63	Corrected.
p. 62, para 3 Spelling mistake in 'Welldeveloped'.	Section 2.4, page 67	Corrected.

p. 63, para 1 This is an engineering contradiction that could potentially be solved by means of a solution that does not make a compromise but rather surmount the contradiction or think out-of-the-box such as proposed by TRIZ. Teoriya Resheniya Izobretatelskikh Zadatch (Theory of the Solution of Inventive Problems).	Section 2.4, page 68	The purpose of the research was to investigate solutions (within the stated scope) that do not result in a compromise. No amendment to the text was made.
p. 66, para 2 Maybe one wants something more than an 'intervention' such as an 'invention'.	Section 3.5, page 71	This research was intended to seek feasible, currently available solutions in the South African context, thus interventions were investigated rather than inventions. An intervention is defined as the action of becoming intentionally involved in a difficult situation in order to improve it or prevent it from getting worse. (https://dictionary.cambridge.org/dictionary/english/intervention). The word 'intervention' here is with reference to the definition of an experiment, as per Welman, Kruger & Mitchel, 2005. No changes were made.
p. 73, para 6 It is assumed that you are referring to "split unit air conditioning" not full ducted air conditioning. In the latter case it is very unlikely that the windows would ever be opened.	Section 3.6.4.1, page 79	The type of air conditioner is not relevant in the context of the paragraph. The reference to air conditioners is in the list of criteria for classroom selection: "if air conditioners or fans are present, they are to be switched off during measurements", regardless of what type of air conditioner is used. No amendment was made.
p. 83, para 3 and 5 It is suggested that names of software are written in italics so that it stands out a little bit more.		Corrected as suggested in all cases.
p. 84, para 2 Spelling mistake in 'envelop'.	Section 3.6.5, page 90	Corrected (in list of criteria)
p. 91, para 2 Rwanda has mostly a hot Tropical Savannah climate (Köppen-Geiger Aw).	Section 4.1.1, page 97	The climate in Rwanda is not relevant to the discussion here but it has been acknowledged in the addition of the phrase: *"When the South African and American solutions (5% and 4% of usable floor area, respectively) are applied to a minimum-sized*

		South African classroom of 47 m², the resultant openable window area (including door as an openable area) is 2.35 m² and 1.88 m² respectively. This is significantly less than the Rwandan recommendation of 5 m², which is probably based on the hot climate in Rwanda."
p. 91, para 3 There is off course also a natural daylight requirement that requires a significant area.	Section 4.1.1, page 97 Section 1.0, page 19	A reference to the whole window area as wells as the opening area has been added, acknowledging the role of daylighting, although this is not within the scope. Refer to Section 1.10, where daylighting is acknowledged but excluded from the scope of this particular study. *"Considering the solution based on the South African National Building Regulations (NBR), the minimum openable window area of 2.35 m² can be translated into a standard door area (0.8 x 2.1 = 1.68m²) plus a window of approximately 1 m by 0.6 m. This is a very small opening area and is not in line with what is generally observed in schools in Gauteng, an example of which is shown in Figure 4-1, where the entire window area (for daylighting) as well as the openable area (for ventilation) is more than strictly required by the NBR."*
p. 92, Figure 4-1 Nothing has been said about natural daylight! This is perhaps a *lacuna*!	(Section 4.1.1, page 97) Section 1.0, page 19	Refer to Section 1.10, where daylighting is acknowledged but excluded from the scope of this particular study. No amendment was made.
p. 94, Figure 4-2 Improve the quality of drawing, especially the fonts size of dimensions. It distracts from the quality of the thesis.	Section 4.1.3, page 100	The drawing has been updated (Figure 4-2).
p. 98, Figure 4-6 One should state that it is *Google Earth* images as it is a requirement of the copyright laws.	Section 4.2.3, page 105	Google maps has been included as a footnote reference.

