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A reduced-scale railway noise barrier's insertion loss and absorption coefficients: comparison of field measurements and predictions

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Abstract

In situ testing determined the insertion loss (*IL*) and absorption coefficients of a candidate absorptive noise barrier (soundwall) to abate railway noise for residents of Anaheim, CA. A 4000 m barrier is proposed south of the tracks, but residential areas to the north have expressed concerns that barrier reflections will increase their noise exposure. To address these concerns, a 3.66 m high by 14.6 m long demonstration barrier was built in the parking lot of Edison Field, Anaheim, as part of a public open house, thereby allowing for acoustical measurements.

Insertion loss (*IL*) was measured in third-octave bands assuming 1/2-scale construction. The *IL* for three, scaled railway noise sub-sources (rail/wheel interface, locomotive, and train horn) was measured at six, scaled distances. The highest total, A-weighted *IL*, after corrections for finite-barrier and point-source speaker effects was 22 dB(A) for rail/wheel noise, 18 dB(A) for locomotive noise, and 20 dB(A) for train horn noise. These results can be compared favourably to *IL* predictions made using algorithms from the US Federal Rail Administration (FRA) noise assessment guidelines. For the actual barrier installation, shielded residential receivers located south of the project are expected to see their future noise exposures reduced from an unmitigated 78 CNEL to 65 CNEL.

Absorption coefficients were measured using time delay spectrometry. At lower frequencies, measured absorption coefficients were notably less than the reverberation room results advertised in the manufacturer's literature, but generally conformed with impedance tube results. At higher frequencies the correspondence between measured absorption coefficients and reverberation room results was much improved. For the actual barrier installation, unshielded residential receivers to the north are expected to experience noise exposure increases of less than 1 dB(A). This factor of increase is consistent with a finding of no impact when assessed using FRA guidelines for allowable increases of noise exposure.

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1. Introduction

In situ testing determined the insertion loss (*IL*) and absorption coefficients of a candidate absorptive noise barrier to abate railway noise in Anaheim, CA. A 4000 m barrier is proposed south of the tracks, but residential areas to the north have expressed concerns that barrier reflections will increase their noise exposure. To address these concerns, a 3.66 m high by 14.6 m long demonstration barrier was built in the parking lot of Edison Field, Anaheim as part of a public open house, thereby allowing for acoustical measurements.

Insertion loss (*IL*) was measured in third-octave bands assuming 1/2-scale construction. The *IL* for three, scaled railway noise sub-sources (rail/wheel interface, locomotive, and train horn) was measured at six, scaled distances. The highest total, A-weighted *IL*, after corrections for finite-barrier and point-source speaker effects was 22 dB(A) for rail/wheel noise, 18 dB(A) for locomotive noise, and 20 dB(A) for train horn noise. These results can be compared favourably to *IL* predictions made using algorithms from the US Federal Rail Administration (FRA) noise impact assessment guidelines.

For the actual barrier installation, shielded residential receivers located south of the soundwall project are expected to see their future noise exposures reduced from an unmitigated 78 CNEL to 65 CNEL, as reported in a complementary environmental and engineering study [1]. Prior to this work, a preliminary study of the same rail corridor recommended use of an absorptive soundwall material to address public concern [2]. Fig. 1 shows photographs of the project area that under evaluation.

Absorption coefficients were measured using time delay spectrometry. At lower frequencies measured absorption coefficients were notably less than the reverberation room results advertised in the manufacturer's literature, but generally conformed with impedance tube results. At higher frequencies the correspondence between measured absorption coefficients and reverberation room results was much improved. For the actual barrier installation, unshielded residential receivers to the north are expected to experience noise exposure increases of less than 1 dB(A). This factor of increase is consistent with a finding of no impact when assessed using FRA guidelines for allowable increases of noise exposure.

