INVESTIGATION OF ADDITIONAL INSERTION LOSS FROM T-PROFILE AND ABSORPTIVE NOISE BARRIERS

Darren Jurevicius[1] and Tom Evans[2]

[1]Resonate Acoustics, Level 1/23 Peel St, Adelaide SA 5000, Australia
Email: darren.jurevicius@resonateacoustics.com

[2]Resonate Acoustics, Level 4/10 Yarra St, South Yarra VIC 3141, Australia
Email: tom.evans@resonateacoustics.com

Abstract

This paper presents the findings into a study of the relative performance of custom-design noise walls of different heights, with and without T-profile noise wall tops of various dimensions. The study was undertaken at a test facility using noise walls of heights 2.4 m and 3.5 m, with T-profile widths of 600 and 1200 mm. The testing was undertaken using measurement positions of varying height behind the wall, with a loudspeaker used to generate an MLS-type signal. The impulse response was stored for post-processing and calculation of the spectral insertion losses was carried out for each test. Additionally, the influence of absorptive treatment on the T-profile was tested. These results were compared to the untreated T-profile, the standard noise wall and a standard noise wall with an absorptive capping but without a T-profile. The reduction achieved with the T-shaped profile is quantified in terms of both an additional spectral insertion loss relative to the base wall as well as the equivalent reduction in noise wall height that can be obtained while maintaining performance by using the modified top. The performance of the different noise wall configurations is also compared to the theoretical and tested performance of other modified noise wall types. Finally, the practical application of the tested insertion loss results to predicted noise levels is discussed.

1. Introduction

The use of barriers to reduce noise levels in residential areas is commonplace throughout Australia, particularly for road infrastructure projects. After road design measures have been exhausted, noise barriers are typically the preferred method of providing noise mitigation where they are cost-effective to implement. In many cases, however, the height of the barrier required to achieve the desired noise reduction may pose urban design issues such as overshadowing, particularly where that barrier is to be located on or near a residential boundary. It has been known for some time that modified barrier tops can be used to increase the effective noise reduction achieved for a barrier of a given height. Barriers of this type may therefore be of interest where the barrier height is constrained for other reasons.

This paper presents the findings of insertion loss tests conducted on barriers with and without T-profiles of various dimensions, and with and without absorptive barrier tops. The tests were carried out on barriers constructed from proprietary sandwich panels, manufactured by Nu-Tek Building Systems, and using a loudspeaker to generate an impulse signal for analysis using the Maximum Length Sequence (MLS) method. The insertion loss performances of the various barrier types are compared, as well as the influence of receiver position relative to the barrier. The inclusion of barrier tops in noise predictions and assessments for road infrastructure projects is also discussed.

2. Previous Studies into Modified Noise Wall Tops

The improved performance of the modified T-shaped noise wall top, as well as other modified barrier tops, has been assessed in a number of previous studies, including theoretical and empirical studies. Recently, commercial modified noise wall tops have also become available.

2.1 Theoretical studies

A recent paper [1] compared the predicted performance of T-shaped, Y-shaped, arrow, inclined cap and inclined barriers using a finite element model, predicting insertion loss of a 3 m high barrier at a receiver at various locations behind the barrier. The different barrier types resulted in broadly similar predicted insertions losses, consistent with those predicted by studies implementing a boundary element method [2, 3]. Of interest, a sharp rise in predicted insertion loss occurred for a receiver located at 1.5 m above ground relative to one on the ground plane, attributed to constructive interference between direct and reflected waves.

Figure 1, from [1], compares the insertion loss predicted for standard and T-shaped 3 m high barriers for a source on the ground 5 m from the barrier and a receiver 1.5 m above ground and 20 m from the barrier. It indicates some increases in insertion loss at frequencies below 1 kHz, although decreases occur at certain frequencies as well, but that there is a marked improvement in insertion loss in the higher frequency range.

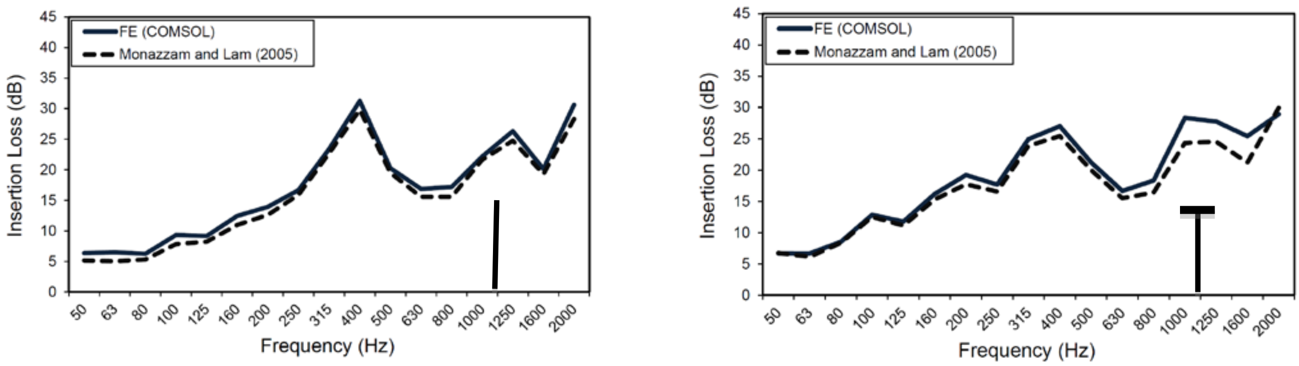

Figure 1. Predicted insertion loss of standard and T-shaped 3 m high barriers for source located on ground and receiver located 1.5 m above ground and 20 m from barrier from Fard et al. [1]