p. 101, Figures 4-7 and 4-8 The quality of the images should be improved as it is almost unreadable. It should be at least 300 dpi.	Section 4.2.4, page 108	These images have been revised to enhance the legibility, however, because they are based on screenshots of the software, the quality cannot be improved.
p. 104, para 2 The requirements of natural daylight should feature somewhere as it is very important in the context of natural ventilation, sustainable design and energy efficiency. This requirement determines to a large extent the size of windows and the relationship between openable and non-openable sections in conventional designs.	(Section 4.4.1, page 111) Section 1.10, page 19	No amendment was made in this section. Refer to Section 1.10, where daylighting is acknowledged but excluded from the scope of this particular study. The following paragraph has been included in Section 1.10 Delimitations to explicitly acknowledge that daylighting is important but is excluded from the scope of this study: *"It is also acknowledged that window design is not only determined by ventilation requirements but also natural daylight requirements. While natural daylight is important to consider in classroom design, it is excluded from the subject of this study. While sound transmission can occur more easily through glazing than through the surrounding construction, solutions, such as double glazing, are available to effectively limit sound transmission while maintaining daylighting requirements. Thus the natural daylight requirement for classrooms does not compromise acoustic insulation in the same way that natural ventilation through open windows does."*
p. 109, Table 5-1 In the right column why are these deviations so high (values 9.8 and 12.2).	Section 5.1.1, page 118	These deviations and the possible reasons are discussed in the two paragraphs following Table 5-1.
p. 111, para 2 Spelling mistake 'Positon'.	Section 5.1.2, page 119	Corrected
p. 113, Figure 5-3 Annotate facade receivers in drawings 5-2 and 5-3 accordingly to make it clearer, although there are many variations it can be written in symbolic format.	Section 5.1.2, page 121	Amended as suggested.

This is important to support **Table 5.3** below better that contains a large amount of important data.		
p. 118, para 3 The statement "In other words, for a naturally ventilated classroom, the wall construction material is acoustically irrelevant.". This statement is only true in this specific context of the thesis and should be stated as such.	Section 5.2.1.1, page 126	Amended to read: *"In other words, for the naturally ventilated classroom considered in this study, in which the open window area on the receiving façade is 11% of the floor area, the wall construction material is acoustically irrelevant."*
p. 122, Figure 5-4 Annotate the façade receiving positions to make it a bit clearer.	Section 5.2.3, page 130	Annotated as suggested to make it clear that receiver ARc1 is the subject of this part of the study.
p. 123, Figure 5-5 Annotate the façade receiver positions to improve readability.	Section 5.2.3, page 131	Annotated as suggested.
p. 128, Figure 5-10 Increase size of lettering. Especially the subscripts are very small and almost unreadable.	Section 5.3, page 136	Amended as suggested.
p. 129, Figure 5-11 Increase size of lettering. The annotations are very small and almost unreadable.	Section 5.3.1, page 136	Amended as suggested.
p. 130, Figure 5-12 The **a**nnotations, especially subscripts are almost unreadable.	Section 5.3.2, page 138	Amended as suggested.
p. 131, Figure 5-13 The small fonts and subscripts are almost unreadable.	Section 5.3.3, page 139	Amended as suggested.
p. 133, Figure 5-14 These figures are a little bit more readable, however they are still very small. Seeing that they are rather important graphs I would try and improve these, e.g. by changing the annotations to black.	Section 5.3.3, page 142	Amended as suggested.
p. 134, Figure 5-14 See comment above.	Section 5.3.3	This was a duplicate, which has been deleted.
p. 134, Table 5-10 Table heading and body should be on the same page.	Section 5.3.3, page 143	Amended as suggested.
p. 136, Table 5-11 See comment above.	Section 5.3.3, page 145	Amended as suggested.

