Investigations on road noise level spatial variability within a specially designed acoustic balcony

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Abstract

An investigation into the spatial distribution of road traffic noise levels on a balcony is conducted. A balcony constructed to a special acoustic design due to its elevation above an 8 lane motorway is selected for detailed measurements. The as-constructed balcony design includes solid parapets, side walls, ceiling shields and highly absorptive material placed on the ceiling. Road traffic noise measurements are conducted spatially using a five channel acoustic analyzer, where four microphones are located at various positions within the balcony space and one microphone placed outside the parapet at a reference position. Spatial distributions in both vertical and horizontal planes are measured. A theoretical model and prediction configuration is presented that assesses the acoustic performance of the balcony under existing traffic flow conditions. The prediction model implements a combined direct path, specular reflection path and diffuse reflection path utilizing image source and radiosity techniques. Results obtained from the prediction model are presented and compared to the measurement results. The predictions are found to correlate well with measurements with some minor differences that are explained. It is determined that the prediction methodology is acceptable to assess a wider range of street and balcony configuration scenarios.

Keywords: balcony, road traffic noise, speech interference level

1. INTRODUCTION

This paper presents an investigation to assess the spatial distribution of road traffic noise levels within an existing balcony that is constructed with acoustic treatments. The existing balcony overlooks an eight lane motorway and is adjacent to a conference room on the 10th floor of a Queensland University of Technology (QUT) building. The overall purpose of this investigation is to continue with a series of research activities conducted by the authors into road traffic noise, particularly speech interference, on residential balconies. Although the balcony in this current investigation is not residential, the principles are consistent.

The indicator selected for this study is the Speech Interference Level (SIL). The SIL is an arithmetic average of sound pressure levels (L_p) in octave bands 500Hz, 1kHz, 2kHz and 4kHz. Speech interference is the primary assessment indicator as balconies are places where conversations will occur.

There have been a number of studies by others into environmental noise on balconies that have advanced the knowledge on acoustics surrounding balconies by using a range of methods from full scale measurements(1-5) to scale modeling(6-13) and theoretical models(2, 3, 6, 8-11, 14-16). Also, the potential benefits of balcony acoustic treatments for a community have been estimated in Queensland study using health costs as the metric of comparison(17). In earlier research by the authors, a computer based theoretical model containing direct, specular reflection and diffuse reflection modules was developed using image sources for specular reflection and the radiosity technique for diffusion(18, 19). The same theoretical model is adopted in this research. The most recent study by the authors(19) confirmed that balcony acoustic treatments has a beneficial effect by improving speech interference and transmission.

To achieve the purpose of this study, firstly, the spatial variations within the balcony space are

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measured and presented as interpolated contours in several selected planes. Secondly, through the use of a theoretical model, spatial predictions throughout the balcony are computed. Finally, the calculated values are compared to the measured values along with discussion on the results.

2. METHODOLOGY

Firstly the measurement site is described in detail. As the study methodology incorporates a measurement part and a theoretical part, each part is separately described in detail below including the method used to compare measured and predicted results.

2.1 Site

The investigation site is located on the 10th level of ‘Z’ block building at QUT’s Gardens Point campus in Brisbane, Australia. It overlooks an 8 lane motorway which is one of the State of Queensland’s most highly trafficked roads. Traffic flow data for the section of motorway in front of the balcony was obtained(20). In year 2010, the motorway carried approximately 126,000 vehicles on a weekday and 99,000 on weekends. The number of vehicles per hour on a weekday between 8am and 6pm is approximately 7,829. This equates to nearly 130 vehicles per minute (approximately 2.2 vehicles per second). As outlined in the next section, all measurements are 30s duration, thus the average number of vehicles during a 30s measurement is 65.2 vehicles.

The width of each lane is 3.0m, with 4 lanes in each direction. Figure 1 shows a recent aerial photo of the whole site, indicating the location the subject building, adjacent buildings, and the motorway. The balcony looks over the Brisbane River beyond the motorway and consequently there are effectively no acoustic reflections from any opposite buildings.