2. Description of candidate wall system

The candidate wall system—supplied by the Industrial Acoustics Company (IAC)—is a post and panel system comprised of I-beam posts with barrier panels that are 0.61 m × 4.88 m (Noishield FSt/S). Each panel has a 12.7 cm thick fibreglass core, with a mass per unit area of about 13.5 $\mathrm{kg\,m^{-2}}$. When sandwiched between 14-gauge metal panels, one panel face is 22.7% perforated using 6.3 mm holes that are spaced at a uniform centre-to-centre distance of 12.7 mm. When galvanized steel is used, with a mass per unit area of 16 $\mathrm{kg\,m^{-2}}$ and 2 mm nominal thickness, the total mass per unit area with one perforated face is 42 $\mathrm{kg\,m^{-2}}$. When aluminum is used, with a mass per unit area of 4.84 $\mathrm{kg\,m^{-2}}$ and 1.6 mm nominal thickness, the total mass per unit area with one perforated face is about 22 $\mathrm{kg\,m^{-2}}$. The perforated metal panel conforms to International Perforators Association (IPA) pattern IPA No. 123 [3]. The perforations are

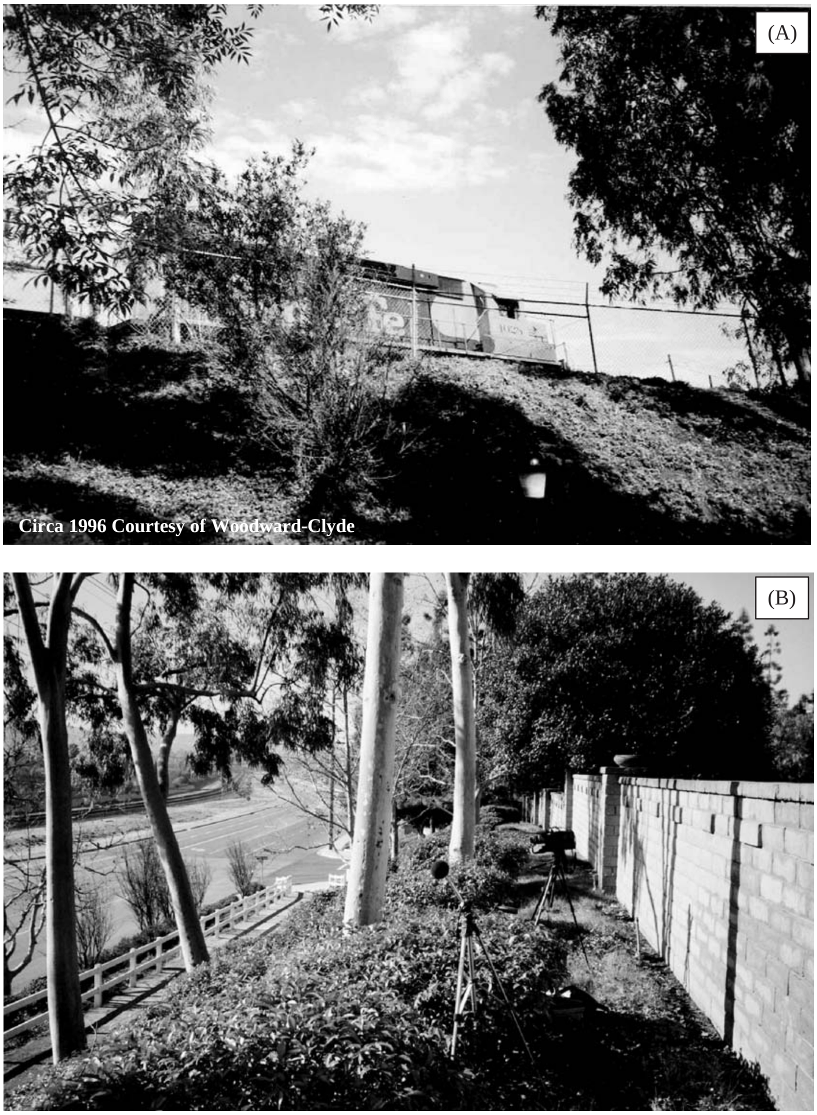

Fig. 1. Photographs of soundwall project area. (A) Looking north from yard. Soundwall would shield train in this view. (B) Looking west parallel to rail corridor (and road). Masonry property wall borders properties concerned about reflection from soundwall.

intended to facilitate the absorption of sound by the fibreglass core, and the parameters affecting the acoustical performance has been studied previously [4].