p. 144, para 7 It is suggested that a drawing is included to illustrate exactly how this works.	Section 5.3.5, page 153	New figures included (Figures 5-17 & 5-18).
p. 150, Figure 5-17 and 5-18 The annotations are very small and in grey, making them almost unreadable. Make sure the figures are at least 300 dpi.	Section 5.3.6, page 159 & 160	Amended as suggested (Figures 5-19 & 5-20).
p. 160, Figure 5-22 Increase the font sizes/ graphs. It is very difficult to read the graphs!	Section 5.4.3, page 170	Amended as suggested (Figure 5-24).
p. 163, Figure 5-24 See comment above.	Section 5.4.4, page 173	Amended as suggested (Figure 5-26).
p. 176, Table 6-5 Some strange non-printing characters appeared in the second column of the table.	Section 6.4, page 186	Amended.
p. 179, para 5 The sentence "New schools present an opportunity to design the school in such a way that intrusive outdoor noise can be suitably attenuated." once again indicates that one should perhaps consider other novel/ inventive methods over and above just walls.	Section 7.1, page 189	This research was intended to seek feasible, currently available solutions in the South African context, thus interventions were investigated rather than novel inventions. A phrase has been added to emphasise this: *"New schools present an opportunity to design the school in such a way that intrusive outdoor noise can be suitably (<u>practically and feasibly</u>) attenuated, <u>while maintaining natural ventilation in accordance with the Regulations</u>."*
p. 182, para 1 The sentence "Large openings in the envelope, preferably on opposite sides to allow cross-ventilation, are required." This statement is true unless other methods of natural ventilation are used.	Section 7.1, page 189	The paragraph has been amended to indicate that natural ventilation by means of windows specifically is the intended meaning: *"Compounding the problem of outdoor noise interference in classrooms is the fact that most South African classrooms rely on natural ventilation via openable windows. Open windows compromise the sound insulating ability of the classroom envelope. Unlike mechanical ventilation, natural ventilation, depends on atmospheric temperature and pressure differentials which are not controllable. The implication is that where natural ventilation is employed, the required rate of fresh air delivery is*

		much higher. <u>For natural ventilation via windows</u>, large openings in the envelope, preferably on opposite sides to allow cross-ventilation, are required."
p. 191, para 4 The sentence "However, an in-depth study of suitable and effective natural ventilation design is recommended. This study stemmed from the tension that exists between natural ventilation and acoustic requirements for classrooms." The conflict between the requirements of natural ventilation and acoustical design once again strongly indicate that one should pursue inventive solutions that do not make a compromise.	Section 7.3, page 199	This comment seems to imply that the solution proposed in the thesis is a compromise. The purpose of the research was to investigate solutions (within the stated scope) that do not result in a compromise. This research was intended to seek feasible, currently available solutions in the South African context, thus interventions were investigated rather than novel inventions. The following changes were made to be more specific regarding the recommendation: "*However, an in-depth study of <u>alternative</u> suitable and effective natural ventilation design <u>that decreases sound transmission and reduces the need for outdoor interventions is</u> recommended*."
Examiner 2		
The topic of the thesis, on the noise attenuation in naturally ventilated classrooms, is interesting, as much work has been done on classroom acoustics, but there is a lack of knowledge about the guideline of school design. The methodology, including field measurements and computer simulations, is appropriate and well-designed. In particular, Chapter 5, which deals with computer modelling, showed novelty by considering many design factors to meet the target background noise level. The thesis is well structured and the presentation is of high quality. The analyses of the results are in detail and at an appropriate level. The figures and tables are presented clearly.		The general comments are addressed in the detailed comments below.

There were some areas could be improved and these are detailed in the attached document. These include making stronger research questions by adding a new specific research question on the development of design guidance. Also, the chapter titles could be slightly revised to make the thesis clearer. Additionally, more information about computer modelling could be added to highlight the novelty of this study. Other requests include further clarification on terms and findings, as well as grammatical errors. When sound pressure levels are expressed as Leq, L should be in italic such as 'L_{eq}'. The core of this thesis was to conduct computer simulations using two software. However, the backgrounds of these were not described in both literature review and methodology. Please rethink about the chapter titles. The current thesis is not clear to show a usual thesis structure such as introduction, literature review, methods, findings, analysis, and discussion.		
Chapter 1		
P11, 1.3: As described in other chapters, many countries already developed design guidance on classroom or school.	Section 1.3, page 13	The paragraph refers specifically to outdoor noise attenuation, of which there is little guidance in South Africa or other countries. The problem statement has been amended to specifically refer to outdoor noise attenuation: *"There is a lack of quantitative guidance for basic acoustic design solutions to attenuate outdoor noise in the context of urban schools exposed to road-traffic noise."*