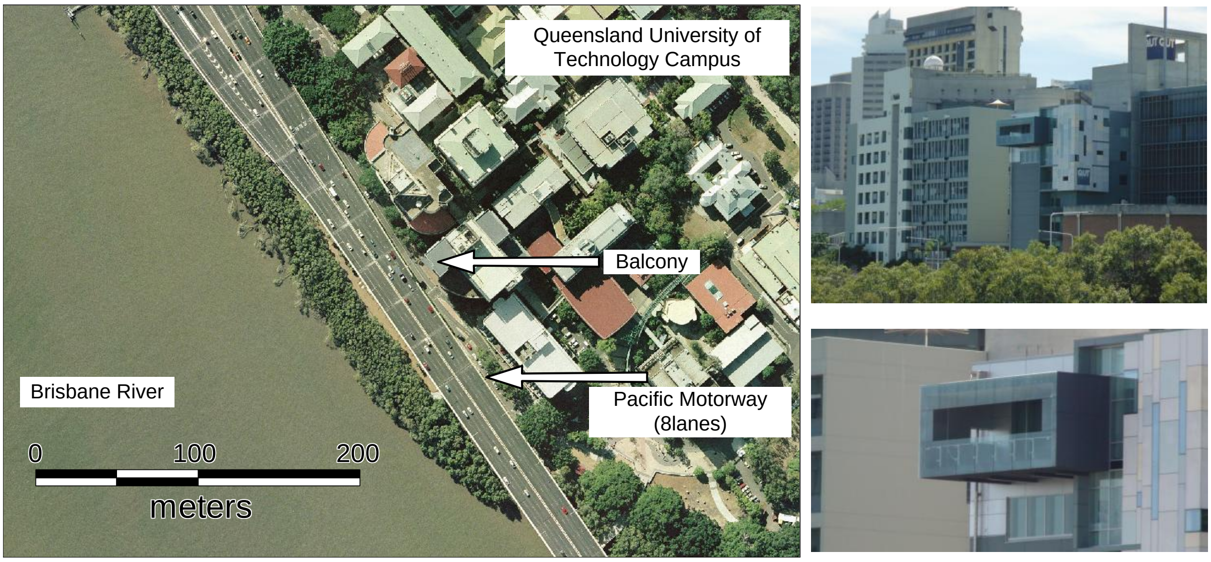

Figure 1: Measurement site location and environment and theoretical model extents. Balcony located at coordinates 27°28′40.75″S, 153°01′38″E.

The balcony floor was surveyed to be 25.5m above the surface of the motorway, with the building façade being 27.75m from the central axis of the motorway (refer to Figure 2(a)). The dimensions of the balcony are shown in Figure 2(b) and (c). The width at the balcony front is 8.2m, depth 3.6m and height 3.0m. An airlock is situated in one corner of the balcony and the remainder of the balcony does not contain any object. The floor material is tiles on concrete slab. The internal wall material to the building and adjacent conference room is double glazing. Acoustic absorption is constructed on the entire ceiling surface and all non-transparent walls as indicated in Figure 2(b) and (c). It is not possible to determine the exact construction of the absorption panel as partial demolition is not permitted, however external examination showed the absorption consisted of corrugated sheet metal perforated with 2.5mm diameter holes at a spacing of 9.5mm. Thus, it is estimated that the perforation rate was 5%. It appears that the sheet metal is offset from the outer surface to form a cavity of 25mm which is filled with an absorptive material like fiberglass. The density of the absorptive material could not be determined.

