Noise reduction of plenum windows on the façade of a high-rise residential building next to heavy road traffic

Xiaolong Li,[a] S.K.Tang,[a,*] Stephen Y.C.Yim,[b] Rudolf Y.C.Lee[b] and Tim Hung[c]

[a]Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong
China

[b]Hong Kong Housing Authority
The Hong Kong Special Administration Region Government
Hong Kong
China

[c]Environmental Protection Department
The Hong Kong Special Administration Region Government
Hong Kong
China

*Corresponding author. Tel. : +852 27667782; fax. : +852 27657189
Email address : shiu-keung.tang@polyu.edu.hk (S.K.Tang)

Abstract

Extensive traffic noise transmission loss measurements were carried out inside selected residential units of a standalone 32-storey housing block located next to a very busy and noisy main trunk road in the present study. A total of 35 units, which were all equipped with plenum windows, was surveyed. These plenum windows are intended to help reduce noise exposure of the residents and at the same time allow for a reasonable level of natural ventilation. The results show that the traffic noise transmission losses of the unit façades installed with the plenum windows adopted in this housing block vary between 10.6 to 13.0 dBA and are only weakly dependent on elevation from the trunk road. The results also validate in-situ the prediction model established previously by the authors using laboratory and site mockup data. Generalized models for both empirical and experimental estimation of the traffic noise transmission loss across a residential flat unit façade installed with multiple plenum windows are developed. The differences between their estimations are well within engineering tolerance.

Keywords : Traffic noise transmission loss, building façade, plenum windows, high-rise buildings

1. Introduction

The population density in cities keeps growing. In the case of tight inhabitable land resources, many residential buildings have to be built next to major traffic lines in order to solve housing problem. The heavy road traffic then results in serious noise pollution, and such problem has become more and more acute as time goes by. Noise, as a pervasive discordant auditory stimulus, has adverse impacts on human health and activities [1]. Excessive exposure to high traffic noise poses a threat to human health in many ways. These noises interfere with human daily living, normal rest, and could arouse negative emotions and reduce work efficiency [2,3]. Statistics from the World Health Organization (WHO) indicates that at least one million healthy life years are lost because of traffic-related noise in Western Europe every year [4]. Traffic noise has also been ranked second (the first is particulate air pollution) among the nine environmental stressors reported in Hänninen et al. [5] in term of health impact. In Hong Kong, there are ~960,000 people exposed excessively to traffic noise [6]. There is an urgent need for practical sound insulation devices to alleviate the agitation brought by noise problem.

To tackle the traffic noise annoyance, much effort has been made by researchers and engineers on noise attenuation technologies. Roadside barriers, enclosures, setbacks and extended podia are commonly adopted noise reduction methods [2, 7-10]. However, these methods tend to sacrifice land space exploitation efficiency, and thus are not good solutions for densely populated cities. Protrusive structures on building façades, such as balconies, lintels, fins, louvers, eaves can act as sound barriers. However, their acoustical protections are not obvious because of the limited allowable protrusion length, and in some cases, even sound absorption has to be added [11-13]. There is also research effort looking into the use of greenery for reducing noise (for instance, van Renterghem et al. [14]). However, the corresponding results are not impressive.

Double glazing windows [15] can provide significant sound insulation when they are closed, but this is done in the expense of natural ventilation. The use of mechanical ventilation in such cases tends to consume lot of energy unnecessarily – a condition which contradicts the concept of sustainable development. De Salis et al. [16] discussed some noise reduction façade devices which could allow some degrees of natural ventilation. A comprehensive review on building natural ventilation against façade noise reduction is recently given by Tang [17].

Plenum window, also known as acoustic window and ventilation window, is recently introduced as a kind of ventilation-enabling façade noise control device. In principle, this window type is a partially opened double glazing window. Details of this window type and its various basic operation modes are presented in Section 2. Its noise reduction capacity was first tested by Ford and Kerry [18]. Tong and Tang [19] has carried out a parametric study on the sound reduction of this window type in the laboratory using a scale down model. Studies for improving the sound reduction performance of plenum windows have also been conducted. For instance, Kang and Brocklesby [20] studied the increase in noise reduction across plenum windows by using thin micro-perforated panels. Huang et al. [21] used the method of active noise control to improve the low frequency sound insulation and Tang [22] showed significant broad band sound transmission loss by installing rigid scatters within the window voids. Plenum windows have become more and more popular recently [23, 24], but the sound transmission loss across a plenum window remains hard to predict in practice. The authors have recently proposed an empirical model for predicting the traffic noise transmission loss across a plenum window based on the results of parametric laboratory tests and site mockup data [25].

Despite much laboratory research effort in recent years, the actual performance of the plenum windows at site remains uncertain because of the many shortcomings of laboratory tests. One of the major problems is the noise source. In traffic noise mitigation research, traffic line is regarded as an incoherent source of infinite length, or at least the length of the source is very long compared to the characteristic dimension of the window. In the laboratory, the size of the test chamber restricts the length of the noise source and thus the above condition can never be met for full scale window test. Scale down model does not solve the problem as the model must be a substantially simplified version of the real window and the acoustical properties can never be scaled properly. No matter whether a full scale or scale down model is adopted, the laboratory source has a much higher degree of coherence than the real traffic noise, and the distance between the source and the window in the laboratory is much shorter than that in the real life. Therefore, in principle, the laboratory source does not produce the general sound field of the real road traffic. There are always debates on how far the laboratory test results can represent the actual performance of a plenum window in practice. The large variation of acoustical performance of plenum window with source orientation angle (thus sound incidence angle) observed by Tong and Tang [19] may not be reproducible in real practice. The size limitation of the test chamber also makes the study of multiple plenum windows not possible. The plenum windows on a flat unit façade tend to couple with each other acoustically through the indoor space, and thus it is not certain on how the single plenum window performance found using laboratory test can be used to predict that of a multiple plenum window system.

All these issues make the results of real site tests as valuable as the laboratory data in this kind of noise mitigation research. The effects of receiver elevation from and the window orientation relative to the ground traffic line on the performance of the full scale windows, which cannot be tested properly inside the laboratory, are also unclear in real life practice.

This study is set to tackle the above open questions and develop a generalized plenum window traffic noise prediction scheme for improved realization of the plenum window concept. An extensive measurement of traffic noise transmission losses across flat unit façade installed with plenum windows was carried out in a housing estate, which is the first housing block in Hong Kong installed with this window type. It was completed in 2018 and is in close proximity of a major trunk road with an average traffic volume of 156,000 vehicles per day. Details of the building layout and the dimensions of the residential units tested are given in Section 3. Before detailed analysis on the results, the basic configuration of a plenum window and its basic operation modes are introduced in Section 2.

2. Plenum Window and its Basic Operation Modes

A plenum window is basically a partially opened double glazing window. Figure 1 shows the schematics of a plenum window and the nomenclature related to the window configuration adopted in the present study. There are one outdoor opening and one indoor opening. This structure impedes sound transmission and thus can offer acoustical protection to the residents. The cavity between the two glass panes and these openings together form an air passage, allowing for natural ventilation. The major dimensional parameters of a plenum window are the outer and inner window opening widths (w_o and w_i respectively), the window height (h), the gap distance (d) and the overlapping length (l). Sound absorption can be installed on the two vertical side walls (mullions) and the ceiling of the window cavity to improve the sound transmission loss across the window.

The outdoor opening is installed with a side-hung casement window so that the residents can close the plenum window whenever necessary. The indoor glass pane is a sliding glass panel. The plenum window can then be set into two basic operation modes (excluding the 'closed' case) as illustrated in Fig. 2. Figure 2a shows the 'acoustic' mode of a plenum window. In this operation mode, the indoor sliding glass panel is located on the side of the outdoor opening to reduce sound transmission into the indoor. This is also the focus of the present study. The window can be set into the 'by-pass' mode by sliding the indoor glass panel to the opposite side of the outdoor opening (Fig. 2b). In this operation mode, air and noise go into the living space with minimum resistance. Since such condition resembles that of a casement window, the corresponding results should represent the acoustical performance of a side-hung casement window of the same opening size as the outdoor opening of the plenum window and thus are used as reference in the foregoing analysis.

3. Methods

This section describes the methods adopted in the present study. The details of the site measurement are presented in the first place, followed by the introduction of the generalized models.

3.1. Site Measurement

3.1.1. Building orientation, floor layout and test unit dimensions

Figure 3 shows the building layout and its orientation relative to the major trunk road. Unlike the case of Tong et al. [26], the present building façade is not parallel to the trunk road. It should be noted that only the flat units facing the trunk road are equipped with plenum windows. Figure 4 illustrates the outlook of the surveyed building and its surrounding environment. There are buildings on the opposite side of the trunk road, but they are not less than 200 m away from the surveyed building. There is therefore no significant reflection from opposite side of the trunk road.

There are 14 flat units on each floor equipped with plenum windows and units U6, U7, U8, U10, U13 and U14 are selected for measurement (Fig. 3). These flat units altogether cover all the four different flat layouts found in the surveyed building (namely 1/2P, 2/3P, 1B and 2B). Table 1 summarizes the flat unit dimensions necessary for later acoustic calculation. The floor-to-ceiling height is 2.75 m. Figure 5 shows the layouts of the four unit types. Unit U9 is excluded from the present study as it is just a mirror image of U8. Units U11 and U12 are not facing the trunk road directly, and thus are also not included in the measurement. There was no partition inside these flat units and the doors of the bathrooms and kitchens were kept closed during measurement. All windows, except the plenum windows, were all closed throughout the site measurement.

Measurements were carried out every 5 floors starting from the fifth floor. Corridor windows and staircase doors were all closed to further minimize flanking transmission of noise into the test units. All the window operation modes indicated in Fig. 2 were included in the present study. The results of the 'closed' mode reflect the extent of flanking transmission (could be regarded as 'indoor background'). The walls, floors and ceilings of the test units were just with basic finishing (plastered walls and ceilings, and plan concrete floors). There was no building services in operation during that period of time.

3.1.2. Measurement setup

The number of microphones adopted for the indoor noise measurement varies with the size of the test unit. The positioning of these microphones is schematically showed in Fig. 5. The indoor microphone positions are determined based on the requirement stipulated in ISO 16283-3 [27] as far as possible.

Each of the test unit is installed with one to three plenum windows. Table 2 summarizes the configurations of the plenum windows tested and the test flat units where these windows are installed. In this housing project, sound absorption of NRC 0.7 is installed on the two vertical side walls (mullions) and ceiling of each plenum window as shown in Fig. 6. For the small plenum windows installed in the outer bedrooms of U8, U10 and U14, the outdoor openings are equipped with a single-leaf side-hung casement window (Fig. 6a), while for the other plenum windows, a double-leaf side-hung one is adopted (Fig. 6b).

Noise measurements at the façade and the interior of each test unit were done simultaneously using the 36-channel Brüel & Kjær Type 3560D PULSE system with Brüel & Kjær Type 4935 ¼" microphones. The sampling rate was set at 64000 samples per second per channel. Each measurement lasted for at least 30 minutes. The reverberation times (RT) were measured in the test flat units in accordance with ISO 3382-2 [28]. The Brüel & Kjær Type 4296 omni-directional sound source and the software DIRAC were adopted for the RT measurement.

