Traffic noise attenuation solutions for naturally ventilated classrooms in South Africa

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Abstract

Traffic noise transmission through the open windows of naturally-ventilated classrooms can reduce speech intelligibility and can negatively impact academic performance. The findings of a numerical study are presented. Software was used to assess effective noise attenuation solutions for naturally-ventilated classrooms exposed to traffic noise. A typical situation in urban schools in Gauteng, South Africa, is considered in which classrooms are ventilated by large open windows in accordance with national building regulations and norms and standards for school design. The aim of the study was to establish a heuristic framework for early design decisions regarding how far from the road a classroom building should be set, and the effective height and position of a solid noise barrier to ensure a suitable ambient noise level inside a classroom with open windows. Efficacy was measured with reference to an indoor ambient sound level of 40 dBA. The findings show that with the insertion of barriers, the required ambient level was achieved for a classroom at least 68 m from the road, if the barrier is at least 3.5 m high. However, it was found that a significant insertion loss (>6 dB) and an improved signal to noise ratio could be achieved for classrooms as close as 17 m from the road with a barrier of at least 2 m high. Though not broadly generalizable, the findings provide a heuristic guide applicable for designing new schools or selecting attenuation interventions in existing city schools that are similar to those used in the study.

Keywords: Classroom acoustics, natural ventilation, noise barriers, sound transmission

Introduction

The traditional concept of the classroom and pedagogy has been challenged in recent years, with trends such as the flipped classroom,[1] the unwalled classroom,[2] and Teaching 4.[03,4] emerging, the important role of the quality of the physical learning environment remain unchanged.[5–7] It is well-established in literature that excessive classroom noise affects the well-being and performance of learners [8–13] as well as the health and well-being of teachers.[14,15] There are multiple potential sources of noise in a classroom, one of which is traffic noise, particularly for urban schools. While ideally schools should not be located adjacent to busy roads,[16] this is not always possible in urban areas. This is potentially detrimental as numerous case studies have shown that traffic noise, specifically, influences learners' academic performance and well-being.[17–21] According to the World Health Organization,[22] 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.[21,22] Traffic noise has been found to be a significant contributor to noise in schools the world over.[21,23–25] Increasing urbanization in South Africa, accompanied by population growth, not only increases the demand for new schools,[26] but also results in an increase in traffic volumes and the resultant noise pollution.[27]

This study is conducted in the context of Gauteng, the most urbanized and densely populated province in South Africa.[28] The expansion of Gauteng cities has led to a number of schools that were originally located in residential areas becoming enveloped by commercial expansion with busier roads. Furthermore, there is a high demand for new schools in the province[29] and locating these away from busy roads is not always possible. As a result, disruptive traffic noise is a challenge for urban schools in Gauteng.[30]

In South Africa, most public schools are naturally ventilated by means of openable windows, as required by the local norms and standards for school infrastructure.16 Ventilation is important, since air quality has a significant effect on the alertness and performance of learners [31,32]; in addition, good ventilation minimizes the risk of air-borne disease transmission, particularly with reference to Tuberculosis in South Africa.[33] For schools that are unavoidably located close to busy roads, the sound insulation of the classroom envelope is compromised when windows are opened. Thus, effective outdoor attenuation of traffic noise is necessary to ensure both acoustic and ventilation requirements can be met.

Architects in South Africa are generally poorly equipped to make good scenario-specific decisions regarding outdoor sound attenuation interventions to achieve a target ambient sound pressure level (SPL). Much of the literature on the topic is either very advanced or in the form of case studies, which are limited in general application, or vague qualitative guidelines, which are not helpful in achieving specific targets. While local standards, such as SANS 10103:2008,[34] specify the design SPL, there is a lack of quantitative guidance upon which to base acoustic design decisions to achieve a specified target.

The aim of this study was therefore to establish heuristic guidelines for architects for the attenuation of traffic noise that is transmitted into naturally ventilated classrooms. A heuristic guideline provides a set of rules that guide one toward a solution that is acceptable for a given set of problems and possible solutions.[35]

Traffic noise in the classroom can be mitigated by changing the traffic noise itself, through speed control or road surface properties—which is not considered in this study; or by improving the sound isolating properties of the building envelope; or by attenuating the outdoor noise as it propagates from the road up to the building envelope.

Envelope isolation is dependent on the materials from which the façade is composed and the shape of the façade. Windows within a facade can significantly reduce the sound reduction across a façade.[36] Although double glazing can improve the sound reduction,[37] this effect is lost if windows are opened for ventilation.[36,38,39] Alternative ventilation designs, such as plenum windows or ducted inlets improve sound reduction but reduce airflow[40] and are not design solutions typically used in South African classrooms. Façade design, such as balcony protrusions, have been found to be somewhat effective[41] however the effect is insignificant when windows are open.[42] Adding absorption to the façade can be effective in a courtyard or canyon type scenario[43] to reduce the sound level at the façade, although the effect on sound transmission with open windows is not quantified. Different window opening designs or conditions can also influence sound transmission, [38,44] although this is also influenced by the direction of the sound relative to the opening direction of the window. In this study, façade interventions are not the focus and a typical classroom façade was assumed, as described in Section 2.

Two main outdoor attenuation interventions were explored in this study, namely, distance between noise source and receiver, and noise barriers of varying heights in one of two positions relative to the source and receiver. It is well-established that increasing the distance between a source and the receiver will decrease the sound pressure level experience at the receiver, and likewise, it is well-known that increasing the height of a noise barrier will decrease the noise level at the receiver. However, useful guidelines in the context of urban South Africa regarding the magnitude of the distance and height to achieve a specific target level are not established. Establishing these variables was achieved through virtual experimentation by modeling various scenarios in *CadnaA* (2018) software and determining which yielded an indoor ambient SPL of 40 dBA in a classroom.

Considering evidence-based research as well as international norms and standards, there is general consensus that classroom ambient SPL should not exceed 35 dBA to ensure a suitable signal-to-noise ratio (SNR) of +15 dBA.[13,45] The SNR refers to the level difference between the signal level, which in a classroom setting is typically the teacher's voice, and the ambient (background) SPL. A low ambient SPL contributes toward good speech intelligibility and also reduces vocal effort required by the teacher, reducing the risk of vocal strain and fatigue which are correlated with noise exposure.[14]

In South Africa, national standards relating to environmental noise, SANS 10103:2008, specify that the design ambient sound level in a classroom should be 35 dBA with a maximum of 40 dBA.[34] However, based on the differentiation between higher grade and standard grade buildings in SANS 10218-1,[46] it may be argued that a standard grade building is more representative of a typical South African classroom, having lower sound insulation, and thus a limit of 40 dBA is deemed suitable to apply. Thus, the study aimed to provide heuristic quantitative guidelines for noise attenuation to achieve an ambient SPL of 40 dBA in typical naturally ventilated classrooms.

Method

Research design

Experimentation requires the erection of noise barriers of differing heights and in different positions relative to the noise source (road) and receiver (classroom). Since it would be costly and impractical to do this in actual schools, a virtual experimental site was modeled based on empirical data measured at existing schools, with a road and a classroom building as controlled variables, the classroom SPL as the dependent variable, and the attenuation interventions as the independent variables. The three independent variables, as shown in Figure 1, were:

(i) the distance between the road and the classroom,
(ii) the height of the noise barrier, and
(iii) the position of the noise barrier relative to the road and classroom.

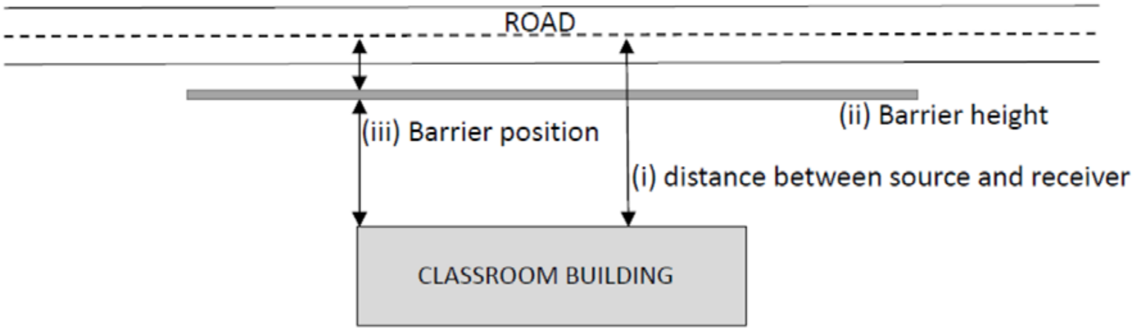

Figure 1. Variables illustrated on virtual site.