A study by Fan et al. [4] investigated the performance of different tops, calculating via the boundary element method that a T-shaped barrier provided an improvement in insertion loss over a straight barrier regardless of the condition of the top. An ideal acoustically soft surface, on which the surface pressure is zero, on the top of the T provided the highest predicted reduction. It was proposed that an active barrier top could be used to best mimic the ideal surface conditions, particularly at lower frequencies. The performance of the active barrier top was validated in an experiment in an anechoic chamber.

2.2 Empirical studies

A 2002 UK study [5] investigated a test site where an MLS signal was used to determine the relative insertion loss of multiple edge, T-shaped (reflective and absorptive) and cylindrical barrier top designs. A single number insertion loss based on a standard traffic noise spectrum was calculated for each barrier based on an average of different speaker and microphone positions. It was found that the multiple edge and absorptive T-shaped barriers performed best, with an average insertion loss of 4 to 5 dB, with the reflective T-shape and cylindrical top barriers providing a lower average insertion loss. In the case of the cylindrical shape, an average insertion loss of -0.6 dB was measured.

A range of empirical studies into the performance of barriers with modified noise wall tops have been undertaken by road agencies and other entities. A 2003 study performed for the Indiana Joint Transportation Research Program [6] focused on absorptive treatment to the top of barriers, developing a boundary element model that agreed well with experimental laboratory results at specific points. A cylindrical absorptive top was found to perform best and trialled in the field, resulting in an insertion loss of between 2 and 5 dB at frequencies from 2 to 5 kHz.

A summary report prepared for the Arizona Department of Transportation in 2006 [7] reviewed the available literature on tests of modified barrier tops and recommended that a T-shaped barrier with absorptive material on the top and a vertical barrier with absorptive material applied to the face of the barrier be considered for implementation in Arizona. The report summarised that those two designs could result in a reduction in noise levels of up to 3 dB and a reduction in overall barrier height by as much as five feet.

The empirical studies do vary in the barrier top types they identify as providing the highest insertion loss, suggesting that there may be a variation in the performance of different constructions of the same barrier top types. Regardless, they do indicate that an insertion loss up to 5 dB is possible with modified barrier tops, particularly at higher frequencies.

2.3 Commercially available products

Nippon Steel & Sumikin Metal Products manufacture and provide data on the "Noise Reducer III" [8], a mushroom-shaped element that can be installed on noise barrier tops. A cylindrical barrier top shape was also previously manufactured. The mushroom top is 660 mm high but is hollow and sits over the top of the noise wall such that the increase in height is relatively minor. At a height of 1.2 m above ground behind a 3 m high noise wall, the reported mean insertion loss of the mushroom-shaped top is 3.2 dB at a distance of 5 m behind the wall, dropping to 1.4 dB at a distance of 10 m.

3. Test and Analysis Procedure

3.1 Test site

The test site selected for the barrier tests was an outdoor area at the Nu-Tek Building Systems manufacturing facility. The test barrier was installed in a clear area, with an example installation shown in Figure 2. The ground around the barrier was flat, with areas of grass, dirt and concrete surrounding the wall. The nearest vertical reflecting surface was the manufacturing building approximately 15 m behind the barrier.

Figure 2. T-profile barrier installed at test site

3.2 Barrier material and configurations

The vertical component of the tested barrier was constructed from nominally 100 mm thick sandwich panels, composed of a 34 kg/m^3 polyisocyanurate (PIR) foam core with one layer of 12 mm thick

Magnesium Oxide board on one side and one layer of 0.55 mm BMT steel on the other. The sandwich panel provides an overall transmission loss of approximately R_W (C,C_{tr}) 30 (-4,-5) and has a characteristic dip in the transmission loss between 500 and 700 Hz that needs to be considered in the analysis of the performance of the different barrier configurations. Based on this basic vertical barrier construction, the tested barrier top configurations are summarised in Table 1. All tested barriers were constructed to a length of 15 m.