P12, 1.5: The second and third research questions are not strong for PhD thesis. The second one can be answered by reviewing current guidance and previous studies. The third cannot be generalised here because road traffic noise is affected by several factors. Instead, a new research question could be made in relation to classroom design guidance such as 'What is the design guidance a naturally ventilated classroom?'	Section 1.5, page 13	The purpose of posing these as research sub-questions was to dedicate research to these issues that are required as variables in the main research. The answers to these questions are required to support the process of answering the main research question. The second sub-question (What is a suitable ambient noise level in a classroom?) was answered through a literature review and considered within the South African context. The third research question (What is the nature of the problem noise source) should not be generalised because of the many factors that affect traffic noise; thus, the traffic noise specific to urban schools in Gauteng needed to be investigated. Changing these research questions would constitute significant changes to the thesis whereas the examiner indicated that only minor changes to thesis were required.
P13, sub-objectives 2 and 3: Please see the comment above. In particular, #2 could be a part of the literature review rather than major research. On page 15, it is already stated that 'The acceptable target SPL (40 dBA) was determined through a review of acoustic literature and regulations pertaining to classroom ambient noise levels, thus meeting the third objective.'	Section 1.6, page 14; Section 1.8, page 17	Refer to response above. Section 1.8.1 is a summary of the research instruments and the research that was done as an introduction to the thesis; thus, the conclusion regarding the target sound pressure level is given here ahead of the detailed report regarding how that conclusion was reached. The text has not been amended.

P20, 1.12: It is not a good idea to state about the limitations of this study – this could be removed because it is described in Chapter 7.	Section 1.12, page 22	Chapter 1 is intended to introduce and provide an overview of the research. Thus, limitations have been included in this chapter. No changes have been made.
Chapter 2		
P51, 2.3.4: Please see the papers below and add them to this section. • Pelegrín-García, D., Brunskog, J., & Rasmussen, B. (2014). Speaker-oriented classroom acoustics design guidelines in the context of current regulations in European countries. Acta Acustica united with Acustica, 100(6), 1073-1089. • Mealings, K. (2016). Classroom acoustic conditions: Understanding what is suitable through a review of national and international standards, recommendations, and live classroom measurements. Proceedings of Acoustics 2016.	Section 2.3.4, page 56-60	These references have been included as pertaining to international standards and guidelines for classroom acoustics.
P58: Please add more literature about the effect of noise on school children (e.g., health and cognitive performance) by expanding Paunovic's study.	Section 2.3.1, page 37	A brief expansion of the effects of classroom noise on children has been added to Section 2.3.1 as part of the discussion regarding the relevance of acoustics in the classroom context.
Chapter 3		
P66, Figure 3.1: This design could be revised concerning the comments above about research questions and objectives. Major research methodologies are computer simulations but they are not mentioned here - computer simulations should be added to Sub-q.4.	Section 3.5, page 71	As mentioned above, the research sub-questions were designed to establish the variables and thus support the process of answering the main research question. Computer simulation is used as a research instrument rather than a methodology. The use of computer simulation as an instrument to perform the research is discussed in Section 3.6.5, referencing other studies that used simulation as an instrument.