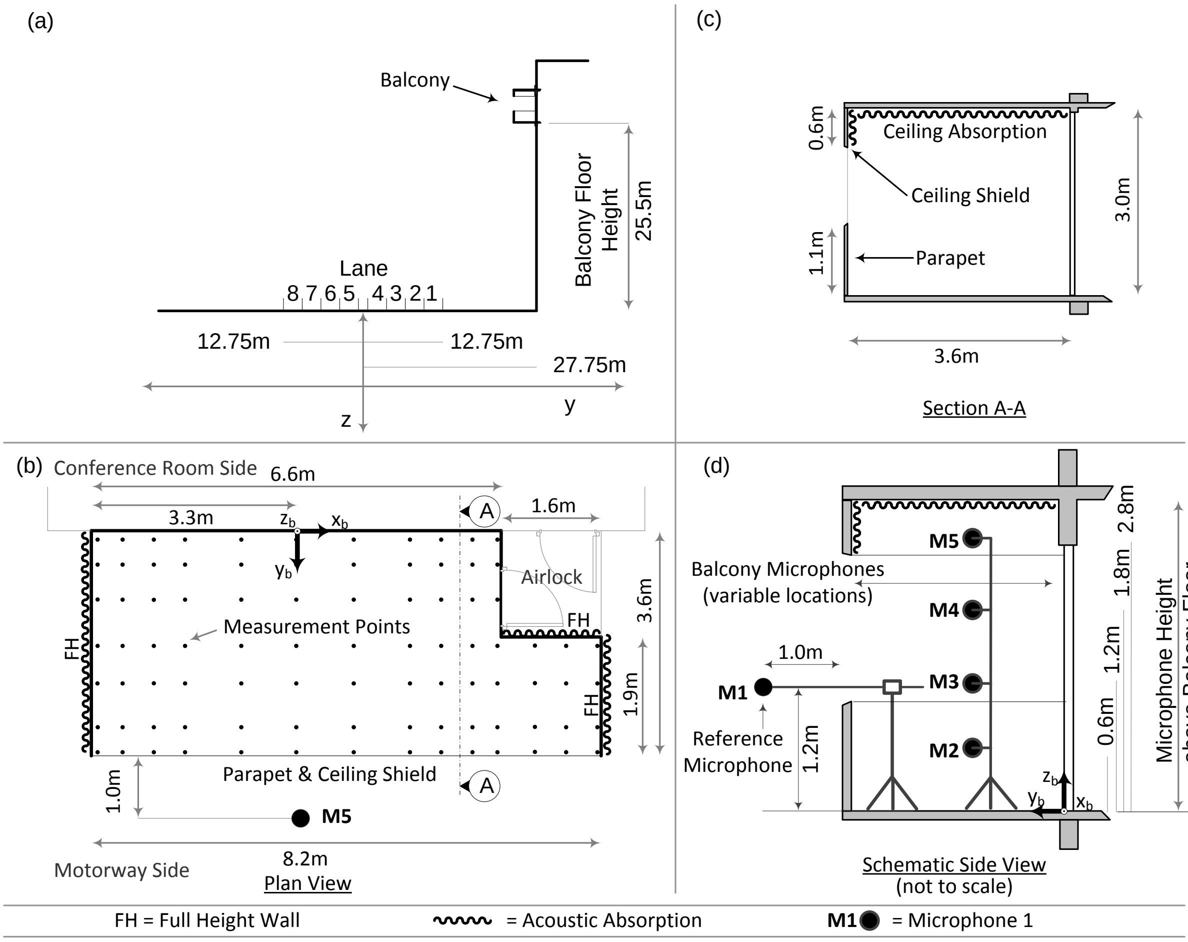

Figure 2: Site and model geometry, (a) dimensions of the street and balcony location, (b) plan view of balcony with relevant dimensions and showing microphone locations in horizontal plane, (c) section view of balcony with relevant dimensions, and (d) section view showing microphone locations designations and vertical locations.

A Cartesian coordinate system (x, y, z) for the overall site is established; the x-axis parallel to the vehicle direction, y-axis perpendicular to the vehicle direction and z-axis the elevation (refer to Figure 1). The origin is at the centre point on the road surface directly in front of the midpoint of the front of the balcony. A local coordinate system (x_b, y_b, z_b) is established for the balcony space, with the origin at the floor level, at the midpoint of the junction between the floor and the building façade (refer to Figure 2(b) and (d)). The localized coordinate system for the balcony is developed for ease of measurements, and appropriate coordinate transformations are made when comparing measurement positions to the prediction positions.

2.2 Measurement method

A Bruel & Kjaer 5-Channel Pulse (Type 3560-B) with five ½ inch microphones (Type 4189) was used to perform the measurements. The locations of all 5 microphones is shown indicatively in Figure 2(d), where 1 microphone is positioned outside the balcony to act as reference and the remaining 4 microphones positioned in a vertical line within the balcony space. The reference microphone (M1) is 1.0m away from the front of the balcony and 1.2m above the balcony floor to be consistent with earlier studies by the authors(19). The height of 1.2m has been selected to represent the average height of a seated person on a balcony. The distance of 1.0m is selected as (i) it matches some historically recommended measurement distances, (ii) this distance is more geometrically representative of the balcony location than any further distances, and (iii) a 1.0m measurement distance reduces safety risks that may be introduced with increased distances. The reference microphone remained in the same location for all measurements, at local balcony coordinates x_b = 0, y_b = 4.6m, and z_b = 1.2m.

The height, z_b, of the four microphones within the balcony space is 0.6m, 1.2m, 1.8m and 2.8m as shown in Figure 2(d). Microphones M2, M3 and M4 are equally spaced in 600mm increments, centered on the average seated person height of 1.2m. Additionally, it is decided that measurements close to the floor are not as important as measurements in the vicinity of the parapet edge where diffraction sensitivity is the highest and therefore microphones M2, M3 and M4 locations satisfy this need. The ceiling is an important reflection plane when balconies are higher than the road and the effect of ceiling shields requires quantification; hence microphone location M5, 200m below the ceiling was selected. Microphones M2 to M5 are used to measure at each point in a horizontal grid (x_b, y_b) as shown in Figure 2(b). In total there are 89 measurement points in the horizontal plane, which equates to 356 measurement points when considering all 4 microphone heights. In order to complete this task efficiently, the microphones are supported on a specially designed and constructed multi-microphone pole (constructed at QUT's Design Laboratory and Workshop). The pole is supported on castors so that translation time to a new position within the balcony space is efficient.

The PULSE instrumentation is linked and controlled via a laptop computer and measurements are controlled via Microsoft Excel spreadsheet software using visual basic syntax so that each measurement is commenced, stopped and stored in a database in a single operation. Each measurement consisted of a 30s equivalent continuous sound pressure levels ($L_{eq,meas}$) in 1/3 octave bands from 20Hz to 20kHz. This data allows subsequent calculation of the measured SIL (SIL_{meas}).