3.2. Generalized sound transmission loss prediction model

One of the major objectives of the present study is to develop a generalized sound transmission loss prediction scheme to cover façades with multiple plenum windows and have it validated using data from extensive site measurement. One starts with the empirical plenum window traffic noise transmission loss ($TL_{traffic}$) prediction scheme for a single standalone plenum window developed by Li et al. [25] :

$$TL_{traffic} = -10\log_{10}\left(Q\frac{d}{4\pi d_s^3} + \frac{K}{R}\right), \tag{1}$$

where R is the room constant of the plenum window cavity, $Q = 1.2088$ and $K = 0.2288$ and they are constants within the wide plenum window dimension range tested by Li et al. [25]. The slant distance d_s, which is the distance between the centres of the two openings, is

$$d_s = \sqrt{d^2 + [l + (w_o + w_i)/2]^2}. \tag{2}$$

The effects of artificial sound absorption inside the plenum window are included in the room constant R :

$$R = \frac{h(w_o + w_i) + d[2h + (l + w_o + w_i)]\alpha}{1 - \frac{h(w_o + w_i) + d[2h + (l + w_o + w_i)]\alpha}{2[hd + d(l + w_o + w_i) + (l + w_o + w_i)h]}}, \tag{3}$$

where α is the average sound absorption coefficient of the artificial sound absorption materials inside the plenum window. Equation (1) relates A-weighted traffic noise transmission loss directly to the physical configuration of a single standalone plenum window. As the sound absorption material used in this housing project is of NRC 0.7, α is set at 0.7 in Eq. (3).

As the noise receiver in practice is usually in the far field of the noise source, sound pressure levels and their spectral characteristics at the outdoor window openings of a test flat unit in the present study should be very similar. For the cases with N number of plenum windows installed on the façade of a flat unit, one can then write, by considering the total acoustical power incidents on the outer openings of the windows, the outer opening area weighted traffic noise transmission loss as :

$$TL_{overall} = 10\log_{10}\left(\sum_{j=1}^{N} w_{o,j}h_j 10^{TL_{traffic,j}/10} \Bigg/ \sum_{j=1}^{N} w_{o,j}h_j\right). \tag{4}$$

The $TL_{traffic,j}$ of individual plenum window can be estimated using Eq. (1).

The estimation of $TL_{overall}$ from the sound pressure levels measured at site is less straight-forward. By conversion of energy, the incident sound power onto the windows should be equal to the sum of the reflected power, the transmitted power and the sound energy absorbed inside the plenum window per second. One can then write for the ith one-third octave band and for the jth plenum window :

$$W_{i,j}^{inc} = W_{i,j}^{ref} + W_{i,j}^{tra} + W_{i,j}^{abs}, \tag{5}$$

where W denotes sound power and the superscripts *inc*, *ref*, *tra* and *abs* denote incident, reflected, transmitted and absorbed respectively. The sound intensity $I_{i,j}$ at each outdoor window opening, which was measured in this study, is the sum of the incident and reflected sound intensity :

$$I_{i,j} = I_{i,j}^{inc} + I_{i,j}^{ref} \Rightarrow I_{i,j}w_{o,j}h_j = \left(I_{i,j}^{inc} + I_{i,j}^{ref}\right)w_{o,j}h_j = W_{i,j}^{inc} + W_{i,j}^{ref} \Rightarrow W_{i,j}^{ref} = I_{i,j}w_{o,j}h_j - W_{i,j}^{inc}. \tag{6}$$

The sound power absorbed within the plenum window is limited even when artificial absorption is installed [26] such that the absorbed sound power in Eq. (5) can be ignored. Combining Eqs. (5) and (6) gives

$$2W_{i,j}^{inc} - I_{i,j}w_{o,j}h \approx W_{i,j}^{tra}. \tag{7}$$

One then obtains by summing up the corresponding cases for all plenum windows :

$$2\sum_{j=1}^{N} W_{i,j}^{inc} - \sum_{j=1}^{N} I_{i,j}w_{o,j}h_j \approx \sum_{j=1}^{N} W_{i,j}^{tra} = W_i^{tra}, \tag{8}$$

where the total transmitted power in the *i*th one-third octave band, W_i^{tra}, is the sum of all the corresponding sound powers transmitted across individual plenum windows. Same applies to the total incident sound power W_i^{inc}. Therefore

$$W_i^{inc} = \sum_{j=1}^{N} W_{i,j}^{inc} = \left(W_i^{tra} + \sum_{j=1}^{N} I_{i,j}w_{o,j}h_j \right) \Big/ 2. \tag{9}$$

The overall sound reduction index (*SRI*) in the *i*th one-third octave band is

$$SRI_i = 10\log_{10}\left(W_i^{inc}/W_i^{tra}\right) = 10\log_{10}\left(1 + \frac{1}{W_i^{tra}} \sum_{j=1}^{N} I_{i,j}w_{o,j}h_j \right) - 3. \tag{10}$$

The overall transmitted power in the *i*th one-third octave band, W_i^{tra}, can be estimated using the average reverberation time and sound pressure level measured inside the flat unit through the standard formula [29]:

$$10\log_{10}\left(\frac{W_i^{tra}}{W_{ref}}\right) = SPL_i^{rec} - 10\log_{10}\left[\frac{4}{A_i}\left(1 - \frac{A_i}{S}\right)\right], \tag{11}$$

where A is the sound absorption, S the total internal surface of the flat unit, SPL^{rec} the average sound level in the flat unit and W_{ref} the reference sound power (= 10^{-12} W). The sound absorption A can be estimated using the measured reverberation time and the Sabine's formula [29].

Since traffic noise is the main concern in this study, the normalized traffic noise spectrum [30] is used in this study as a weighting to estimate the A-weighted traffic noise transmission losses of the multiple plenum window system, $TL_{overall}$, from the *SRI*s :

$$TL_{overall} = 10\log_{10}\left(\sum_{i=1}^{18} 10^{(L_i - SRI_i)/10} \Big/ \sum_{i=1}^{18} 10^{L_i/10}\right), \tag{12}$$

where L_i is the one-third octave band normalized traffic noise weighting level. This weighting has been applied in similar studies (for instance, Tong and Tang [19], Garai and Guidorzi [31] and Buretti [32]). Details of the corresponding estimation procedure can be found in Garai and Guidorzi [31] and EN 1793-3 [30]. Thus, only a brief summary of the weighting levels are presented graphically in Fig. 7 for the sake of completeness. One can notice that this weighting procedure heavily weighs down the low frequency noise components, such that their contributions in the traffic noise transmission loss are much less significant than those within and above the 500 Hz one-third octave bands.

4. Results

4.1. Reverberation times (RTs)

The RT represents the time taken for the indoor sound pressure level to decay by 60 dB after the sound source is switched off. For the reverberant surveyed flat units in the present study, it is related simply to the total sound absorption (in m^2 Sabine), the unit room volume and total internal surface area through the Sabine's formula [29]. It therefore reflects the sound absorption property of an enclosed space and is always an important parameter in this kind of study. The total sound absorption is used in this study for the estimation of the sound transmission loss across the plenum window(s) (Eq. 11).

Figure 8a shows the one-third octave band RTs measured in U6, U7, U8 and U10. The conditions of U13 and U14 are basically the same as those of U7 and U10 respectively (Table 2) and thus RT measurements were not done in these flat units. Since measurements were carried out every 5 floors, the data in Fig. 8a are the averages over flat units of the same layout. The corresponding standard deviations are presented in Fig. 8b. The RTs are in general long, confirming that the present surveyed flat units are very reverberant. One can notice that the RTs of U6 are relatively shorter, but with larger percentage standard deviations. The measurements at low frequency in U6 and U7 are less reliable probably because of the lower order acoustic room modes. It is observed that the larger the flat unit, the smaller the percentage standard deviation in general.

4.2. Traffic noise transmission loss across a single plenum window

The sound transmission loss of a plenum window is calculated from the façade noise spectra together with the indoor average sound levels after correction for the reverberation effect [30]. In this sub-section, the results of U6, U7 and U13 will be presented. It should be noted that U13 is very close to the main noise source (Fig. 3) such that there is no U13 flat below the ninth floor of the surveyed building. There are a total of six U6 flats, six U7 flats and five U13 flats included in this section.

Figure 9 illustrates an example of the spectral distributions of the noise reductions recorded in one of the test flat unit under different operation modes of the plenum window. The noise reduction here is defined as the difference between the outdoor and indoor noise level. One can notice that the noise reduction under the 'closed' window case is very much larger (15 – 20 dB) than those under the 'acoustic' mode and 'by-pass' mode, confirming that flanking transmission is negligible and its contribution in this study is insignificant. The noise reduction under the 'by-pass' mode is also small compared to that under the 'acoustic' mode, manifesting the importance of the plenum windows for traffic noise control. Since the performance of the by-passed plenum window is similar to that of the conventional side-hung casement window, the corresponding results are not the focus of the foregoing analysis, but are presented as a reference to highlight the acoustical protection of the plenum windows in 'acoustic' mode.

Figure 10 illustrates the one-third octave band spectra of the façade noise and average indoor noise under the two operation modes of the plenum window. Owing to the limited number of microphones available, only the measurements associated with a particular flat unit were done simultaneously. As the measurements at different floors were not carried out simultaneously, the façade noise levels do not decrease monotonically with increasing floor probably due to some minor changes in the traffic volume. However, the spectral shapes of the recorded noise spectra are very similar, indicating that the traffic composition along the nearby major trunk road was fairly constant within the busy hours during which the measurements were carried out. The spectra suggest that the ground traffic produced strong sound energy below 2000 Hz, especially around the 1000 Hz frequency bands.

For U6 and U7, the average indoor noise levels appear relatively independent of floor level though the measurements at different floors were not done at the same time. There is slightly higher variation of façade noise levels with floor level but such variation is also small as far as environmental noise is concerned. While it is expected that the noise levels inside the flat unit under the ‘by-pass’ window mode should be higher than those under the ‘acoustic’ window mode, the major improvement of the ‘acoustic’ mode is found between the 500 Hz and 2000 Hz one-third octave bands. This is also the major frequency range of the traffic noise [30] and the most sensitive audio-frequency range of human ear [1], manifesting the effectiveness of the plenum window in practice. U13 is much closer to the main noise source and the façade traffic noise levels are understandably higher than those of U6 and U7. The variations of sound levels with floor level are also larger than those of U6 and U7, and these levels decrease with increasing floor level. This is due to the fact that U13 is the closest flat unit to the major traffic line, such that the distance effect on the sound level decay is the strongest among the three flat types considered here. The differences between the indoor noise levels under the two plenum window operation modes are inline with those of U6 and U7.

The one-third octave band noise reductions obtained in U6, U7 and U13 are presented in Fig. 11. The flat size of U6 is the smallest among these flat types and its RTs, especially the low frequency ones, fluctuate more from flat unit to flat unit of the same type (Fig. 8). Low frequency measurements are also affected by the room modes of the flat unit as well as the acoustic modes of the plenum window cavity and thus may be not very representative. As the focus in this study is traffic noise, contributions from frequencies below 315 Hz are not significant after the traffic noise weighting process [30, 31]. The low frequency issue is therefore not further discussed.

For frequencies higher than the 315 Hz one-third octave band, one can notice that the noise reductions are in general higher as frequency increases regardless of the operation mode of the windows, which is a commonly observed phenomenon in building acoustics. There is an increase of the noise reduction of around 10 dB in this frequency range when the operation mode of the plenum windows is changed from ‘by-pass’ to ‘acoustic’. It should be noted that though the results presented in Fig. 11 could be affected by the reverberation characteristics of the indoor spaces, they represent the actual noise level changes.

