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NOISE BARRIER REVIEW

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Executive summary

Traffic noise barriers are constructed to a variety of designs and in a wide range of materials and yet the basic acoustical performance in terms of reducing noise levels in the vicinity is governed largely by the height and length of such devices. However, performance can be enhanced by the addition on the top of the barrier of devices such as absorptive T-shaped and cylindrical profiles and multiple edge devices. In certain circumstances the addition of sound absorptive material to the front, rear or both faces of the barrier can be advantageous. Partial or complete covers can be provided by extending the barrier horizontally over the road. Some research also suggests that sensitivity to noise can be increased if the noise source cannot be seen and the findings suggest that there may be tangible benefits in using transparent screens.

Photovoltaic (PV) cells can be combined with T-shaped or other suitable profiles, providing additional screening without raising the height of the barrier and supplying electricity when there is sufficient natural illumination.

The positioning of the barrier with regard to the receivers it is designed to protect is critical. If reflective surfaces, such as a brick or concrete façade, are present close behind the barrier, this may seriously degrade the performance of the barrier.

It was found that reflective barriers can make an important contribution to reducing noise, although it will be necessary to consider returns on barriers where it is only possible to erect a short length of screening along the main road, which will be a common situation in many parts of London. Sound leakage through the barrier needs to be considered both at the procurement stage and when installed, especially where the required noise screening is relatively high. BS EN 1793-2 and BS CEN/TS 1793-5 can be used to assist in ensuring an adequate standard is achieved.

The cost of materials varies widely with timber being the lowest cost option and transparent screens at the higher end. Transparent screens alone or in combination with other materials are an option worth considering, due to their possible advantage in terms of noise and personal safety perception and transmission of natural light.

Absorptive barriers add substantially to the cost and can be justified where reflected noise is likely to be a significant problem. Absorptive materials need to be selected so that they are strongly absorbent at frequencies that are dominant in typical traffic noise. BS EN 1793-1 can assist in the procurement of suitable panels or claddings.

The use of novel barrier profiles can be used to obtain additional screening benefits without raising the height of the barrier. This may be useful where visual impact needs to be limited or where views need to be preserved. However there are few commercial products worldwide and there is no known supplier in the UK. Prototype barrier profiles can of course be assembled for test purposes and a trial was successfully carried out at three locations on the M25 with a multiple edge profile.

The use of PV barriers in combination with novel barrier profiles would produce a ‘win-win’ situation i.e. additional noise screening and the generation of electricity. Using the boundary element method, some promising improvements in screening have been demonstrated. Further work is required to optimise the system in terms of both noise reduction and solar energy conversion.

The robustness and ease of cleaning of materials needs to be carefully considered in urban areas due to the likelihood of vandalism and graffiti. Some absorptive panels are not very robust (e.g. timber absorptive) and other materials such as wood-cement products may be more appropriate, although costs are significantly higher. Some vegetative barriers with
sloping sides may encourage climbing and other inappropriate action, and there are therefore issues of personal safety and damage to the barrier structure itself. Vegetation growing in close proximity to more conventional barriers is worthy of consideration as it could protect from vandalism and enhance the visual appearance. The acoustic benefits of the use of vegetation used in this way are not known and further research is required.
1 Introduction
Traffic noise barriers are produced from a variety of materials and to various designs. A world wide review of the literature has revealed a wide variety of constructions.

These can be considered in the following terms:

- Reflective barriers;
- Earth mounds and vegetative barriers;
- Absorptive barriers and claddings;
- Median barriers;
- Barriers with novel caps;
- Retained cuts;
- Covers (full and partial).

The screening efficiency of each of these types of barrier is examined based on an examination of the literatures, and indicative costs will be given where available.

To aid in the procurement, a number of European standards (European CEN) have been developed. These assess the acoustic performance and give a single number rating of efficiency:

- Sound absorption test described in BS EN 1793-1 and BS CEN/TS 1793-5 (British Standards Institute, 1998a).
- Airborne sound insulation or sound transmission test described in BS EN 1793-2 and BS CEN/TS 1793-5 (British Standards Institute, 1998b).
- Diffraction efficiency described in pr EN TS 1793 Part 4 (European Committee for Standardisation, 2002)

These are intrinsic characteristics and are concerned with the product and not how it is used. They are useful in specifying the product during procurement. On the other hand the extrinsic characteristics of a barrier are concerned with performance in the far-field and depend on the height and length of the barrier and where it is positioned with regard to the source of noise and the receiver. An ISO standard, ISO 10847, has been developed to determine the extrinsic performance in terms of insertion loss (International Organisation for Standardisation, 1997). This is defined as the difference in noise level with and without the barrier present.

This report examines the options for noise barriers, claddings and covers and discusses acoustic performance and cost effectiveness and the situations in which they are most effective in providing noise mitigation.

A further aim of the report is to consider how photovoltaic (PV) surfaces can be incorporated into noise barriers in order to optimise the gains of both electricity generation and additional screening.
2 Theory

The three acoustical factors affecting the performance of the barrier are outlined in this section.

2.1 Transmission

The barrier or cover should be constructed of sufficiently dense material so as to block a significant proportion of the sound energy incident on the traffic face. Leaks generally occur at the interface between barrier components such as between the panels themselves and between panels and post. These leaks can be significant where the screening provided by the barrier is high and some previous work has allowed the effects of leaks to be calculated. Any barriers installed in urban environments would benefit from in-situ testing when erected and regular maintenance checks.

Figure 2.1 shows the predicted changes in noise levels behind a barrier as a result of 3% leaks in 3 m and 6 m high screens. This level of leaks would just qualify it for category B2 (i.e. the middle category of performance). Generally it can be seen that this effect is relatively large within 20 m of the tall barrier but is small, i.e. less than 3 dB(A), beyond this distance. This is due to the diffracted wave being more important as the receiver moves away from the barrier. For the short barrier the effect is relatively small and approximately 1 dB(A) at a distance of 10 m.

