Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Performance of passive and reactive profiled median barriers in traffic noise reduction*

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Received Feb. 20, 2010; Revision accepted July 5, 2010; Crosschecked Dec. 13, 2010

Abstract: Median noise barriers, like parallel noise barriers, can be employed to reduce the impact of traffic on roadside communities via the direct propagation path. The performance of different shapes of median barriers was compared using reactive and passive surfaces and a 2D boundary element method (BEM). In the case of reactive surfaces, quadratic residue diffusers (QRDs) and primitive root diffusers (PRDs) were used on the top and stem surfaces of median barriers. To introduce passive barriers, two different absorbent materials including fibrous material and a grass surface with flow resistivity of 20000 and 2500 kg/(s·m^2), respectively, were similarly applied. The effect of thin absorptive barriers was similar at lower frequencies and better at mid and high frequencies to that of their equivalent rigid barriers. More improvement was achieved by covering the top surface of thick barriers with grass rather than with fibrous material. The performance of QRD and PRD barriers where the diffuser was located on the top surface was more frequency dependent than that of barriers coated with fibrous material. A comparison of the average A-weighted insertion loss in the thick barriers showed that the greatest improvement (2.59 dB (A)) was achieved using a barrier of 30-cm thickness covered with grass.

Key words: Absorption, Quadratic residue diffuser (QRD), Primitive root diffuser (PRD), Noise barrier
doi:10.1631/jzus.A1000065 **Document code:** A **CLC number:** TB53

1 Introduction

Noise barriers as a noise control technique are used to reduce the exposure of humans to noise from transportation. The performance of noise barriers at high frequencies is well-known, and as most traffic noise occurs at mid and high frequencies, different shapes of barriers are designed to make an effective sound attenuation. However, geometry considerations such as height and cost of construction are two major concerns in noise barriers. Many studies have demonstrated the application of active noise control using different types of barrier. The three main areas of research on noise barriers have been the use of profile barriers with extra diffracting edges, the use of soft or absorbent material, and fixing common diffusers.

Hothersall *et al.* (1991) reviewed the effects of various top parts such as T-, Y- and arrow-profile using a 2D boundary element method (BEM). They found that a wide (2 to 3 m) T-profile was the best option among these barriers in the shadow zone and that when an absorbent material was used on the top surface of the cap, further insertion loss can be obtained. Indeed, passive structures were suited to the reduction of high frequency contributions of noise and vibration (Galland *et al.*, 2005). May and Osman (1980) found high noise reduction for wide top barriers, especially those of T-profile and particularly T-profile absorptive top barriers with cap widths of 0.6 m or more and of small cap thickness. Studies of rigid, absorbing and soft surfaces showed that a uniform series of wells in the upper surface of a T-shaped

* Project (No. 8707) supported by the Tehran University of Medical Sciences, Iran

barrier produces insertion loss values identical to those of a soft surface over a significant range of frequencies (Fujiwara *et al.*, 1998). Monazzam and Lam (2005) found that introducing more variation in the wells improved the performance of profile barriers. They also reported that the use of a quadratic residue diffuser (QRD) on the top surface of T-, arrow-, cylindrical- and Y-profile can improve the efficiency of barriers compared with absorptive coverage at the receiver positions tested.

Like parallel noise barriers, median noise barriers can be used to reduce the impact of traffic on roadside communities via the direct propagation path. Median barriers can be an appropriate solution to cross-median accidents on multi-lane (two or more lanes in each direction) expressways and multi-lane conventional highways (Donnell and Hughes, 2005). Numerical calculations and experimental studies of median noise barriers by Martin and Hothersall (2002) showed that differences between their insertion loss values over a range of receiver positions were within 1 or 2 dB. However, more studies need to be carried out to predict the efficiency of edge modified median barriers in access-controlled highways. To the author’s knowledge, no analytical studies of median barriers have been published.

Thus, the objective of this study was to compare the ability of different median barriers to achieve effective energy loss. This paper is divided into three sections. First, the absorption ability of different profiled median barriers is compared to their rigid structure. Then, the performance of a top screen covered with absorbent material and grass is investigated using a thick barrier. Finally, a comparison is made between two common diffusers (QRD and primitive root diffuser (PRD)) fixed to the upper surface of a thick barrier.