Table 1. Tested barrier configurations

ID	**Barrier type**	**Construction**
–	No barrier	No barrier
A	Standard vertical	Standard 2.4 m high and 3.5 m high vertical barriers tested. Conventional steel cap on top of barrier.
B	Vertical with absorptive top, 100 mm wide x 75 mm high	75 mm high cap perforated steel top/sides filled with 168 kg/m^3 rockwool insulation. Conventional steel cap below absorptive top. 2.4 m high and 3.5 m high vertical barriers tested.
C	T-shaped top, 600 mm wide x 50 mm thick, perforated top and sides	50 mm thick panel with perforated steel top/sides, solid steel underside, filled with 168 kg/m^3 rockwool insulation. Conventional steel cap on vertical barrier component below. 2.4 m high and 3.5 m high vertical barriers tested.
D	T-shaped top, 600 mm wide x 50 mm thick	50 mm thick panel with solid steel top, sides and bottom, filled with 168 kg/m^3 rockwool insulation. Conventional steel cap below. 2.4 m high and 3.5 m high vertical barriers tested.
E	T-shaped, 600 mm wide x 1.6 mm thick	1.6 mm thick solid steel sheet for ‘T’. Conventional steel cap on vertical barrier component below. 2.4 m high and 3.5 m high vertical barriers tested.
F	T-shaped, 1200 mm wide x 50 mm thick	Solid 50mm thick proprietary Nu-Tek Panel (sandwich construction) 2.4 m high and 3.5 m high vertical barriers tested.

3.3 Measurement and analysis procedure

Measurements were carried out using the following system:

- Desktop PC running Windows 7 and SoundEasy software
- EasyLab as incorporated into SoundEasy v18 software [8]. EasyLab is a software package dedicated to frequency and time domain measurements incorporating a digital MLS measurement system.
- Beringer EURORACK UB1002 (gain control)
- M-Audio Delta 44 professional sound card (analogue to digital conversion).
- Brüel & Kjær 2238 Class 1 sound level meter (microphone and analogue signal out).
- JBL EON 15G2 loudspeaker (sound source).

Sound pressure level measurements were carried out at three microphone heights for each wall system under test, namely 1.2, 1.8 and 2.5 metres. Care was taken to ensure that each measurement height was replicated consistently for each test. An MLS impulse signal was generated through the loudspeaker and the impulse response from each test was stored using EasyLab to allow post-processing flexibility.

Conversion of the impulse time response to one-third octave band spectra was carried out using a 5 ms rectangular time window, which allowed for low frequency resolution down to 200 Hz. The spectral data below 200 Hz was not considered valid as 5 ms was chosen to exclude the influences of the delayed sound diffraction coming from the sides of the barrier. This was a limit of the length of the barrier construction. The rectangular window was chosen to maximise the FFT resolution over the available time. The captured impulse response was typically averaged over three impulse 'shots' on site to provide an average response. However, in some cases, multiple single-shot impulse responses were stored and later averaged to avoid the effects of occasional wind gusts on the measurements. For all measurements, the FFT was compared for each test until the test engineer was satisfied that the measured results were consistent.

The loudspeaker was located 7 m from one side of the barrier and the microphone at 5.35 m from the opposite side of the barrier. The ground level at the base of the microphone was 170 mm higher than the ground level at the base of the wall and loudspeaker. This means that the microphone heights are 170 mm higher than the nominal heights noted. Figure 3 provides a diagram of the test set-up. Photos of the test set-up are also provided in Figure 4.

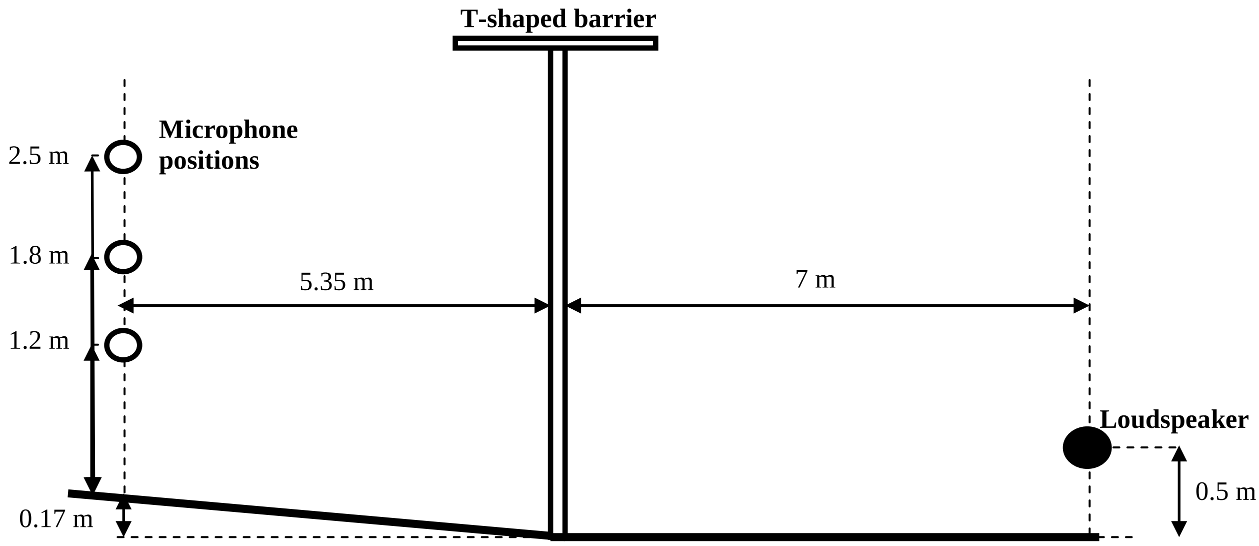

Figure 3. Test site diagram (not to scale)

Figure 4. 2.4 m high 600 mm wide T-profile barrier installed at test site with microphone at 2.5 m high above ground and loudspeaker on opposite side of barrier.