		Figure 3.1 indicated modelling as an instrument, which refers to computer simulation. The Figure 3.1 has been amended to clarify this.
P70: Only one per school might cause a biased result as described on page 71 – but not described in Chapter 7.	Section 7.1, page 189	A brief discussion of the survey and questionnaire findings has been added in Chapter 7 (Section 7.1).
P72: If you have measured SPLs at each school, you can then make relationships between the SPL and teachers' responses.	Section 3.6.3, page 78; Section 4.2.3, page 105	A note regarding this relationship has been added in section 3.6.3 and a brief discussion regarding the relationship between the measured and perceived noise level has been added in section 4.2.3.
P70-72: It is mandatory to describe the sample size of the survey.	Section 3.6.3, page 78	The sample size (five) has been included at the end of section 3.6.3 and is also reported in Chapter 4.
P74: Why didn't you locate multiple SLMs inside the classrooms. This position is very close to the window so the SPLs could be overestimated.	Section 3.6.4.3, page 80	Section 3.6.4.3 discusses the rationale for the selected measurement location in the classroom, with a major constraint being the availability of measuring equipment. This is mentioned in the limitations section in chapter 1 and in paragraph 3 of section 3.6.4.3.3. The following sentence has been added to the first paragraph of section 3.6.4.3.3 for clarity: *"A major constraint was that only one Class 1 sound level meter was available for the study."* The measurement location was based on local standards (SANS 10103) as mentioned in the text.
P89 • In general, low response rate should be expected when using a questionnaire sent by	Section 3.8, page 95	While a high response rate was not expected, a 5% response is too low to be able to confidently generalise the results, although the results are informative. This brief explanation and the number

postal services. So this wouldn't be a limitation of this study. • It is not clear how many participants you had in two separate surveys.		of participants has been added by amending the following sentence: *"The survey response rate was low (5% out of 3 065 schools), which can be viewed as a limitation in that the results cannot be confidently generalised, although they are informative."*
Chapter 4		
P90: It is not natural to introduce the results of the literature review which is a previous chapter.	Section 4.1.1, page 96	As described in Chapter 3, the literature review was used as a research instrument. The Literature Review in Chapter 2 provided background and context for the problem, part of which is the existing ventilation requirements in local and international standards. Here, in Chapter 4, these are referenced, summarised and applied as a benchmark for establishing the controlled variable (typical classroom ventilation design).
P97 • The sample size is too small to extract significant findings so I recommend deleting this result. • Figure 4-5: Separate the questions (e.g., disturbance, effect of noise, and action to prevent noise disturbance)	Section 4.2.2, page 96	This section has been amended to acknowledge that this is a case study and the results are not intended to be generalised. However, they do confirm that traffic noise is a relevant problem to study and provide a reference for comparing perceived noise level to actual measured noise level. Figure 4-5 has been amended as suggested.
P99 • Please add traffic flow information (hourly traffic flow and % of heavy vehicle) of other schools as well. • RLS-90 was used in the CadnaA so it is important to describe the speed of vehicles in each school.	Section 4.2.3, page 106; Section 3.8, page 95	Traffic flow was only recorded as School B as stated in section 4.2.3. This has been added as a known limitation in Section 3.8. The traffic speed has been added to the discussion in Section 4.2.3.

P99, Table 4.3: Please add L_{10}-L_{90} to show temporal characteristics of the road traffic noise.	Section 4.2.3, page 106	Included as suggested.
P100, Table 4.4 • It would better to show a figure, presenting spectral characteristics of the recorded noise. • Typical road traffic noise has dominant sound energy at low frequencies but the noises at four schools here show peaks at high frequencies. Is it because the vehicles were fast?	Section 4.2.3, page 107	A spectral plot has been added (Figure 4-7) in place of Table 4-4. The traffic speed was approximately 60 km/h, based on the legal speed limits on the roads. The frequencies are similar to another studies (Burutti & Moretti, 2010; Kim, Barber & Srebric, 2017) for urban roads of similar traffic volumes and speeds; references to these studies have been added.
P100, 4th paragraph • It sounds like RLS-90 is the only method to be implemented in CadnaA which is not true. • More descriptions about noise mapping procedure should be provided. • Other buildings were not modelled in simulations (Figure 4-7) so sound reflections from surroundings were ignored. Please specify why the modelling was simplified.	Section 4.2.4, page 107	A phrase has been added to the paragraph indicating that there are other standards used in CadnaA for modelling roads (second paragraph of section 4.2.4): *"This method is <u>used by a number of</u> European standards <u>used in CadnaA, such as RSL-90, Nordic Prediction Method, Nouvelle Méthode de Prévision du Bruit and others</u>, and accounts for the frequency spectrum, road surface, gradient and the ratio of heavy and light vehicles."* Refer to discussion on acoustic modelling in section 3.6.5. Refer to section 3.6.5.2 for the modelling set-up and rationale.
P105, 1st sentence of 2nd paragraph: Please add references supporting this (i.e. sound attenuation by vegetation).	Section 4.4.1, page 112	Reference added. Also refer to section 2.3.3.2.7