2 Materials and methods

2.1 Boundary element method

The BEM is a powerful numerical method that has been used to study the acoustic performance of various noise barriers of complex profile. This method has been used successfully to determine the effectiveness of various barrier profiles in reducing noise levels in the shadow zone of barriers (Watts *et al.*, 1994; Crombie *et al.*, 1995; Fujiwara *et al.*, 1998). The Helmholtz wave equation is solved by the boundary integral equation at a single frequency when using the BEM. The surface of the barrier is divided into a number of straight line elements. In numerical simulations, the dimension of elements is taken to be less than 1/5 of wavelength to give a reasonable representation of constant surface pressure over an element (Hothersall *et al.*, 1991). The two main advantages of this model, its accuracy and ability to deal with different types of barriers, make it applicable to analytical solutions of wave diffraction. Comparisons of theoretical models with experimental results have shown an acceptable agreement over a wide range of frequencies (Monazzam and Lam, 2008).

To evaluate barrier performance, insertion loss at each frequency was calculated:

$$\mathrm{IL} = 20\log(p_{\mathrm{g}} / p_{\mathrm{b}}),$$

where p_{b} and p_{g} is the sound pressure in the presence and absence of acoustic barriers at the receiver point, respectively.

2.2 Efficiency of profiled diffusers

The QRD and PRD are two main Schroeder diffusers that scatter the energy of incident waves in different directions. Each diffuser consists of a series of wells of the same width but different depths, divided by thin fins. The well depth sequence of these diffusers is determined by a mathematical sequence based on prime numbers. Calculation of the depth sequence number is described in detail by Cox and D’Antonio (2004).

By changing the prime number and the well sequence, it is possible to increase the efficiency of diffusers. Fujiwara (1995) showed that a higher absorption coefficient is achieved by QRDs with higher prime numbers N (from N=11 to 7). Furthermore, converting the wells from QRD to PRD was shown to give better absorption (Wu *et al.*, 2001).

2.3 Impedance of Schroeder diffusers

The method described by Wu *et al.* (2000) was applied to calculate the surface impedance of the wells.

2.4 Absorption efficiency

The acoustic absorption coefficients of fibrous material and vegetation cover (grass) were computed using the method of Delany and Bazley (1970).

In this study, the flow resistivities of fibrous material and grass were assumed to be 20000 kg/(s·m^2), (Monazzam and Lam, 2008) and 2500 kg/(s·m^2) (Lamancusa, 2009; Londhe *et al.*, 2009), respectively, the same as those in previous studies of roadside barriers.

3 Results and discussion

3.1 Barrier geometry

In this study, barriers were separated into two groups: thin and thick barriers (Fig. 1). Thin barriers were profiled barriers with different angles and caps. The angles of tilted barriers (models V and R) and profiled barriers (models A, Y and Z) were fixed at 10° or 60° to be consistent with previous studies (Watts, 1996; Monazzam and Lam, 2005). Barriers with a stem thickness of 100 cm were included in the thick barriers group. Note that in all barrier models the height was fixed at 1 m to be in accordance with previous studies (Martin and Hothersall, 2002). The top surfaces of thin barriers were covered by fibrous material with a thickness of 10 cm. In the case of thick barriers, the efficiency of grass and fibrous material of 10 or 30 cm thickness was tested. Also, QRD and PRD were used either on the upper surface or on the stem surface of thick barriers. Stem surfaces of barriers coated with QRD and PRD were placed facing towards the source point.

In the BEM calculations, the QRD and PRD are represented by a box with a variable impedance surface. To enable a valid comparison, the thicknesses of absorbent material in barrier models "FA2" and "FG2" were equivalent to those of the barriers that were covered by QRD or PRD boxes, and the thicknesses of absorbent material in barrier models "FA1" and "FG1" were equal to those of the absorptive caps of thin barriers. A more detailed description of these barriers is shown in Tables 1 and 2.