The single A-weighted rating $TL_{traffic}$ will reflect the performance of the plenum window in the presence of traffic noise. The plenum window in ‘acoustic’ mode is the focus. Figure 12 illustrates the $TL_{traffic}$s of U6, U7 and U13 calculated using the measured data and the approach of Li et al. [25] and a comparison between these measured $TL_{traffic}$ with the predictions of Eq. (1). The effects of indoor reverberation are naturally eliminated in these methods. Thus, one can regard this parameter, as well as $TL_{overall}$, as an acoustical property of the window. It is noticed that, under the current surrounding environment of and with various scattered reflections from the surveyed building façade, the $TL_{traffic}$s of the plenum windows in U6, U7 and U13 actually do not vary much with floor level (i.e. elevation angle of the window from the trunk road). The maximum variation is that of U6, which is only about 2 dB for a vertical height difference of 75 m (25 floors). Though the $TL_{traffic}$s of U6 and U7 show a trend of slow increase with floor level, the small variation suggests that the $TL_{traffic}$s of the plenum windows can practically be assumed constant. For U13, there is a dip of $TL_{traffic}$ at the 25/F, but the corresponding variation of $TL_{traffic}$ is still practically small. The formula proposed by Li et al. [25] gives very good prediction with a discrepancy of within ± 1 dB. It should be noted that Eq. (1) gives a single $TL_{traffic}$ for a plenum window with a fixed configuration.

4.3. Cases of multiple plenum windows

There are two plenum windows in U8 and three plenum windows in U10 and U14. Effort is made in this section to develop a traffic noise reduction prediction formula for these cases. Each of these windows are supposed to look after a particular space inside the flat units. The acoustical coupling between these spaces has not been taken into account by Li et al. [25] because there is no laboratory data related to multiple plenum window system so far due to laboratory space limitation.

The U8 unit consists of a bedroom space and a living room space but there was no partition between these spaces at the time the unit was tested (Fig. 5). Figure 13a shows the average one-third octave band sound levels associated with the U8 unit. In fact, the differences between the average band levels of the bedroom and the living room are very small in general, except at frequencies below 200 Hz where a maximum difference of 2 dB can be observed in limited isolated cases (not shown here). Same applies to the outdoor measurements at M1 and M2. However, as this study is focused on traffic noise reduction, which is an A-weighted index, low frequency transmission characteristics are not significant. The variations of these sound levels with floor height basically follow those of U6, U7 and U13 and thus are not further discussed. The shapes of the spectra are also very similar to those shown in Fig. 10 though the measurements were taken at different times. These data further confirm the relatively steady traffic composition along the trunk road in concern.

Figure 13b illustrates the corresponding spectral noise levels of U14. U14 is close to the noise source and thus the façade noise levels are high and a definite trend of noise level decay with increasing floor level is observed (as in Fig. 10c). The U14 results are very much inline with those of U13 and thus they are not further discussed.

The benefit of setting the plenum windows in U8 from ‘by-pass’ mode to ‘acoustic’ mode is not as impressive as that of U6 or U7 as illustrated in Fig. 14a. The improvement within the major human ear audio frequency range is just 6 – 7 dB. The plenum window installed in the bedroom of U8 is the smallest type in this study (Table 2), such that opening the bedroom window (that is, by-passing this plenum window) has less impact on the indoor noise levels. The total opening area on the U14 façade is about 40% larger than that on the U8 façade and thus the higher acoustical improvement of the U14 plenum windows (Fig. 14b). The overall spectral characteristics of the noise reduction in U14 are similar to those in U13.

Before using the generalized traffic noise transmission loss prediction models, it is interesting to have an understanding on how Eq. (1) performs in the presence of coupled spaces. To do this, the bedroom and living room data of U8 are separately analyzed. The $TL_{traffic}$s of the bedroom and living room plenum windows are 11.88 dB and 11.96 dB respectively (from Eq. 1). A comparison between the measured $TL_{traffic}$ obtained using the approach of Li et al. [25] and that estimated using Eq. (1) are given in Fig. 15a. One can observe that the prediction model of Li et al. [25], though is not developed for coupled spaces, can give reasonable agreement with the living room window measurements. For the bedroom window, the agreement is less satisfactory but the deviation is still within 2 dB with a root-mean-square deviation of 1.1 dB.

In Fig. 15b are presented the corresponding data of U10 and U14. Again, one can notice the large deviations between the predicted and measured bedroom window $TL_{traffic}$s. Such deviations in these triple plenum window cases are more serious than that in the dual plenum window case of U8. On the contrary, the measured living room window $TL_{traffic}$s are in general lower than the predictions.

However, one should note that the transmitted powers calculated above for the bedrooms using the approach of Li et al. [25] and the measured data are likely to be overestimations. The larger living room, which has similar finishing as the bedrooms, has longer reverberant sound decay in principle, resulting in net acoustical power flow from the living room into the bedrooms. The fact that longer reverberation time for larger room is also illustrated in Fig. 8. The reverberant field inside the each bedroom is thus resulted from the acoustical power transmitted across the bedroom plenum window as well as that comes from the living room reverberation, which is a condition not catered by Li et al. [25]. The overall sound powers transmitted into the bedrooms are underestimated as only the powers transmitted directly through the plenum windows have been considered in building up the prediction models. Such power flows from living room to bedrooms also result in underestimation of the net power transmitted into the living room, resulting in the lower $TL_{traffic}$s than that predicted by Eq. (1), especially for the two-bedroom cases (U10 and U14) as shown in Fig. 15b.

It can be observed from Fig. 16 that the predictions of Eq. (4) agree very well with the measured $TL_{overall}$s estimated using the generalized approach presented in Section 2.2, especially for the larger flat units U10 and U14, which are of the same layout. For U8, the agreement is slightly less, but the average measured $TL_{overall}$ is very close to that predicted by Eq. (4), which is 11.93 dBA, with a root-mean-square deviation of 0.8 dBA, which is well within the tolerance of environmental noise control practice. It should be noted that the maximum and minimum deviations are less important in environmental noise studies as they are of a lower repeatability. It is also noticed that the $TL_{overall}$ of U8 agrees well with the corresponding mockup results of Tong et al. [26] presented in Li et al. [25]. Table 3 summarizes the performance of the overall traffic noise transmission loss prediction model. One can find that the differences between predictions and measurements are very small and are well within engineering tolerance.

5. Discussions

Though there were isolated laboratory studies on the acoustical performance of partially opened double glazing windows before and around the millennium [18, 20], it is not until the 2010s that rigorous research and development works are being done in sub-tropical and tropical regions [19, 21, 24, 26] because of urban noise control and climate needs as well as sustainability consideration. This study is the first comprehensive investigation into the actual performance of plenum window in practical use relative to that of the conventional side-hung casement window. The latter is represented by the by-passed plenum window in this study. Also, the present effort clarifies the important but unclear issues related to laboratory test results as presented in Section 1.

The test units in this study are not parallel to the noise source, which is a case cannot be accommodated in the laboratories. Two source orientations were tested. However, the plenum window performances measured in-situ tends to suggest that source orientation in practice, where the traffic noise is a long incoherent source, is not important. The effect of elevation also appears small, though one can observe in general that there is a weak trend of traffic noise sound transmission loss increase with increasing floor height. However, this elevation angle / height effect of maximum ~0.03 dB/m (~0.1 dB per floor) can practically be ignored. Sound incidence angle appears to have insignificant effect on the traffic noise transmission losses of plenum windows in real life practice. This is not the case found in the laboratory [19].

There is no practically implemented plenum window outside the city of the authors at least to the knowledge of the authors, further test of the generalized prediction model is not possible at the time being. However, there is one traditional façade device which can offer sound insulation and allow for natural ventilation at least for practical performance comparison. This is the relatively massive balcony installed with sound absorption [33]. The basic structure of balcony resembles that of an enlarged plenum window, but with a very large outdoor opening size and there is no overlapping length. The acoustical performance of a balcony depends very much on floor level (elevation from source), especially at lower floors where weak noise reduction and even noise amplification can be observed as shown in the site measurement of May [33]. The increase in the balcony noise transmission loss is ~1dB per floor (3 ft) at lower floors. The present plenum window appears to be a much better option in term of noise protection.

The good agreement between predictions and site measurements in this study, together with the weak dependency of the traffic noise transmission loss with floor level observed in this site study, confirming the high practicality of the prediction model established in the present study for high-rise building plenum window applications in an environment where there is no reflection from the opposite side of traffic noise source.

Apart from acoustical measurement, the commonly used tracer gas decay test [34] has also been conducted in order to understand the natural ventilation conditions when the plenum windows are set in the 'acoustic' mode. However, it is too lengthy to discuss the corresponding results in detail here and thus only an indicative account of the natural ventilation rates in term of air change per hour (ACH) is given. The measured ventilation rates are between 2 to 3 ACH and between 7 to 12 ACH when the plenum window(s) is/are set in the 'acoustic' and 'by-pass' mode respectively. However, it has to be emphasized that these ventilation rates depend very much on the outdoor wind conditions and thus an appropriate normalization has to be carried out before a meaningful discussions can be done. More details of the natural ventilation effectiveness and the related analysis are left to future reports.

6. Conclusions

Extensive measurement of the noise transmission across plenum windows was carried out in the present study in a newly erected 32-storey single housing block located next to a busy trunk road. There was no significant reflection from nearby buildings and from opposite side of the trunk road at the time of measurement. The major noise source was the nearby trunk road. A total of 35 flat units facing the trunk road, located between the fifth to the thirtieth floor and with four different layouts were surveyed. Among these flat layouts, two of them consisted of a single plenum window, one of them had two windows and the last one had three.

It is observed that the shapes of the one-third octave band spectra of the façade noise do not vary much with increasing elevation from the trunk road. For the flat units with a single plenum window, the results of the present site measurement validate directly the empirical model developed earlier by the authors based on laboratory and site mockup tests. The corresponding discrepancy is within engineering tolerance.

A generalized traffic noise transmission loss prediction scheme is developed for the multiple plenum window façades. Again, the corresponding predictions agree very well with site measurement results with a root-mean-square deviation of about 0.8 dBA for the dual plenum window cases and that for the triple plenum window cases is even smaller. Such deviations are very satisfactory in environmental noise studies.

It is also observed that the variations of the measured traffic noise transmission loss with elevation from the noisy trunk road (floor level) and source orientation are practically insignificant. The close agreement between predictions and measurements and the very weak variations of the major acoustical parameters with floor level manifest the practical significance of the present generalized prediction model for high-rise building applications at least in environments, where sound reflections from neighbouring buildings are not important.

Acknowledgments

XL is supported by a grant from the Research Grant Council, The HKSAR Government under Project number GRF 152164/15E.

References

[1] K.D. Kryter, The effects of noise on man, second ed., Academic Press, New York, 1985.

[2] E. Öhrström, A. Skånberg, H. Svensoon, A. Gidlöf-Gunnarsson, Effects of road traffic noise and the benefit of access to quietness, J. Sound Vib. 295 (2006) 40–59.

[3] J. Khan, M. Ketzel, K. Kakosimos, M. Sørensen, S.S. Jensen, Road traffic air and noise pollution exposure assessment – A review of tools and techniques, Sci. Total Environ. 634 (2018) 661–676.

[4] WHO Regional Office for Europe, Burden of disease from environmental noise – Quantification of healthy life years lost in Europe, L.B.A. Fritschi, A.L. Brown, R. Kim, D. Schwela, S. Kephalopoulos (Eds.), World Health Organization, Bonn, 2011.