The efficacy of outdoor noise attenuation interventions for a typical classroom with open windows was modeled using the acoustic software packages, *CadnaA*, for outdoor noise, and its companion, *Bastian*, for envelope transmission. *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°.[38,47] *CadnaA* makes use of both these approaches in combination and integrates the approaches for determining sound levels contained in ISO 9613-21, NMPB 20082 and Harmonoise,[48] which are models for predicting environmental noise. Diffraction around and over barriers is calculated in *CandaA* and reflection and barrier density are accounted for when calculating the transmission of sound. *Bastian* bases calculations on EN 12354 (part 1–3) for the estimation of the acoustic performance of buildings from the performance of elements and has the ability to create complex facades. *CadnaA* was used to

calculate the outdoor noise level at the façade, which was imported as an input in *Bastian* to calculate the sound transmission through the building envelope.
A number of different scenarios were modeled and the resulting classroom SPL was analysed against the target level of 40 dBA to determine which intervention scenarios were effective for achieving the target. This exercise was performed for ground floor classrooms in a single-storey building and first-floor classrooms in a double-storey building.

Establishing controlled variables

The classroom SPL is affected by the size of the classroom,49 the size of the window openings,[38] and the magnitude of the source noise. Thus, these factors needed to be established as controlled variables.

The size and facade design of a typical classroom in Gauteng was established by averaging the classroom size and window area of normal classrooms at four case study schools in Gauteng, which were selected based on their exposure to traffic noise throughout the school day. The resulting classroom was 7 m × 8 m (56 m2) with a ceiling height of 2.7 m and an external façade height of 3 m. The effective façade of interest, referred to as the receiving façade, was 21.6 m2. The openable window area was 6.1 m2 (28% of the receiving façade area) and the fixed (closed) window area was 1.64 m2 (about 7.5% of the receiving façade area). This design is compliant with the local regulations for the minimum classroom size.16

The following materials were assigned to the façade: the wall construction material—240 mm thick masonry with a plaster render on one side with a density of 200 kg/m3, which represents a common construction type found in three out of the four case study schools; the window glazing—4 mm thick clear float glass, which is the most common glazing material used in South Africa. The effect of the window framing was found to be negligible and was not specified; a third “material” was assigned to the open sections of windows with a sound reduction index of zero.

The exact configuration of the various surfaces was inconsequential since the modeling software for sound transmission (*Bastian*) only applies each material as a percentage of the façade area. It is also assumed that (a) the opening sections are horizontal pivot windows, which provide minimal influence to air and sound transmission,38 and (b) no sound was transmitted through any other elements of the classroom envelope, such as the roof, floor, or side walls and the model was configured to represent this. Diffraction around window openings is not specifically accounted for in the sound transmission modeling in *Bastian*.

CadnaA makes use of traffic volume to model road noise. Actual traffic volume data taken outside an actual urban school was used to model the road. Using this traffic volume (1120 vehicles per hour with 3% heavy vehicles) the modeled roadside SPL was only 0.7 dB higher than the actual measured roadside SPL. The traffic volume was adjusted to 1000 vehicles per hour with 2.5% heavy vehicles so that the modeled SPL was the same as the actual SPL. Thus, the model was calibrated to represent the actual site.

The resulting controlled variable for traffic noise was 63.6 dBA as calculated 20 m from the center of the road, which for this experiment was deemed to represent the typical noise exposure of urban schools in Gauteng.

Establishing independent variables

The independent variables are interventions that can be implemented to attenuate sound propagation between the noise source and the receiver. There are a number of factors that influence sound propagation outdoors, such as distance between source and receiver, orientation of the receiving façade relative to the source, ground absorption, screening (barriers), vegetation, topography, atmospheric absorption, and meteorology. Atmospheric and meteorological conditions are not design factors and were thus excluded as independent variables in the model and were fixed at the default values in *CadnaA*. The effect of ground absorption and vegetation was eliminated; the worst-case scenario of no vegetation and reflective ground was assumed. This ensures that any vegetation that is added to a site during or after the design and construction phase provides an acoustic benefit, yet the efficacy of the design does not depend on it. Topography was not considered and a flat site on a level with the road was assumed as a generic site.

Distance was identified as a relevant design factor to be considered in this study. For a line source (such as a busy road), a theoretical decrease of 3 dB per doubling of distance is expected.[50] In reality, this attenuation value 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.[50] The attenuation of noise over distance, as well as the orientation of the façade relative to the road, can be modeled, and the distance at which a significant effect is achieved could be determined. However, distance can only be a useful intervention on a new school site, where the designer has the liberty to position the school building optimally; it is not useful to apply to an existing site, where the distance between the road and the classroom building is fixed.

Screening by the insertion of a solid noise barrier is known to have a significant effect on sound attenuation, depending on the barrier dimensions; barrier dimensions (height and width) can be modeled and the effect calculated. The height of the barrier and the position of the barrier relative to the noise source and the receiver were identified as two separate independent variables. Barriers are applicable on both new and existing sites.

Model set-up

The effects of road noise was calculated in *CadnaA* at a receiver 1.2 m in front of each building façade. For the single-storey buildings (ground floor classroom), the receiver height was 1.5 m above ground level and for the double-storey building (first floor classroom), the receiver level was 4.5 m above ground level, which in each case represented the mid-height of the classroom window. The classroom building was orientated so that the receiving façade was parallel to the road. The outdoor noise level at the façade receiver under each scenario in *CadnaA* was imported as the external noise source in *Bastian* and the sound transmission through the façade with open windows was calculated.

The various scenarios were modeled and calculated by activating or deactivating objects in *CadnaA*. General default settings were used in setting up the model.

The model was designed to represent a generic site with the worst-case conditions where possible. The reason for this was to eliminate confounding factors so that the results could be applied in actual cases regardless of the specific conditions. The road was assumed to be on one side of the site and effectively extend infinitely either side of the receiver and on the same level as the classroom building. The model configuration of the road assumed one reflection order, no lateral diffraction, no housing attenuation, no foliage attenuation and no meteorology. The ground surface was set to be reflective; the classroom building assumed a reflection of 0.5, and no surrounding structures were assumed. The barrier was set to be a dense solid wall (configured with no acoustic transparency, having a closed surface and an assumed surface density of at least 10 kg/m^2) of insignificant thickness, representing a typical masonry boundary wall such that only sound carried over it or around would be considered. The classroom building was 32 m long (representing four adjacent classrooms of 8 m long), 7 m wide and with an external façade height of 3 m (single-storey) or 6 m (double-storey).

The classroom was modeled in *Bastian* according to the typical classroom design already established.

In this study, the weighted standardized 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 concerns as to the accuracy of the various descriptors for sound transmission in practice,[51] the descriptors currently accepted and used in local and international standards were used. These terms are used in *Bastian* and are in accordance with standards [52,53] and have been used by others[54] 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 standardized 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 SPL 2 m in front of the façade ($L_{1.2m}$) and the space and time averaged SPL (L_2) in the receiving room. This is accounted for in SANS 140-5:1998[53] by assuming a reverberation time of 0.5 s.

Scenario-building

In order to establish the attenuating effect of distance, four basic building positions were constructed in the modeled environment at different distances from the noise source. These basic building positions were labeled A, B, C, and D, with position A being closest to the road and D being the furthest. Single-storey and double-storey buildings were constructed at each position.

The distance from the center 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 center of the road that a building could be constructed was calculated to be 17 m (5 m building line + 5 m road reserve + 7 m to center of road) as illustrated in Figure 2. This was the position for building position A.

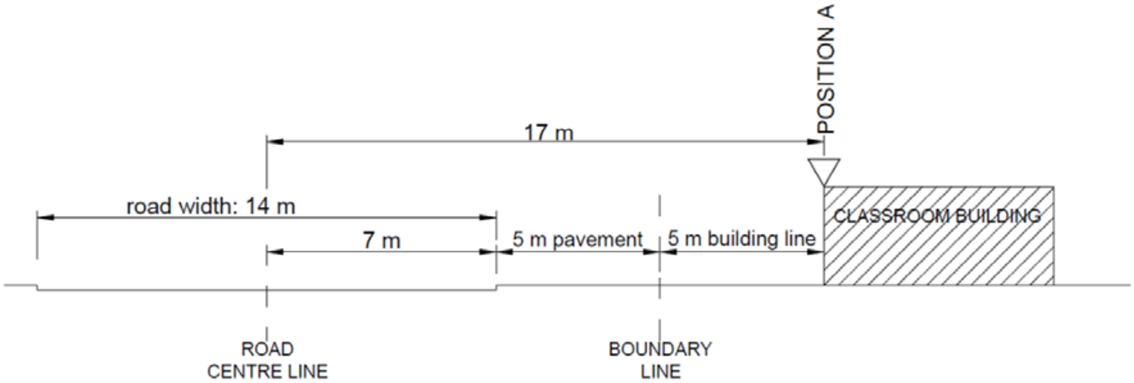

Figure 2. Basic set-up of virtual experimental site, showing distance from noise source to building position A.