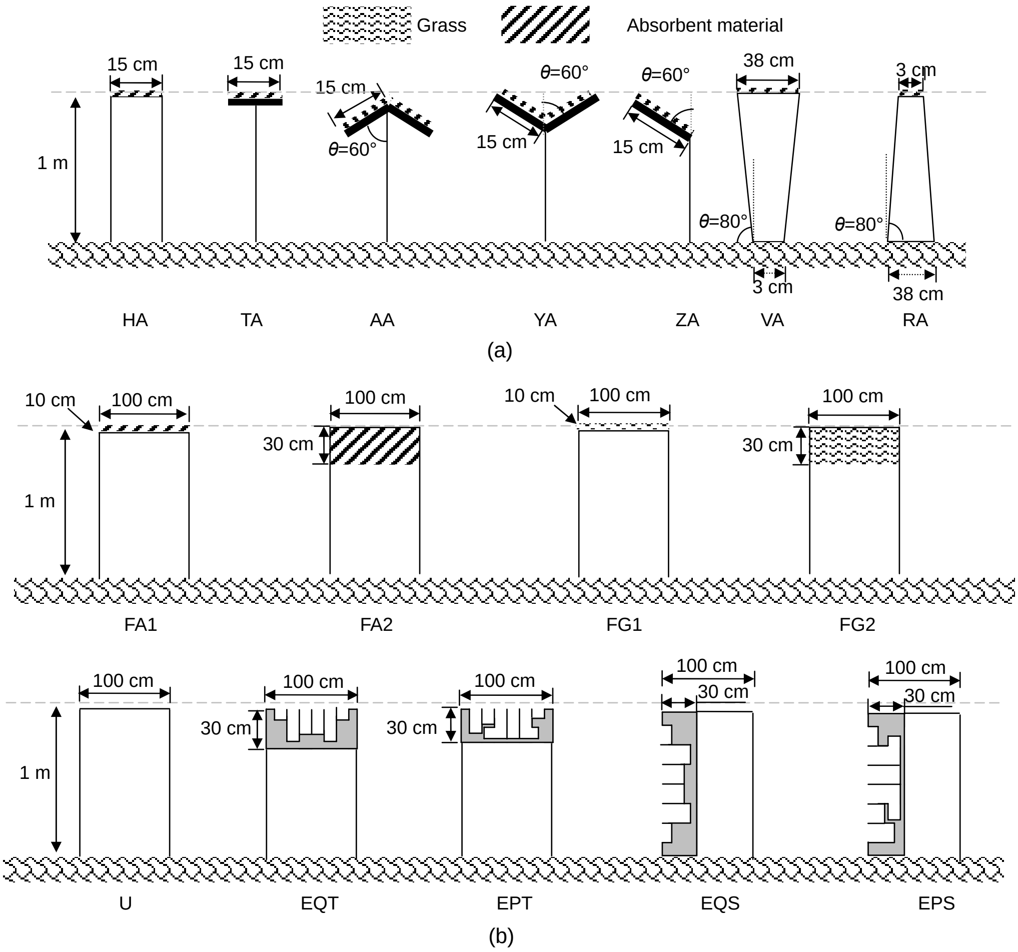

Fig. 1 Schematic definition of profiled thin barriers (a) and thick barriers (b) covered with absorbent and reactive surfaces

Table 1 Characteristics of rigid and passive tested barriers

Model	Flow resistivity (kg/(s·m^2))	Description
U	Infinity	–
AA	20000	θ=60°
HA	20000	–
TA	20000	–
YA	20000	θ=60°
ZA	20000	θ=60°
VA	20000	θ=80°
RA	20000	θ=80°
FA1	20000	Fibrous material with a thickness of 10 cm
FA2	20000	Fibrous material with a thickness of 30 cm
FG1	2500	Grass with a thickness of 10 cm
FG2	2500	Grass with a thickness of 30 cm

All calculations were performed before and after barrier erection at different distances from the barrier (20 m, 50 m, and 100 m), on rigid ground, at heights of 1.5 and 3 m above the ground, and at 1/3-octave centre frequencies between 50 and 4000 Hz. The source was placed on the ground −8.5 m from the centre line of the barriers to simulate the average distance of vehicles crossing on a typical highway. For diffusive barriers, viscous and thermal conditions in the wells were also considered. In this research, the efficiency of each thin barrier was compared with that of its equivalent rigid barrier and for thick barriers, model "U" was used as a reference barrier for comparison.