2.3 Theoretical Model

The basis of the theoretical model has been presented elsewhere(18, 19) and only a general overview is provided here. The model combines direct sound paths with an image source technique to calculate specular reflection and with the radiosity technique to simulate diffusion. The model allows for up to 10 orders of specular reflection of predefined allowable propagation paths and provides for up to 2 orders of diffuse reflection across two different compartments. It includes the ability to calculate diffraction from balcony edges. This model has been used in a detailed study on speech interference and transmission for a large number of street to balcony acoustic and geometric configurations(19). In that study, a single lane of traffic consisting of a passenger car at 60km/hr located directly in front of a balcony was simulated. Calm meteorological conditions were modeled, not allowing for the effects of wind velocity and direction, or changing temperature and humidity and the same assumptions were used in this current study.

An additional aim of this study is to produce a fast calculation method to simulate actual road traffic noise. Roads with high traffic volumes have numerous simultaneously contributing moving noise sources from vehicles of many different types, including (i) the propulsion components; (ii) the tire and road interface; and (iii) aerodynamic effects. Any attempt to model such a highly complex traffic flow scenario will result in very long calculation times and thus ensures it is difficult to model a larger number of theoretical scenarios. Conversely, a fast calculation method that produces acceptable similarities with measured levels can be utilized for a larger set of theoretical scenarios. It is the diffuse path which adds the most time to the calculation process. To establish a fast calculation method, the theoretical model is set to the configuration presented in Figure 3(a). The motorway below the balcony consists of 8 lanes. In each lane, the road traffic noise source is modeled as a series of moving point sources 5m apart moving at 70km/hr for a distance of 125m in front of the balcony. All point sources calculate the direct and specular reflection paths, whereas only those point sources directly in front of the balcony are utilized to calculate diffusion. Figure 3(b) demonstrates the conceptual time domain predictions. Direct and specular energy increases until the moving point source is directly in front of the balcony and sound pressure level (L_p) reaches its maximum, afterwards as the source moves away from the balcony and L_p declines. Diffuse energy from numerous simultaneous moving sources in high traffic flow conditions is relatively constant, termed here as the ambient constant. Thus it is assumed all the diffuse energy from those point sources directly in front of the balcony can be summed across all lanes and logarithmically averaged across all receivers within the balcony space to calculate the ambient constant, SIL_{Amb}. The total energy being the sum of the direct, specular and diffuse energy from either a single vehicle in one lane or multiple vehicles in numerous lanes can then be quickly simulated.

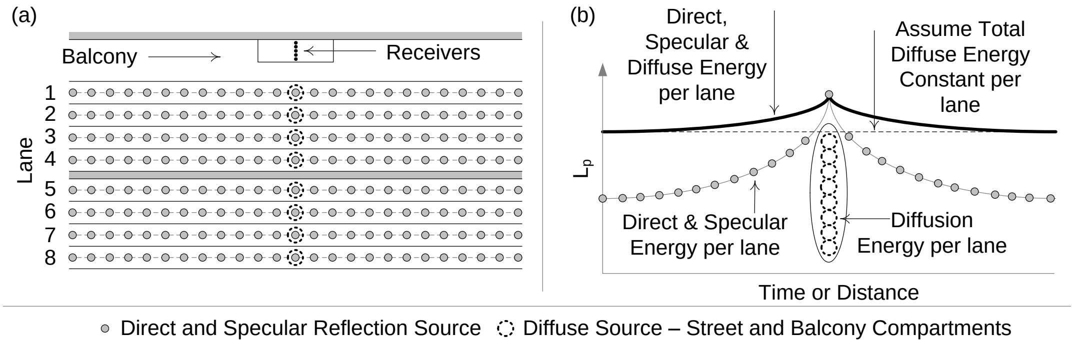

Figure 3: Source and path configuration in prediction model, (a) conceptual combination method for direct, specular and diffuse paths for a balcony receiver, and (b) source type location.

Each moving point source and diffuse source is assigned the same average sound power level, L_w, in each 1/3 octave band. In order to simulate real traffic noise levels including different vehicle types, measured vehicle L_w data is extracted from a previous study conducted by the principal author(21). All individual vehicles are classified into two vehicle types, (i) cars, and (ii) trucks. The spread of measured L_w data in 1/3rd octave bands from 400Hz to 5kHz for each vehicle type is shown in Figure 4 with quartile plots along with the arithmetic average for each vehicle type, $L_{w,avg,car}$ and $L_{w,avg,truck}$. Utilizing the average sound power level for both vehicle types, and assuming a traffic flow composition of 90% cars and 10% trucks which is an average vehicle composition for this motorway, the overall average sound power level, $L_{w,avg}$ (Figure 4(c)) is calculated and implemented in the calculations.