3. Spectra of railway noise sources

The total *IL* (energy average *IL* over a range of frequencies) is a function of a source's frequency content and the amount of energy absorbed by the absorptive soundwall material as a

Table 1
Relative third-octave A-weighted spectra of railway noise sources

f (Hz)	Locomotive		Rail cars	
	Third-octave	Octave	Third-octave	Octave
50	−32.8		−22.4	
63	−21.9	−17.9	−18.5	−15.2
80	−18.1		−12.3	
100	0.0		−5.4	
125	−5.0	0.0	−5.5	−5.4
160	−13.1		−7.3	
200	−14.4		−10.1	
250	−17.0	−10.8	−8.4	−8.0
315	−12.5		−7.6	
400	−7.2		−5.4	
500	−6.8	−3.8	−2.5	−2.3
630	−7.6		−1.6	
800	−3.9		−1.8	
1000	−2.8	−0.5	−0.8	−0.7
1250	−5.6		−1.3	
1600	−5.0		−0.1	
2000	−6.4	−3.1	0.0	0.0
2500	−9.2		−1.9	
3150	−11.3		−2.6	
4000	−10.5	−8.4	−4.5	−3.6
5000	−14.8		−6.4	

function of frequency. To evaluate the barrier performance within the context of railway noise sources, spectra were measured for locomotive and rail/wheel noise (see Table 1) by taking average values of field measurements conducted along track in the project area, at a distance of 15 m from the track centreline. Examining the octave-band levels, it can be seen that the locomotive noise level clearly peaks in the 125 Hz band, with the 1000 Hz band only 0.5 dB lower. For the railcar noise source, the energy is distributed over a wider range of frequencies, with the energy peaking in the 2000 Hz band. Relative to the level in the 2000 Hz band, the levels decrease by 0.7 dB in the 1000 Hz band and by 2.3 dB in the 500 Hz band.

4. Measurement of barrier insertion loss

A 3.66 m × 14.6 m test barrier was constructed (see Figs. 2 and 3). The *IL* testing assumed that this mock-up was a half-scale representation of the proposed soundwall, such that the corresponding full-scale dimensions are 7.31 m × 29.3 m. The test barrier was constructed in an asphalt parking area of Edison Field in Anaheim, and with no other vertical surfaces within a distance of 150 m.

A set of full-scale dimensions was assumed as recommended by the Federal Transit Administration (FTA) for freight trains and locomotives [5]. Locomotive noise sources were

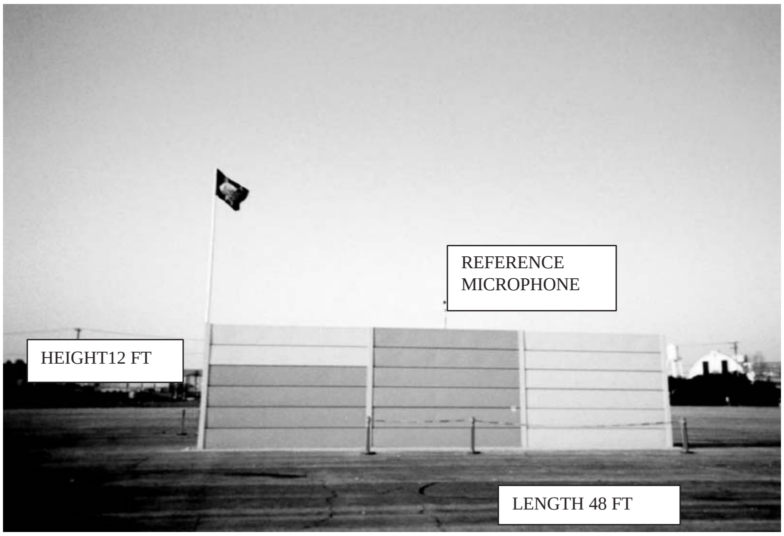

Fig. 2. Photographs of demonstration soundwall (parallax evident), Edison Field, Anaheim.

Fig. 3. Photograph of demonstration soundwall (parallax evident), Edison Field, Anaheim.

assumed to be 2.44 m above the ground and rail/wheel noise sources were assumed to be 0.61 m above the ground. The receiver was situated at a height of 1.83 m for all tests. Representative source distances from the barrier were assumed: for the track centreline (12.2 m), the nearest receiver (6.1 m), a typical first-row backyard (12.2 m), and several subsequent rows of homes (15.2 m, 30.5 m, and 48.8 m).