3.2 Absorptive surfaces

3.2.1 Thin barriers

The performance of each absorptive thin barrier was compared with that of its equivalent rigid barrier. The efficiency of the "HA barrier" relative to its rigid barrier is shown in Fig. 2. Putting a 10 cm absorptive surface on the upper surface of a plain barrier produced an increase in insertion loss with a maximum value of 1.7 dB (A).

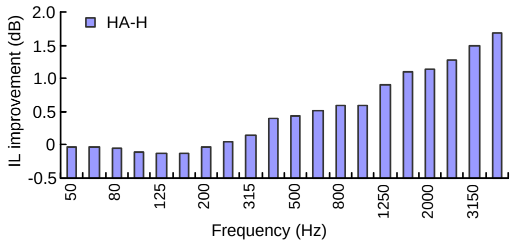

Fig. 2 Insertion loss improvement of "HA barrier" with H barrier at the receiver point (50, 0)

The insertion losses of different profiled thin absorptive barriers along with those of their equivalent rigid barriers are shown in Fig. 3. Use of absorbent material on the top surface of a thin T-shaped barrier in barrier model "TA" did not provide significant improvement at low and mid frequencies, although improvement was found at frequencies above 1000 Hz. Similarly, in other thin barriers, at frequencies above 125, 160 and 315 Hz improvement was achieved by the addition of fibrous material to the top surfaces of YA, ZA and AA barrier models, respectively. By comparing the four graphs in Fig. 3, it can be seen that by changing the top surface profile from T to arrow and Y shapes, the effective frequency is shifted to lower frequencies. This can be explained by wider absorbent coverage by Y and arrow shapes compared with T-profile barriers. Note that the only difference between the profiled barriers was their absorptive caps. The results indicate that applying absorbent materials can affect the efficiency of a barrier. However, this conclusion was questioned by Watts and Godfrey (1999) who stated that the effect of an absorptive barrier is likely to be overestimated by these models.

Fig. 4 shows the insertion loss improvement of barrier models "RA" and "VA" compared to their equivalent rigid barriers. The contribution of the top surface of barrier model "V" was higher than that of barrier model "R" when absorbent material was applied, as a result of wider absorption coverage. Moreover, in barrier model "V" the incident wave is reflected towards the ground while in barrier model "R" it is reflected upwards.

Table 2 Characteristics of reactive tested barriers

Model	Diffuser	N	Design frequency (kHz)	Well width (cm)	Sequence	Description
EQT	QRD	7	0.4	12	[0 1 4 2 2 4 1]	Diffuser on the top surface
EPT	PRD	6	0.4	14	[3 2 6 4 5 1]	Diffuser on the top surface
EQS	QRD	7	0.4	12	[0 1 4 2 2 4 1]	Diffuser on the stem surface
EPS	PRD	6	0.4	14	[3 2 6 4 5 1]	Diffuser on the stem surface