P107: As commented above, the spectral characteristics of the traffic noise are quite different from those of typical urban road traffic noise – in general, noise from the motorway (highway) shows dominant energy at high frequencies.	Section 4.5, page 115	The modelling software automatically calculates the traffic noise and spectral content as mentioned in Section 4.2.4 (second paragraph).
Chapter 5		
Chapter title:		Chapter 4 and 5 are both a report on the findings of the research and are separated for easier reading and to differentiate between the sub-objectives and the main objective. The chapter headings have been changed from "Data collection and findings" to "Research results"
P100, 2nd paragraph: It is not clear how Bastian works? It is likely that it doesn't consider reverberation time but other variables or mechanism are not clear.	Section 5.1. (see Section 3.6.5, page 91)	Refer to Section 3.6.5 which mentions the factors that are accounted for in *Bastian*.
P100, 3rd paragraph: How about Schools A and D? The deviations at Schools A and D are also acceptable?	Section 5.1.1, page 118	The following paragraph elaborates on Schools A and D with the addition of the underlined parts: *"It is speculated that the deviation at School A could be due to the low-pitched sheet metal roof, which would offer low resistance to sound transmission, and which is not represented in the model. At School D, the high indoor sound level could be due to the high reverberation time which was observed on site and which is not accounted for in the model, <u>which had a set reverberation time of 0.5 seconds. Thus School A and D were disregarded as validation benchmarks</u>."*
P101: The first assumption is not realistic as commented above.	Section 5.1.2	This is addressed in paragraph 2 of section 3.6.5.2 and in the discussion and limitations of findings in Section 7.3.
P118, 3rd paragraph: Please specify the condition of natural ventilation in this study (i.e. 11% of the floor area).	Section 5.2.1.1, page 126	Amended as suggested. Section 5.2.1.1, third paragraph: *"In other words, for the naturally ventilated classroom <u>considered in this study, in which the open window area on the receiving</u>*

		<u>façade is 11% of the floor area</u>, the wall construction material is acoustically irrelevant."
P124, Figure 5-6 • Please add two more lines indicating inverse square law and inverse law for comparisons. • The difference is because the ground is assumed to be reflective. So please comment that the difference would be less than this in practice.	Section 5.2.4, page 132	Amended as suggested.
P126, Figure 5-8: the differences look greater than 1.1 dB – please check the graph.	Section 5.2.4, page 134	Corrected.
P139, Table 5-12: Please discuss the effect of the on this. In this study, the ground is reflective so the ground absorption at high frequencies would be less than realistic situations.	Section 5.3.4, page 147	This is mentioned in an added sentence before Table 5-12 and is also addressed in the discussion in Section 7.3.
Chapter 6		
P70, 2nd paragraph • 'However, considering the attenuation of the signal noise (?) over distance,…' • Please define abbreviation when it first appears (i.e. SNR).	Section 6.2, page 180	It is unclear what the comment here is but clarity regarding the signal noise (teacher's voice) has been added in second sentence of second paragraph of section 6.2. Refer to Section 1.1.4, where SNR first appears earlier in the document and is defined there, as well as in the beginning of this chapter (Section 6.1) and in the added List of terms.
Chapter 7		
Chapter title: 'Conclusion' would be better.	Chapter 7	The chapter heading has been changed from "Conclusion and recommendations" to "Conclusion"
In general, it is too long so please make it concise by focusing on 'summary of findings'. • 7.1-7.3 could be omitted	Chapter 7	Sections 7.1 (Background and purpose), 7.2 (Literature review) and 7.3 (Research design) have been condensed into one section (7.1) to briefly reflect upon the background and context of the study.