Since the test barrier was constructed at half-scale, it was necessary to apply a scaling factor ($n = 2$) to both the test frequency and test geometry [6]. The scaling relationships are determined knowing that the dimension (d) of a test object relative to the wavelength (λ) of sound must remain constant. If the dimension (d) is reduced by a scale factor (n), the wavelength must be reduced by the same factor. Since the full-scale object and model-scale object are being tested in the same medium—air—the speed of sound (c) is identical in the two test conditions. Knowing the relationship, $c = f\lambda$, it can be seen that reductions in the wavelength by a scale factor (n) will only cancel if each frequency (f) is increased by the same scale factor. The frequencies of interest were therefore doubled and the test dimensions (distances and heights) were halved.

An amplifier, third-octave-band equalizer, and speaker system were employed to generate adequate levels of broadband noise (scaled up in frequency by $n = 2$). Measurements were conducted at half-scale with reference to the full-scale heights and distances. To evaluate the barrier *IL*, the tests were repeated for a with-barrier condition and without-barrier, open-ground condition. The speaker was placed at the appropriate, scaled height and oriented to bisect the angle formed by the paths from the speaker to the top of the barrier and from the speaker to the receiver. A reference microphone was placed at a location 1.52 m above the top of the soundwall for tests with the barrier, and at an equivalent location for open-ground tests without the barrier. Noise levels measured at this microphone were used to normalize the test results to control for test-to-test variations in level.

Data were reviewed in every third-octave band to ensure that the levels measured both with and without the test barrier were at least 10 dB above the maximum observed background noise level. A correction was applied to the measured data to account for the finite length of the test barrier in comparison to a longer barrier. Also considered and corrected for was the difference in *IL* expected between a train travelling along a line parallel to the proposed barrier and the point-source speaker. Since the finite length allows for some sound to diffract around the ends of the barrier, some consideration was given to the test geometry in order to minimize this effect. The relative amount of energy diffracted over the top of the barrier, in relation to the sound diffracted around the barrier ends, will determine the extent to which the sound energy at the receiver is increased. Based on simple calculations of the diffraction around the barrier ends, minor adjustments (of 0.6 dB or less) were applied to the measurements, effectively increasing the *IL*, so that the results were representative of a long barrier. When the source-receiver path is perpendicular to the barrier, the Fresnel number and hence the *IL*, are maximized. When a noise source travels along a path that is parallel to a noise barrier—a line source—the Fresnel number with respect to a fixed receiver position varies in a predictable way, and the effective *IL* is reduced. Since the speaker acts as a point source, and a train acts as a line source, a correction of up to 4.9 dB was applied to the measurements to reduce the measured *IL* to that expected for a line source.

Fig. 4 shows the *IL* measurement results for total, A-weighted sound levels. The rail/wheel noise is attenuated more greatly (on average over the distances shown by 4.7 dB) than locomotive noise

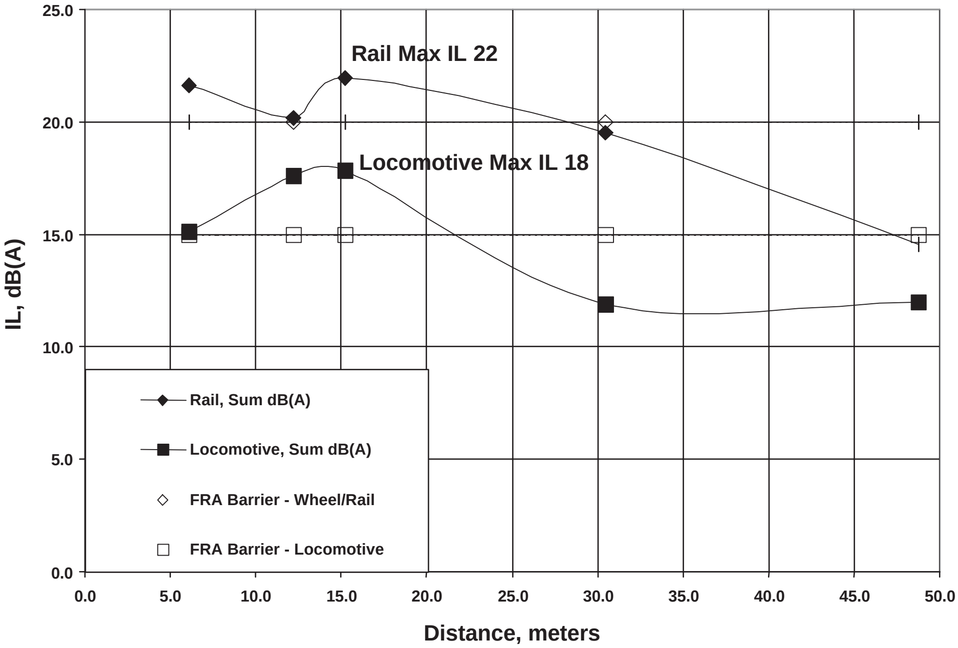

Fig. 4. Measured insertion loss versus distance (adjusted to a line-source/long barrier equivalent).