[5] O. Hänninen, A.B. Knol, M. Jantunen, T.A.Lim, A. Conrad, M. Rappolder, P. Carrer, A.C. Fanetti, R. Kim, J. Buekers, R. Torfs, I. Iavarone, T. Classen, C. Hornberg, O.C.L. Mekel, EBoDE working group, Environmental burden of disease in Europe: Assessing nine risk factors in six countries, Environ. Health Perspect. 122 (5) (2014) 439–446.

[6] Environmental Protection Department, A comprehensive plan to tackle road traffic noise in Hong Kong, Hong Kong Special Administration Region, Hong Kong, 2006.

[7] U.J. Kurze, G.S. Anderson, Sound attenuation by barriers, Appl. Acoust. 4 (1971) 35–53.

[8] Environmental Protection Department, Hong Kong planning standard and guidelines, The HKSAR Government, Hong Kong, 1990.

[9] G.M. Echevarria Sanchez, T. van Renterghem, P. Thomas, D. Botteldooren, The effect of street canyon design on traffic noise exposure along roads, Build. Environ. 97 (2016) 96–110.

[10] P.J. Lee, Y.H. Kim, J.Y. Jeon, K.D. Song, Effects of apartment building façade and balcony design on the reduction of exterior noise, Build. Environ. 42 (2007) 3517–3528.

[11] S. Sakamoto, A. Aoki, Numerical and experimental study on noise shielding effect of evas/louvers attached to building façade, Build. Environ. 94 (2015) 773–784.

[12] Z. Martello, N. Fausti, P. Santoni, S. Secchi, The use of sound absorbing shading systems for the attenuation of noise on building façades, an experimental investigation, Buildings 5 (2015) 1346–1360.

[13] Y.G. Tong, S.K. Tang, M.K.L. Yeung, Full-scale model investigation on the acoustical protection of a balcony-like façade device, J. Acoust. Soc. Am. 130 (2) (2011) 673–676.

[14] T. van Renterghem, M. Hornikx, J. Forssen, D. Botteldooren, The potential of building envelope greening to achieve quietness, Build. Environ. 61 (2013) 34–44.

[15] A.J.B. Tadeu, D.M.R. Mateus, Sound transmission through single, double and triple glazing. Experimental evaluation, Appl. Acoust. 62 (2001) 307–325.

[16] M.H.F. de Salis, D.J. Oldham, S. Sharples, Noise control strategies for naturally ventilated buildings, Build. Environ. 37 (2002) 471–484.

[17] S.K. Tang, A review on natural ventilation-enabling façade noise control devices for congested high-rise cities. Appl. Sci. 7 (2017) 175, 16p.

[18] R.D. Ford, G. Kerry, The sound insulation of partially open double glazing, Appl. Acoust. 6 (1) (1973) 57–72.

[19] Y.G. Tong, S.K. Tang, Plenum window insertion loss in the presence of a line source – A scale model study, J. Acoust. Soc. Am. 133 (3) (2013) 1458–1467.

[20] J. Kang, B.M. Brocklesby, Feasibility of applying micro-perforated absorbers in acoustic window systems, Appl. Acoust. 66 (6) (2005) 669–689.

[21] H.H. Huang, X. Qiu, J. Kang, Active noise attenuation in ventilation windows, J. Acoust. Soc. Am. 130 (1) (2011) 176–188.

[22] S.K. Tang, Reduction of sound transmission across plenum windows by incorporating an array of rigid cylinder, J. Sound Vib. 415 (2018) 25–40.

[23] C. Cheung, C. Wong, T. Hung, S. Yim, R. Lee, Development and application of specially designed windows and balconies for noise mitigation in Hong Kong, Proc. InterNoise 2019, Madrid, Spain, (2019) Paper no. 2101.

[24] L. Du, S.K. Lau, S.E. Lee, Experimental study on sound transmission loss of plenum window, J. Acoust. Soc. Am. 146 (2019) EL489–EL495.

[25] X. Li, Y.G. Tong, S.K. Tang, K.K. Lau, Empirical prediction of traffic noise transmission loss across plenum windows, Appl. Acoust. 151 (2019) 45–54.

[26] Y.G. Tong, S.K. Tang, J. Kang, A. Fung, M.K.L. Yeung, Full scale field study of sound transmission across plenum windows, Appl. Acoust. 89 (2015) 244–253.

[27] BS EN ISO 16283-3, Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 3: Façade sound insulation, BSI, London, 2016.

[28] BS EN ISO 3382-2, Acoustics – Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms, BSI, London, 2008.

[29] A. Fry, Noise Control in Building Services, Pergamon, Oxford, 1988.

[30] BS EN1793-3, Road traffic noise reduction devices – Test methods for determining the acoustic performance, Part 3. Normalized traffic noise spectrum, BSI, London, 1998.

[31] M. Garai, P. Guidorzi, European methodology for testing the airborne sound insulation characteristics of noise barriers in situ : Experimental verification and comparison with laboratory data, J. Acoust. Soc. Am. 108 (3) (2000) 1054–1067.

[32] C. Buretti, Indoor noise reduction index with open window, Appl. Acoust. 63 (4) (2002) 431–451.

[33] D.N. May, Freeway noise and high-rise balconies, J. Acoust. Soc. Am. 65 (1979) 699–704.

[34] ISO 12569, Thermal performance of buildings and materials – Determination of specific airflow rate in buildings – Tracer gas dilution method, BSI, Geneva, 2017.

Captions

Figure 1 Basic configuration of a plenum window and the dimension-related nomenclature.

Figure 2 The operation modes of a plenum window.

(a) Acoustic mode; (b) by-pass mode; (c) closed window.

Figure 3 Typical floor layout of the surveyed building and its orientation relative to the noise source.

Figure 4 (Colour online) The surveyed building and its surrounding.

(a) Façade of the surveyed building facing the main trunk road (Wings A and D in the front);

(b) the trunk road, left of the surveyed building;

(c) the trunk road, right of the surveyed building;

(d) view of a U8 unit at high floor level.

Figure 5 (Colour online) The four flat layouts and the microphone locations.

(a) 1/2P; (b) 2/3P; (c) 2B; (d) 1B.

● : microphone.

Figure 6 (Colour online) Examples of practical plenum windows

(a) Bedroom; (b) living room.

Figure 7 The normalized traffic noise spectrum [36].

Figure 8 One-third octave band reverberation times.

(a) Mean reverberation times; (b) percentage standard deviations.

○ : U6; □ : U7; △ : U8; ▽ : U10.

Figure 9 Noise reduction of plenum window under different operation modes.

○ : ‘Closed’; □ : ‘acoustic’; △ : ‘by-pass’.

Figure 10 One-third octave band sound levels of flats with one single plenum window.

(a) U6; (b) U7; (c) U13.

● : 5/F; ■ : 10/F; ▲ : 15/F; ▼ : 20/F; ◆ : 25/F; ⬢ : 30/F.

Opened symbols : indoor averages (‘acoustic’ mode);

grey symbols : indoor averages (‘by-pass’ mode);

closed symbols : façade (‘acoustic’ mode).

Figure 11 One-third octave band noise reductions for the single plenum window cases.

(a) U6; (b) U7; (c) U13.

● : 5/F; ■ : 10/F; ▲ : 15/F; ▼ : 20/F; ◆ : 25/F; ⬢ : 30/F.

Opened symbols : ‘acoustic’ mode; grey symbols : ‘by-pass’ mode.

Figure 12 (Colour online) The measured and predicted $TL_{traffic}$s of U6, U7 and U13.

○ : U6; □ : U7; △ : U13;

– – – : Prediction for U6; – · – : predictions for U7 and U13.

Figure 13 One-third octave band sound levels of flats with multiple plenum windows.

(a) U8; (b) U14.

Legends : same as those of Fig. 10.

Figure 14 One-third octave band noise reductions for multiple plenum window cases.

(a) U8; (b) U14.

Legends : same as those of Fig. 11.

Figure 15 (Colour online) Comparison between estimated $TL_{traffic}$s of U8, U10 and U14 plenum windows.

(a) U8; (b) U10/U14 (closed symbols for U14, opened for U10).

Measurement (approach of Li et al. [30]) :

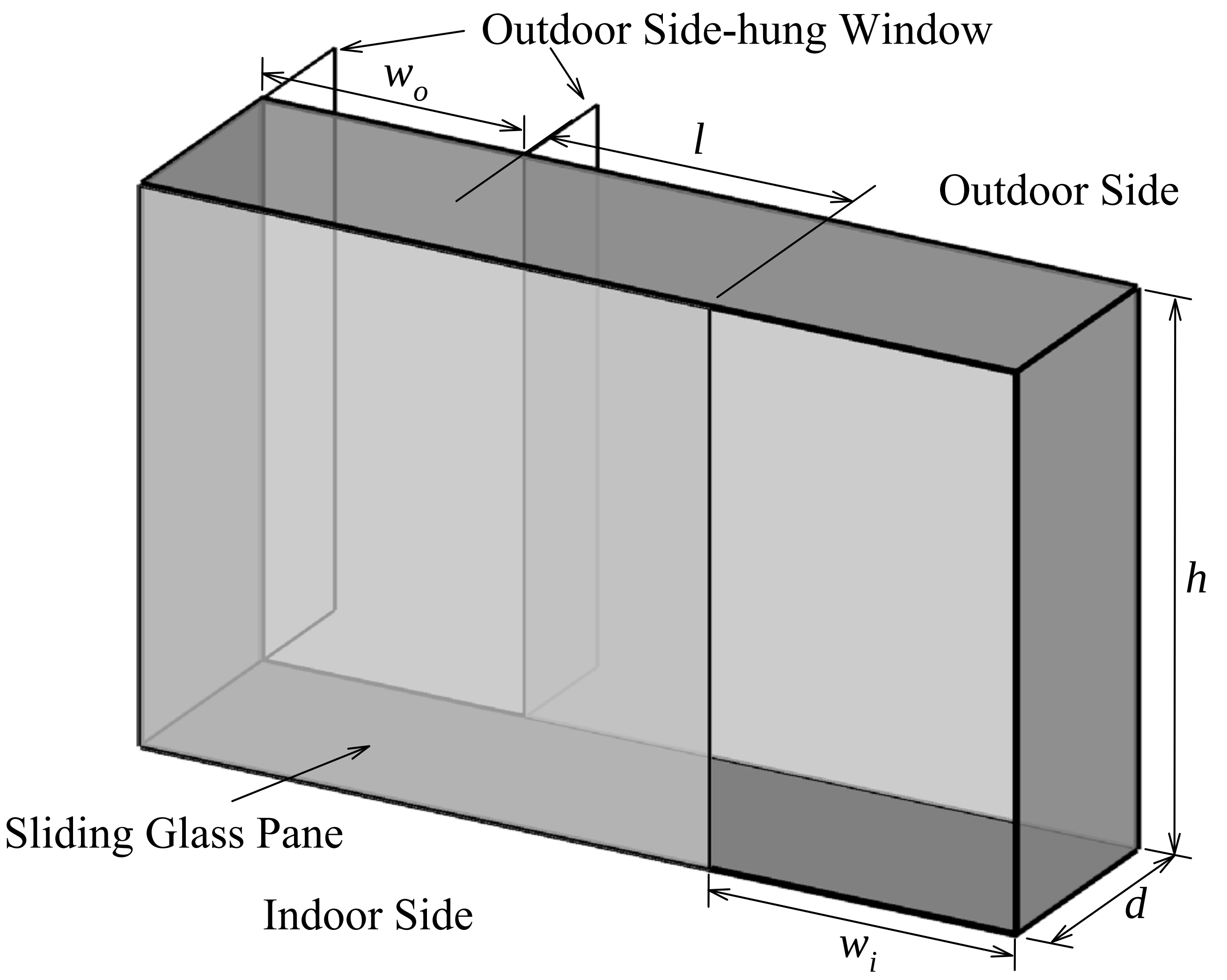
○: living room; □ : outer bedroom; △ : inner bedroom.