4. Measurement Results

The first test conducted was to compare the response without a barrier to the response with a standard vertical barrier with a solid top. The insertion loss determined through comparing these tests has been used as the base for all future tests. Figure 5 presents the measured insertion loss for the standard 2.4 m high and 3.5 m high barriers for the various microphone positions.

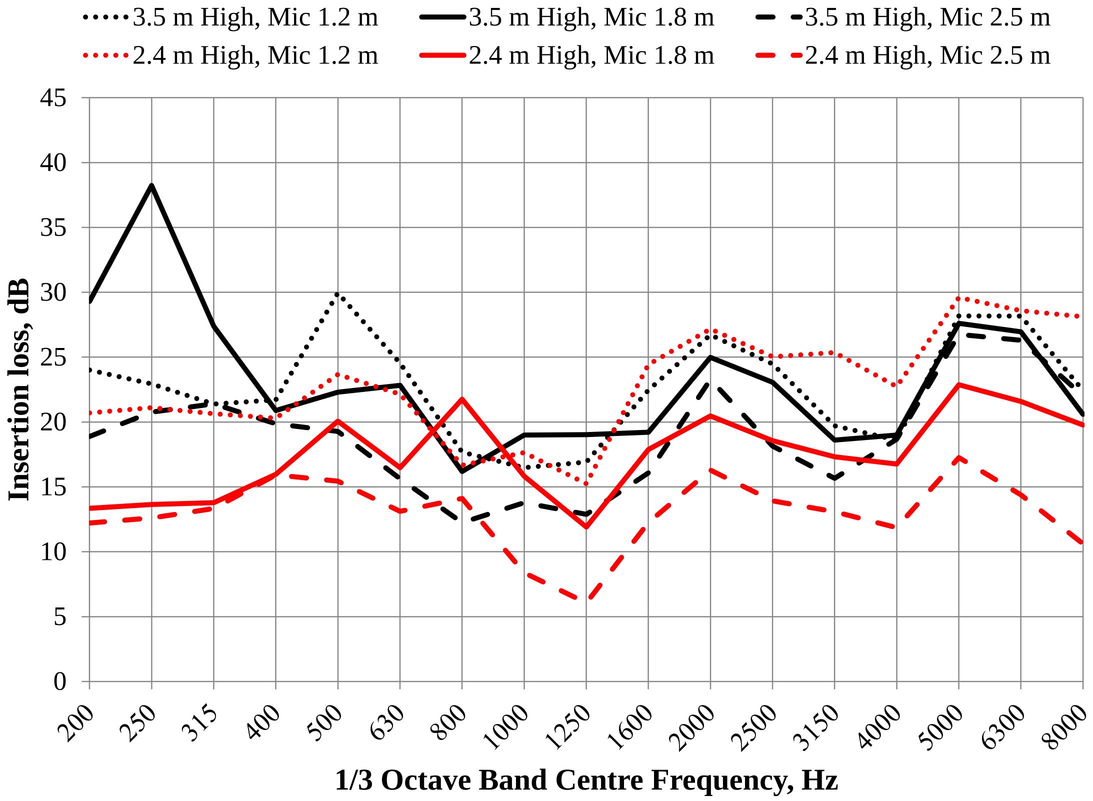

Figure 5. Base barrier insertion loss achieved with 2.4 m high and 3.5 m high vertical barrier

Table 2 summarises the additional IL achieved through the different barrier top modifications for the 2.4 m high barrier. An overall additional insertion loss has also been calculated based on the overall noise reduction that the top treatment would provide to a standard traffic noise spectrum. The standard traffic noise spectrum was first adjusted by the standard vertical barrier insertion loss to provide an accurate indication of the additional insertion loss that could be achieved for traffic noise. Note that the results are only shown for the microphone heights at 1.8 m and 2.5 m for brevity. Analysis of Table 2 provides the following insights:

- Adding a T-profile over a standard capping on a 2.4 m high wall, whether reflective or absorptive, provides an overall acoustic reduction.
- The 'T' shape improves the low to mid-frequency attenuation, while absorption improves the high-frequency attenuation.
- The 75mm absorptive cap provides markedly increased attenuation above 2 kHz, however while there is generally a small degree of attenuation at lower frequencies it lacks the attenuation performance of the T-profile within this range.
- Generally, with the receiver 'deeper' in the shadow zone (i.e. a lower microphone height), the absorptive cap or T-profile has less attenuation effect compared to a standard barrier. In some cases, the performance of the modified tops is worse than a standard cap, particularly in the frequency region 800 Hz to 1 kHz.