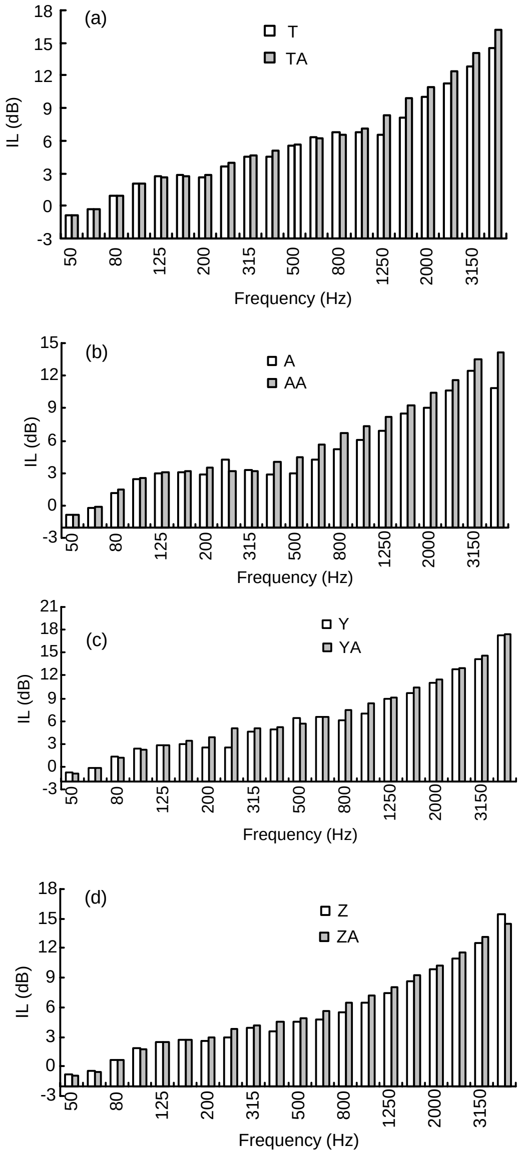

Fig. 3 Performance of different profiled barriers relative to their equivalent rigid barriers at the receiver point (50, 0). (a) T barrier; (b) A barrier; (c) Y barrier; (d) Z barrier

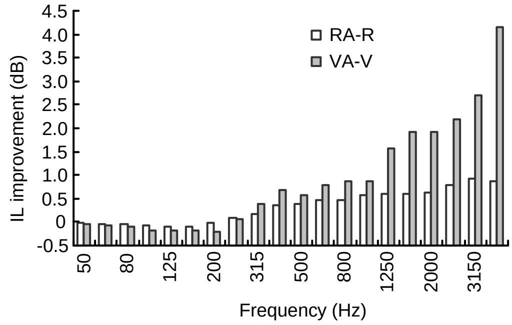

Fig. 4 Insertion loss improvement of two different thin barriers, namely "RA barrier" and "VA barrier", relative to their equivalent rigid barriers at the receiver point (50, 0)

3.2.2 Thick barriers

The effect of addition of grass and absorbent material to the upper surface of thick barriers is shown in Figs. 5 and 6. The acoustic efficiency of thick barriers increased with the addition of fibrous material and grass. The results obtained for both materials with 10 and 30 cm thickness showed a similar pattern by further values at higher frequencies (Fig. 5). The efficiency of FG2 was enhanced from 100 Hz but for FG1 this effect appeared from 315 Hz. This explains why the A-weighted insertion loss of FG2 is greater than that of FG1, confirming that a more absorptive surface gives greater improvement.

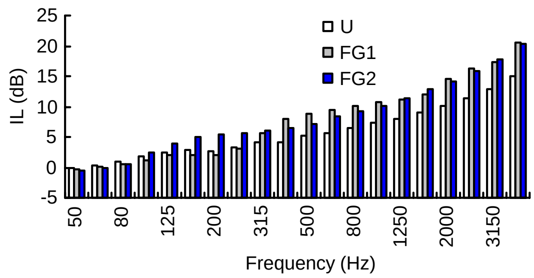

Fig. 5 Performance of thick barriers employing grass on the top surface relative to their equivalent rigid barrier "U barrier" at the receiver point (50, 0)

Although the efficiencies of barrier models FA1 and FA2 are higher than those of barrier model "U", the patterns for these thick barriers are very similar across the entire frequency spectrum (Fig. 6). A decrease in absorbent material on the surface, such as occurs from the use of grass in barriers, causes a decrease in insertion loss.