for two reasons. First, the noise source is lower in height with respect to the top of the wall, thereby increasing δ and the Fresnel number. Second, the dominant sound energy found at higher frequencies is attenuated to a progressively greater extent by the barrier, as indicated by the increase of Fresnel number with increasing frequency. Fig. 4 shows that the *IL* decreases with distance. This is because δ decreases with distance, resulting in a decreasing Fresnel number with distance. The most useful information derived by these measurements relates to the highest *IL* that was observed for each type of rail noise source. For rail/wheel noise this was 22 dB(A), and for locomotives this was 18 dB(A).

Fig. 4 also shows predicted *IL* as determined using FRA prediction' procedures [7]. For this geometry and absorptive barrier type, the procedures recommend use of a constant *IL* across all distances shown. The constant is 20 dB(A) for wheel/rail noise, and 15 dB(A) for locomotive noise. At receiver distances within 30 m of the barrier, the differences between measured and procedurally determined *IL* are within less than 1 dB(A) of each other. At distances of 20–30 m, the FRA-recommended constant *IL* values appear to be too high for this configuration and ground surface relative to the reported measurements.

5. Measurement of barrier absorption coefficients

A test system (TEF 20) was employed that allows for the complete separation of the energy in the direct, incoming sound from the reflected, outgoing sound [8]. The system determined the impulse response with components corresponding to the direct and reflected sound energy. The impulse response is the most-generalized indicator of the response of a linear system to an arbitrary input signal. The impulse response was examined and the arrival time of the reflected sound was identified. Thereafter, a frequency response test was conducted on both the “reflective” and “absorptive” surfaces of the test barrier to quantify the identified sound energy reflected from these surfaces.

Utilizing this Time Delay Spectrometry (TDS) technique, narrow intervals of time and frequency are examined. The test signal was a “chirp” that sweeps over a known, pre-defined range of frequencies (from low to high). By setting a time delay corresponding to the travel time of the reflection, the device has an exceptional ability to isolate the sound it generates from other ambient noise sources that would otherwise influence the test. The lower and upper ranges of frequency selected corresponded to the limiting frequencies of each third-octave band of interest. Tests were conducted for each test barrier surface by evaluating each of 19 third-octave frequency bands. The data in each third-octave band were smoothed to generate a representative third-octave band level.

Two speaker-microphone configurations were employed to study the difference between the reflections from the reflective and the absorptive sides of the barrier. The selection of source–receiver geometry hinged upon the separation time (in milliseconds) of the sound reflected along four paths (direct, ground reflected, barrier reflected, and ground-barrier reflected). The primary objective was to isolate in time the direct sound path from the paths reflected from the ground and the barrier. The secondary objective was to employ a time window with a duration that provided a bandwidth that was less than the bandwidth of the lowest third-octave frequency band of interest (63 Hz). To satisfy these two objectives a time delay and time window were used that measured energy from both the barrier-reflected path and ground-barrier-reflected path. The barrier-reflected path is however, the dominant one. Importantly, the only substantial change for tests on opposing surfaces is the surface material.

As shown in Fig. 5, the speaker and microphone were placed at a height of 1.52 m. Set-up 1 had the speaker at a distance of 6.1 m from the barrier face, with the microphone placed directly on the soundwall surface. Set-up 2 had the same speaker placement, with a microphone located adjacent to the speaker at a 6.1 m distance from the soundwall.