- The 600mm T-profile with an absorptive top provides significantly increased attenuation above 2 kHz i.e. up to 15 dB more than a standard cap above 3 kHz.
- The 600mm T-profile with an absorptive top was the best performing T-profile providing for an overall increased barrier insertion loss of 3.1 dB (over 200 Hz to 8 kHz considering a typical traffic noise spectrum) at a microphone height of 2.5 m above ground. However, when considering a typical receiver height of 1.8 m, the non-absorptive barrier top actually performed better than the absorptive top across the frequency range of interest for road traffic noise.
- Comparing the 1200 mm wide 'T' and the 600 mm wide 'T', there was no observable additional insertion loss resulting from placing a wider 'T' on the barrier top.

Table 2. Additional IL achieved through different barrier top treatments to 2.4 m high barrier

Freq, Hz	**Additional insertion loss for 2.4 m high barriers at given microphone height, dB**									
	B – 75 mm high absorptive cap		**C – 600 mm wide 50 mm thick 'T' with absorptive top**		**D – 600 mm wide 50 mm thick 'T', with reflective top**		**E – 600 mm wide 1.6 mm thick 'T', with reflective top**		**F – 1200 mm wide 50 mm thick 'T', with reflective top**	
	1.8 m	**2.5 m**	**1.8 m**	**2.5 m**	**1.8 m**	**2.5 m**	**1.8 m**	**2.5 m**	**1.8 m**	**2.5 m**
200	0.6	0.3	1.9	1.5	2.1	1.8	1.7	1.5	1.8	1.5
250	0.9	0.5	2.2	1.8	2.7	2.2	2.4	2.1	2.1	1.5
315	0.7	0.5	2.3	1.8	3	2.4	2.7	2.5	2	1.4
400	0.1	0.7	1.5	1.4	2.2	2.2	2.5	2.6	1.6	1.5
500	1.3	1.5	1.3	2	1.9	2.1	2.3	2.3	3.5	2.6
630	1.1	1.6	1.5	2.2	2.6	1.7	2.6	2.1	2	1.8
800	-2	0.7	-1.6	1.5	-0.1	1.4	1.4	0.2	-1.3	0.8
1000	-1.9	2.4	-0.6	4.6	-0.1	3	1.5	3.4	-0.2	4
1250	0.4	2	0.5	3.3	1.1	1.8	1.2	1.4	0.8	1.6
1600	0.6	1.6	1.6	4.2	1.6	1.2	1	2.3	0.4	0.5
2000	2.6	2.7	4.8	6.6	3.1	2.6	3.1	3.9	3.8	3.3
2500	4.2	3.8	6.8	10.1	4.8	3.3	4.4	5.8	4.5	4.3
3150	7.5	5	11.2	14.8	8.1	4.6	5.5	6.6	5.3	5.9
4000	7.3	5.1	10.4	15.5	7.7	5	4.4	8.1	7.1	6.3
5000	9.5	7.9	12.1	15.4	10.8	7.8	5.8	9.2	6.5	7.5
6300	9.4	9.2	12.1	13.3	9.2	11.4	8.3	8.9	5.2	8.4
8000	7.2	9.9	10	13	8	12.2	5.9	8.7	4.8	6.7
Overall	**-0.2**	**1.7**	**0.5**	**3.1**	**1.2**	**2**	**1.8**	**2**	**0.7**	**1.9**

Table 3 summarises the additional IL achieved through the different barrier top modifications for the 3.5 m high barrier.

Table 3. Additional IL achieved through different barrier top treatments to 3.5 m high barrier