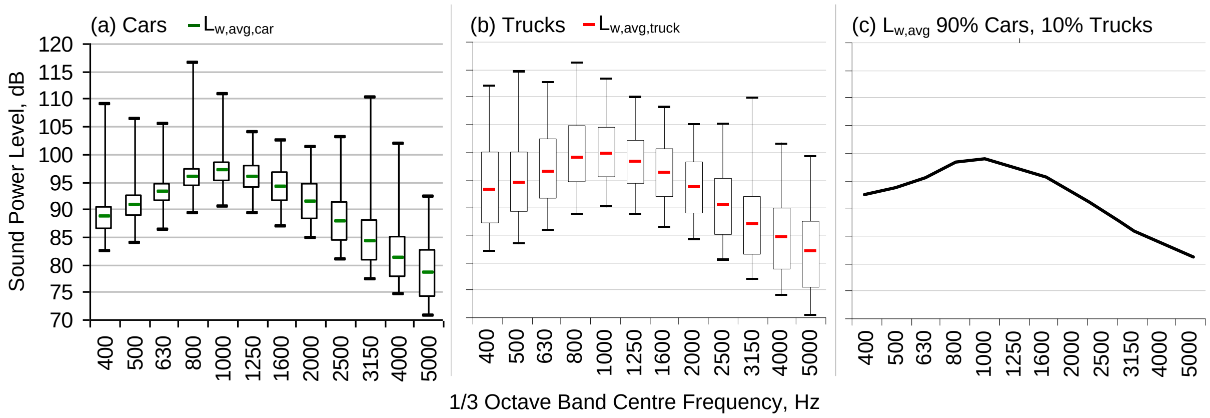

Figure 4: Spread of measured sound power levels using quartile plots and arithmetic average per vehicle classification (a) cars, (b) trucks and (c) $L_{w,avg}$ 90% cars, 10% trucks (color online).

Balcony receivers included in the predictions are only those in a vertical cross section in the geometric middle (x_b=0) of the space. An 11×11 receiver point grid is established, with one receiver located at the reference position as per the measured reference position. In total, there are 122 prediction points per lane, resulting in 976 calculations.

The L_p due to a theoretical vehicle pass-by result is calculated on the balcony receivers for each lane using $L_{w,avg}$ so that the equivalent continuous sound pressure level, L_{eq}, pass-by per lane ($L_{eq,lane,n}$) result is obtained; where n is the lane number from 1 to 8. The $L_{eq,lane,n}$ is calculated for each third octave band, and from these results the $SIL_{lane,n}$ is derived which is a L_{eq} based parameter being the arithmetic average of the $L_{eq,lane,n}$ octave bands from 500Hz, 1kHz, 2kHz and 4kHz. SIL_{meas} is based on a 30 second L_{eq} so it is necessary to convert the predicted eight lanes of $L_{eq,lane,n}$ to another overall combined lane SIL parameter, SIL_{pred}, which represents a 30 second period. To do this in terms of the direct and specular paths, the $SIL_{lane,n}$ was converted to the sound exposure level ($SEL_{lane,n}$) using Eq. 1 including the theoretical pass-by time (T_i) of 6.43s (125m / 70km/hr). Then, with approximately 65.2 vehicles in 30s, it can be assumed that on average there will be 8.2 vehicles/lane/30s ($V_{lane,n,30s}$). The

SEL for each lane based on 30s of vehicle traffic ($SEL_{lane,n,30s}$) can be calculated using Eq. 2. The total SEL ($SEL_{total,30s}$) combining all eight lanes is then calculated (Eq. 3), and then converted using Eq. 4 to a predicted 30s SIL, SIL_{DS}, where ‘D’ represents the direct path and ‘S’ represents the specular path. Finally, the diffuse component representing the ambient constant, SIL_{Amb} is added to calculate SIL_{pred} (Eq. 5) which is then in an appropriate form to be compared to SIL_{meas}.

$$SEL_{lane,n} = SIL_{lane,n} + 10\log_{10}(T_i) \quad \text{Eq. 1}$$

$$SEL_{lane,n,30s} = SEL_{lane,n} + 10\log_{10}(V_{lane,n,30s}) \quad \text{Eq. 2}$$

$$SEL_{total,30s} = 10Log_{10}\left(\sum_{n=1}^{8} 10^{0.1(SEL_{lane,n,30s})}\right) \quad \text{Eq. 3}$$

$$SIL_{DS} = SEL_{total,30s} + 10\log_{10}\left(\frac{1}{30}\right) \quad \text{Eq. 4}$$

$$SIL_{pred} = 10\log_{10}\left(10^{0.1(SIL_{DS})} + 10^{0.1(SIL_{Amb})}\right) \quad \text{Eq. 5}$$

3. RESULTS AND DISCUSSION

The measured and predicted results are presented in two forms, (i) SIL difference between any balcony position and the reference position where a negative value indicates the balcony position SIL is lower than the reference position SIL (ΔSIL_{meas} or ΔSIL_{pred}), and (ii) the overall SIL (SIL_{meas} or SIL_{pred}). All measurements, sound power levels and theoretical predictions are recorded in 1/3rd octave bands. However the results presented here are only in terms of the SIL. Consequently, extraneous events such as truck engine compression braking or low frequency exhaust noise will not directly influence the measured SIL results.