– · – : living room/inner bedroom (Eq. 1); – – – : outer bedroom (Eq. 1).

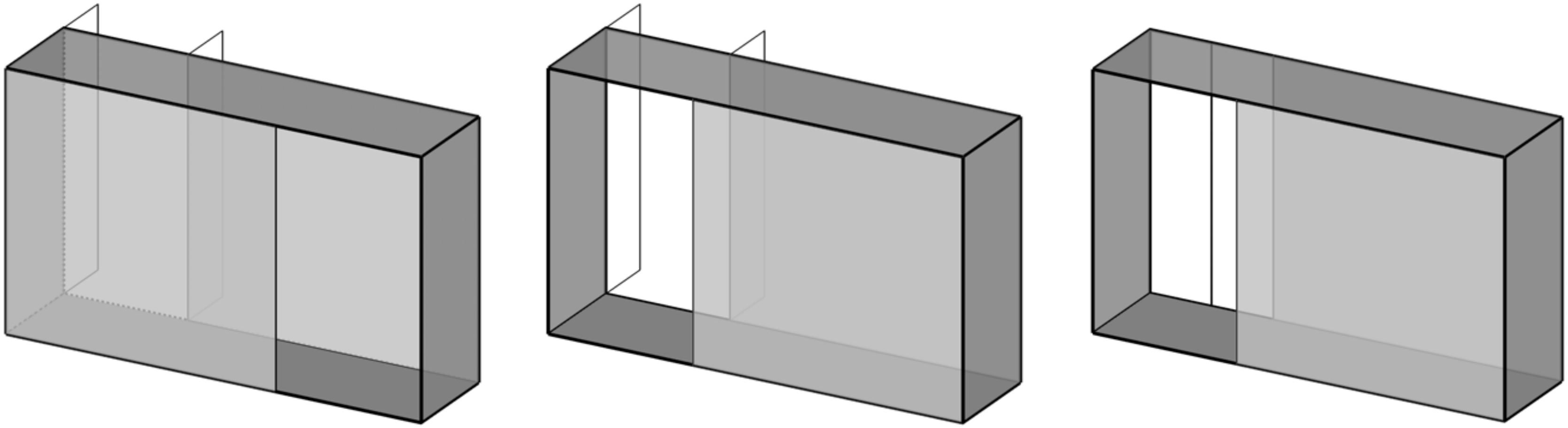
Figure 16 (Colour online) Comparison between estimated $TL_{overall}$s of U8, U10 and U14.

Measurement (Eq. 12) : ○: U8; □ : U10; △ : U14.

Eq. (4) : – · – : U10 / U14; – – – : U8.

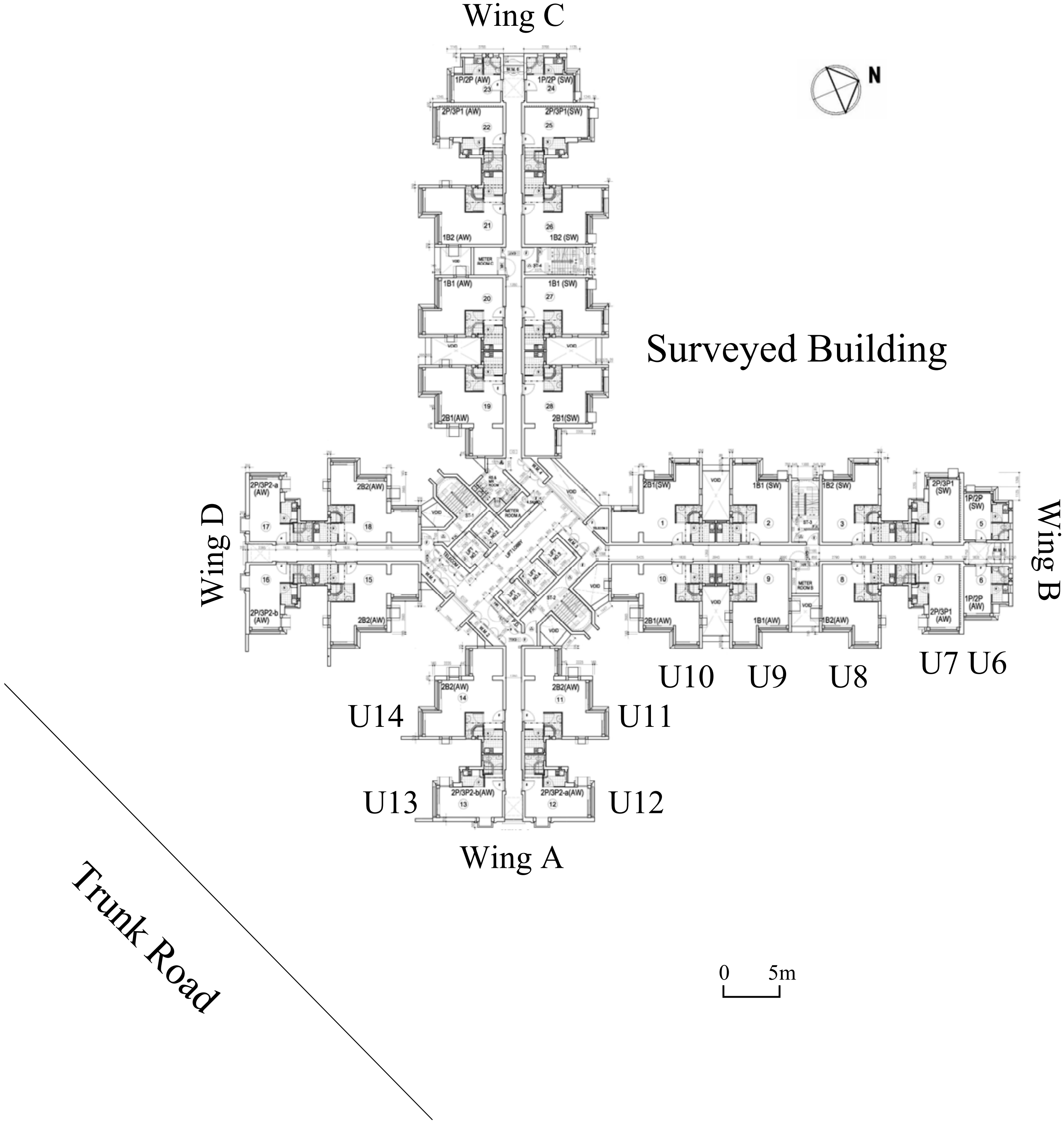

Outdoor Side-hung Window
w_o
l
Outdoor Side
h
Sliding Glass Pane
Indoor Side
d
w_i

Li et al. Fig.2



(a) (b) (c)

Li et al. Fig.3


Wing C
N
Surveyed Building
Wing D
Wing B
U10
U9
U8
U7 U6
U14
U11
U13
U12
Wing A
Trunk Road
0
5m

Li et al. Fig.4

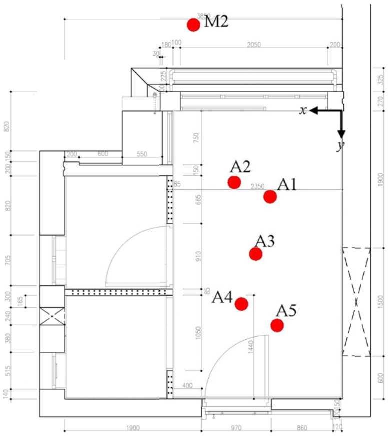
(a)

(b)

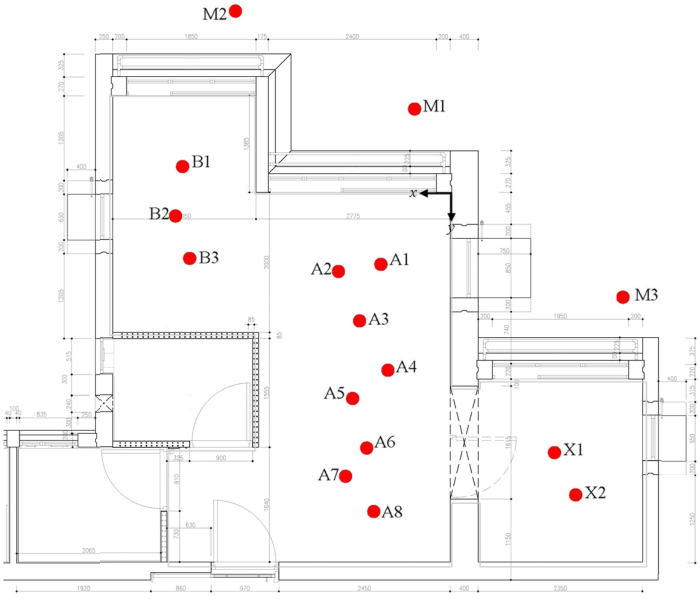
(c)

(d)