Building position B was double the distance (34 m), since a doubling of distance theoretically (in a free field) produces a significant reduction in the sound pressure level of 6 dB. Building position C was double this distance again (68 m) and position D double that again (136 m).

Interim building positions were inserted in between the main positions in increments of 8.5 m (half the distance of A) to provide a higher resolution of results; these were labeled according to the number of increments away from the previous main building position. Thus, 15 building positions were created at the distances shown in Table 1.

Noise barriers were modeled in two different positions, as illustrated in Figure 3. In the first, barrier condition 1, the barrier was at a fixed position close to the noise source; in the second, barrier condition 2, the barrier was in a fixed position close to the receiver, which varied with the building position. For barrier condition 1, the barrier was at the boundary of the site, assumed to be 12 m from the center of the road. For the second barrier condition, the barrier was inserted 3 m from the classroom façade (d_{h2} = 3 m in Figure 3).

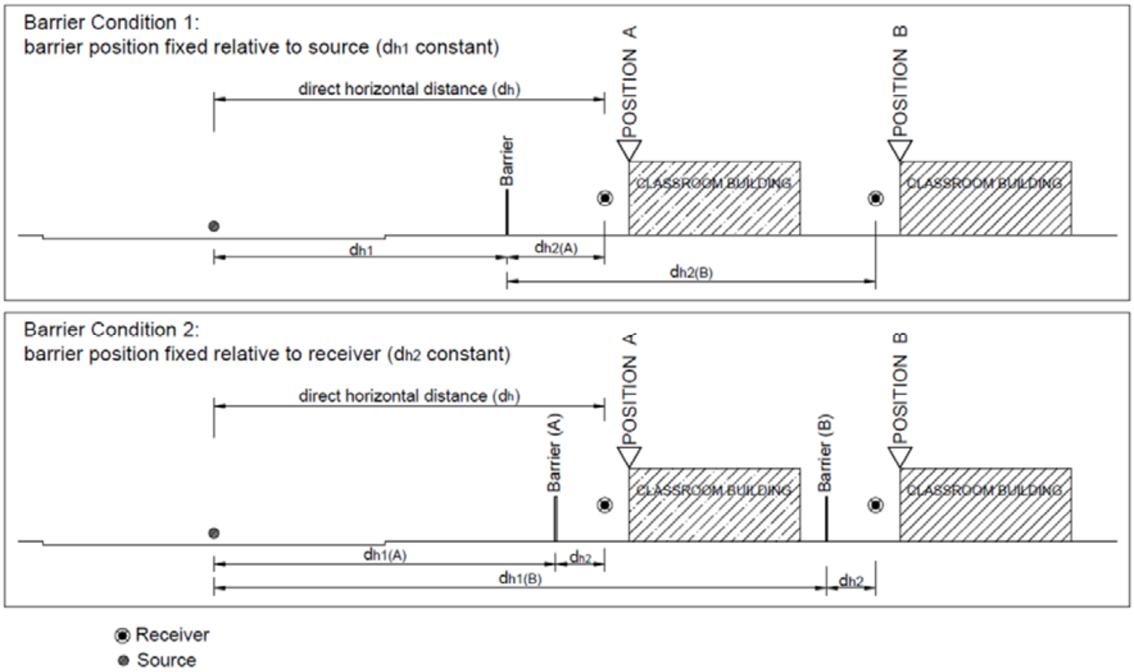

Figure 3. Illustration of barrier position under Condition 1 and Condition 2.

The length of the barrier was established according to the 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.[55] Accordingly, the barrier length was constant under barrier condition 2, in which the distance between the barrier and receiver was constant, regardless of the building position. With the receiver 1.2 m from the façade, the distance from the receiver to the barrier was 1.8 m and thus the barrier extended 7.2 m (4 × 1.8) in either direction, making it 14.4 m long. For barrier condition 1, the distance between the barrier and the receiver changed for each building position and the barrier length changed accordingly. The resulting barrier lengths for each building position are indicated in Table 1.

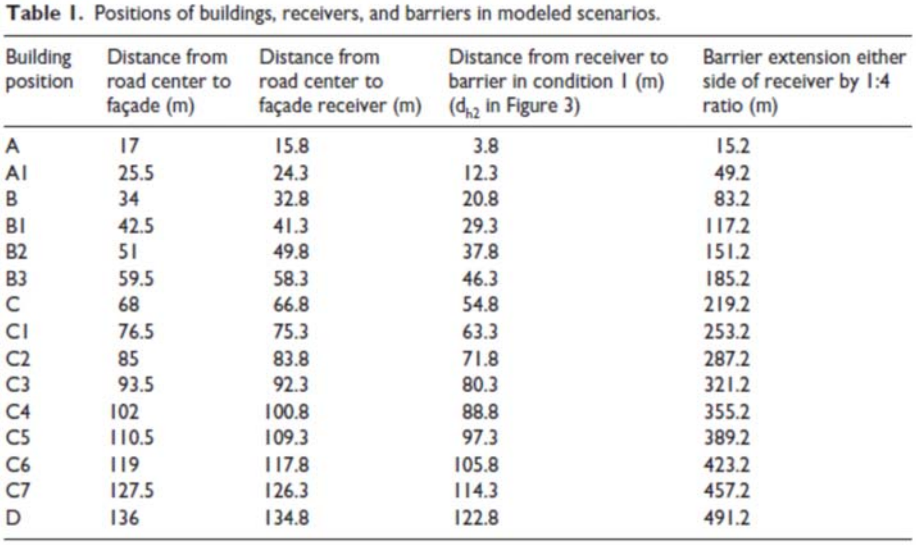

Table 1. Positions of buildings, receivers, and barriers in modeled scenarios.

Building position	Distance from road center to façade (m)	Distance from road center to façade receiver (m)	Distance from receiver to barrier in condition 1 (m) (d_{h2} in Figure 3)	Barrier extension either side of receiver by 1:4 ratio (m)
A	17	15.8	3.8	15.2
A1	25.5	24.3	12.3	49.2
B	34	32.8	20.8	83.2
B1	42.5	41.3	29.3	117.2
B2	51	49.8	37.8	151.2
B3	59.5	58.3	46.3	185.2
C	68	66.8	54.8	219.2
C1	76.5	75.3	63.3	253.2
C2	85	83.8	71.8	287.2
C3	93.5	92.3	80.3	321.2
C4	102	100.8	88.8	355.2
C5	110.5	109.3	97.3	389.2
C6	119	117.8	105.8	423.2
C7	127.5	126.3	114.3	457.2
D	136	134.8	122.8	491.2

At each of these barrier positions, the height of the barrier was varied between 1.5 and 7 m in increments of 0.5 m, although only barriers up to 3.5 m are used in this report, since walls higher than this are not practical, being unsightly and costly.

Data analysis

The target indoor sound pressure level was 40 dBA. All data was collected and tabulated and the scenarios that produced the target SPL were identified.

It was found that the typical classroom modeled in *Bastian* had a façade sound reduction of 10 dB. This meant that if a sound level of 50 dBA was achieved at the outer façade of the classroom, the indoor SPL would be 40 dBA. Thus, a target SPL of 50 dBA was set for the receiver outside the classroom modeled in *CadnaA* and further modeling of the indoor sound level in *Bastian* was not necessary. The resulting façade receiver SPL for each scenario was tabulated and sorted to find the intervention scenarios that achieved the target outer façade SPL of 50 dBA (40 dBA indoors). Assuming that sites are usually constrained and the objective for a designer is to position the classrooms as close to the road as possible without encountering noise disturbance, the nearest distance at which the target SPL is found was identified.

Scenarios that produced a significant decrease in the classroom noise level were also identified, even if the target was not achieved. A significant decrease was considered to be at least 6 dB, which is a significant perceived change.56 This is helpful in scenarios in which the distance between the road and the classroom is fixed, such as in an existing school, and an improvement in the ambient noise level is sought.

Results

The effect of distance

A series of simulations were run to determine the sound pressure level (SPL) at the facade receiver for each building position (with no barriers).