Firstly, it is important to indicate the relative constancy of the measured noise source energy as the measurements were taken at various times throughout the day. The SIL_{meas} at the reference position and the average SIL_{meas} for all positions within the balcony space is plotted in Figure 5. The graph shows that over the duration of the measurements, SIL_{meas} at the reference position does not fluctuate more than 6.8dB and shows a clear extraneous event at 2:05pm. If this event is removed, the fluctuation range reduces to 3.9dB which shows that the road traffic noise source is relatively constant. Due to the diffracting edges on the balcony and the geometric differences for all balcony measurement positions it is expected that the fluctuations within the balcony measurements over time will be higher than at the reference position. It can be seen for the average SIL_{meas} within the balcony a periodic increase and decrease over time, which is a result of the microphones being moved closer and away from the front edge of the balcony. The fluctuation range in SIL_{meas} within the balcony space is 8.4dB with an overall average SIL_{meas} of 59.5dB. Thus, overall, the average difference between SIL_{meas} within the balcony minus the reference position is -9.9dB.

Investigating the spatial variance across the four horizontal measurement planes reveals the attenuations provided by the parapet and ceiling shield. These attenuations can be observed in Figure 6. At z_b=0.6m (Figure 6(a); z_b is the height above the balcony floor) SIL_{meas} is relatively constant, being between -10dB to -12dB below the reference SIL_{meas} as the plane is all within the diffraction shadow zone of the parapet and it is within this plane that diffusion ambience, SIL_{Amb}, is dominant. When z_b=1.2m (Figure 6(b)) which is similar to the height of the parapet, the range in SIL_{meas} is greatest when closer to the parapet and in this region diffraction attenuation becomes significantly less. At a height of 1.8m above the balcony floor (Figure 6(c)), neither the parapet or ceiling shield are providing diffraction attenuation near to the road, however with increasing distance from the road (towards the rear of the balcony) the difference in SIL_{meas} increases. The range in the difference of SIL_{meas} when z_b=1.8m is from -3dB to -12dB (-9dB range) which demonstrates the significance of location within the balcony space. The highest horizontal measurement plane (z_b=2.8m) (Figure 6(d)) is partially within the attenuation zone of the ceiling shield and this attenuation can be seen as an area of approximately -5dB reduction behind the ceiling shield. In this plane, difference in SIL_{meas} ranges from -5dB to -13dB, which demonstrates the effectiveness of ceiling shields in reducing specular reflection intensity off the ceiling plane.

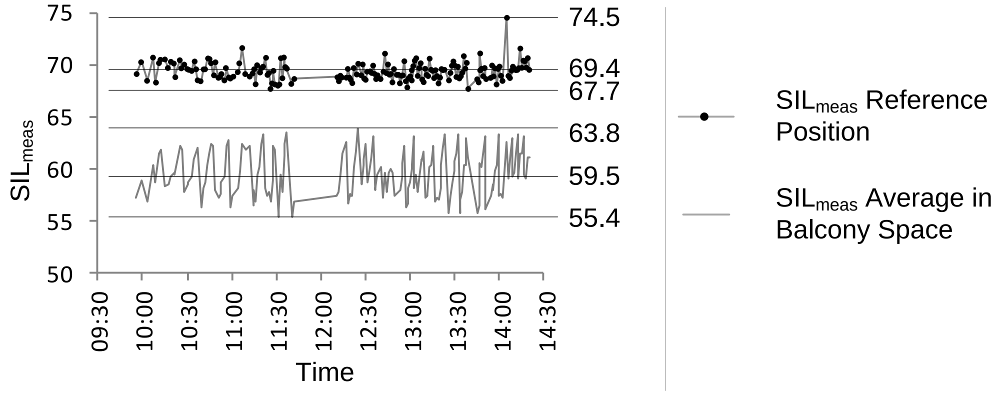

Figure 5: SIL_{meas} at the reference position and the average SIL_{meas} across all receivers within the balcony space.