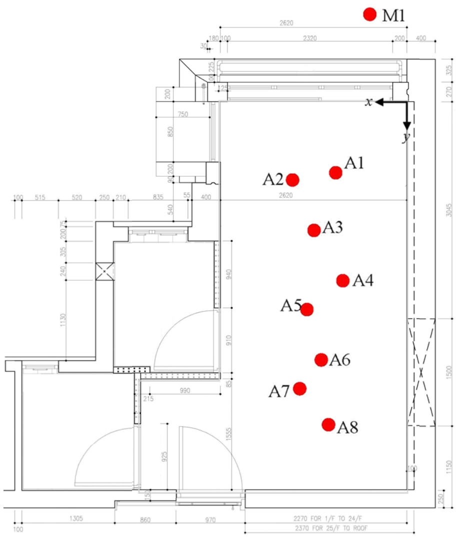
Li et al. Fig.5



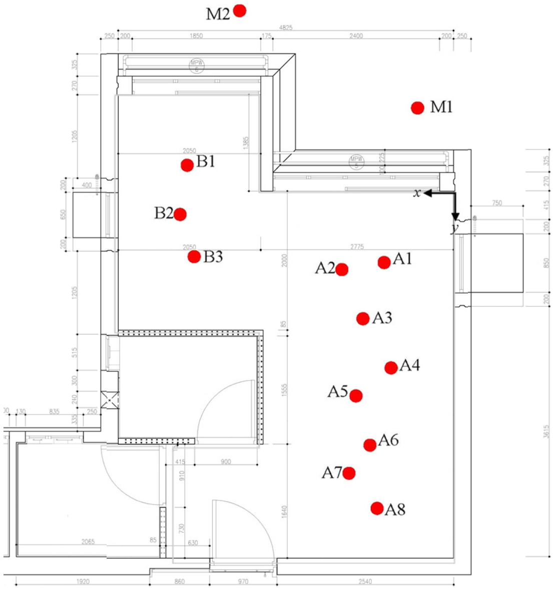
(a) 1/2P



(c) 2B



(b) 2/3P

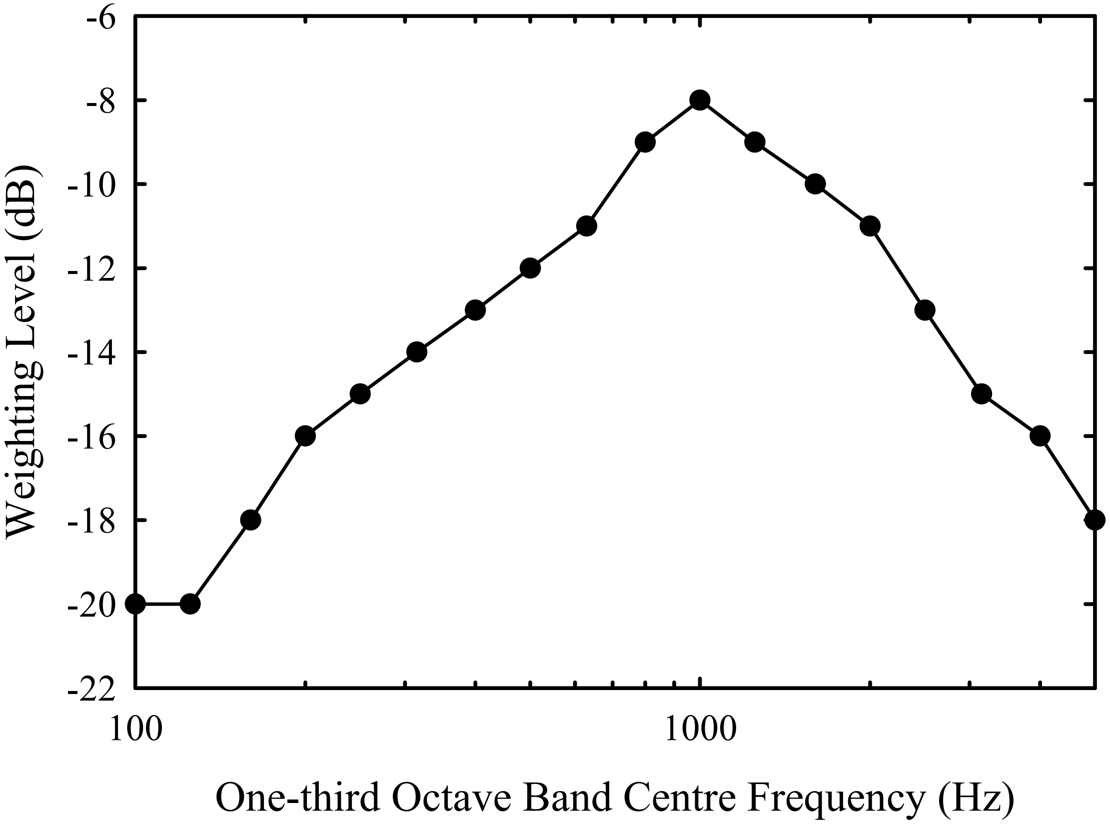


(d) 1B

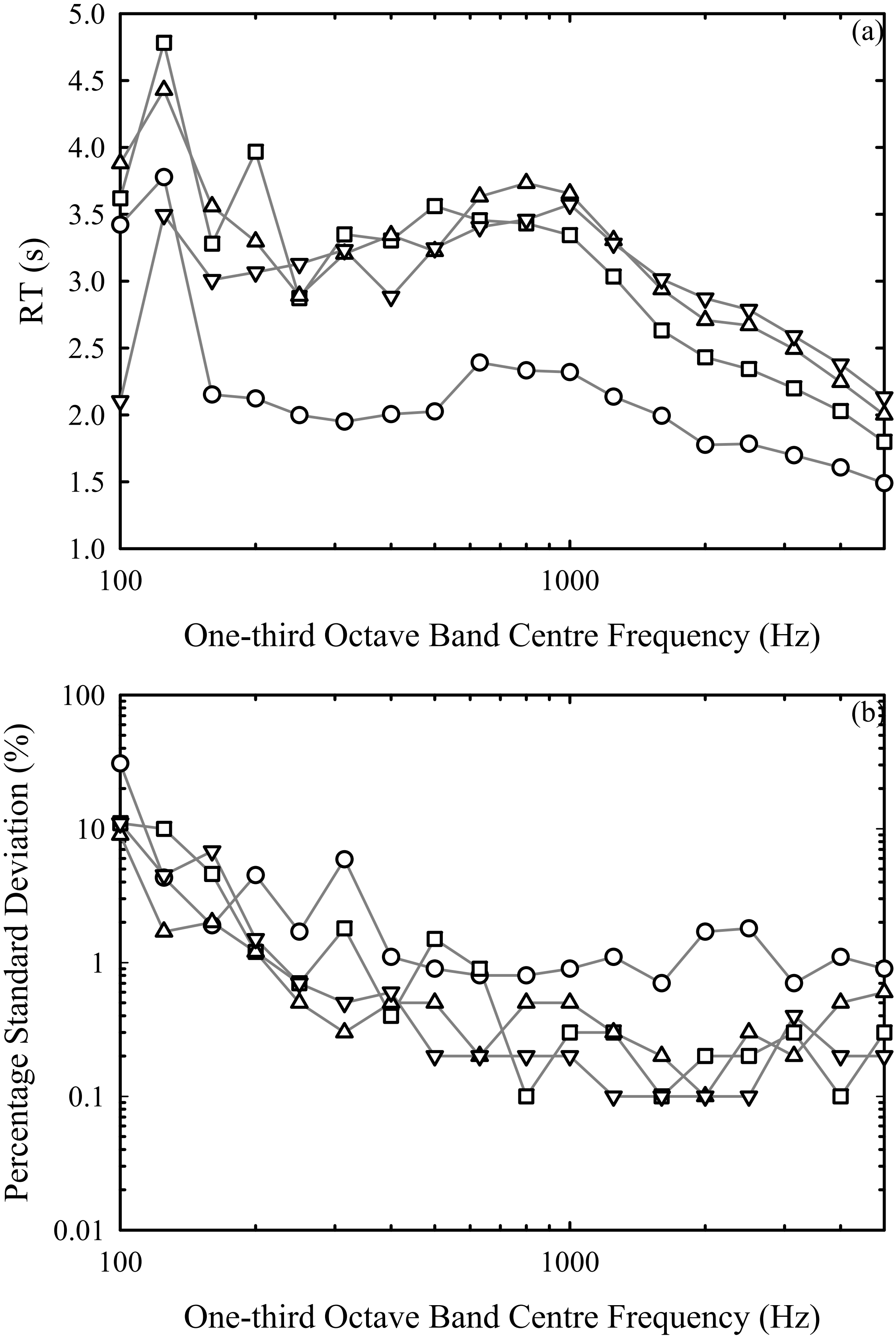
Li et al. Fig.6

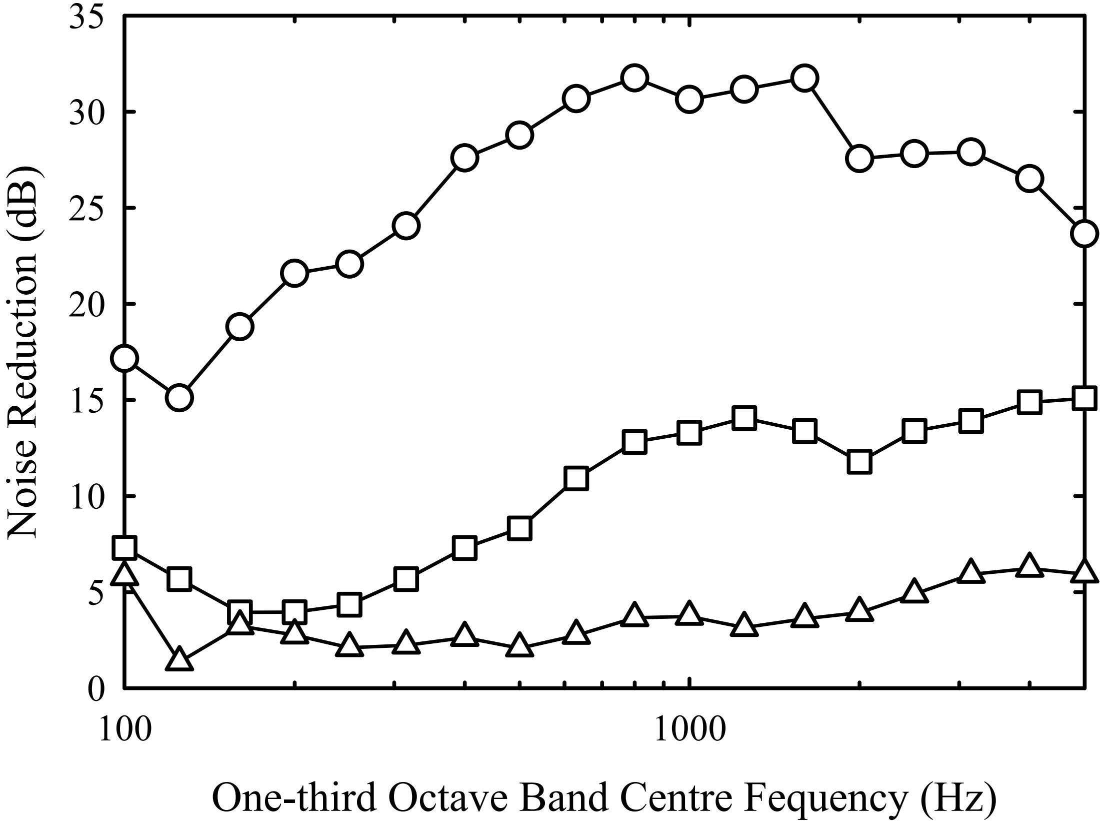
(a) (b)

Li et al. Fig.7

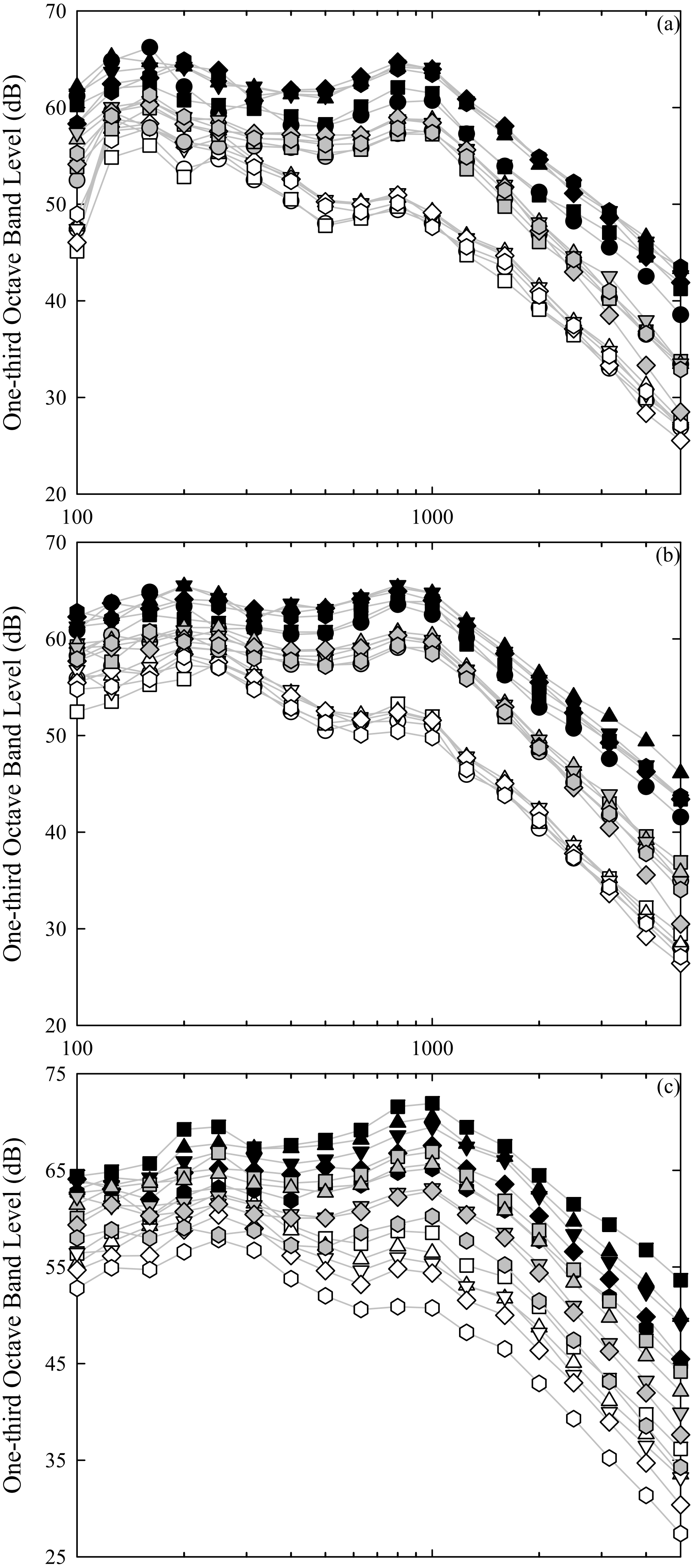

-6
-8
-10
-12
-14
-16
-18
-20
-22
Weighting Level (dB)
100
1000
One-third Octave Band Centre Frequency (Hz)