The results, graphically illustrated in Figure 4, show that as the receiver position (building) recedes from the noise source, the calculated SPL decreases. The lowest SPL recorded (52.3 dBA) was at the façade receiver for a single-storey building at position D, 136 m from the road, and the highest (68.9 dBA) was recorded at building (double-storey) position A, 17 m from the road. This is expected due to geometric divergence and indicates the magnitude of sound attenuation due to distance only. The SPL at the first-floor façade was found to be consistently higher (by between 0.8 and 2 dB) than at the ground floor facade. This could be attributed to the effect of ground absorption reducing sound propagation at the lower level. The target SPL (50 dBA) at the façade receiver was not achieved at any of the building positions tested.

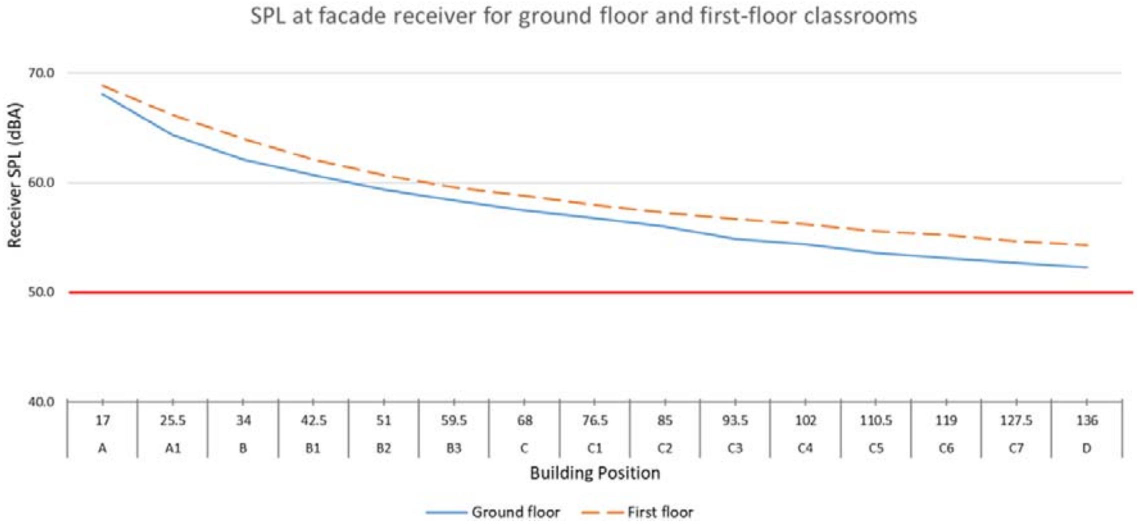

Figure 4. Graphic representation of calculated SPL at each position for single- and double-storey buildings.

The effect of barrier insertion

The effect of inserting a barrier was tested at each building position and classroom floor level, first under barrier condition 1 and then barrier condition 2.

The effectiveness of a barrier is normally described in terms of the insertion loss (IL), which is the difference (in dB) between the measured SPL with and without the barrier. However, in this exercise, the effectiveness was determined against the target SPL of 50 dBA. Thus, the SPL rather than the IL was recorded. The Figures 5 and 6 show the resultant SPL at each building position for different barrier heights.

For barrier condition 1, the results clearly indicate that the higher the barrier and the greater the distance between the source and receiver, the lower the SPL (see Figures 5 and 6). It is also evident that the SPL outside a ground floor classroom is lower than that outside a first-floor classroom, with the difference between ground floor and first floor receiver levels for each scenario ranging from 1.2 to 8.5 dBA. This is expected, since the maximum barrier height (3.5 m) is lower than the first-floor receiver height (4.5 m), as illustrated in Figure 7.

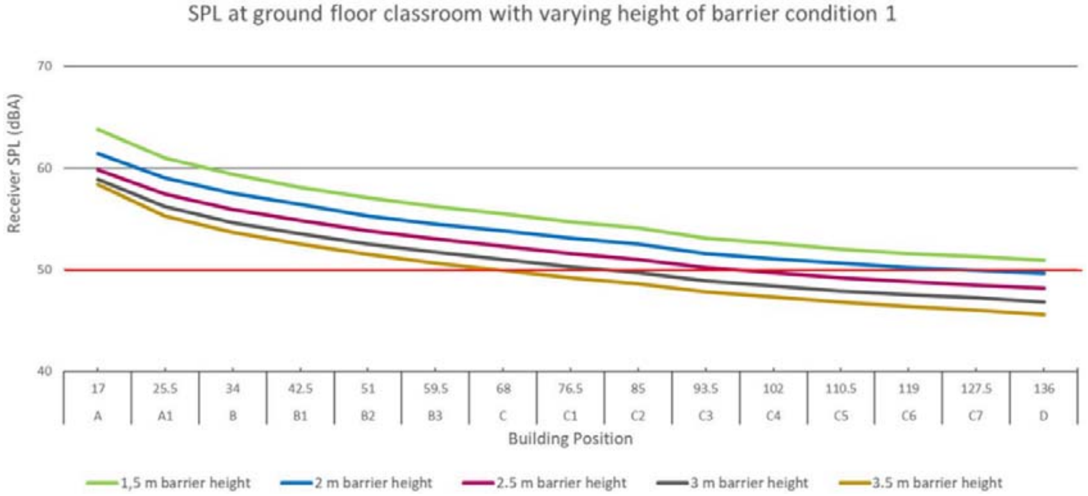

Figure 5. SPL at ground floor facade receiver at each building position for different barrier (1) heights.

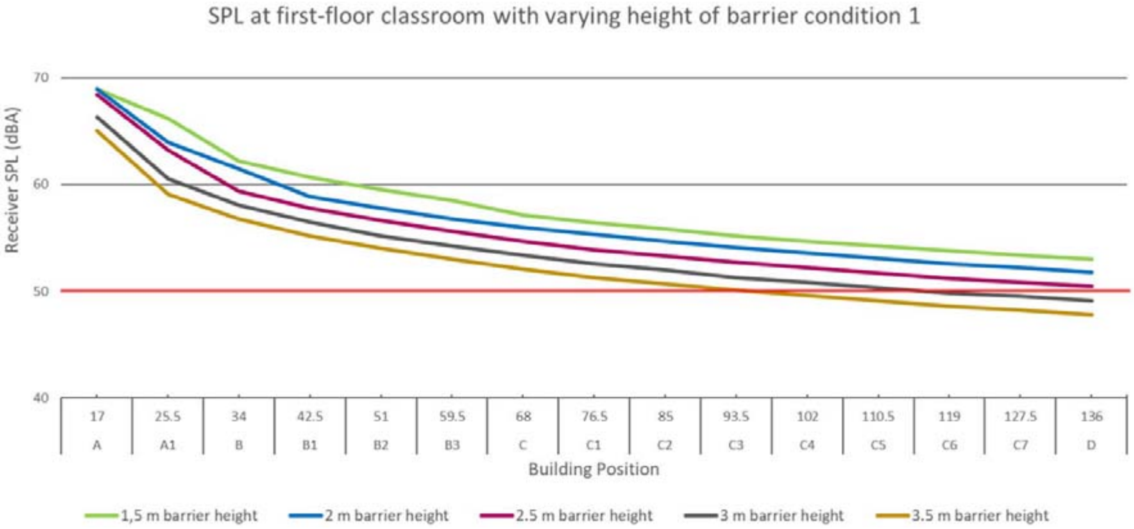

Figure 6. SPL at first-floor facade receiver at each building position for different barrier (1) heights.