The tests for each set-up were repeated on each face of the barrier and absorption coefficients for the barrier material were determined by comparing the energy reflected from the “absorptive” side to the energy reflected from the “reflective” side (assumed to be 100% reflective). Each speaker–microphone configuration required a different equation to evaluate the absorption coefficients, with parameters including the absorption coefficient (α), an assumed reflection

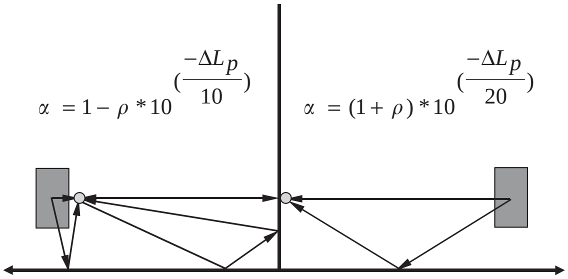

Fig. 5. Geometry for absorption coefficient testing (Set-up 1 to right, Set-up 2 to left).

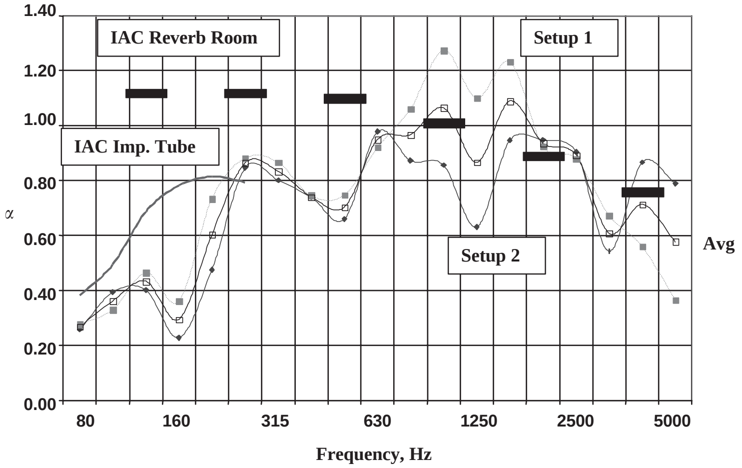

Fig. 6. Absorption coefficients of soundwall system.

coefficient for the "reflective" face ($\rho = 1$) at all frequencies, and the change in sound-pressure level between the two test surfaces (ΔL_p). The equation for Set-up 1 is $\alpha = (1+\rho)*10^{(-\Delta L_p/20)}$ and for Set-up 2 is $\alpha = 1 - \left(\rho * 10^{(-\Delta L_p/10)}\right)$.

Fig. 6 presents the results of the analysis, merged with the measurement data supplied by the manufacturers of the soundwall panel system tested. Presented are the third-octave-band data supplied by the manufactures that show the material absorbing over 100% of the incident energy in the 125, 250, 500, and 1000 Hz third-octave bands when tested in a reverberation room [9,10]. Shown also are impedance tube data supplied by IAC, showing the absorption coefficients of the material at a series of discrete frequencies, ranging from 60 to 250 Hz [11,12].

Test results are presented for 19 third-octave bands, from 80 to 5000 Hz. The number of tests of each surface in each third-octave band ranged from three to eleven, with standard deviations ranging from 0.1 to 0.9 dB. The results for the two test set-ups used show a consistent variation in terms of shape, with good agreement in the third-octave bands between 80 to 630 Hz and between 2000 and 5000 Hz. A greater variation is seen in the 800, 1000, 1250, and 1600 Hz bands, where the results for Set-up 1 display some anomalous behaviour, with absorption coefficients greater than 1. In this case the microphone was placed on the barrier surface. For Set-up 2, the highest absorption coefficient ($\alpha = 0.98$) is found in the 630 Hz third-octave band.

For a layer of fibreglass, assumed to be semi-infinite in thickness, the absorption is expected to asymptotically approach 100% as frequency increases [13]. When the layer is of finite thickness, predictive modelling of the behaviour and measurement, indicate that an oscillation is introduced into the curve that can result in decreases of absorption with frequency, but the overriding trend over the audible range is still towards 100% absorption as frequency increases. The creation of a bounded cavity by the addition of two surfaces, one solid and the other perforated, has two acoustical effects [4].

Firstly, a resonant frequency is introduced due to the reactive interaction of incident sound with sound oscillating in the cavity between the two metal faces of the material. In the case of this particular wall system, the tuned resonant frequency of air in the cavity is approximately 900 Hz (see nomograph in Ref. [4]). Referring to Fig. 6, the discrepancies between Set-up 1 (at the surface) and Set-up 2 tests from the 800 to 1600 Hz bands are attributed to this band-limited resonance effect.