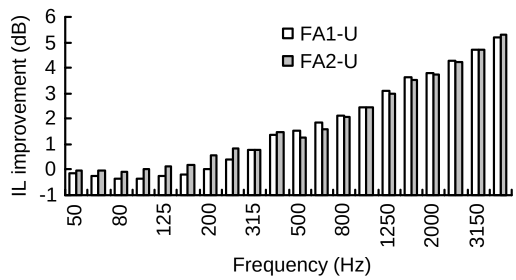

Fig. 6 Insertion loss improvement of thick barriers employing absorbent material on the top surface relative to their equivalent rigid barrier "U barrier" at the receiver point (50, 0)

Our results show that while it is possible to make an effective insertion loss among profiled barriers, the initial cost and the maintenance cost will be high.

Maintenance will be difficult and no material can provide a fully absorptive performance at all frequency bands (Cheng and Ng, 2001). So it seems that a comparison with the use of other effective surfaces such as reactive surfaces may be worthwhile.

3.3 Reactive surfaces

To investigate the efficiency of QRD and PRD surfaces on the source face of thick barriers relative to their equivalent rigid barriers, a comparison was made between the insertion loss of barrier models "EPS" and "EQS" (Fig. 7). The performance of barrier model "EPS" relative to its equivalent rigid barrier was higher than that of barrier model "EQS" at lower frequencies, but except at 500 and 2000 Hz the reverse condition was seen at mid and high frequencies. The frequency selectivity in barriers coated with diffusers was dominant within the tested frequency range (Fig. 7). This is consistent with previous studies on single diffusive noise barriers (Monazzam, 2009; Monazzam and Nassiri, 2009).

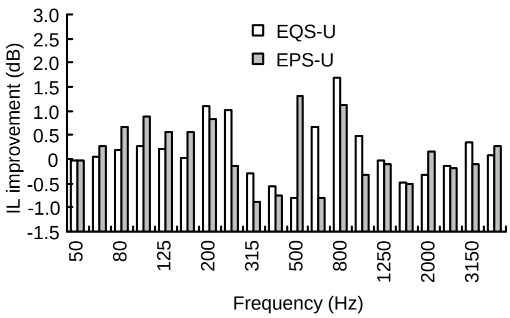

Fig. 7 Comparison of insertion loss improvement of barriers with QRD and PRD faces along with their equivalent diffusive barrier (barrier model U) at the receiver point (50, 0)

The effect of the QRD and PRD on the top surface of a thick barrier was also compared with the reference plain barrier (barrier model "U") (Fig. 8). The spectra insertion loss of the plain barrier employing PRD was smoother than that of the barrier with QRD coverage. This can be explained by the higher number of impedance changes in PRD. The insertion loss improvement of barrier model "EPT" began at lower frequencies compared with that of barrier model "EQT". This explains why the A-weighted traffic noise spectrum of barrier model "EPT" at the receiver point (50, 0) was higher by further 0.3 dB (A). As expected, at the design frequency along with its integer in diffuser barrier model "EQT" including 200 and 800 Hz, and at 400 Hz (the design frequency of the EQT barrier), the efficiency of the employed barrier was decreased.

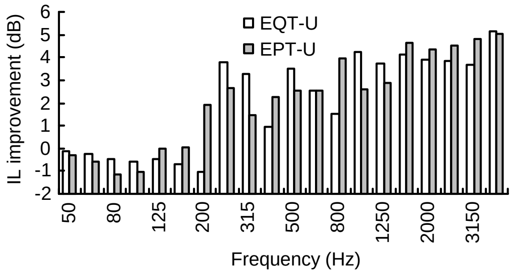

Fig. 8 Comparison of insertion loss improvement of barriers with QRD and PRD tops along with their equivalent diffusive barrier (barrier model U) at the receiver point (50, 0)

3.4 Shadow zone

The amount of improvement achieved by barrier models "FA2", "EPT" and "FG2" in the far field at 2500 receiver points was compared with those achieved by barrier model "U" at a frequency of 500 Hz (Fig. 9). The receivers were placed behind the barriers at a distance of from 20 to 270 m and from ground level to a height of 10 m.

The use of fibrous material in barrier model "FA2" improved the performance of its equivalent rigid barrier across almost the entire tested area (Fig. 9a). The greatest improvement of 2 dB (A) was found at higher heights at a distance of 100 m from the barrier.