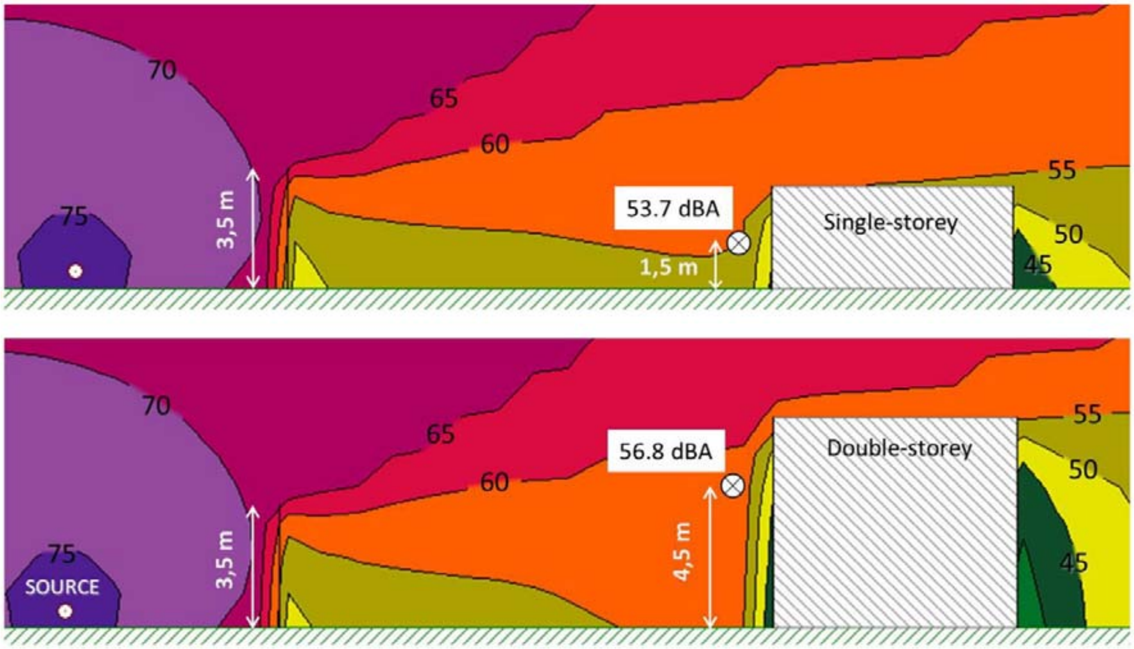

Figure 7. Comparing the sound contours at a single- and double-storey building at position B.

The position closest to the road at which the target SPL is achieved for a ground floor classroom, is position C (68 m from the center of the road) with a barrier height of 3.5 m (49.9 dBA). For a first-floor classroom, the position closest to the road at which the target is achieved is position C3 (93.5 m from the center of the road) with a barrier of 3.5 m high.

As the receiver position recedes from the noise source, the barrier height at which the target SPL is achieved is lower. For ground floor classrooms, the insertion loss decreases as the distance from the source increases, ranging from 9.7 to 6.7 dB, indicating the diminishing effect of a barrier over distance. For first floor classrooms, the insertion loss is more constant regardless of distance from source, ranging from 7.1 to 6.5 dB, except at position A, where the IL is 3.9 dB.

These findings show that the insertion of barriers is more effective for attenuating traffic noise for ground floor classrooms compared to first floor classrooms.

Under barrier condition 2, the position closest to the road at which the target SPL was reached for a ground floor classroom was at position B2 (51 m from the center of the road) with a barrier height of at least 3.5 m (50.3 dBA)—see Figure 8. It is noted the target is achieved at a position closer to the source than under barrier condition 1 with a barrier of the same height. This seems to indicate that it would be preferable to insert a barrier closer to the receiver than closer to the source when trying to achieve the target SPL on a constrained site.

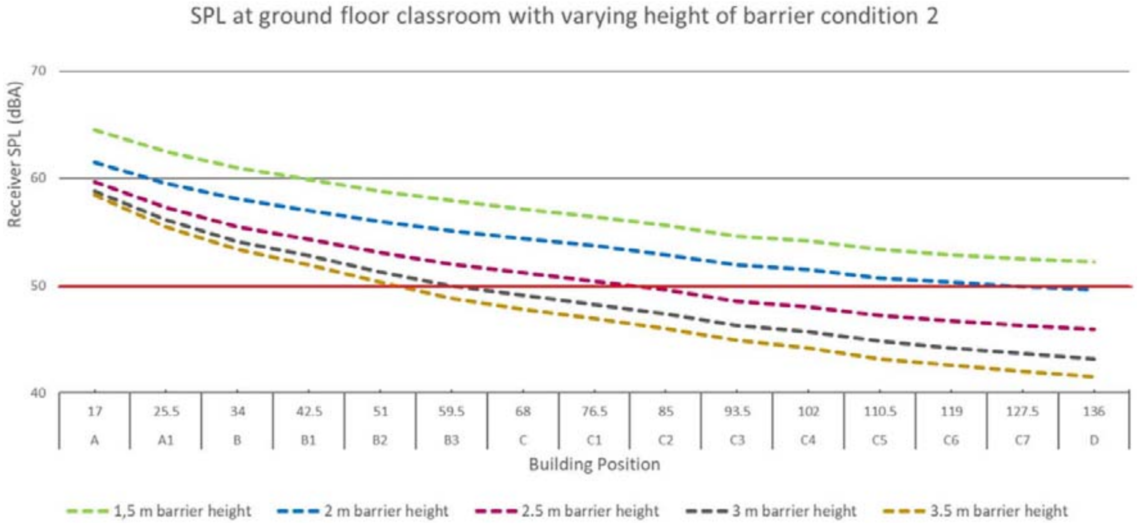

Figure 8. SPL at ground floor facade receiver at each building position for different barrier (2) heights.

The target was not reached in any of the scenarios under barrier condition 2 for a first-floor classroom (see Figure 9), demonstrating poorer performance than under barrier condition 1. This indicates that for a first-floor classroom, it is preferable to insert a barrier closer to the noise source than to the receiver.

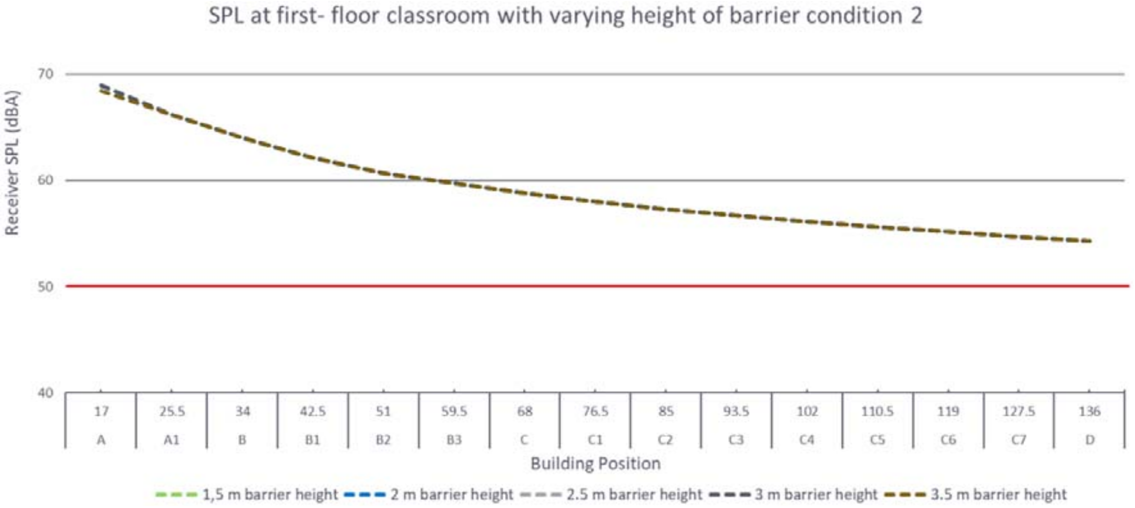

Figure 9. SPL at first-floor facade receiver at each building position for different barrier (2) heights.

When the results for barrier condition 1 and 2 are plotted on one graph, for ground floor and first floor respectively, as shown in Figures 10 and 11, it is easy to see the difference in performance for each condition. It is noted that the difference in performance for barrier condition 1 and 2 increases with receiver distance from the source for barriers more than 2 m high, showing that a barrier close to the receiver attenuates more noise than a barrier close to the source. For first-floor classrooms, it is evident that a barrier closer to the source is more effective, which can probably be attributed to the fact that the maximum barrier height considered here is lower than the receiver height. The difference in findings for ground floor and first floor classrooms under the different barrier conditions lead the researchers to construct a third barrier condition in which barriers were inserted at both positions.