![Figure 2.1: The effects of leaks on noise levels behind the barrier](image)

The change in noise level can be related to the percentage of air gaps ($G$), the distance of the source and receiver from the barrier ($d_s$ and $d_r$), the height of the barrier ($h$) and the barrier potential ($b$) which is calculated from the Calculation of Road Traffic Noise prediction method (Department of Transport and Welsh Office, 1988). The following prediction equation has been developed (Watts, 1999b):
A test for airborne sound transmission is given in the standards BS EN 1793-2 and BS EN/TS 1793-5. The former standard is a laboratory test while the latter uses an in-situ test. The in-situ test is more appropriate as the build quality can vary widely in the field yet is carefully constructed in the laboratory. The most important frequencies in traffic noise lie around 1 kHz and the standard test weights the sound transmission at various frequencies (100 Hz to 5 kHz) to take account of this using a standardised traffic noise spectrum defined in BS EN 1793-3 (British Standards Institute, 1998c). The normalised traffic noise spectrum is given in Figure 2.2. The individual weighted sound reduction indices are summed to obtain the single number rating of sound transmission $DL_R$ in decibels.

$$DL_R = -10 \log \left[ \sum_{i=1}^{18} 10^{0.1L_i} 10^{0.1R_i} \right]$$  \hspace{1cm} (2.2)$$

where $R_i$ is the sound reduction index in the $i$th one-third octave band and $L_i$ is the normalised A-weighted sound pressure of traffic noise in $i$th one-third octave band.

A similar formula is used if the in-situ method is used.

Performance can be rated according to the following classification system:
Table 2.1 Categories of airborne sound insulation

<table>
<thead>
<tr>
<th>Category</th>
<th>$DL_R$ (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0</td>
<td>Not determined</td>
</tr>
<tr>
<td>B1</td>
<td>&lt;15</td>
</tr>
<tr>
<td>B2</td>
<td>15 – 24</td>
</tr>
<tr>
<td>B3</td>
<td>&gt;24</td>
</tr>
</tbody>
</table>

For timber barriers widely used in the UK the single number rating can vary over B1 to B3. If the barrier is a single leaf construction then typically ratings lie in the range B1 to B2. With a double leaf or single leaf absorptive the ratings can be B2 to B3.

### 2.2 Absorption

In situations where reflected sound is a problem the incorporation of absorptive materials on the face of a barrier or as a cladding to a retained cut can be helpful in reducing the problem. The greatest benefit is achieved where tall barriers are on both sides of a narrow road or where there is a deep but narrow cut. Figure 2.3 shows typical situations where reflections from noise barriers may be a problem. For the case in Figure 2.3 (a) the single barrier reflects vehicle noise to the far-side of the road and consequently raises noise or there are multiple reflections between the reflective side of a high-sided vehicle and the barrier. This leads to an increase in noise on the nearside. In Figure 2.3(b) the effects of double barriers can be seen. In this case multiple reflections between the barriers can lead to a loss in performance of the barriers. The multiple reflections between opposite sides can produce a build up of sound energy resulting in excessive noise levels.

(a) Single reflective barrier

(b) Double reflective barrier
The benefit of applying absorptive material depends on the separation of the barriers and their height. Table 2.2 shows the increase in noise due to the presence of a reflective barrier on the farside with a reflective barrier on the nearside. Applying a good absorptive material to both traffic faces will virtually eliminate the increases shown in Table 2.2. Where the ratio of width to height is large the effect of applying absorptive material is small. As an example where this ratio is approximately 9:1 then applying absorptive material to the faces of parallel barriers should reduce noise levels by a maximum of 2.8 dB(A). The receivers were within 50 m of the rear of the barrier and ranged up to a height of 4.9 m above the barrier.

<table>
<thead>
<tr>
<th>Experimental design</th>
<th>Barrier separation / height ratio</th>
<th>Maximum increase in $L_{Aeq}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pairwise comparison</td>
<td>8.6 : 1</td>
<td>2.8</td>
</tr>
<tr>
<td>Barrier alteration</td>
<td>9.3 : 1</td>
<td>2.3</td>
</tr>
<tr>
<td>Barrier erection</td>
<td>15 : 1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

To reduce the problem, porous materials are often applied to the reflective faces that cause the problem. These can take the form of fibreglass, porous concrete or wood fibres bound with cement to form a matrix of inter-connecting pores. To control low frequencies Helmholtz resonators are sometimes used. These are cavities with narrow openings to the outside. These cavities resonate at frequencies dependent on the volume and dimensions of the opening. Figure 2.4 (a) shows a common type of metal barrier composed of a perforated aluminium box with a fibrous absorber. Figure 2.4 (b) shows a slotted concrete block which acts as a Helmholtz resonator.
As for the case of sound transmission it is important to consider the frequencies in typical traffic noise. In the test for absorptive material in BS EN 1793-1 a single number rating is obtained by weighting the individual sound absorption coefficients from 100 Hz to 5 kHz using the standard traffic noise spectrum referred to above.

The single number rating can be used to gauge the efficiency of the material in absorbing sound and is defined as:

\[
DL_{\alpha} = -10 \log \left[ 1 - \frac{\sum_{i=1}^{18} \alpha_{Si} 10^{0.1L_i}}{\sum_{i=1}^{18} 10^{0.1L_i}} \right] \quad (2.3)
\]
The categories are:

<table>
<thead>
<tr>
<th>Category</th>
<th>$DL_a$ (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>Not determined</td>
</tr>
<tr>
<td>A1</td>
<td>&lt;4</td>
</tr>
<tr>
<td>A2</td>
<td>4 – 7</td>
</tr>
<tr>
<td>A3</td>
<td>8 – 11</td>
</tr>
<tr>
<td>A4</td>
<td>&gt;11</td>
</tr>
</tbody>
</table>

Typically a good absorber would have a $DL_a$ value of at least 8 dB(A).

Figure 2.5 shows the absorption spectra of some typical absorbers: The masonry block absorber produces a peak in absorption at 300-400 Hz which is lower than the peak in the traffic noise spectrum and so would not be suitable for controlling broad band traffic noise. The perforated metal box barrier with a fibrous fill material is effective over a wide range of frequencies and therefore has more acceptable performance.

![Sound absorption coefficient graph](image)

**Figure 2.5: Variation of absorption with frequency**

### 2.3 Diffraction

The sound diffracted over the top of the barrier is the most important factor limiting the performance of a barrier. If the receiver is in the shadow zone of the source then significant reductions in noise levels will occur, i.e. >5 dB(A). It has been found that the path length difference is an important parameter affecting the performance and this approach is used to calculate the screening of traffic noise (Department of Transport and Welsh Office, 1988).
Figure 2.6 shows how the path difference is calculated. The path length of the direct path joining source and receiver (c) is taken from the path length of the shortest path between source and receiver which goes over the top of the barrier (a+b). The greater the path length difference the greater the screening performance. A greater path length difference occurs for tall barriers with low receivers close to the barrier. Conversely small path differences will occur for low barriers and tall receivers. The Figure shows that the barrier attenuation changes rapidly for small path differences in the region between the illuminated and shadow zone.

In a typical situation with buildings say 20 m from a barrier 3m high the screening performance is 13 dB(A) at ground level and perhaps 11 dB(A) at first floor level.

