Feature

FINAL REPORT

TECHNICAL ASSESSMENT OF THE EFFECTIVENESS OF NOISE WALLS

APPROVED BY THE INTERNATIONAL INSTITUTE OF NOISE CONTROL ENGINEERING.

Executive Summary

This initiative of International INCE deals with noise walls—the outdoor barriers erected in parallel with highway and rail lines, and in other areas (such as airport runways), where there is a demand to reduce the noise levels of surface transportation sources. There is worldwide interest in the control of noise by the erection of such barriers. Walls are composed of wood, metal, masonry, earth, and other materials, both opaque and transparent. Most of the walls that have been erected to date completely block the sight lines between vehicles and roadside housing. The cost of installation usually exceeds USD one million per kilometre. In some countries, governmental authorities have authorized the use of highway construction funds for the erection of noise walls. When building a new highway or widening an existing highway, the construction of noise walls is required in some jurisdictions when the predicted noise levels of the road traffic exceed defined governmental guidelines. The key questions are: how valid are the traffic noise predictions, and how effective are the noise walls acoustically after they have been erected? Over the years, a number of analytical studies have facilitated the prediction of the noise reduction afforded by such barriers. It is reported, however, that barriers may not always perform acoustically as well as intended.

The principal objective of this study is to obtain a global view of the effectiveness of noise walls—the outdoor barriers erected in parallel with highway and rail lines, and in other areas (such as airport runways). The report summarizes the scientific basis of noise barriers, including measures of barrier efficiency, the physical phenomena involved (including effects associated with the propagation and effects associated with the noise wall as well as different barrier shapes), and the various models used to predict barrier performance. Different barrier materials are briefly described. The measurement of barrier effectiveness is also discussed. A section discusses the three main application areas where barriers are used: road traffic noise, railroad noise, and ground-based aircraft operations.

The main conclusions of the Working Party are summarized below:

1. There is a strong body of evidence to support the use of barriers as an effective method of abating transportation noise.
2. The best descriptor of barrier performance is its insertion loss, which is the difference in the noise environment before and after the barrier is constructed.
3. It is the collective experience of the Working Party that the most common values for A-weighted insertion loss range between about 5 to 12 dB.

4. Barrier height is of fundamental importance to the effectiveness of a barrier. Proximity of source/receiver relative to the barrier is also of fundamental importance to the insertion loss provided by a barrier.
5. The material used to construct barriers must be such that there is sufficient transmission loss of sound through the wall. It is also important that there be no significant air gaps in the structure nor between the barrier and the ground.
6. Sound-absorbing material may be important in reducing noise between parallel reflective walls

Finally, recommended directions for future research are presented.

Foreword

The International INCE General Assembly on 1994-08-31 approved an initiative to review current knowledge and practice concerning *Effectiveness of Noise Walls* with the objective of obtaining a review of the technical aspects of the acoustical performance afforded by noise barriers for transportation noise sources. This initiative deals with the important physical phenomena and how to model them.

The study was undertaken with the following objectives:

1. Identify the development of barrier usage and performance during the past few decades.
2. Examine the scientific basis behind noise barriers by listing the physical phenomena affecting their performance. Discuss which phenomena are important and to what extent. Review the use of parallel barriers and the need for absorptive material.
3. Collect the available information regarding the performance afforded by noise barriers separated into three areas of application: road, rail, and ground-based airport operations.
4. Provide information on tolerance/spread of prediction to provide an informed judgement for legislation.
5. Discuss the generic properties of products used in the construction of noise barriers.
6. Identify outstanding issues and direction for future work.

The study started in 1995 April, when members of a Working Party on the Effectiveness of Noise Walls were appointed by the Member Societies of I-INCE. The study was completed in 1997 and published as a draft report in *Noise/News International* in 1998 (Vol. 6, No. 1, pp. 11-36), 1998 March. After review and changes, this report was approved for publication by the International INCE General Assembly on 1998-11-15.

Each member of the Working Party which prepared this report represents a different Member Society that supports the International Institute of Noise Control Engineering; in addition, there was a Convenor. Countries and members of the Working Party as follows:

Convenor: Gilles A. Daigle

Australia: Ron Rumble
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Italy: Alessandro Cocchi
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Sweden: Leif Åkerlöf
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This report was approved for publication by a unanimous vote of the General Assembly at its meeting in Christchurch, New Zealand, on 1998.11.15. The Board concurs with the decision of the General Assembly and the final report is published herewith.