Freq, Hz	**Additional insertion loss for 3.5 m high barriers at given microphone height, dB**									
	B – 75 mm high absorptive cap		**C – 600 mm wide 50 mm thick 'T' with absorptive top**		**D – 600 mm wide 50 mm thick 'T', with reflective top**		**E – 600 mm wide 1.6 mm thick 'T', with reflective top**		**F – 1200 mm wide 50 mm thick 'T', with reflective top**	
	1.8 m	**2.5 m**	**1.8 m**	**2.5 m**	**1.8 m**	**2.5 m**	**1.8 m**	**2.5 m**	**1.8 m**	**2.5 m**
200	6.2	2.1	0.3	3.7	0.4	4.0	1.7	2.4	0.4	2.7
250	-6.6	2.7	-5.8	4.4	-8.1	5.3	-3.1	2.9	-3.8	2.5
315	-3.3	2.6	1.2	4.9	-0.7	6.6	2.1	4.5	1.5	1.9
400	-0.8	1.0	2.5	3.2	2.5	4.0	2.9	4.3	2.6	1.2
500	1.2	0.9	3.3	1.2	4.7	2.0	2.8	2.6	3.8	0.1
630	2.3	2.5	1.9	1.5	3.8	2.6	2.2	1.8	3.3	-0.1
800	4.2	3.6	1.0	3.1	3.3	4.3	0.4	0.9	2.0	1.1
1000	-4.7	-1.6	-3.7	0.4	-3.3	0.3	-3.2	0.8	-5.2	-1.4
1250	-6.9	-0.8	-4.7	1.8	-4.4	1.7	0.4	3.1	-7.5	-1.2
1600	1.5	4.6	9.0	8.9	3.1	5.3	4.9	4.0	3.1	3.8
2000	0.7	2.6	7.4	6.1	2.8	3.4	5.1	5.8	3.7	3.1
2500	1.4	7.8	6.6	9.9	1.8	6.8	12.0	12.6	1.5	10.3
3150	6.4	8.8	7.5	9.3	4.2	8.0	10.0	12.9	7.0	6.0
4000	9.1	10.1	10.3	15.0	7.4	9.4	11.3	10.3	13.0	4.5
5000	7.1	8.5	12.2	11.9	5.7	6.7	8.1	9.7	12.9	7.8
6300	8.8	10.0	12.0	14.0	8.5	7.5	8.3	10.2	10.0	8.6
8000	9.6	10.5	13.3	12.5	12.0	6.5	10.4	10.1	11.2	7.5
Overall	**-2.6**	**1.0**	**-1.1**	**2.5**	**-1.0**	**2.5**	**0.3**	**2.3**	**-2.7**	**0.4**

Analysis of Table 3 indicates similar results to the 2.4 m high barrier results although with some differences. As with the 2.4m wall results, with the receiver 'deeper' in the shadow zone (i.e. a lower microphone height), the absorptive cap or T-profile has less attenuation effect compared to a standard cap and, for some frequency bands, significantly worse than a standard vertical barrier with reflective top. This is particularly apparent in the frequency region 1 kHz to 1.25 kHz. This result has meant worse attenuation performance overall compared to a standard barrier. Although this result raises questions regarding the validity of the data, we note that the results are consistent over the change in barrier tops, and the no barrier top (i.e. standard wall) was measured on two separate days with different meteorological conditions and near identical measurement results were observed between these two days. Figures 6 and 7 present comparisons of the insertion loss between the different barrier constructions achieved at a microphone height of 1.8 m above ground for the 2.4 m high and 3.5 m high barriers respectively. The marked improvement in insertion loss at higher frequencies is evident in both figures.

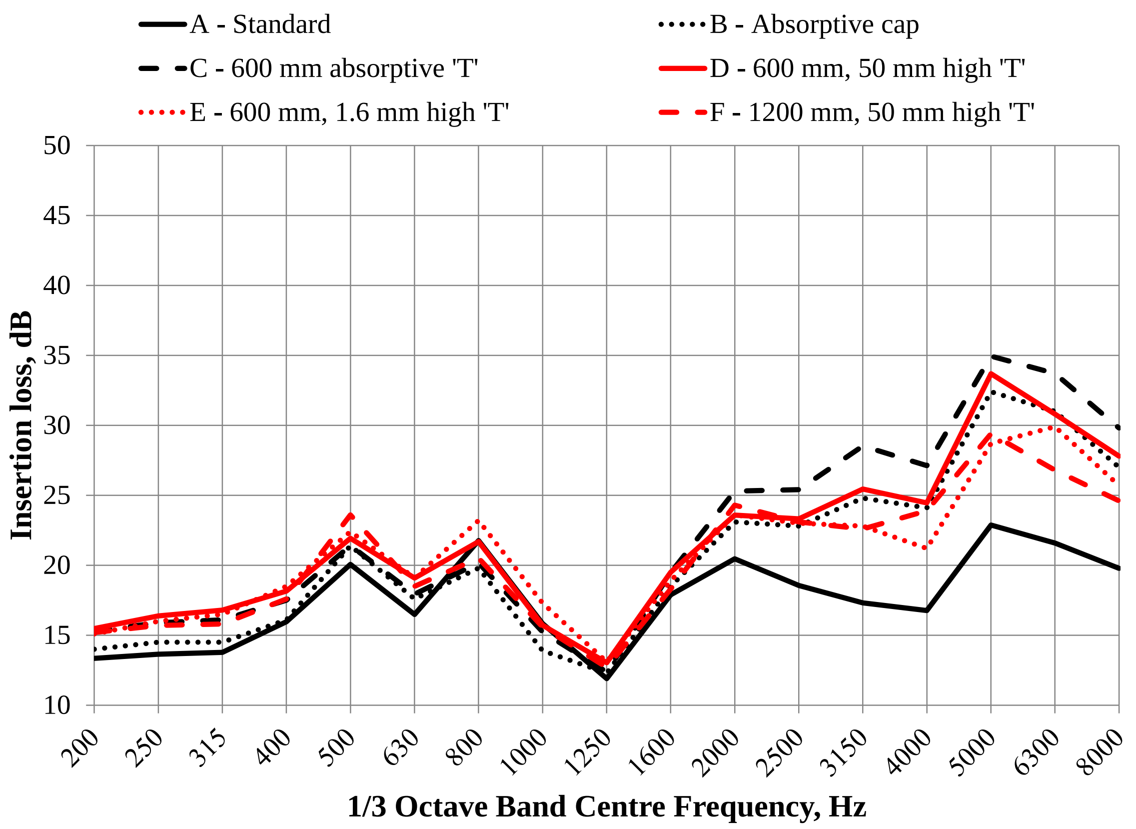

Figure 6. One-third octave band insertion loss of 2.4 m high barrier at 1.8 m microphone height