• 7.4 could be 7.1. And summarise the findings in relation to research questions. • 7.6 could be 7.2. Discuss future research directions based on the limitations of this study. For instance, you could add research questions for future research.		The main research question findings, which originally constituted Section 7.4 are now in Section 7.2. The discussion, limitations and recommendations are now consolidated into Section 7.3 A future research areas have has been recommended in Section 7.3.
P184-185: Please remove a list of tables.	Section 7.2	Amended as suggested.
Examiner 3		
Detailed comments		
p. 7: first word on page is misspelled	Section 1.1.4, page 8	corrected
p. 51, Section 2.3.4, 2nd paragraph: Fix definition of reverberation time to be the time it takes for sound energy to decay specifically 60 dB in a room	Section 2.3.4, page 56	Amended as suggested.
p. 60, 3rd paragraph: likely all of these absolute decibel units should be dBA, rather than dB? (relative decibel units, where one sound level is being compared to another of the same type, can be left as dB or changed to dBA if you wish)	Section 2.3.7, page 64	Amended as suggested.
p. 61, Section 2.3.8 (incorrectly labeled as 2.3.1?): with regards to the 2009 Department of Education reference, should the ambient noise levels be dBA, or dB?	Section 2.3.8, page 66	Section numbering corrected. dB has been amended to dBA; although the Department of Education does refer to dB, it is assumed that the intention is dBA.

p. 62, 2nd paragraph: Phrase starting with 'For example,' is a sentence fragment; perhaps attach to previous sentence.	Section 2.3.8, page 67	Amended as suggested.
p. 63, 3rd paragraph: I'm not familiar with the acronym IBTs here … has this been introduced earlier? If not, perhaps spell it out here if it's the first time?	Section 2.4, page 68	The full term 'innovative building technologies' for IBTs has been added, although the term was introduced in section 2.1.2 and has also been added in the List of terms.
p. 85, last paragraph: delete first word 'As'	Section 3.6.5.2, page 92	Amended as suggested.
p. 99, last paragraph: could you include plot(s) of the full frequency spectra (octave band on x-axis, level on y-axis) of the noise, rather than just indicating which frequencies were dominant in Table 4.4?	Section 4.2.3, page 107	Spectral plot has been included (Figure 4-7) in place of Table 4-4.
p. 105, 4th paragraph: The theoretical decrease of 3 dB per doubling of distance is for a specific case of a line source in a free field … this should be explicitly stated.	Section 4.4.1, page 113	Amended as suggested: *"…a theoretical decrease in SPL of 3 dB for every doubling of distance for a line source in a free field."*
p. 112, 2nd paragraph: The theoretical decrease of 3 dB per doubling of distance is for a specific case of a line source in a free field … this should be explicitly stated.	Section 5.1.2, page 120	Amended as suggested.
p. 155, 3rd paragraph: I believe there have been other modelled and empirical studies about barrier crowns. Could perhaps add references to those here or elsewhere in the thesis?	Section 5.4.2, page 163 (see Section 2.3.3.2.6)	See Section 2.3.3.2.6 where the effect of the shape of a barrier is discussed.

p. 179, first paragraph under Section 7.1: Phrase starting 'More specifically,' is a sentence fragment.	Section 7.1, page 189	Amended as suggested.
p. 180, 1st paragraph: add 'or greater' to the last sentence of this paragraph.	Section 7.1, page 190	Amended as suggested.
Other comments		
Good job on this, Coralie! I hope to meet you again soon at an acoustics professional conference. My research group has been working on classroom acoustics and impact of acoustic conditions on learning and speech comprehension in the past decade, as well; these articles could be pertinent to add to your references: L. M. Ronsse and L. M. Wang. (2013) "Relationships between unoccupied classroom acoustical conditions and elementary student achievement." *J. Acs. Soc. Am*. 133, 1480- 1495. Z. E. Peng and L. M. Wang (2016) "Effects of noise, reverberation and foreign accent on native and non-native listeners' performance of English speech comprehension." *J. Acs.* *Soc. Am*. 139, 2772-2783. L. C. Brill, K. H. Smith, and L. M. Wang (2018) "Building a sound future for students –		

considering the acoustics in occupied active classrooms." *Acoustics Today*, 14(3), p. 14-22.		