Li et al. Fig.8

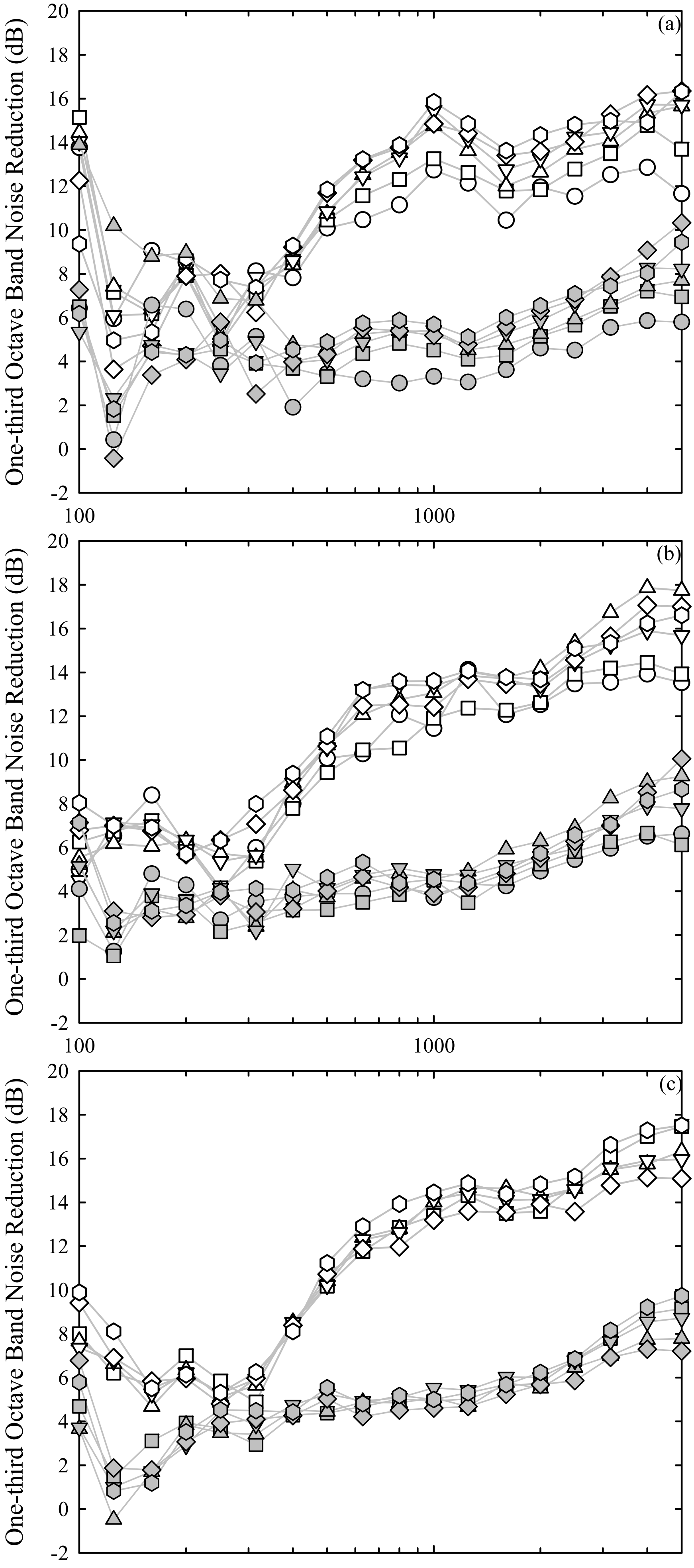

(a)
RT (s)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
100
1000
One-third Octave Band Centre Frequency (Hz)
(b)
Percentage Standard Deviation (%)
100
10
1
0.1
0.01
100
1000
One-third Octave Band Centre Frequency (Hz)

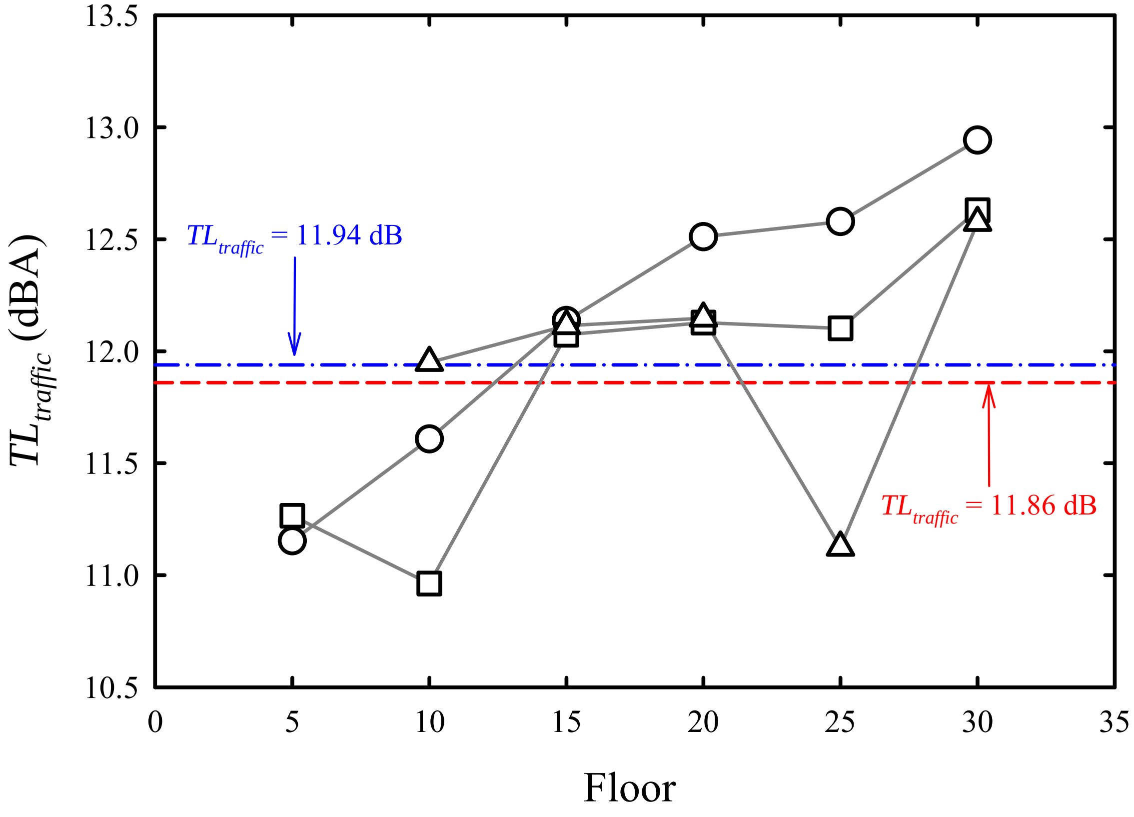

Noise Reduction (dB)
0
5
10
15
20
25
30
35
100
1000
One-third Octave Band Centre Fequency (Hz)