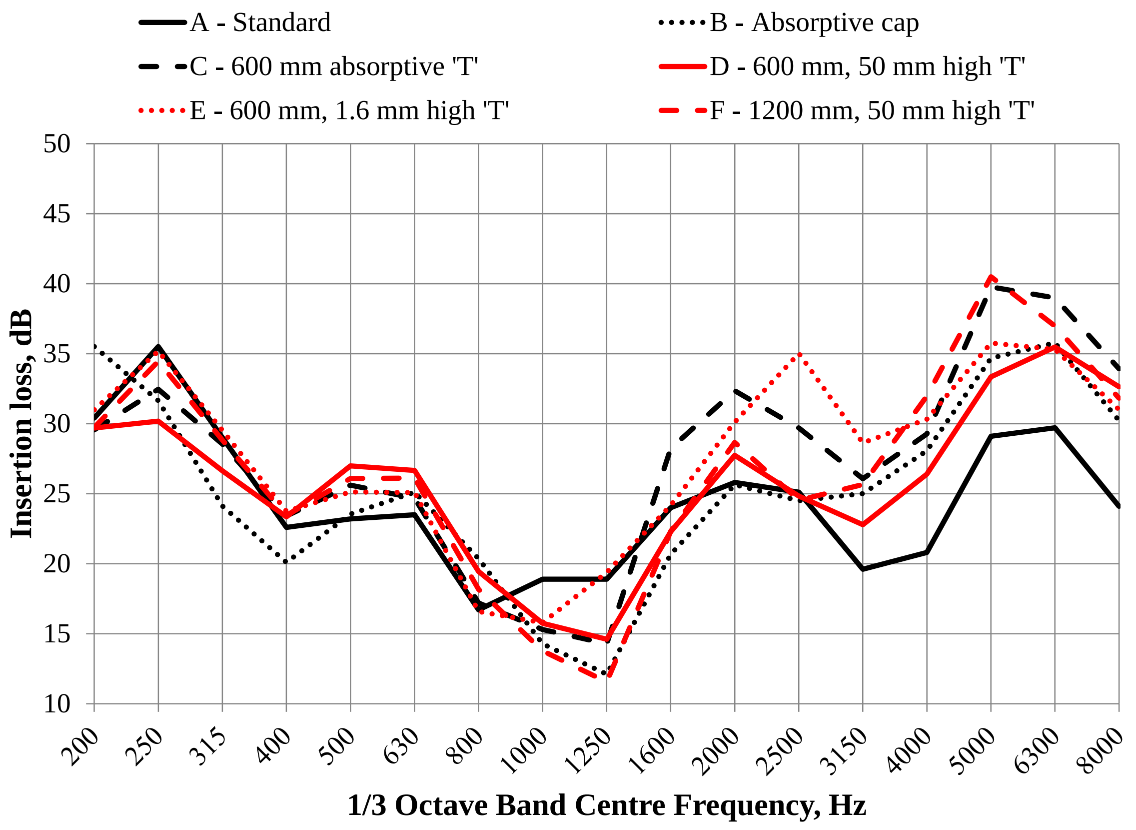

Figure 7. One-third octave band insertion loss of 3.5 m high barrier at 1.8 m microphone height

Although not shown in this paper for reasons of brevity, the additional insertion loss provided by the modified barrier tops for a microphone height of 1.2 m above ground varied with barrier height. For a 2.4 m high barrier, the overall additional insertion loss at 1.2 m above ground was typically 0 to 1 dB lower than that at 1.8 m above ground. The barrier with the absorptive cap (Barrier B) was the outlier with an overall decrease in insertion loss of -2.2 dB at 1.2 m above ground. For a 3.5 m high barrier, the additional insertion loss at 1.2 m above ground improved, with the overall insertion loss typically increasing by 2 to 3 dB relative to the additional insertion loss at 1.8 m above ground.

5. Discussion

The results in this paper support the findings of other studies that barrier top treatments can provide additional insertion loss and result in an additional noise reduction at receivers behind the barrier. While the overall noise reduction achieved for a typical road traffic noise spectrum may only be in the order of 1 to 2 dB, this additional insertion loss can still result in a reasonable reduction in barrier height. Using the Calculation of Road Traffic Noise [9] procedures for the tested situation shown in Figure 3, a 2 dB increase in insertion loss is broadly equivalent to an increase in barrier height from 2.4 m to 3 m or, in other terms, a horizontal 600 mm solid T-shaped top to a 2.4 m high barrier provides a similar noise reduction to increasing the height of a the barrier by 600 mm.