The amount of reduction in insertion loss from barrier model "PRD" compared with barrier model "U" is shown in Fig. 9b. Clearly, barrier model "EPT" had better performance across a wide area. In the near field especially at higher heights, the improvement from "EPT" was not as pronounced as in other zones as a result of the upward diffraction of sound caused by PRD. For this zone, covering QRD on roadside barriers has shown similar results (Monazzam and Lam, 2005). At a distance of more than 100 m at both low and high heights, the amount of improvement reached from 2 to 2.7 dB (A).

For barrier model "FG2" (Fig. 9c), the location of the zone with the highest efficiency was the same as that found for "FA2" (Fig. 9a), though the efficiency of 'FG2" was higher by 0.55 dB (A). The overall pattern was the same for both models, although grass was more effective than absorbent material, giving higher performance across almost the entire area.

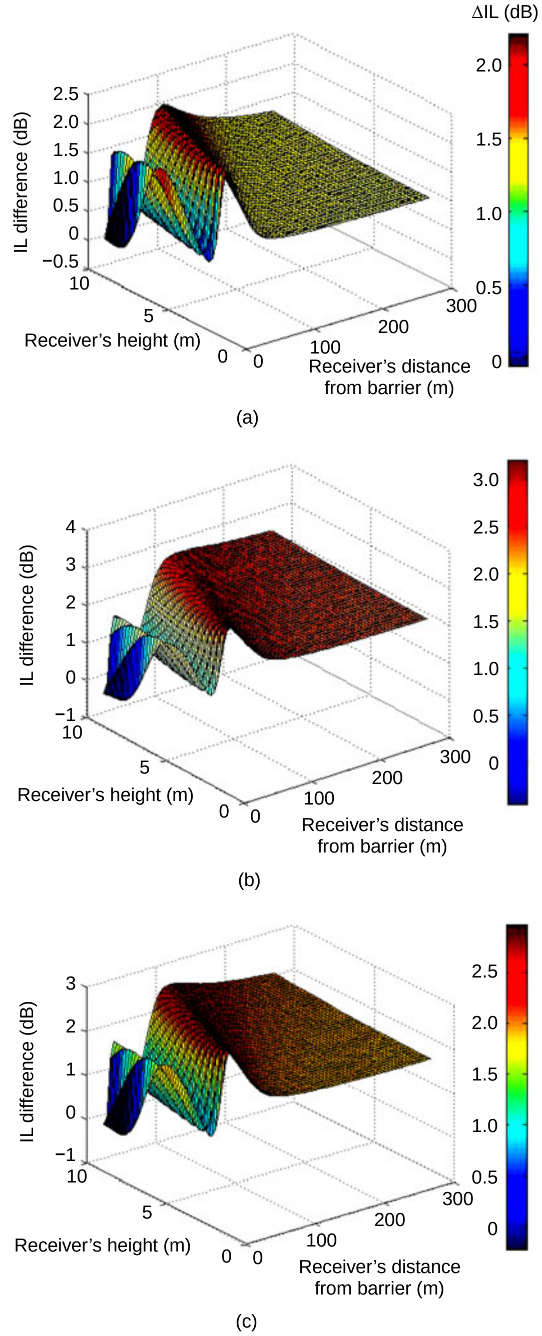

Fig. 9 Improvement of A-weighted insertion loss by barrier models (a) FA2, (b) EPT, and (c) FG2 compared to the "U barrier"

3.5 Broadband insertion loss

To compare barrier performance in the context of insertion loss, the overall A-weighted insertion loss was calculated over the range of 50 to 4000 Hz at 9 receiver positions (BS EN 1793-3:1998). The barriers, including thin and thick barriers, were each compared with their equivalent rigid barrier separately (Table 3).