Report by the International Institute of Noise Control Engineering Working Party on the Effectiveness of Noise Walls

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INCE Classification Numbers:
31, 52, 24

Introduction

Transportation activities are one of the most commonly occurring sources of noise outdoors. Sources can be classified into air, road, and rail transportation. Noise levels from these transportation sources are not usually sufficiently high to cause permanent hearing loss in communities affected, but they may cause considerable annoyance and activity interference. For example, recent reports indicate that a large number of persons worldwide are exposed to outdoor time-average A-weighted sound levels L_{Aeq8h} greater than 65 dB. The most effective noise control measures are those affected at the source, particularly by quieter designs, together with the application of careful land use planning measures in the community. Tangible progress has been made in the abatement of aircraft noise through new generations of quieter engines. Also, in motor vehicles, quieter engines, better air-intake and exhaust mufflers, quieter tires, and more recently, low noise road surfaces reduce the impact of traffic noise in communities along roadways. These advances have been directed by legislation in many countries in which the allowed maximum noise levels from road vehicles and aircraft have been progressively reduced. Recently, I-INCE reviewed the effects of regulations on road vehicle noise.

There are also many ways of modifying the transmission path to reduce the level of noise at the receiver. At the land use planning stage, the distance between source and receiver can be increased by setting aside sufficiently large areas of land along new roads and around new airports. The receiver can be screened from ground transportation noise by erecting noise barriers. Barriers are now in common use as a method of abating noise. They are used to reduce the noise from vehicle traffic, railways, and to some extent, to control noise from ground-based airport operations such as start of take-off roll. A large body of research work has been carried out aimed at understanding the diffraction of sound around barriers, predicting their performance and developing more efficient designs.

This report reviews the scientific basis for the performance afforded by noise barriers. Barriers derive their performance by blocking the line-of-sight as illustrated in Fig. 1 thus creating a sound shadow. Barrier performance is measured by its insertion loss defined as the difference in sound pressure level before and after the barrier is constructed

$$D_{IL} = L_p(\text{before}) - L_p(\text{after}).$$

In some cases L_p(before) is not available and the insertion loss is approximated by some other measure.

The factors affecting the performance of noise walls can be grouped as those relating to the source, to the surrounding total environment, and to the noise wall itself. After a brief discussion of the various source factors, the physical phenomena associated with outdoor noise propagation are then discussed in detail, followed by a review of the effects associated with the noise wall.

Accurate prediction of barrier insertion loss must account for a wide variety of physical phenomena simultaneously. This is beyond current capabilities and thus limits the accuracy of any prediction model. There are currently a large number of models in use today around the world to predict barrier performance. The accuracy of various models depend on how many physical mechanisms are included and to what level of detail they are considered and how the source is modeled. This report will therefore stress that results from models should only serve as a guide to expected barrier performance, as different models will yield differing results.

The report includes a brief discussion of the generic properties of the products and materials used to construct noise barriers. The issues related to the measured field performance of noise barriers are discussed. Finally the report reviews the three main areas of application: road noise, rail noise, and noise from ground-based airport operations.

Purpose

The main purpose of this report is to undertake a state-of-the-art review of the technical aspects of the acoustical performance afforded by noise barriers for transportation noise sources; road, rail, and airport ground operations (runup, taxi, take off, landing). The report describes different types of barriers and focuses on the important physical phenomena and how to model them. The document is intended for the non-specialist as well as technical designers and practicing engineers. Extensive references are provided. The report is also intended as an educational paper to review all the relevant issues as they are understood by the Working Party. The report identifies outstanding issues and directions for future work. The objective is to develop a program of
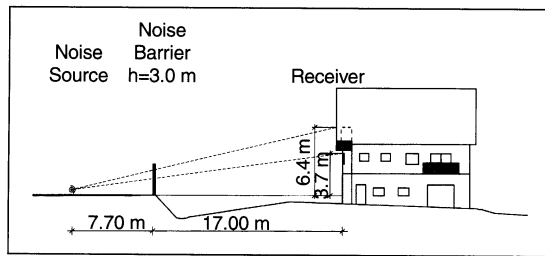
Fig. 1. Barriers derive their performance by blocking the line-of-sight.

work for a future I-INCE Working Party dealing with the measurement and evaluation of noise walls.