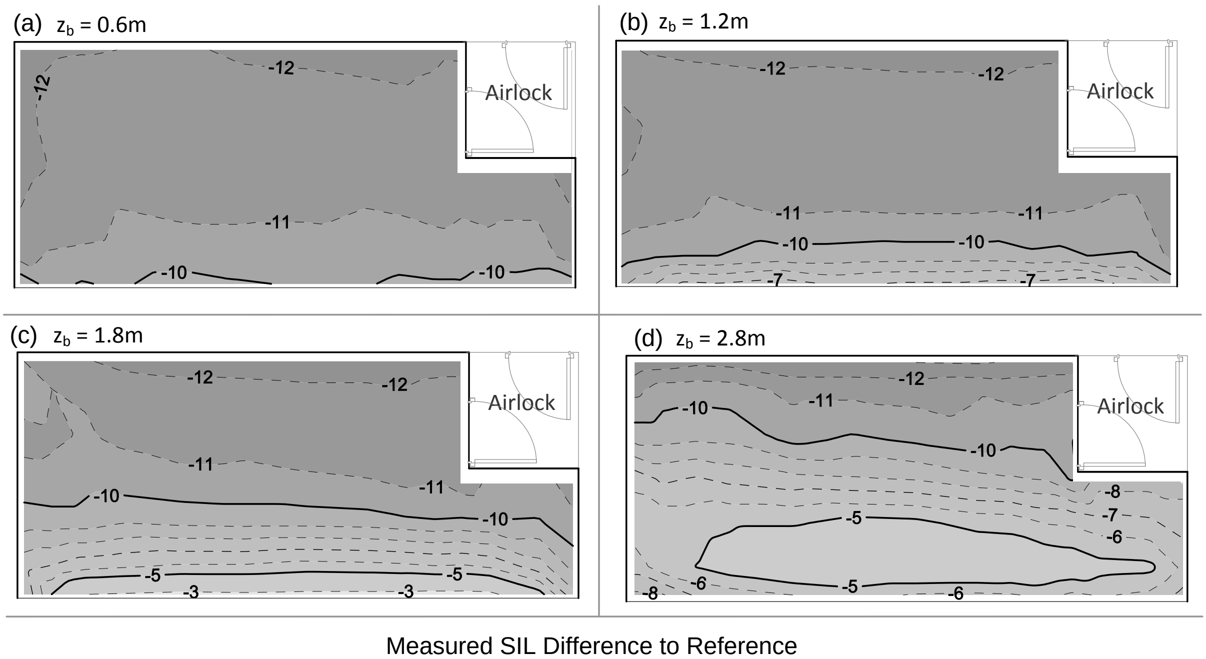

Figure 6: ΔSIL_{meas} contours over horizontal planes (a) z_b=0.6m, (b) z_b=1.2m, (c) z_b=1.8m, and (d) z_b=2.8m.

During the calculation of SIL_{pred}, the calculation of SIL_{Amb} is determined to be equal to 53.7dB. SIL_{Amb} is compared to the overall arithmetic average of the measured minimums, L_{min}, which is 56.4dB, and is considered to be an adequate correlation. SIL_{pred} is compared to SIL_{meas} in Figure 7 by comparing the spatial variation in a vertical plane along the centre of the balcony space (x_b=0). The first comparison is the difference with the measured and predicted reference position SIL shown in Figure 7(a) and Figure 7(b) respectively. Both measured and predicted SIL differences demonstrate similarities, however it is observed that the theoretical model overestimates the intensity of ceiling reflection which could be due to (i) geometric sensitivity in the model in using conglomerated vehicle point sources, (ii) possibly underestimating the absorption capacity of the ceiling, or (iii) overestimating the intensity of higher specular reflection orders (orders greater than two). The predicted SIL difference in the illuminated zone of the balcony space is less than the same zone from the measurements, particularly near the illuminated part of the ceiling which indicates that the third reason listed above is the cause of the overestimation in predicted SIL in the shadow zone. There is strong similarity in the overall magnitudes of the reductions provided by the balcony compared to the reference position, with the range of measured and predicted SIL differences being between -1dB to -12dB. Directly comparing SIL_{meas} (Figure 7(c)) and SIL_{pred} (Figure 7(d)) highlights the same differences observed in Figure 7(a) and (b). However, it is observed that there is almost an exact correlation between SIL_{meas} and SIL_{pred} in the illuminated zone which indicates that the derived average L_w for all the theoretical point sources is very close to actual conditions. The spatial variance behind the parapet and over the rear balcony façade is relatively constant for SIL_{meas} compared to SIL_{pred}. In this zone, SIL_{pred} is approximately 3dB lower which suggests the theoretical prediction underestimates the diffusion energy, SIL_{Amb}. Another possible reason for the difference is that the parapet has 10mm gaps between adjacent panels and approximately 30mm overlapping gap between the parapet and the balcony floor which may reduce the attenuation benefits of the parapet. Although transmission through the parapet panels is not included in the predictions, it is not considered that intensity from such paths will significantly add to SIL_{meas}. Although SIL_{pred} appears to underestimate diffuse energy, the difference of 3dB is considered an acceptable result when considering the needs to develop a fast calculation method.