Table 3 Comparisons of mean A-weighted insertion loss between studied barriers relative to their reference barriers

Thin barrier			Thick barrier		
Barrier model	Mean IL	ΔIL	Barrier model	Mean IL	ΔIL
H (ref)	7.42	0	U (ref)	7.62	0
AA	7.62	0.21	FA1	9.10	1.48
HA	7.86	0.44	FA2	9.19	1.58
RA	7.48	0.06	FG1	9.57	1.95
TA	8.02	0.60	FG2	10.20	2.59
VA	8.30	0.88	EQT	9.55	1.93
YA	8.59	1.17	EPT	9.87	2.26
ZA	7.68	0.26	EQS	7.82	0.20
A	6.73	−0.70	EPS	7.61	−0.0030
R	7.15	−0.30			
T	7.60	0.18			
V	7.60	0.18			
Y	7.92	0.50			
Z	7.10	−0.30			

The highlight parts show the highest performance in thin and thick barrier models

For thin barriers, the efficiency of absorptive barriers was reasonably high compared with that of their equivalent simple rigid barriers, although negative insertion loss was found in barrier models "A", "R" and "Z".

Barrier model "Y" showed the best improvement among the rigid thin barriers, and likewise performs well in its absorptive form. Covering rigid thin barriers with fibrous material has some effects, and if the angle and corner of designed barriers are effective, higher insertion loss can be achieved. This point is evident from barrier models "V" and "R". Barrier model "V", by reflecting the incident wave downwards, had better efficiency either in a rigid or absorptive barrier than barrier model "R" with conversed reflections.

Comparing the overall results from the thick barriers, it appears that changing the absorbent material from fibrous to grass makes the barrier more efficient as a result of the lower flow resistivity of grass compared with fibrous material. Applying PRD to the top surface of a barrier improved the mean A-weighted performance of its equivalent QRD barrier by 0.33 dB (A) which is in agreement with previous studies on roadside barriers (Mechel, 1995; Monazzam and Lam, 2008). Also, the contribution of QR and PR barriers where the diffuser is located on the top surface is higher than that of barriers coated with fibrous material (Monazzam and Lam, 2005). Poor and negative effects of barriers with diffusers on the stem side can be explained by the construction effects of incident and reflected waves that are achieved over the source side of barriers.

4 Conclusions

Several profiled thin and thick median highway barriers were considered. Using a 2D BEM the significance of grass and fibrous material and diffuser surfaces on the design tested barriers was investigated with the following results:

1. Applying absorbent material on the top surface of a rigid Y shape barrier shifted the performance improvement towards lower frequencies. As a result, the A-weighted traffic noise spectrum of this barrier showed the highest improvement among the thin barriers.

2. The mean A-weighted insertion loss of absorptive barriers with wider top surfaces showed better performance. Barrier model "FA1" showed an additional insertion loss of 1.24 dB (A) compared to barrier model "HA".

3. Using reactive surfaces (QRD and PRD) on the top surface of barriers can increase the overall A-weighted insertion loss of the designed barriers, although using reactive surfaces on the source side of a barrier's stem produces lower efficiency and can even produce a negative value in PRD barrier. This can be explained by the deflection of the specular reflection wave with more upward wavelets on the source diffraction edges of these reactive barriers. As shown in (Wu *et al*., 2001), covering the top surface of thick barriers with PRD gives higher performance compared with results obtained from QRD edge barriers. This can be explained by the higher number of impedance changes in PRD compared with QRD.

4. Although the efficiency of barriers covered with grass (barrier model "FG2") was better than that of barriers with QRD and PRD on tops and faces, their maintenance costs are prohibitive and therefore, reactive surfaces are likely to remain the preferred option. However, artificial types of grass such as Astroturf have different characteristics relative to real grass, depending on the water content of the soil. The absorption coefficient of grass is affected by the blade length, moisture and soil conditions (Londhe *et al.*, 2009), which can greatly influence the insertion loss reduction of barriers.

5. Barrier model "U" covered with grass (barrier model "FG2") was found to be effective across the entire area. Although, the performance of barrier model "FA2" was higher than its equivalent rigid barrier, the only exception was at the area close to the barrier at the heights of 8–10 m. The performance of barrier model "EPT" was lower than its equivalent rigid barrier only at heights above 3 m behind the barrier.

The main objective of this study was to compare the performance of different median barriers. Further studies comparing the performance of median and roadside barriers would be helpful.

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