Devices can be added to the tops of barriers to reduce the diffracted sound propagating into the shadow zone. For example T-shaped tops, multiple edge profiles and absorptive cylinders can be added to the top to reduce noise levels by up to 3 dB(A) in the shadow zone without increasing the height of the barrier. CEN/TS 1793-4 provides a standard test method for evaluating these devices.

Figure 2.7 indicates the average benefit that can be achieved with these types of device based on the average noise levels recorded behind the test options at the Noise Barrier Test Facility at TRL. Measurements were based on receivers at a distance behind the barrier of 20, 40 and 80 m and at two heights 1.5 m and 4.5 m. The source was position in front of the barrier at a distance of 8.5 m.

Increasing the height of the barrier by 1 m can increase the average screening by 3.6 dB(A). However with a wide absorptive T-shaped profile (design f) a similar level of performance was obtained (3.1 dB(A)) using a 2 m high barrier. Multiple edge barriers (design g-j) produce lower benefits (approximately 2.5 dB(A)).

An absorptive cylinder shape (design k) was found to yield a smaller benefit of just 0.8 dB(A) when the increased height of the barrier was taken into account. A passive sound...
interference device (Calmzone, design l) yielded a benefit of 1.9 dB(A). The performance of this latter design is further examined in section 3.5.

Figure 2.7: Barrier caps shown in cross-section with posted average improvements relative to a 2 m tall simple barrier

Further designs have been investigated mainly by the Japanese.
3 Barrier types

3.1 Reflective barriers

Reflective barriers are widely used on the UK network. They usually take the form of a vertical timber planking attached to horizontal cant rails. Where higher sound transmission is required the planking is attached to both sides of the rail. A typical cross-section is given in Figure 3.1 below.

![Diagram of Reflective Barriers](image)

Figure 3.1: Example of a reflective timber barrier

The performance of these barriers can be evaluated by applying the Calculation of Road Traffic Noise (CRTN) prediction method (Department of Transport and Welsh Office, 1988) without additional correction.

If the transmission loss is high (single number rating >24 dB(A) i.e. class B3) the screening performance is dependent on the path length difference as outlined above and whether the surrounding ground is absorptive or reflective. With absorptive ground the benefits of erecting the barrier (insertion loss) are smaller since the absorptive ground, such as grass land, can provide some attenuation which is lost when the barrier is erected. This is taken care of in the calculation method since a prediction is made with the barrier present and then without and the greater reduction in these two cases is taken as the insertion loss of the barrier.

It has been found that human sensitivity to noise appears to be greater when the source of noise cannot be seen (Watts et al, 1999d). This means that it is predicted that the rated noisiness is lower behind a transparent screen than an opaque screen with the same noise level. It therefore appears that opaque barriers may not provide the optimum protection. It would be useful to test the hypothesis that transparent barriers provide an advantage in this
respect by examining the relationship between seeing and hearing traffic noise in more detail.

There are further benefits in having transparent screens, as residents can see across the road and the light levels are reduced much less. The visual impact is also reduced especially on elevated structures. The feeling of personal security is also likely to be higher where the pedestrian is not hidden from view. One downside is that the surface is easily defaced by graffiti artists and to maintain the transparent qualities regular cleaning may be required. There is also the problem of birds flying into the panels and various techniques have been devised to overcome the problem e.g. attachment of silhouettes of sparrow hawks, addition of fine lines or grids and introduction of tints during manufacture.

Examples of clear panels are given in Figure 3.2.

![Figure 3.2: Plexiglas transparent barrier on an elevated carriageway (Renzo Tonin and Associates Pty Ltd)](image)

Transparent barrier panels can be combined with timber to produce a pleasing effect for pedestrians and cyclists as can be seen in Figure 3.3.
By tilting the barrier away from the road it is possible to reduce the problem of reflected noise in some cases. An example is shown in Figure 3.4. Modelling work and measurements at full scale have shown that an inclination of 10 to 15 degrees from the vertical is required to prevent additional noise on the farside of the road (Watts, 1996b). However these are measurements normalised to zero wind speed and the modelling work is carried out assuming a still homogeneous atmosphere. Where there is significant wind the sound waves curve through the atmosphere due to refraction. Hence sound waves which under still air conditions may propagate away from the receiver may instead curve downwards to the receiver and increase noise levels. This may cause problems if tilted barriers are used on raised sections of highways where propagation distances to the receiver can be relatively large and the curvature of sound waves becomes important. At ground level in urban areas it is important that properties on the farside of the road are considered since the reflected noise may cause problems for residents living on upper floors. In urban areas with relatively short uninterrupted propagation the refraction effect is likely to be insignificant.
3.2 Earth mounds and vegetative barriers

Earth mounds are widely used at the sides of motorways to provide screening. This is possible where there is sufficient space within the corridor. In urban areas space is usually at a premium so that they are rarely seen in such situations. Generally, for the same height as a simple noise barrier, earth mounds are less efficient at screening noise. This is due to two reasons: (i) the flat or rounded top leads to more noise being diffracted into the shadow zone and (ii) because the base of the mound is relatively wide the top cannot be placed close to the traffic source leading to lower screening performance. Figure 3.5 shows the problem of the displaced diffracting edge for a typical bund with 20 degree slopes. If the bund is 3 m high the base of the slope will be a least 8 m from the road verge. By steepening the slope the leading edge is then less than 1 m away, resulting in a greater path difference and higher screening performance. Note that the base of the earth bund with a typical slope is 17 m while for the steep slope bund it is only 2 m.

One benefit is that there is unlikely to be a build up of sound energy (reverberant field) due
to multiple reflections of sound between mounds on opposite sides of the road. The sloped sides and grassed sides reduce this effect.

Vegetative barriers are barriers made of usually living vegetation. Willow barriers have been erected at a number of sites throughout the UK. These have taken the form of woven willow branches containing an earth core as shown in Figure 3.6(a). It can be seen that the barrier in cross-section is similar to the retained mound (b) in Figure 3.5. The earth core is irrigated by a series of horizontal pipes. They take up less space than conventional earth mounds and have a pleasing green appearance in the growing season as shown in Figure 3.6(b) and the woven willow is attractive in the winter months. However, as well as needing irrigation, these barriers need regularly pruning. A survey of such barriers has indicated that several have failed due to poor irrigation and maintenance.

![Figure 3.6(a): Construction details of woven willow barrier (Weavewall Ltd)](image)

![Figure 3.6(b): Willow barrier in leaf (Weavewall Ltd)](image)
Another form of this barrier consists of a woven basket composed of dead wood retaining an earth core but with evergreen creepers growing over the barrier. An example is shown in Figure 3.7. Potentially this should be more robust as once the creepers have been established there is no requirement to irrigate.