Secondly, the access factor (*AF*) as a function of frequency for a given transparency index (*TI*) is described and presented graphically in Ref. [4]. The *TI* for the wall system under study is calculated to be 59. As frequencies increase for a given *TI*, the proportion of absorption "visible" to the incident sound is progressively reduced, as quantified by the *AF*. The *AF* is estimated using third-octave centre frequencies to be as follows: up to 630 Hz approximately 1, 800 Hz 0.98, 1000 Hz 0.97, 1250 Hz 0.95, 1600 Hz 0.92, 2000 Hz 0.88, 2500 Hz 0.83, 3150 Hz 0.77, 4000 Hz 0.69, and 5000 Hz 0.60. The effective absorption can be estimated by multiplying the *AF* by the absorption coefficient at a given frequency; thus, the *AF* is the limiting factor as frequency increases.

The average absorption coefficients found using the two testing set-ups display close agreement with the reverberation room in the higher frequency ranges. When compared to the lower frequency data supplied by the manufacturer from impedance tube tests, the correspondence is much better than the coefficients determined in a reverberation room. Examining Table 1 and Fig. 6, the differences in absorption coefficients estimated using the various techniques are of interest for locomotive noise, whose third-octave noise emissions were highest in the 100 Hz band. For rail/wheel noise at 2000 Hz, it is the level of agreement for estimating absorption coefficients amongst techniques that is of interest. In any event, the primary descriptor of impact for the project of concern, noise exposure in terms of CNEL, is controlled by the rail/wheel noise from lengthy freight trains.

6. Conclusion

A comparison of the measured *IL* of a demonstration soundwall to that derived using FRA procedures supports a complementary environmental and engineering analysis of the expected noise-reducing performance [1]. Noise exposure for shielded residences behind the 4000 m soundwall are expected to change from 78 CNEL to a more acceptable 65 CNEL. A novel technique for the measurement of reflections from soundwalls has been described. More realistic absorption coefficients based on measurements have been reported at low frequencies below 1000 Hz, while the same test technique also obtains realistic absorption coefficient data at higher frequencies on the order of 5000 Hz. The expected changes in noise exposure were estimated, with barrier-reflected energy added, for sensitive receivers on the source side of the soundwall. The change in noise exposure was estimated using the relative, third-octave train spectra in Table 1, and the smallest absorption coefficient within each third-octave band measured (see Fig. 6). For an assumed direct path railway-receiver distance of 80 m, and a reflected path distance of about 125 m, the estimated change in noise exposure due to the reflected energy is less than 1 dB(A).

References

[1] Acentech, BNSF rail corridor soundwall noise study report, Report No. 255, Anaheim, CA, 2001.

[2] Woodward-Clyde, Final Report Orangethorpe/Esperanza railroad corridor noise and vibration study, Anaheim, CA, 1996.

[3] International Perforators Association, *Designers, Specifiers and Buyers Handbook for Perforated Metals*, International Perforators Association, 1993.

[4] T.J. Schulz, *Acoustical Uses for Perforated Metals: Principles and Application*, International Perforators Association, 1986.

[5] Federal Transit Administration, Transit noise and vibration assessment, DOT-T-94-16, Washington, DC, 1995.

[6] T.A. Busch, Scale-Model Investigation of Highway Traffic Noise Barriers. M.A.Sc. Thesis, University of British Columbia, Vancouver, BC, 1997.

[7] Federal Rail Administration, High speed ground transportation noise and vibration impact assessment, DTFR53-94-A-00056, Washington, DC, 1998.

[8] Gold Line, TEF System 20 Sound Lab TDS Software User's Manual, Connecticut, 1998.

[9] Industrial Acoustics Company, Noishield sound barriers, Transportation Bulletin 8.0001.1.

[10] ASTM C423-90a. Sound absorption and sound absorption coefficients by the reverberation room method, 1990.

[11] Industrial Acoustics Company, Communication from Gus Sauter of C.E. Pickup Co. regarding the results of impedance-tube testing of the IAC panels, 2000.

[12] ASTM C384-90a, Impedance and absorption of acoustical materials by the impedance tube method, 1990.

[13] M.E. Delany, E.N. Bazley, Acoustical properties of fibrous absorbent materials, *Applied Acoustics*, 1970.