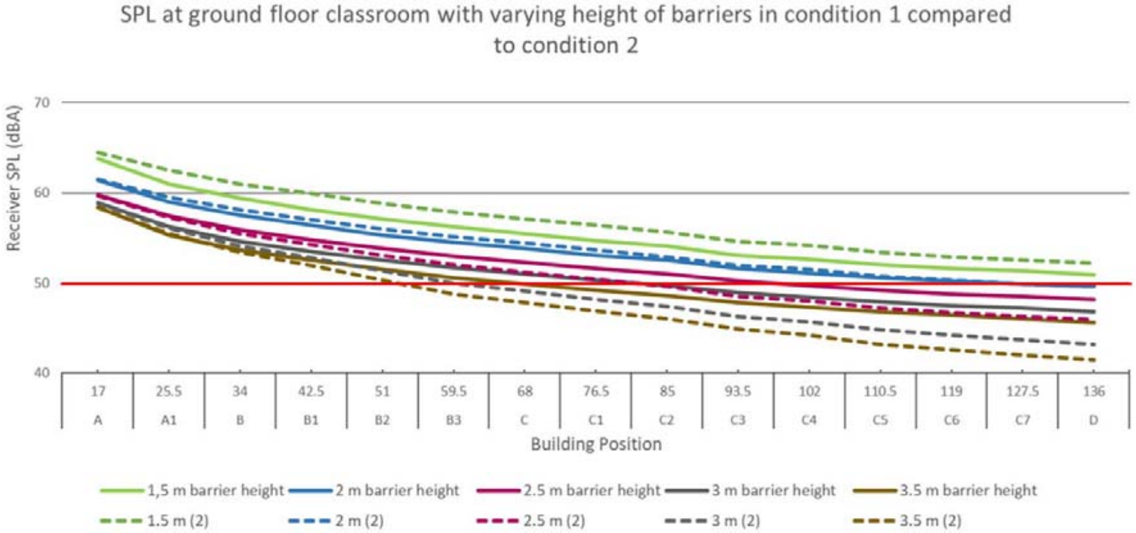

Figure 10. Resultant SPL at each building position under barrier condition 1 or 2 for ground floor classrooms.

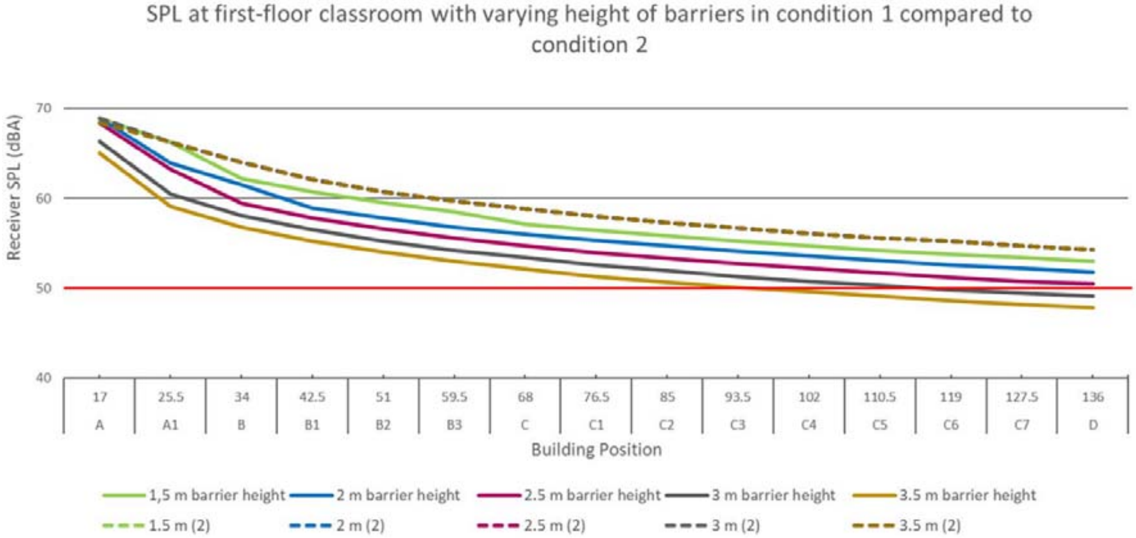

Figure 11. Resultant SPL at each building position under barrier condition 1 or 2 for first-floor classrooms.

The results when double barriers were inserted showed some improvement in the insertion loss compared to barrier conditions 1 and 2 individually. For ground floor classrooms, there is a slight but insignificant improvement in insertion loss when both barriers are inserted relative to only one or the other. However, the target SPL remained unachievable for ground floor classrooms less than 68 m from the road and first-floor classrooms less than 136 m from the road, demonstrating little benefit in using double barriers.

In summary, it can be said that the position of a noise barrier relative to the noise source and receiver influences the SPL at the receiver. For a ground floor classroom, the target SPL can be reached at a distance closer to the road with a barrier is close to the classroom rather than close to the noise source, but only if the barrier is more than 2 m high. For first-floor classrooms, a barrier close to the source is more effective for attenuating traffic noise, although the target SPL is only reached at a minimum of 93.5 m from the road.

Discussion and application

The data generated by the modeled scenarios shows that the target SPL of 50 dBA at the outer façade (or 40 dBA inside the classroom) could not be achieved at any of the building positions, with the maximum distance considered being 136 m, when there are no physical barriers, the site is level with the noise source and the façade consists of a solid wall with 28% its area open and 7.5% of its area glazed.

When a barrier, in the form of a dense, solid wall was inserted between the noise source and the receiver, the target SPL could be achieved at a ground floor classroom located at least 51 m from the noise source if the barrier was 3.5 m high. It has been noted that the target SPL can be achieved at a receiver closer to the noise source for a ground floor classroom than for a first-floor classroom. Thus, when considering a new school design, a preference for ground floor classrooms should be applied if the site is close to a busy road and space on the site requires classrooms to be as close to the road as possible.

For ground floor classrooms, the insertion of a barrier (<2 m high) close to the façade of the building, in the form of a solid wall 3m from the façade, is more effective than a barrier at the boundary (i.e. close to the road). This may be particularly applicable at existing school sites where it is not only more effective, but may also be more economical, to erect a shorter wall close to the façade, rather than a long wall along the road.

Insertion loss assessment

Considering that a just-meaningful difference (JMD) in signal-to-noise ratio (SNR) is 6 dB,[56] it can be argued that a significant improvement in the SNR in a classroom can be achieved by a decrease in SPL of 6 dB, even if the target classroom noise level is not achieved. This is particularly useful when considering existing sites, where the closeness of the classroom to the road makes it impossible to achieve a suitable ambient sound level, yet a noticeable decrease in the ambient noise level will still be of value. While it is acknowledged that this will not necessarily constitute a good listening environment, it will at least provide a slight improvement, where no other options are available.

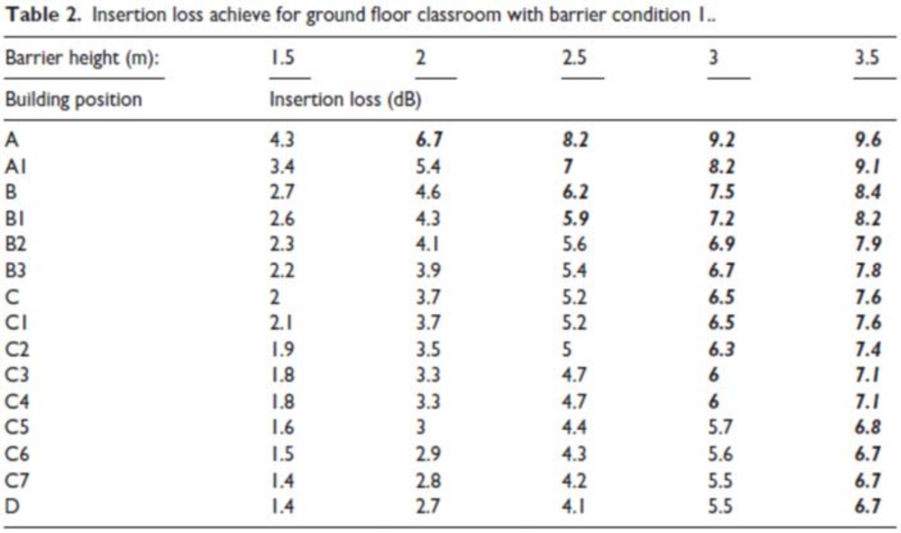

Table 2. Insertion loss achieve for ground floor classroom with barrier condition 1..

Barrier height (m):	1.5	2	2.5	3	3.5
Building position	Insertion loss (dB)				
A	4.3	**6.7**	**8.2**	**9.2**	**9.6**
A1	3.4	5.4	**7**	**8.2**	**9.1**
B	2.7	4.6	**6.2**	**7.5**	**8.4**
B1	2.6	4.3	**5.9**	**7.2**	**8.2**
B2	2.3	4.1	5.6	**6.9**	**7.9**
B3	2.2	3.9	5.4	**6.7**	**7.8**
C	2	3.7	5.2	**6.5**	**7.6**
C1	2.1	3.7	5.2	**6.5**	**7.6**
C2	1.9	3.5	5	**6.3**	**7.4**
C3	1.8	3.3	4.7	**6**	**7.1**
C4	1.8	3.3	4.7	**6**	**7.1**
C5	1.6	3	4.4	5.7	**6.8**
C6	1.5	2.9	4.3	5.6	**6.7**
C7	1.4	2.8	4.2	5.5	**6.7**
D	1.4	2.7	4.1	5.5	**6.7**

The insertion losses achieved by inserting a barrier of various heights under barrier condition 1 are shown in Tables 2 and 3 for ground floor and first floor respectively. The entries in bold italics indicate the scenarios that result in an insertion loss of at least 6 dB, constituting a just-meaningful difference (JMD) in sound level. It is evident that a significant improvement in the SNR is possible for ground floor classrooms as close as 17 m from the road and for first floor classrooms as close as 25.5 m from the road. While this will not correct other factors that influence speech intelligibility, such as reverberation time, it will contribute to improved intelligibility.