A further design which takes less space is essentially a woven willow fence with ivy growing on the outside. In this case the earth core is replaced by fibrous sound absorbing panels. The willow is dried so no irrigation is required. Figure 3.8(a) shows an example.

A living willow barrier is shown in Figure 3.8(b). This design requires irrigation and is likely to be less robust than the ivy equivalent.

Because vegetative barriers are made of natural materials with growing creepers or willow, the barrier has the potential to enhance the urban environment by providing an attractive contrast with hard man-made surfaces such as brick, concrete, glass and steel. They may also be less attractive to graffiti artists although the sloping sides of the woven willow designs may encourage children to climb the structure which may result in damage or personal injuries.
Belts of trees may also provide some additional reduction compared with grass covered areas. However, studies have shown that the belt needs to be wide and dense to have any appreciable effect. In a study examining the effects on traffic noise of belts of trees of varying density it was found that an open deciduous woodland, shown in Figure 3.9(a), provided much less attenuation than a dense spruce forest as shown in Figure 3.9(b). In order to maximise attenuation it is clearly important to select the most appropriate vegetation for the area, having regard to biodiversity and other issues. It was found that a dense belt of vegetation 10 m deep close to the road could achieve attenuation in the A-weighted $L_{10}$
value of 5 dB compared with grassland. The benefits over hard ground may be 8 dB(A) (Huddart, 1990).

(a) Open deciduous woodland

(b) Dense Spruce forest

Figure 3.9: Range of vegetation measured

The high price of land and pressure of competing uses in many areas, imply that vegetation belts of much greater depth than 10 m are unlikely to be cost effective in many London locations. Possible uses of such tree belts would be to protect parks or gardens where the vegetation could provide an attractive boundary where suitable in biodiversity and other terms.
3.3 Absorptive barriers and claddings

Absorptive barriers reduce reflected sound and can be useful where this is significant and causes disturbance. The absorptive material can take a number of different forms and the following are some of the most widely used absorbers:

- Perforated metal panels or open timber panelling with fibre fill;
- Wood cement materials where the wood fibres are coated with cement to form a porous matrix of bound fibres;
- Flint particles held by a binder to form a porous material;
- Concrete blocks with cavities connected to the outside by narrow slits (Helmholtz resonators).

Figure 3.10 shows examples of a perforated metal panel. The absorber is placed inside the perforated panels to support and protect it from the elements.

(a) Traffic face of metal absorptive barrier panels

(b) Timber absorptive barrier

Figure 3.10: Absorptive metal and timber barrier panels
In the case of an absorptive timber barrier, the traffic face typically consists of widely spaced cover strips and a woven plastic membrane to retain the fibrous absorptive material. This arrangement enables incident sound waves to penetrate the absorber and little sound to be reflected.

The front and rear faces of a typical absorptive timber barrier installation are shown in Figure 3.11. The absorptive face will not be as mechanically robust as a reflective face and therefore may be prone to damage by vandals. The rear of the barrier consists of closely spaced timber planks with cover strips to reduce the direct transmission of sound to the protected area behind the barrier.

Another form of absorber consists of panels of wood/cement construction which is probably more robust than the timber panels discussed above. In this construction wood fibres are coated with cement and combined to form a rigid but porous panel. These can then be supported on the traffic face of a concrete wall at the road side or on the sides of a retained cut to reduce the reverberant build up of sound. Such products as ‘Beton Bois’ are widely used in France and parts of Switzerland to reduce reflected sound. The Beton Bois panels are corrugated and climbing plants appear to thrive on such a surface, creating a visually pleasing effect.

A novel absorber consists of tiny flint particles of the order of 1 mm in diameter in a resin binder. The material can be readily coloured and contoured into various shapes. This may provide an attractive alternative texture to a plane concrete barrier. Figure 3.12 shows the use of different colours for an urban application.
A method of reducing reflected sound in concrete walls is to introduce cavities into the building blocks to form Helmholz resonators. The volume of the cavity, the dimensions of the slit or hole connecting the cavity to the outside determines the frequencies over which the material is effective. Figure 3.13 shows an example of a masonry block barrier.

It is important that the absorbers are tuned to the dominant frequencies in traffic noise as outlined above.

The benefits of such barriers in different situations have been examined both by modelling the situation, by full scale tests and by roadside measurements. In field trials with single and parallel barriers it was found that the effects varied depending on the exact geometry. Replacing the traffic face of a 3 m high absorptive barrier on one side of the road which extended for a distance of 330 m with a reflective face increased noise levels by less than 1 dB(A) on the farside and behind the barrier. Where absorptive barriers up to 3.7 m tall were placed on opposite sides of the road the measured improvement over reflective panels was up to 2.3 dB(A) (Watts and Godfrey, 1999).
Note that the acoustical effects of vegetation growing in close proximity to barriers, e.g. creepers or thin hedges, are not fully understood and further research is required to quantify any benefits.

3.4 Median barriers
Where roads are wide and separated into two or more carriageways there is the possibility of placing low barriers in the central reservation. This limits the spread of sound from the farside carriageways thereby reducing overall noise levels on the nearside. Modelling work and practical tests at full scale have indicated the advantages of this type of barrier in reducing reflected noise especially where reflective barriers have been used on both sides of the road. A median absorptive barrier only 1.12m tall was found to eliminate the contribution of reflected sound from the farside reflective barrier (Watts, 1996b). However, there may be safety implications of cladding median barriers with such material as vehicles may “snag” on impact rather than slide along the face of the barrier. Further work is required to develop this concept further.

3.5 Barriers with novel caps
It has been demonstrated that the performance of plane barriers can be enhanced by the addition of novel shaped caps to the top of the barrier without raising the overall height of the barriers. A number of profiles have been tested alongside roads. A prototype multiple edge barrier (Watts, 1996a) was tested in three locations alongside the M25. It was estimated that the device would produce an additional reduction in noise behind the barrier of up to 3 dB(A) relative to the original plane barrier. Figure 3.14 shows an asymmetric design applied to the top of a timber barrier near Egham. It can be seen that the additional edges are applied on the non-traffic face of the barrier. This is to prevent errant vehicles impacting the edges of the device.

![Figure 3.14: Multiple edge barrier on the M25](image)

T-shaped barriers may be advantageous in an urban setting where a tall barrier may prove visually intrusive. However, the flat surface needs to be supported, and if this is wide the additional cost may be high. Figure 3.15 shows an absorptive T-shaped barrier that is 2 m wide which was recently tested in the Netherlands. The supporting struts can be seen at the extremes of the profile. The cap was so wide that it overhung the road and had to be protected by a concrete safety barrier. An additional noise reduction up to 3 dB(A) was
achieved following installation of the cap.