Given that a similar amount of material will be required for either the T-shaped top or an increase in the barrier height, it is unlikely that a T-shaped barrier will provide a cost reduction relative to a standard vertical barrier that provides an equivalent insertion loss unless there is a significant reduction in barrier footing costs. Despite this, the benefit of the T-shaped barrier could be in the reduction of the overall barrier height, which can reduce undesirable overshadowing and improve urban design outcomes for a project. A T-shaped barrier in itself may also be able to be incorporated as part of the urban design plan for a project.

Another factor that should be considered with any barrier top treatment is that any treatment is much more effective at reducing higher frequency sound than it is at reducing lower frequency sound. This means that a top treatment can effectively act as a low pass filter for a source that it is trying to provide mitigation of. While this is true of any barrier, it suggests that it may not be worthwhile incorporating absorptive treatment into a T-shaped barrier providing mitigation of road traffic noise as the primary effect of the absorptive treatment will be to further reduce higher frequency sound while providing little or no reduction of lower frequency sound. As road traffic noise already tends to include a relatively high proportion of lower frequency sound, absorptive treatment will likely be relatively ineffective for locations behind the barrier and, in certain cases, may have the effect of increasing annoyance if the lower frequency component of the traffic noise becomes relatively more noticeable at locations behind the barrier (i.e. less higher frequency masking noise).

One finding of this paper is that, while it is clear from the results that the barrier top treatments assessed can provide an additional insertion loss, the insertion loss achieved is specific to the treatment and the situation in which it is applied. Variations in receiver position and source height can result in changes in insertion loss and, therefore, consideration of a potential barrier top treatment on a project in the planning stage should involve test data specific to that treatment. In assessing the feasibility of a top treatment it may be possible to approximate the performance by calculating the additional insertion loss that would be achieved by increasing the height of the barrier by the same amount as the width of the treatment. Yet the findings of this paper would strongly suggest that specific test data for a top treatment is preferable in all cases.

6. Conclusions

In summary, the T-profile can improve the barrier insertion loss performance by 1 to 2 dB for a typical road traffic noise spectrum. It was observed that the insertion loss improvement was greater for a lower wall height (i.e. 2.4m in comparison to a 3.5m wall). This was due to the T-profile having a negative attenuation effect in comparison to a standard wall cap for a few mid-frequency one-third octave bands when the microphone was 'deeper' in the shadow zone. The taller wall worsened the observed negative attenuation effect at mid-frequencies for a specific fixed microphone height. It is concluded that a modest 2.4 m wall height can be improved with the addition of a 600mm T-profile to perform similarly to a standard cap wall that is 600mm taller for road traffic noise. However care is required in the application of the T-profile, particularly in relation to source and receiver heights.

Acknowledgement

We wish to acknowledge the significant contribution of Nu-Tek Building Systems who provided funding and materials for the study, and constructed the tested barriers.

References

[1] Fard, S.M.B., Kessissoglou, N., Samuels, S. and Burgess, M. "Numerical Study of Noise Barrier Designs", *Proceedings of Acoustics 2013*, Victor Harbor, Australia, 17–20 November 2013.

[2] Hothersall, D.C., Crombie, D.H. and Chandler-Wilde, S.N. "The performance of T-profile and associated noise barriers", *Applied Acoustics*, **32**(4), 269-287, (1991).

[3] Monazzam, M.R. and Lam, Y.W. "Performance of profiled single noise barriers covered with quadratic residue diffusers", *Applied Acoustics*, **66**(6), 709-730, (2005).

[4] Fan, R., Su, Z. and Cheng, L. "Modeling, analysis and validation of an active T-shaped noise barrier", *Journal of the Acoustical Society of America*, **134**(3), 1990-2003, (2013).

[5] Watts, G.R., Surgand, M. and Morgan, P.A. "Assessment of noise barrier diffraction using an in-situ measurement technique", *Proceedings of the Institute of Acoustics Spring conference 2002*, Salford, UK, 25–27 March 2002.

[6] Mongeau, L., Bolton, J.S. and Suh, S. *Investigation of Novel Acoustic Barrier Concepts, Phase I: Concept Development and Preliminary Evaluation*, prepared for Purdue University Joint Transportation Research Program, West Lafayette, USA, 2003.

[7] Watson, D. *Evaluation of Benefits and Opportunities for Innovative Noise Barrier Designs*, prepared for Arizona Department of Transportation, Phoenix, USA, 2006.

[8] Bodzio Software. *SoundEasy Software Version 18*, Bodzio Software, Rowville, Australia, 2014.

[9] Department of Transport Welsh Office. *Calculation of Road Traffic Noise*. Department of Transport, HMSO Publications, London, UK, 1988.