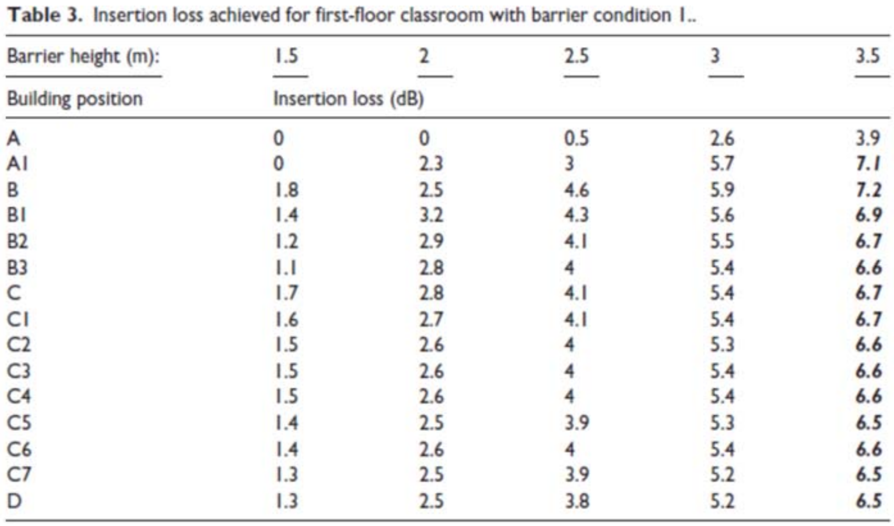

Table 3. Insertion loss achieved for first-floor classroom with barrier condition 1..

Barrier height (m):	1.5	2	2.5	3	3.5
Building position	Insertion loss (dB)				
A	0	0	0.5	2.6	3.9
A1	0	2.3	3	5.7	***7.1***
B	1.8	2.5	4.6	5.9	***7.2***
B1	1.4	3.2	4.3	5.6	***6.9***
B2	1.2	2.9	4.1	5.5	***6.7***
B3	1.1	2.8	4	5.4	***6.6***
C	1.7	2.8	4.1	5.4	***6.7***
C1	1.6	2.7	4.1	5.4	***6.7***
C2	1.5	2.6	4	5.3	***6.6***
C3	1.5	2.6	4	5.4	***6.6***
C4	1.5	2.6	4	5.4	***6.6***
C5	1.4	2.5	3.9	5.3	***6.5***
C6	1.4	2.6	4	5.4	***6.6***
C7	1.3	2.5	3.9	5.2	***6.5***
D	1.3	2.5	3.8	5.2	***6.5***

For barrier condition 2, a significantly lower SPL can be achieved for ground floor classrooms close to the road, as shown in Table 4, with results of at least 6 dB (a JMD) indicated in bold italics. However, no change is detected for first floor classrooms.

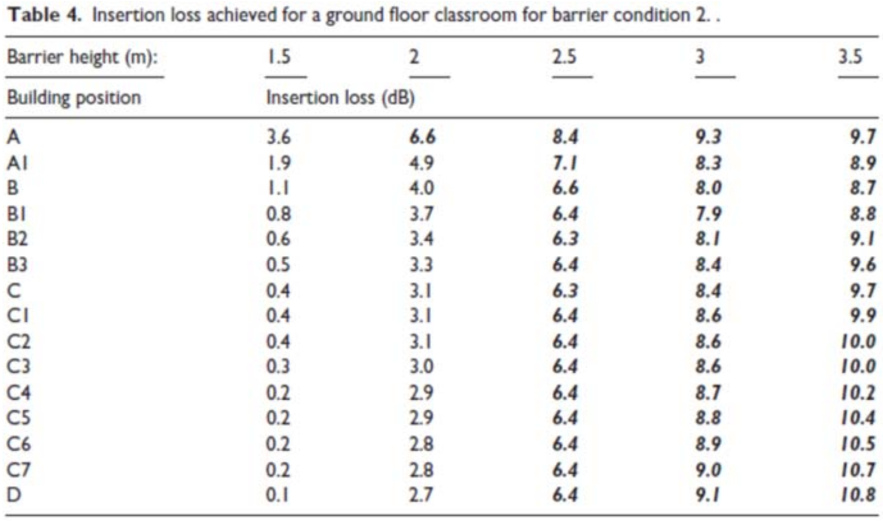

Table 4. Insertion loss achieved for a ground floor classroom for barrier condition 2. .

Barrier height (m):	1.5	2	2.5	3	3.5
Building position	Insertion loss (dB)				
A	3.6	***6.6***	***8.4***	***9.3***	***9.7***
A1	1.9	4.9	***7.1***	***8.3***	***8.9***
B	1.1	4.0	***6.6***	***8.0***	***8.7***
B1	0.8	3.7	***6.4***	***7.9***	***8.8***
B2	0.6	3.4	***6.3***	***8.1***	***9.1***
B3	0.5	3.3	***6.4***	***8.4***	***9.6***
C	0.4	3.1	***6.3***	***8.4***	***9.7***
C1	0.4	3.1	***6.4***	***8.6***	***9.9***
C2	0.4	3.1	***6.4***	***8.6***	***10.0***
C3	0.3	3.0	***6.4***	***8.6***	***10.0***
C4	0.2	2.9	***6.4***	***8.7***	***10.2***
C5	0.2	2.9	***6.4***	***8.8***	***10.4***
C6	0.2	2.8	***6.4***	***8.9***	***10.5***
C7	0.2	2.8	***6.4***	***9.0***	***10.7***
D	0.1	2.7	***6.4***	***9.1***	***10.8***

Achieving a suitable signal-to-noise ratio

A signal-to-noise ratio of at least 15 dB will achieve speech intelligibility for most learners, even those with some hearing loss or learning disabilities, or learning in a second language.[13] This means that if the average teacher's voice is 65 dBA (measured 1 m from the speaker),[57] the background SPL should be 50 dBA. However, the decay of the signal over distance must be taken into account to ensure a suitable SNR at the back of the classroom. Klatte et al.[58] showed that SNR measured at 3, 6, and 9 m from the speaker, changed with 3 dB for each position, amounting to an SNR reduction of 6 dB over 6 m. Thus, it can be calculated that, in order to achieve a suitable SNR at the back of the class, the background SPL in the room should be 44 dBA (6 dB lower than what is calculated at 1 m from the speaker). This is assuming that there are no other negative acoustic factors present, such as a high reverberation time or other user-generated noises.

While the difference between the target level of 40 and 44 dBA is not significant, and would barely constitute a just-noticeable difference (JND) in SNR,[59] an exercise was performed to determine the conditions under which this condition was met. The findings show that, with a barrier, this target can be met at classrooms that are at least 34 m from the road. This is much closer than the minimum distance at which the 40 dBA target was met. In application, this means that arguably suitable ambient conditions can be achieved at existing schools that have classrooms close to busy roads, and that new schools can locate classroom buildings at this distance from the road if the site constraints prevent alternative locations. However, it must be noted that the difference is not significant and thus this finding should be applied with an understanding of the minimal cost-benefit and only where no other solutions are available in the specific context.

Summary table

In this research, conditions were sought in which the target classroom ambient SPL of 40 dBA could be achieved. This was established as an acceptable requirement for classrooms, although the ideal classroom SPL is held to be 35 dBA. Apart from achieving an ambient SPL of 40 dBA, conditions that produced a significant reduction in the classroom SPL of 6 dB were also identified. Furthermore, an adjusted SPL target of 44 dBA, based on the SNR at the back of the classroom, was applied to determine conditions that met this relaxed target.

The results of these analyses are summarized in Tables 5 and 6 below. These tables indicate the interventions that can be applied to achieve various acoustic targets discussed and can be used as a heuristic guide to determine which interventions (barrier design) can be effectively applied at existing school sites or to determine which design decisions (distance and barrier design) can be effectively applied for new school designs.