Figure 3.15: T shaped profile in the Netherlands

A T-shaped profile yields a benefit of up to 3 dB(A) if the top face is absorptive and 2 m wide. Note that it would be of interest to experiment with natural potential absorbers such as grass or sedums if it was shown that they provided sufficient absorptive properties. Such a “green roof” concept may be particularly attractive in an urban environment.

Multiple edge barriers produce a similar benefit while absorptive cylinders and an interference device were found to be less effective.

An absorptive cylinder design produced commercially has been tested alongside highways in Japan (Yamamoto et al., 1995). When attached to a 3 m tall barrier on an elevated road 8 m above the receivers at horizontal distances of 5 m and 20 m from the road edge it produced average noise reductions of 2.3 and 1.8 dB(A) Figure 3.16 shows a similar product that was tested at the noise barrier test facility at TRL (Watts, 1995). The noise reduction in this case averaged 0.8 dB(A) compared with a barrier of similar overall height. The greater performance in the Japanese study may result from the fact that placing the cap on the barrier increases its effective height by nearly 0.5 m. In addition the receivers were well below the top edge of the barrier and this may have increased its effectiveness as the critical sound waves would need to travel around the contour of the whole profile. However such a design does not project horizontally to any great amount and can therefore be attached relatively cheaply to the tops of existing noise barriers without additional support.
A sound interference device called Calmzone, shown in cross-section in Figure 3.17, was developed to improve the acoustic performance of noise barriers and tested with a vehicle noise source (Iida et al., 1984). The authors claim that the sound entering the ducts at the front of the device is channelled down through the ducts and then destructively interferes with the sound that has propagated directly across the top edge of the device. The sound interference effect is due to the additional distance travelled by the ducted component of the sound compared with the sound propagating directly across the top edge. In tests at the TRL Noise Barrier Test Facility it was shown that the device improved average screening by 1.9 dB(A) when compared with a plane barrier of identical height.

Figure 3.16: Rounded absorptive cap (Nittobo)

Figure 3.17: Sound interference noise barrier profile (Calmzone)
Such a device is made from light plastic sections and can be attached to existing barriers without additional support.

A further device shown in Figure 3.18 attempts to create an acoustically “soft” surface on the profile top by including a series of ¼ wavelength channels of varying length (Fujiwara et al, 2000). Such a surface produces close to zero acoustical pressure at the top of the channels due to the standing waves that are excited in the cavities. Space doesn’t allow more than seven cavities to be included in the profile so clearly the full range of frequencies in the traffic noise spectrum cannot be affected.

![Figure 3.18: Barrier profile with a “soft” surface (Fujiwara et al., 2000).](image)

Using an artificial sound source weighted to simulate traffic noise, it was found that behind a barrier 3.25 m in height at a receiver height of 1.5 m a reduction of up to 3.7 dB was measured when the device was added. Note that the geometry of barrier height, source and receiver positions differs between the tests on Calmzone at TRL and the tests on the “soft” surface cap by Fujiwara et al.

The device is made from a synthetic resin material and is injection moulded. Eight separate units are joined to form a single unit 1 m in length.

Cranked barriers are another sort of novel shape that has been used for many years, especially in Japan and Hong Kong to protect high rise buildings. The added effectiveness is due to extending the diffracting edge towards the road, and thereby steepening the angle of the line from source to receiver separating the illuminated and shadow zones. The shadow zone therefore reaches to higher levels on the building producing greater benefits to residents on upper floors. Figure 3.19 shows an installation in Hong Kong designed to protect a high rise apartment block behind. The barrier incorporates tinted transparent panels allowing natural light to penetrate and residents on lower floors to have a largely unimpeded view beyond. Note that due to the limited length of the barriers its effectiveness is somewhat limited (see discussion in section 4.1 below). The effectiveness of reflective cranked barriers can easily be calculated from the path length difference calculations (see Section 2.3 above).
3.6 Photovoltaic barriers

It is possible to incorporate photovoltaic (PV) cells into a novel shaped barrier in order to produce electricity with improved screening performance. A T-shaped or cranked barrier design may be appropriate as its flat surface would be appropriate for collecting sunlight. The PV cells are likely to be reflective to sound so a method of combining absorptive material with the cells would be required in many situations. One method would be to incorporate absorptive panels into a proportion of the total area of the horizontal surface (say 50%). However this would cut electricity production by half and reduce the advantage of the T-shaped profile in terms of noise reduction. If PV panels were incorporated into multiple edge barriers, acoustic performance would be little affected as absorptive material is not required for adequate performance. However, it may be difficult to find arrangements that are optimal for solar incidence. Clearly there is a need for a detailed investigation of the PV cell / barrier profile system so that gains of both noise screening and electricity generation can be optimised. Section 4.4 below examines one option that has been modelled.

The PV elements can be incorporated into acrylic sheeting for protection without reducing energy production significantly. Figure 3.20 indicates the appearance of such panels that could be incorporated into a multiple edge, T-shaped profile, cranked barrier design or possibly the top sections of covers (see below).
TRL have recently been involved in the first public trial of PV cells in a noise barrier. The design involved a series of tilted panels along the front face of a barrier. Figure 3.21 shows a view of the prototype design. It was erected on the Eastbound section of the M27 near Southampton. This motorway runs east-west so that the panels were south facing which maximised the light energy collected.

However, the barrier would need further development to produce a viable noise barrier as it can be seen in Figure 3.21 that there are significant gaps at the top and bottom of the panels which would allow sound leakage. It was demonstrated that these tilted panels did not produce any significant increase in noise on the far side. This agrees with previous modelling work where tilting the whole barrier or a section of it by at least 10 degrees virtually eliminates the reflected noise problem at receiver points opposite the barrier at heights up to 4.5 m. However, the reflected noise could be problem for residents living on upper floors of high rise buildings opposite the barrier.
Weavewall Ltd who supply and construct vegetative barriers are currently investigating the incorporation of PV cells into their products. However few details are available at the present time except that it is known that the PV cells are not glass covered and are being promoted as being of an extremely rugged design.