Scope

The report describes the work on barriers worldwide and comments on the current state of knowledge. The scientific basis behind noise barriers is reviewed. The report comments on the height of the barriers, the effects of parallel barriers, modification of performance due to multiple edge barriers and the use of absorptive treatments, and the effects of gaps and holes on transmission loss. Particular attention is paid to existing design solutions. Measurement methods are discussed including intrinsic properties and extrinsic *in-situ* performance. The report includes general non-acoustical parameters such as long-term performance but excludes aesthetic, structural and maintenance considerations. Three areas of applications are reviewed; road noise, rail noise, and noise from ground-based airport operations. This document focuses on free standing vertical noise walls.

The International Organization for Standardization (ISO) has an active standards development group that has recently completed a Draft International Standard on a general method of calculating the attenuation of sound during propagation outdoors and includes the presence of noise walls. It is intended that the program of work of the I-INCE working party will not duplicate or overlap the work of the ISO. In addition, the European Committee for Standardization (CEN) is developing acoustical test methods for road side noise barriers in TC226/WG6/TG1. These include tests of sound transmission, sound absorption and definition of the traffic noise spectrum.

Scientific Basis

A noise barrier can be defined as any solid obstacle that is relatively opaque to sound, that blocks the line-of-sight from sound source to receiver, thus creating a sound shadow. Since the dimensions of the barrier are usually of a similar order of magnitude as the wavelength of the sound, the shadow is not sharply defined. Significant sound energy propagates into the shadow region. The

factors affecting the performance of noise walls can be grouped into those relating to the source, to the surrounding total environment, and to the noise wall itself.

There are various types of sources. At distances that are large compared with the effective size of the noise source, most sources can be considered a localised point source. Very often barriers are installed close to the noise sources, and these sources must be considered as extended sources. In the case of long moving sources such as trucks or trains, there are often time-related effects on the attenuation associated with multiple reflections between the source and the barrier. Vehicle traffic noise sources can be a distribution of sources such as road vehicles or a line source such as railway vehicles. The spectral characteristics of the source or sources are also important. Many models assume a dominant octave frequency and calculations are performed directly in A-weighted sound levels. In other models, the spectral components of the source are used to perform calculations per octave or 1/3 octave frequency band.

Sound propagating outdoors through the atmosphere generally decreases in level with increasing distance between source and receiver. This attenuation is the result of several mechanisms, principally geometrical divergence from the sound source, absorption of acoustic energy by the air through which the sound waves propagate, and the effect of propagation close to different ground surfaces. Atmospheric conditions, principally wind and temperature, have major effects on the propagation of sound over distances greater than about 100 m. All these effects must be considered to assess accurately the acoustical effectiveness of sound barriers.

There are several effects associated with the noise wall itself. Barrier height is of fundamental importance to the attenuation produced by the barrier. The higher the barrier, the more the line-of-sight is blocked, the greater the path difference (difference in length between the unobstructed path and the path over the barrier top) and the greater the attenuation. The nature of the noise wall is also a factor. There are modifications of performance due to shape of the noise wall, the nature of the diffracting edge, the finite length of the noise wall such as at access gaps, and the addition of absorptive material.

The position of the source or receiver relative to the barrier is also of fundamental importance to attenuation. There is also degradation due to parallel barriers, and interaction between the source and barrier when large sources are close to the wall. In the case of parallel barriers, the ratio of the width (W) separating the two barriers to the height (H) of the barriers is an important factor. Other aspects also

come into play such as the construction and transmission loss of the barrier as well as gaps due to deterioration of the structure and gaps between the barrier and the ground. It is important that there be no significant air gaps.