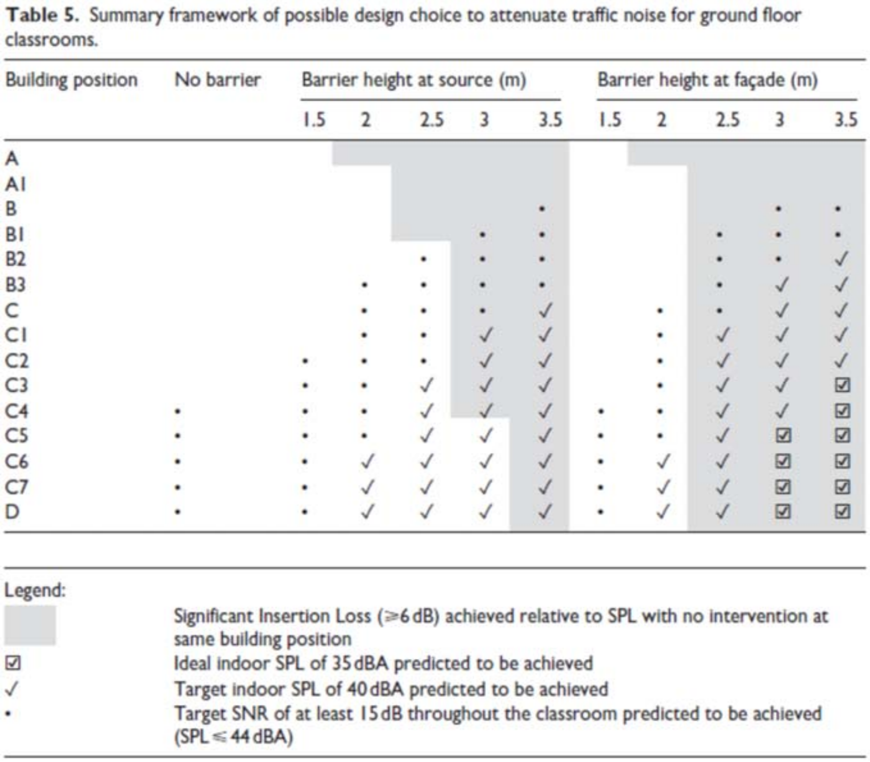

Table 5. Summary framework of possible design choice to attenuate traffic noise for ground floor classrooms.

Building position	No barrier	Barrier height at source (m)					Barrier height at façade (m)				
		1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5
A			▨	▨	▨	▨		▨	▨	▨	▨
A1				▨	▨	▨			▨	▨	▨
B				▨	▨	▨ •			▨	▨ •	▨ •
B1				▨	▨ •	▨ •			▨ •	▨ •	▨ •
B2				•	▨ •	▨ •			▨ •	▨ •	▨ ✓
B3			•	•	▨ •	▨ •			▨ •	▨ ✓	▨ ✓
C			•	•	▨ •	▨ ✓		•	▨ •	▨ ✓	▨ ✓
C1			•	•	▨ ✓	▨ ✓		•	▨ ✓	▨ ✓	▨ ✓
C2		•	•	•	▨ ✓	▨ ✓		•	▨ ✓	▨ ✓	▨ ✓
C3		•	•	✓	▨ ✓	▨ ✓		•	▨ ✓	▨ ✓	▨ ☑
C4	•	•	•	✓	▨ ✓	▨ ✓	•	•	▨ ✓	▨ ✓	▨ ☑
C5	•	•	•	✓	✓	▨ ✓	•	•	▨ ✓	▨ ☑	▨ ☑
C6	•	•	✓	✓	✓	▨ ✓	•	✓	▨ ✓	▨ ☑	▨ ☑
C7	•	•	✓	✓	✓	▨ ✓	•	✓	▨ ✓	▨ ☑	▨ ☑
D	•	•	✓	✓	✓	▨ ✓	•	✓	▨ ✓	▨ ☑	▨ ☑

Legend:

▨	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)

Table 6. Summary framework of possible design choice to attenuate traffic noise for first-floor classrooms.

Building position	No barrier	Barrier height at source (condition 1) (m)					Barrier height at façade (condition 2) (m)				
		1.5	2	2.5	3	3.5	1.5	2	2.5	3	3.5
A											
A1						▨					
B						▨					
B1					▨	▨					
B2						▨ •					
B3					▨ •	▨ •					
C					•	▨ •					
C1				•	•	▨ •					
C2				•	•	▨ •					
C3			•	•	•	▨ ✓					
C4			•	•	•	▨ ✓					
C5		•	•	•	✓	▨ ✓					
C6		•	•	•	✓	▨ ✓					
C7		•	•	•	✓	▨ ✓					
D	•	•	•	•	✓	▨ ✓	•	•	•	•	•

Legend:	
▨	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)

Table 7. Summary framework of possible design choice to attenuate traffic noise for ground-floor classrooms.

Building position	Barrier height at façade (condition 2) (m)	Height of barrier at source (condition 1) (m) (if single-storey)					Height of barrier at source (condition 1) (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:	
▨	Significant Insertion Loss (≥6 dB) achieved relative to SPL with barrier at source only
☑	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 (SPL ≤ 44 dBA) SNR)

Table 7 can be used to determine which combination of double barriers will achieve the targeted results. While double barriers were deemed to be minimally effective compared to single barriers, they may be useful in extreme cases where every effort is needed to attenuate reduce traffic noise.

Limitations

The study is also limited to the specific environmental noise conditions (traffic noise) and the modelled conditions described in Section 2.

These findings are limited to the selected barrier designs, particularly in terms of barrier length. In application, it might not be possible to insert a barrier that complies with the 1:4 length ratio used in this study. However, the evidence established through this experiment provides a useful guide. It is recommended that the study be extended, using the same methodology to establish further guidelines relating to the length of barriers and the effect of barriers that enclose the entire school site, rather than only the boundary parallel to the road.

This study was deliberately limited in the assessment of natural ventilation design. The typical design established was assumed to provide sufficient ventilation based on its compliance with regulations. However, an in-depth study on suitable and effective natural ventilation design for all seasons relative to sound transmission is recommended.

It must be noted that the above heuristic guide was established based on models that assume specific design limitations, in terms of classroom construction materials, site topography, noise source, barrier length, etc., which are described in Section 2. Thus, the heuristic framework should only be used as an indicative guide for the early stage of design.

Conclusion and recommendations

This study was conducted to determine which design options are feasible to ensure a classroom noise level of 40 dBA in naturally ventilated classrooms (with open windows) adjacent to busy roads in urban areas. The modeled evidence established through this study was used to create heuristic guidelines for architects, aiding in early design decisions regarding traffic noise attenuation at urban schools. The design interventions that were investigated were distancing the classroom from the noise source and inserting noise barriers.

It was established that the target level is not achieved without the use of noise barriers if the classroom building is within 136 m of a busy road, which was the maximum distance considered. This is true for ground floor and first-floor classrooms.

With the insertion of a noise barrier of maximum 3.5 m high, the target classroom SPL could be achieved. Using such barriers, it was proven possible to achieve the target sound pressure level in classrooms closer to the road. It was established through the modeled scenarios that the insertion of a barrier near the noise source is more effective than a barrier close to the classroom facade if the classroom is on the first floor. For a classroom on the ground floor, the opposite was observed—the target level could be achieved at a classroom closer to the road if the barrier was inserted close to the facade, rather than close to the noise source, but only if the barrier is more than 2 m high; below this height, the barrier position makes little difference. In application, this means that where possible, classrooms should be located on the ground floor (single storey building) to achieve a lower ambient noise level.

Even with a noise barrier, the target could not be achieved at classrooms closer than about 50 m from the road; however, a significant decrease in the classroom SPL was observed with the insertion of barriers of at least 2 m high for buildings as close as 17 m from the road. This is an encouraging finding, showing that a low-cost barrier can be applied to improve conditions in existing city schools, where the distance between the road and the classroom cannot be increased.

Infrastructure investment decisions are made at very early planning stages prior to engagement with expert consultants and designers. Quantitative guidance for the South African 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.

The evidence established through this study provides a point of departure for decision-making and planning for new or existing schools. School planners and architects can use the heuristic guidelines to avoid poor decisions in the early stages of infrastructure projects, minimizing the need for costly retrofitting and specialist consultations. While the findings will help guide decisions, they are limited in scope of application and do not necessarily eliminate the need for acoustic specialists in all cases.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication
of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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