3.7 Covers and retained cuts

Roads can be covered partially or completely to reduce the spread of noise. A cranked barrier such as that shown in Figure 3.19 can be thought of as a small partial cover. A numerical prediction method, the Boundary Element Method (BEM), has been used to examine the benefits of cranked barriers of various designs. The method has been used extensively to model complex shaped barriers and a brief description of the method is given in Appendix A. Figure 3.22 shows some of the options that have been examined. For each option the value in the rectangle gives the decrease in noise level compared with a plane barrier 6 m tall (option (a)). The receivers are 1.5m above the ground and at a distance of 20 m behind the barrier.

![Figure 3.22: The effects on average noise levels of horizontal extensions to noise barriers.](image)

Significant benefits of over 10 dB(A) or greater are possible with an extension of 8 m (options (d) and (e)). Note that the application of an absorptive treatment to the top edge of the barrier produces a large effect (over 9 dB(A)). However even a relatively short extension of 2 m (options (b)) produces a benefit of nearly 4 dB(A).

Figure 3.23 shows a partial concrete cover extending over the nearside carriageway of the A28 motorway in the Netherlands. In this case the diffracting edge is brought close to the vehicles sources thus extending and deepening the acoustic shadow compared with a plane vertical barrier of the same overall height.
In Hong Kong such partial covers can reach very large dimensions as can be seen in Figure 3.24. In this case the high rise apartment block is protected from both rail and road noise by the cover attached to the front of the building.

A fully enclosed road is the ultimate in screening residential properties and of course all receivers no matter how high above the road will be screened. Figure 3.25 shows a complete cover over a dual carriageway road in Hong Kong which protects the residents in the high rise apartment blocks.
Figure 3.25: Full cover in Hong Kong (EPD)

Figure 3.26 shows a design of cover in concrete on a raised highway in Melbourne.

Figure 3.26: Concrete cover over a raised road section (Melbourne)

A further design involves the use of a transparent material (acrylic) to form a tunnel. Transparent materials allow natural lighting of the tunnel and may be visually more acceptable to residents than concrete or steel panels. Figure 3.27 shows a twin tunnel installation covering a total of four traffic lanes on the SS 36 near Monte Barro in the neighbourhood of Milan.
Such covers can reduce noise levels by substantial amounts (e.g. >20 dB(A)) although there may be problems at the entrances to covers if they do not extend far enough away from the properties the

cover is intended to screen. It some cases it may be necessary to treat the area within the portals with sound absorptive materials in order to reduce noise levels.

If large enough, the area above a cover can be used for recreational areas so that space is not wasted. The tunnel on the M25 near the junction with the M11 and just north of Theydon Bois is an example of such an innovative design. It is possible to build over the road so that the land take of the road is kept to a minimum. There are examples in Hong Kong where the top of the cover has been used as a garden area for residents of tower blocks on each side of the road. In some cases it is possible to sink the road below the level of the surrounding ground in order to reduce noise pollution. However, where the sides are reflective the effectiveness is greatly reduced. Sometimes it is possible to place a roof over the cut so as to produce a tunnel or a set of louvres to reduce the transmission of noise beyond the highway boundary but allow exhaust gases to escape and natural light to reach the road below.

Figure 3.28 shows some of the designs that have been examined using the BEM method. Examining the predicted reduction in noise levels compared with a narrow cut with fully reflective sides it was found that option (a), (b) and (c) with fully absorptive sides with and without absorptive louvers reduced noise levels by more than 14 dB(A) at a distances of up to 80 m from the edge of the cut. Removing the louvres and reducing the amount of absorptive materials on the sides (options d and e) reduced levels by less than 10 dB(A).
Modelling work has shown the importance of including absorptive material on both the sides of the cut and also on the sides of the louvers if present. Very large reductions in noise can be obtained in this way. Further reductions can be obtained by placing barriers on the edges of the retaining wall. An example if this at Eilenburg, Germany is shown in Figure 3.29.

There are examples where the road at ground level or elevated is placed within a complete cover so that sound can only escape at the entrances to the covered section. In these cases it is necessary to control the escaping noise by treating the surfaces inside the cover near the entrances with suitable absorptive material. Partial covers have also been utilised especially where there is a development on one side of the road but not the other.
4 Local solutions

4.1 Barriers of limited length

The acoustic performance of barrier types discussed in the preceding sections is based on very long barriers where the situation is simplified such that there is a single straight road and the barrier is built to the road edge. Thus there is no diffraction around the vertical edges at the ends of the barrier. In practice this is rarely the case, particularly in urban areas where junctions are frequent. In some cases barriers of limited length have been placed in front of the building to be protected as shown for example in Figure 3.19. However the screening performance of such installations may only be a few decibels especially if the barrier covers less than half the visual angle that the road subtends at the receiver. For example in the Calculation of Road Traffic Noise prediction method (Department of Transport and Welsh Office, 1988) if the barrier screens only 90 degrees of the visual angle subtended by a long straight road, then the effectiveness of the barrier is predicted to be 3 dB(A) or less.

To overcome the disadvantage of short barrier runs it may be possible to put returns on the barrier so that the barrier encloses the protected space on three sides, but this will depend on the access required. If vehicular access is required to the space in front of the building then this will pose greater problems than if pedestrian only access is required due to the greater width requirements.

![Figure 4.1: Use of a barrier with returns where side roads are present](image)

On a smaller scale the solution can be applied to protect a garden or playground where it is necessary to preserve a relatively quiet area for relaxation, enjoyment, or, indeed, outdoor educational purposes.

4.2 Reflective facades

Where a reflective facade lies close to the rear of the barrier there may be a problem of reflected sound. Sound which would otherwise miss the receiver may be reflected off the façade and contribute to the overall noise level in the protected area. This is illustrated in Figure 4.2. The noise levels will be increases especially if the ground behind the barrier is also reflective. Reflections between the façade and the rear of the barrier are also possible.
and should not be neglected when examining possible solutions. Treating the ground, rear of
the barrier and even the façade with absorptive materials would be possible mitigation
measures.

Figure 4.2: Effects of a tall façade behind a barrier showing some significant
reflections

Figure 4.3 shows the effects of a 3 m high barrier on the A-weighted noise levels in the
space between the barrier and the building façade (separation 10 m). The source was 6.5 m
from the front of the barrier at a height of 0.05 m. Predictions were made using the BEM
assuming a typical light vehicle noise spectrum.

In Figure 4.3(a) it can be seen that noise levels before the barrier was erected ranged from
75 to 85 dB(A), the average A-weighted level being 79.2 dB. In contrast with the barrier
present (see Figure 4.3(b)) noise levels are reduced and range from approximately 55 to 70
dB(A) with an average level of 63.4 dB. The overall average reduction in the space behind
the barrier was therefore 15.8 dB(A). There is no obvious shadow zone close to the barrier
probably as a result of significant reflections from the building façade.