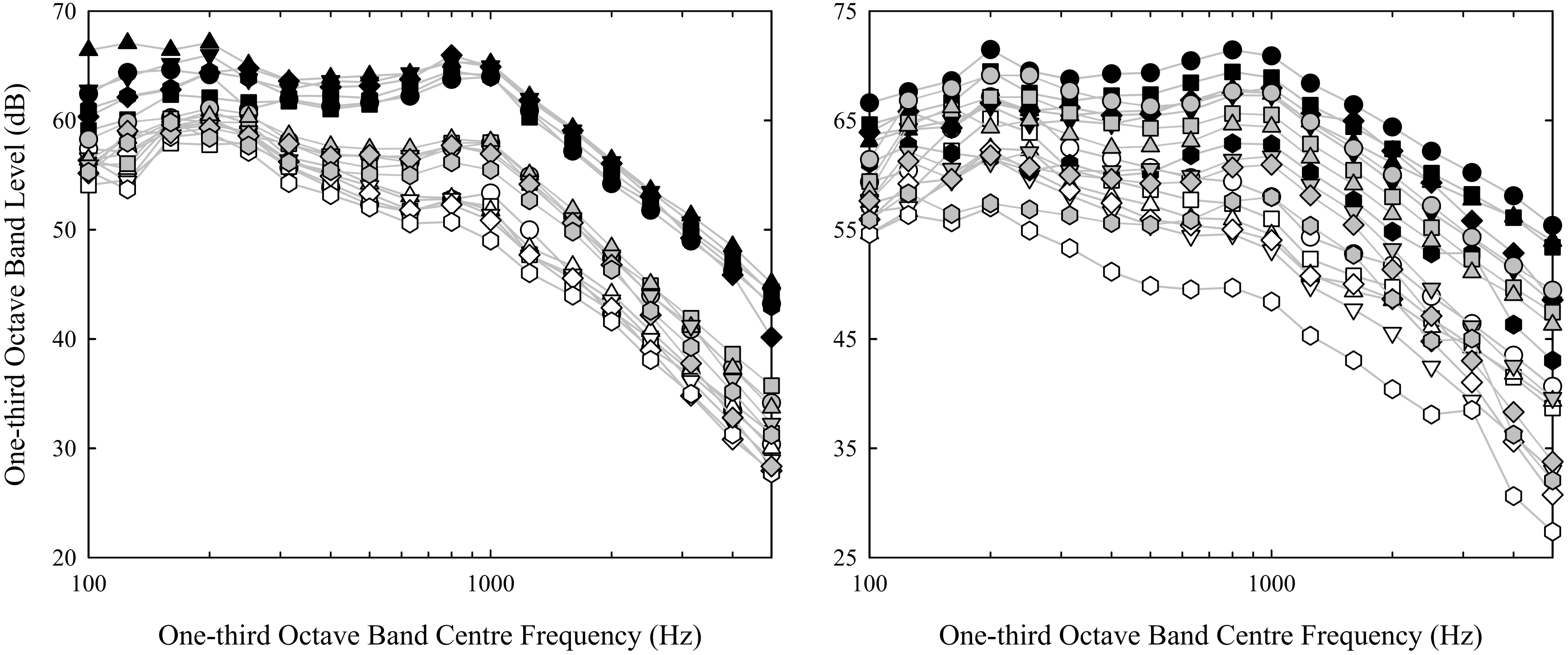
Li et al. Fig.10

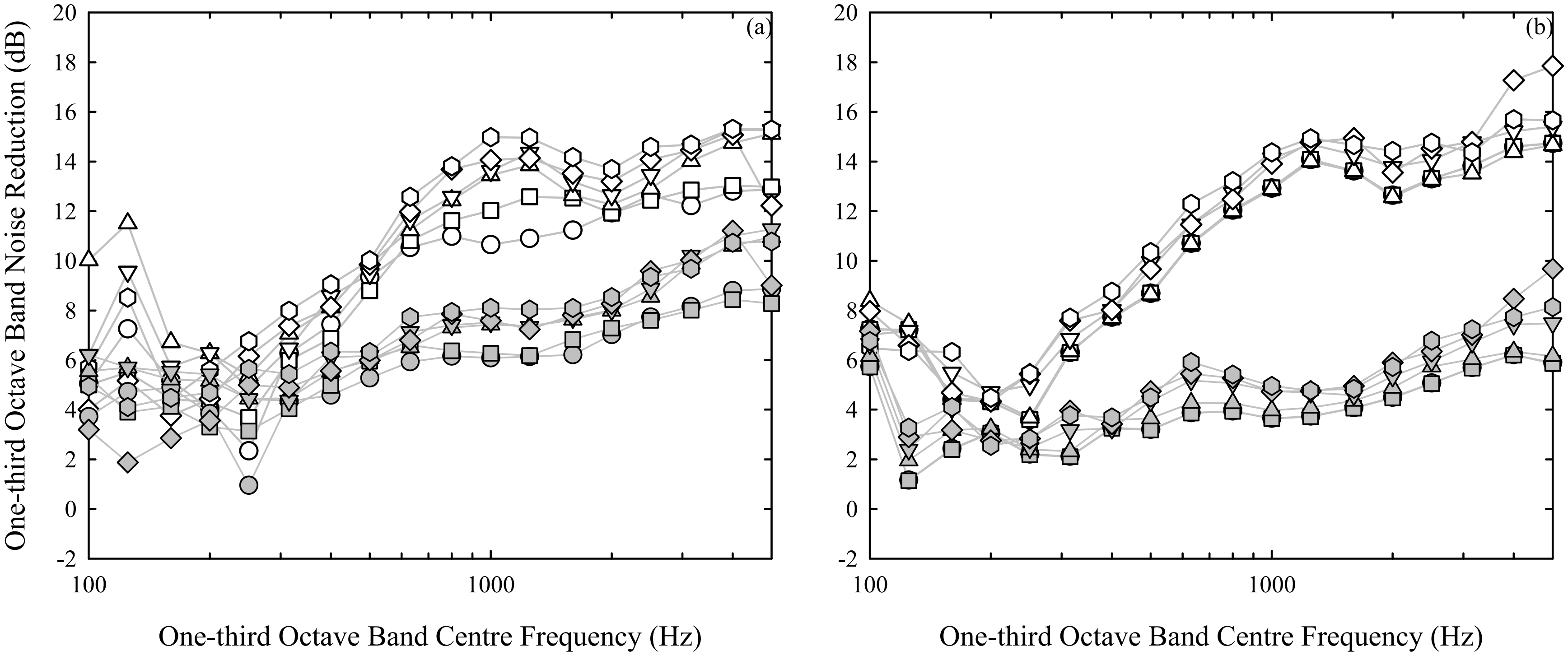


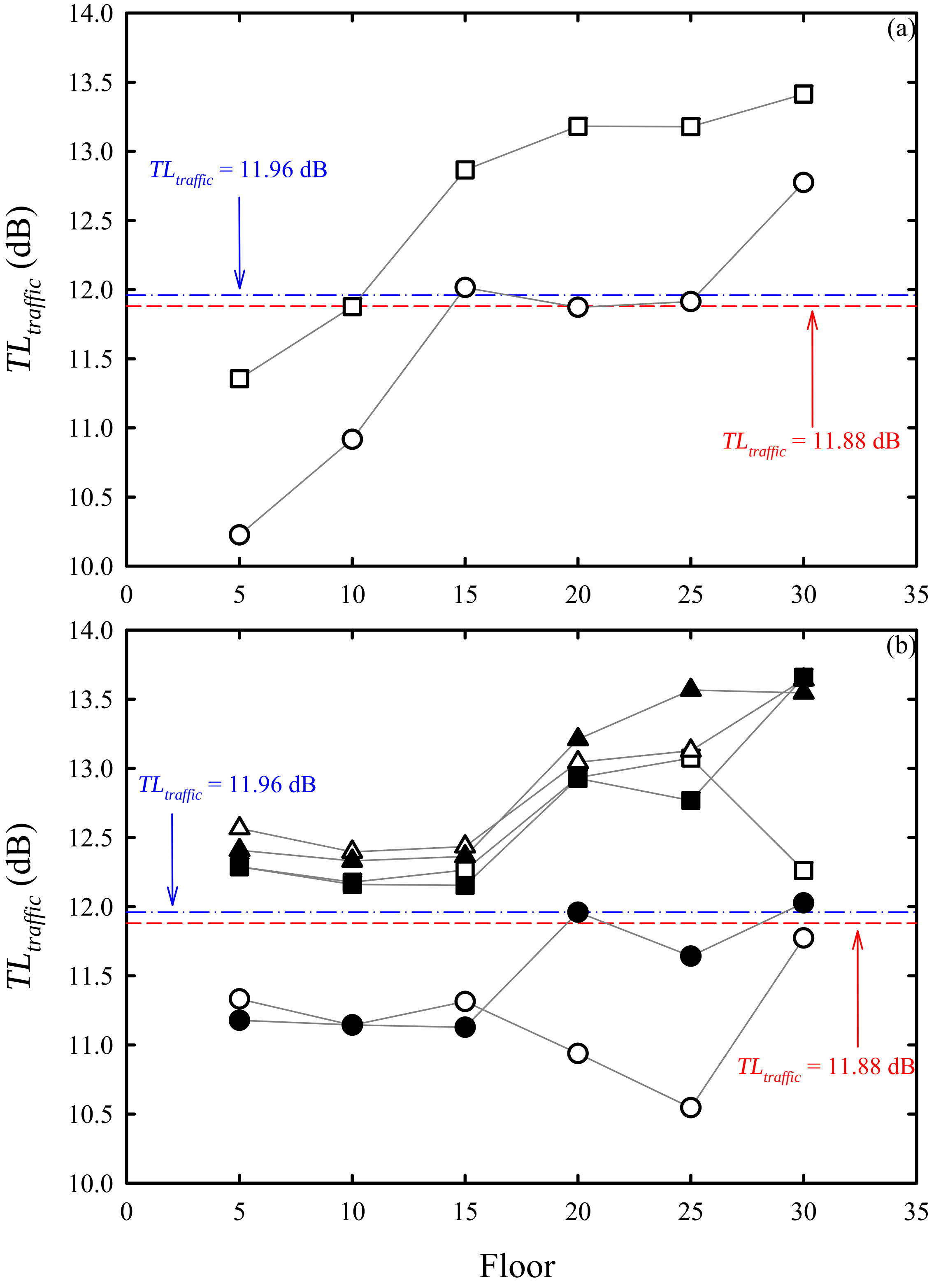
Li et al. Fig.11

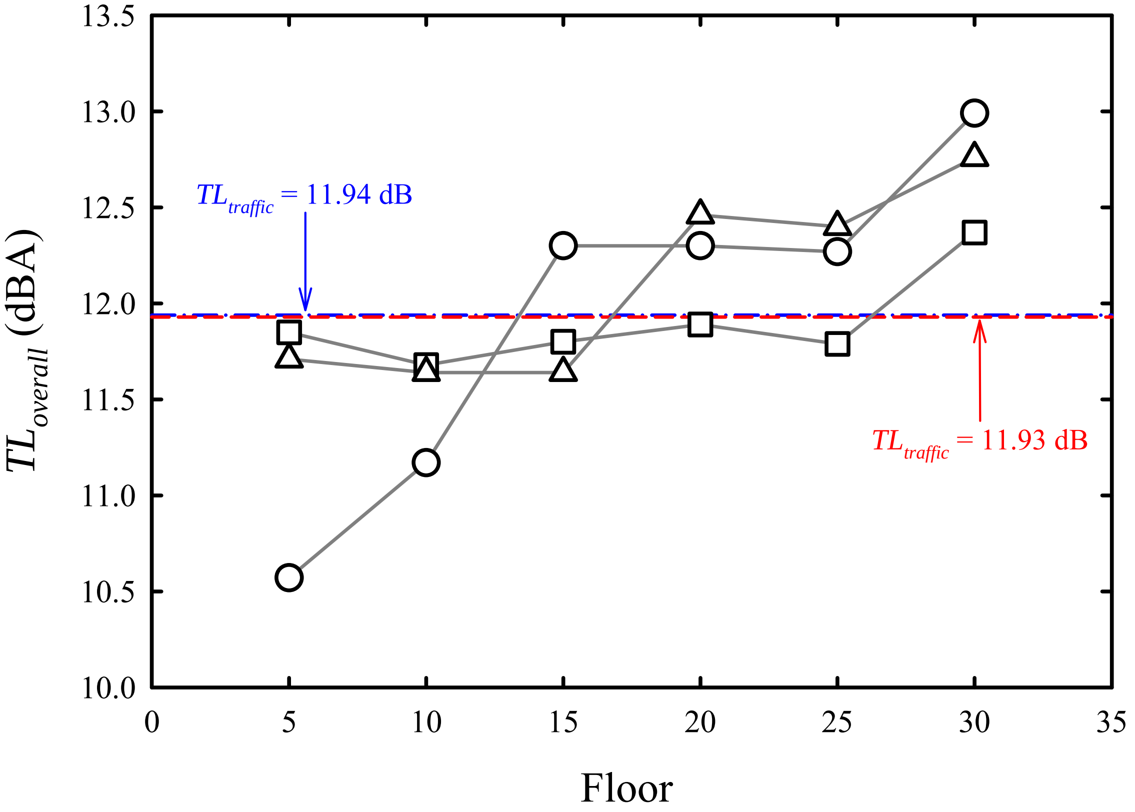



13.5
13.0
12.5
12.0
11.5
11.0
10.5
0
5
10
15
20
25
30
35
$TL_{traffic}$ (dBA)
Floor
$TL_{traffic}$ = 11.94 dB
$TL_{traffic}$ = 11.86 dB


One-third Octave Band Level (dB)
70
60
50
40
30
20
100
1000
One-third Octave Band Centre Frequency (Hz)
75
65
55
45
35
25
100
1000
One-third Octave Band Centre Frequency (Hz)


(a)
(b)
One-third Octave Band Noise Reduction (dB)
20
18
16
14
12
10
8
6
4
2
0
-2
100
1000
One-third Octave Band Centre Frequency (Hz)
One-third Octave Band Centre Frequency (Hz)


(a)
$TL_{traffic}$ = 11.96 dB
$TL_{traffic}$ = 11.88 dB
$TL_{traffic}$ (dB)
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
0
5
10
15
20
25
30
35
(b)
$TL_{traffic}$ = 11.96 dB
$TL_{traffic}$ = 11.88 dB
$TL_{traffic}$ (dB)
Floor


$TL_{traffic}$ = 11.94 dB
$TL_{traffic}$ = 11.93 dB
$TL_{overall}$ (dBA)
Floor
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
0
5
10
15
20
25
30
35