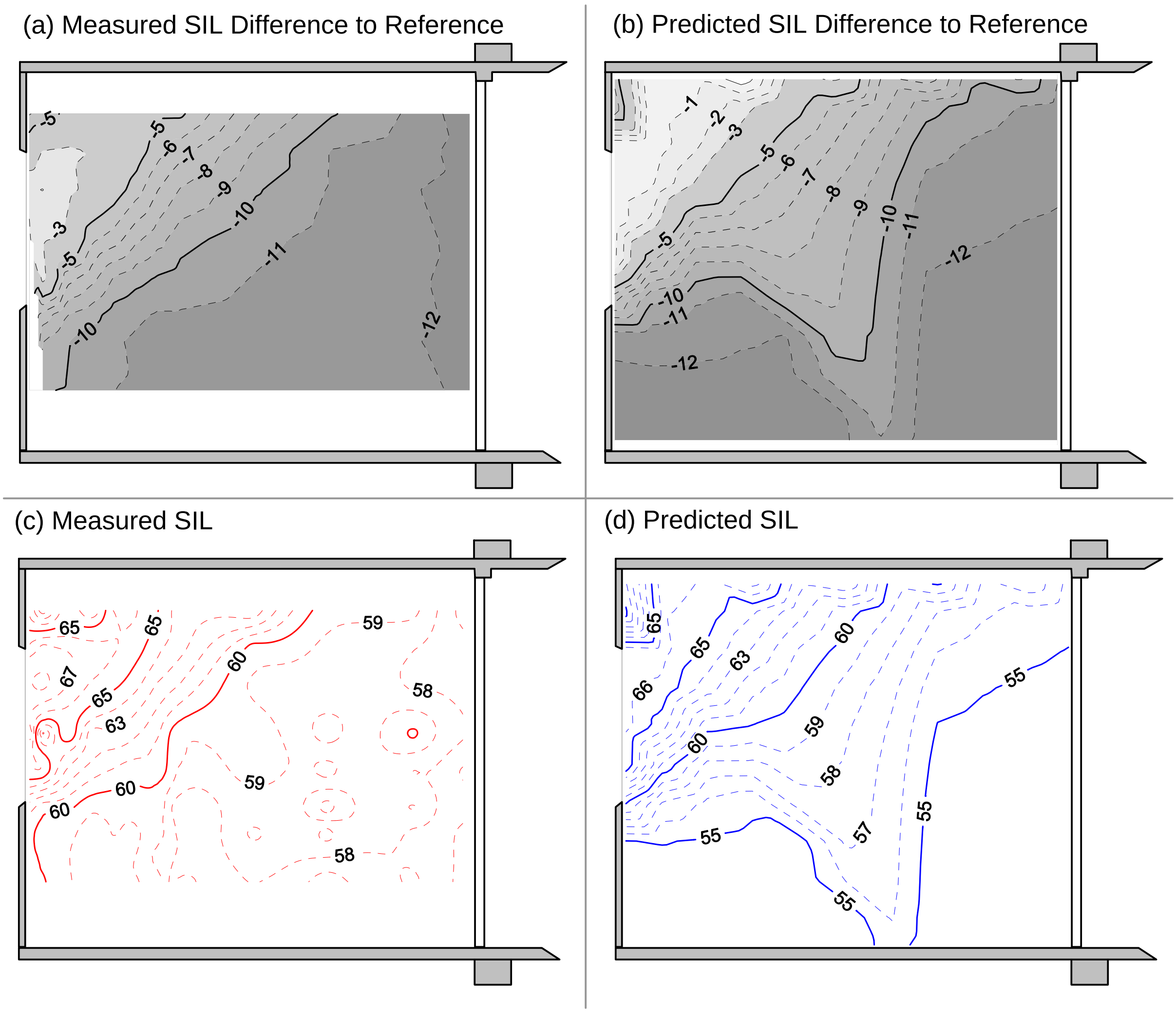

Figure 7: Measured and calculated SIL contours in central vertical plane (a) ΔSIL_{meas}, (b) ΔSIL_{pred}, (c) SIL_{meas}, and (d) SIL_{pred} (color online).

4. CONLUSIONS

The theoretical model and the prediction configuration achieve an adequate level of correlation with the measurements. The prediction configuration allows relatively fast calculations to be performed whilst maintaining an acceptable level of simulation of actual high density road traffic noise. Thus, the aims of this study are fulfilled by demonstrating that (i) the combined specular reflection and diffusion theoretical model is capable of simulating actual road traffic noise, and (ii) this can be achieved via a fast prediction configuration set up. It is noted that the study does not explicitly explore low traffic flow roads, or the extreme scenario of a single moving vehicle. However, as SIL_{pred} is derived from predictions of singular vehicles passing the balcony receiver, it is reasonable to expect that the theoretical model can be set up for a low traffic flow prediction configuration to satisfactorily predict low traffic flow situations if needed. Considering it is high traffic flow scenarios that are likely to cause higher incidence of health effects(22), the ability for an acoustic professional, architect or town planner to quickly asses high traffic flow situations is more important than low traffic flow scenarios in terms of improving the quality of life for communities.

The SIL indicator can be used as a direct comparison between different balcony designs and their effects on mid-frequency L_p. Although in this study some minor differences are apparent between SIL_{meas} and SIL_{pred}, these differences do not prevent the development of design guides based on a comparative type analysis. Practical design guides would provide the building design and town planning professionals an efficient and broad scale application of optimized balcony acoustic treatments. Wider application of balcony acoustic treatments will assist the reduction of road traffic noise induced annoyance across communities. Future work aims to use this method to assess a larger number of scenarios for the development of design information to be used by building design and transport noise professionals.

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