The situation for residents can be improved further by applying absorptive material to the
rear of the barrier, applying absorptive cladding to the front of the building and by laying
porous asphalt on the ground surface. Porous asphalt because of its pore-like structure is
sound absorptive. Figure 4.3(c) shows the benefits. In this case the reduction is on average
21.7 dB(A). Hence the additional benefit of applying the absorptive is nearly 6 dB(A). A
distinct shadow zone now appears behind the barrier that was not apparent when surfaces
were all reflective.
4.3 Tall facades

Clearly there is a problem of using barriers (reflective or absorptive) in urban areas to protect residents of high rise buildings as the receivers may be in the illuminated zone and receive little or no protection. Note that at the boundary between the illuminated and shadow zone (see Figure 4.2) the predicted reduction would be 5 dB(A). The use of tall curving or cranked barriers, partial and complete covers are possible solutions which have been covered in Section 3. The use of transparent materials will be an important consideration in such tall constructions in order to reduce visual impact, and allow natural light to penetrate into
protected spaces. The effects at receivers close to the façade of the building (5 cm off-set) are shown in Figure 4.4, the results calculated using the BEM. The geometry of the source, barriers and façade is the same as in Figure 4.2 above. The height of the building that was modelled was limited to 12 m due to the constraints of the computer program. However, as can be seen, the receiver heights continue beyond the height of the building. The predicted results on a building taller than 12 m can be obtained by adding 6 dB(A). This is the correction due to pressure doubling close to a hard reflective surface. Figure 4.4 shows the kink in the curves at 12 m due to this effect.

As the receiver height is lowered noise levels increase as the receiver gets closer to the noise source. Below approximately 10 m the noise levels begin to reduce due to the screening effects of the barrier. The transition between the illuminated zone and shadow zone of the barrier occurs at a height of approximately 7.5 m. At this point the noise levels are about 5 dB(A) down on the levels without the

![Figure 4.4: Sound pressure levels at the façade](image)

The analysis demonstrates the usefulness of absorptive materials in combination with a barrier and the need to consider the noise screening of the barrier on upper floors. When designing for effective noise mitigation the intersection of the shadow zone boundary with the façade is a critical parameter.
4.4 Novel barrier profile incorporating PV cells

A simulation of a multiple edge barrier with a PV panel suspended above has been examined using the BEM. A cross-section of the novel profile on the 3 m tall barrier is shown in Figure 4.5.

![Diagram of a novel barrier profile incorporating PV cells](image)

**Figure 4.5: PV panels suspended 250mm above a multiple edge barrier profile**

The underside of the PV panel is treated with absorptive material to reduce reflected noise which might increase noise in the shadow zone.

BEM predictions were made for the source, barrier and façade geometry shown in Figure 4.2 above. Separate predictions were made with and without the profile attached to an absorptive barrier with absorptive ground beyond and an absorptive facade. The predictive noise levels in the space between the rear of the barrier and façade are shown in noise level contour plots in Figure 4.6.
The average noise levels reduced from 57.5 dB(A) to 56.0 dB(A), i.e. a reduction of 1.5 dB(A). At the building façade the noise reductions were greater. At a height of 1.5 m the reduction due to the profile was 3.0 dB(A) and at 3 m it was nearly 4 dB(A).

5 Recycled materials in noise barriers and claddings

Recycled plastic materials are currently finding applications as efficient sound absorbers in a number of products including domestic appliances and tractor cabs. However, the material has not so far been used in noise barriers.

A life cycle analysis performed on a noise barrier at Huggenes as part of the Norwegian roads recycled material R and D programme showed that the environmental effects of shredded tyres were less than the corresponding effects from stone aggregate. If positive recycling effects are also considered and compared to the use of virgin materials, recycling of shredded tyres has an advantage.

The Norwegian organisation involved in the research (www.gjenbruksprosjektet.ne) recommended that more projects are carried out in order to provide more information on the technical properties of the material and also further documentation and knowledge about its environmental properties.

However, results of a public trial of recycled material in roadside noise barriers including tests of acoustic performance have not been found within the timescale of the current project.
6 Costs

The costs of barriers and covers of various designs will depend critically on the material, type of construction and dimensions. In attempting to compare costs, some indicative costs for installing a barrier in London have been obtained. Costs are given in terms of costs of supply and erection of a 1 m length of barrier with a height of 3 m.

It can be seen that the timber barriers are the cheapest option both for absorptive and reflective options. The concrete option is also relatively cheap but is reflective. A wood cement absorptive or metal absorptive barrier is considerably more expensive.

<table>
<thead>
<tr>
<th>Barrier type</th>
<th>Type</th>
<th>Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber (single leaf)</td>
<td>Reflective</td>
<td>210</td>
</tr>
<tr>
<td>Timber (double leaf)</td>
<td>Reflective</td>
<td>275</td>
</tr>
<tr>
<td>Timber (single leaf)</td>
<td>Absorptive</td>
<td>350</td>
</tr>
<tr>
<td>Vegetative barrier (living willow)(^1)</td>
<td>Partially absorptive</td>
<td>360</td>
</tr>
<tr>
<td>Concrete</td>
<td>Reflective</td>
<td>360</td>
</tr>
<tr>
<td>Vegetative barrier (ivy covered)(^2)</td>
<td>Partially absorptive</td>
<td>415</td>
</tr>
<tr>
<td>Aluminium panels</td>
<td>Absorptive</td>
<td>575</td>
</tr>
<tr>
<td>Wood / cement</td>
<td>Absorptive</td>
<td>590</td>
</tr>
<tr>
<td>Transparent acrylic</td>
<td>Reflective</td>
<td>600</td>
</tr>
<tr>
<td>Transparent cover(^3) over 2 lanes (acrylic)</td>
<td>Reflective</td>
<td>10,350</td>
</tr>
<tr>
<td>Transparent cover(^3) over 2 lanes (laminated glass)</td>
<td>Reflective</td>
<td>15,870</td>
</tr>
</tbody>
</table>

\(^1\) Not included are costs of water throughout its life and annual pruning
\(^2\) Not included are costs of water over first 3 years after which no further irrigation is required
\(^3\) Maximum height is likely to be of the order of 8 m

Note that it is possible to obtain aluminium panels with absorptive materials behind both faces. The total installed cost is unlikely to be significantly higher than a standard absorptive panel with one face absorptive.

The use of transparent covers, although achieving very large reductions in noise levels is relatively very expensive when compared with the barrier options. However both sides of the road are protected and the benefits are felt on upper floors of high rise buildings. Table 6.1 shows that costs are of the order of 20 times those for a 3m high transparent barrier. However, where housing densities are high the cost per apartment protected may be more comparable to the cost of protecting 2 storey homes with conventional barriers.

The design life of these barriers is unknown except for timber barriers where a 30 year design life is required by the Highways Agency. Typically manufacturers will not guarantee the acoustic performance of absorptive barriers beyond a 10 to 20 years time span.

Vegetative barriers with living willow are prone to problems of irrigation failure and attack by...
pests so a useful life may only be 10 years. However, barriers including ivy should prove more robust as they do not require irrigation after the plants are established.

It can be seen that for both absorptive and reflective barriers, timber is likely to be the most cost effective solution purely in cost per decibel reduction. However, looking at whole life costs over say a 20 to 30 year period a more robust barrier may be more cost effective under urban conditions.
7 Summary and Conclusions

The following conclusions can be drawn from a review of noise barrier types, performance and costs.

- Reflective barriers make an important contribution to reducing noise although it will be necessary to consider returns on barriers where it is only possible to erect a short length of barrier along the main road. Sound leakage through the barrier needs to be considered at the procurement stage, when installed, and periodically thereafter. Standards BS EN 1793-2 and BS CEN/TS 1793-5 can be used to assist in ensuring an adequate standard is achieved.

- There is a wide variety of materials available with timber being the lowest cost option and transparent screens at the higher end. Transparent screens, alone or in combination with other materials, are an option worth considering due to their possible advantage in terms of noise, personal safety perception and transmission of natural light. Complete covers may be of the order of 20 times as expensive as conventional barriers. However, where housing densities are high e.g. high rise apartment blocks on both sides of the road, their use may be justified.

- Absorptive barriers add substantially to the cost and can be justified where reflected noise is likely to be a significant problem. Absorptive materials need to be selected so that they are strongly absorbent at frequencies that are dominant in typical traffic noise. BS EN 1793-1 can assist in the procurement of suitable panels or claddings.

- Novel barrier profiles can be used to obtain additional screening benefits without raising the height of the barrier. This may be useful where the visual impact needs to be limited or where views need to be preserved. However there are few commercial products world-wide and there is no known supplier in the UK. Prototype barrier profiles can of course be assembled for test purposes and a trial was successfully carried out at three locations on the M25 with a multiple edge profile.

- The use of Photovoltaic (PV) barriers in combination with novel barrier profiles would produce a 'win-win' situation, i.e. additional noise screening and the generation of electricity. Using the boundary element method approach some promising improvements in screening have been predicted. Further work is required to optimise the system in terms of both noise reduction and solar energy conversion. One supplier of a vegetative barrier is considering the inclusion of a robust PV cell material into a barrier scheme although no definite details are available at the present time.

- The robustness and ease of cleaning of materials needs to be carefully considered in urban areas due to the likelihood of vandalism and graffiti. Some absorptive panels are not very robust (e.g. timber absorptive) and other materials such as wood / cement products may be more appropriate although costs are significantly higher (estimated to be 70% increase). Some vegetative barriers with sloping sides may encourage climbing and there are therefore issues of personal safety and damage to the barrier structure itself. Vegetation growing in close proximity to more conventional barriers is worthy of consideration as it could protect surfaces from vandalism and graffiti and enhance the visual appearance. The acoustic benefits of the use of vegetation used in this way are not known and further research is required.

- Vegetative barriers are attractive because they can provide a welcome relief to hard man-made surfaces such as brick, concrete and asphalt. However the living willow variants require continuous irrigation and their long-term robustness can be
questioned. Similar barriers covered with ivy have the potential for greater useful life as irrigation is not required after the creepers are established. They also do not need annual pruning and can exist in shady conditions. They may be less attractive to graffiti artists than conventional barriers.

- Noise is diffracted around the ends of barriers and short runs of barrier may be ineffective in reducing noise. To overcome the disadvantage of short barrier runs it may be possible to put returns on the barrier so that the barrier encloses the protected space on three sides, but this will depend on the access required. Where barriers are placed directly in front of buildings there may be a problem of reflected noise which reduces the effectiveness of the barrier. Boundary element modelling has demonstrated the advantage of applying sound absorptive material on the surfaces behind the barrier.
Acknowledgements

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References


Appendix A. Boundary element method (BEM)

The BEM is a numerical approach which obtains accurate solutions to the Helmholtz wave equation that governs the propagation, reflection and scattering of acoustic waves in a homogeneous atmosphere. The approach has the advantage over ray-tracing methods and other numerical techniques since it provides an accurate treatment of the diffraction, scattering and absorption of sound that occurs in the presence of obstacles such as noise barriers. A further advantage is that the cross-sections that can be modelled can be complex and specified with considerable precision and absorptive surfaces can be accurately defined.

TRL’s experience with the model extends back to the early 1990s. Projects undertaken for customers such as the Highways Agency have required significant adaptation/improvement of the basic BEM model. These modifications have improved the calculation efficiency when studying large site cross-sections, particularly those including physical features such as cuttings and embankments, and allowed the use of the state-of-the-art in road surface and barrier materials and an improved representation of traffic noise sources. These improvements allow the model to be readily applied for identifying and assessing the effectiveness of state-of-the-art solutions for reducing the impact of transport noise. Examples of application include examination of novel barrier shapes and earth bunds (e.g. Watts et al, 1994; Watts and Morgan, 1996; Watts 1999a), the combined effects of porous road surfaces and noise barriers (Watts et al, 1999c) and propagation through barrier gaps and louvres (Watts, 1999b; Watts et al, 2001).

Huygens (1690) developed the idea that every point on a wavefront (surface) of constant phase can be represented as a source of secondary wavelets and that the further development of the wave can be obtained by superimposing these wavelets. It is obvious that a wave disturbance of some sort spreads out from every point disturbed by the passage of the wave, but the phase of the wavelet and the distribution of amplitudes in different directions are not immediately apparent. An analytical approach is made by transforming the Helmholtz equation which governs the propagation, reflection and scattering of acoustic waves in a homogeneous atmosphere. This transformation is made in such a way as to obtain the disturbance at a given point in terms of the behavior of the wave at any point on the scatterer’s surface. It has been found that that the contribution from each element on the surface depends not only on the amplitude of the incident wave but also on the gradient of the wave’s amplitude in the vicinity of the surface.

The BEM basically uses this approach to accurately solve the governing Helmholtz wave equation in two dimensions. The method is most commonly applied in two-dimensions (2-D) for transport noise propagation calculations. Although the true physical problem has distinct differences from the two-dimensional approximation, results from 2-D BEM calculations can be successfully and accurately related to physical measurements.