Measures of Barrier Efficiency

In general, a barrier's performance is measured by its insertion loss (D_{IL}). The insertion loss of a barrier at a given point is defined as the difference in sound pressure level (measured at that point) before and after the barrier is constructed.

$$D_{IL} = L_p(\text{before}) - L_p(\text{after}) \tag{1}$$

Insertion loss can be defined for sound of a single frequency, a band of frequencies or a broad band source. Insertion loss is of direct practical interest to those considering the construction of a barrier; it also avoids the ambiguity that arises because the barrier, besides introducing attenuation due to diffraction, also commonly reduces the attenuation due to the ground (by increasing the height of the sound path above the ground). The insertion loss of a barrier varies with several parameters, most notably the frequency of the sound (the higher frequencies are more attenuated). Insertion loss can be determined by means of calculation or measurement.

In some cases, especially when a barrier is already in place, $L_p(\text{before})$ is not available and the insertion loss is approximated by some other means. The Nord Test Nr. 496-84 defines an index called the Barrier Noise Reduction (B.N.R.). According to this index, the "before" condition is estimated from sound pressure levels measured by a microphone located at a height of 1 m above the barrier and correcting these levels to the required distance. The B.N.R. index has sometimes been used in Japan. In the USA, ANSI S12.8-1987 standard describes a similar method, as well as an approach that employs an equivalent site without a barrier.

In many cases, barrier noise reduction is expressed as "attenuation." The term attenuation can have many definitions. The most widely used definition for attenuation is to describe the amount of diffraction behind a barrier and usually refers to sound levels behind the barrier relative to the sound levels in the absence of the barrier and the ground, i.e., in free field.

For lightweight construction, the transmission loss of the barrier is an important measure. The transmission loss (TL) of a partition or test section of a noise wall, for a specified frequency band, is given by

$$TL = L_{pS} - L_{pR} + 10 \lg(S/A) \tag{2}$$

where L_{pS} and L_{pR} are the average sound pressure levels in a reverberant source room and receiving room respectively (expressed in decibels), S is the area of the common partition and A is the Sabine absorption in the receiving room. The construction of the barrier must ensure that it has a closed surface without large cracks or gaps and the surface mass is at least 10 kg/m^2 to ensure adequate TL.

The most commonly used noise index to describe road and rail traffic noise is the A-weighted equivalent continuous noise level, L_{AeqT}, which is specified over a time period T. Other statistical noise level indices are used in some countries, including L_{A10}, L_{A50}, L_{Amax}, L_{Ax} or SEL. For example, L_{A50} is currently used in Japan for road traffic noise and L_{Amax} for railway noise (although the use of L_{Aeq} is currently being proposed).

Physical Phenomena—General

Sound levels in the vicinity of an outdoor source are influenced by the medium through which the sound propagates. Normally occurring variations in meteorological conditions result in sound level variations and the presence of the ground, in particular, or other surfaces normally influence levels. In order to design a noise barrier, it is imperative to understand and consider the influence of environmental variables on the sound levels. Embleton (1996) has recently published a tutorial on sound propagation outdoors. This section summarizes the physical phenomena associated with outdoor sound propagation.[1]

Sound propagating outdoors through the atmosphere generally decreases in level with increasing distance between source and receiver. The octave-band (or 1/3-octave band) sound pressure level L_p, in decibels, at a microphone can be approximated by

$$L_p = L_W - A_T - 10 \lg(4\pi) \tag{3}$$

The term L_W in Eq. (3) is the effective sound power level of the source (in decibels re 1 pW) for radiating sound in the direction of propagation from source to receiver. (A temperature of 20° C and an atmospheric pressure of 1 atm has been assumed). The total attenuation in each octave band, A_T in decibels, is the result of several mechanisms and can be approximated by

$$A_T = A_s + A_a + A_e \tag{4}$$

In Eq. (4) the first three terms give the attenuation from three principal mechanisms—geometrical spreading from the sound source (A_s), absorption of acoustic energy by the air through which the sound waves propagate (A_a), and the effects of the environment (A_e). The environmental effects arise principally from propagation close to different ground surfaces in the presence of ambient atmospheric conditions, especially wind and temperature variations. The last term (A_e) also covers attenuation from

additional effects which arise only in specific cases, in particular, diffraction by a noise barrier.

In the case of a line source the total attenuation can be obtained by integration of a series of point sources along the line.

Geometrical Spreading

At large distances from a source in a homogeneous, non-dissipative atmosphere in the absence of a reflecting plane, the sound pressure varies inversely with distance from the source. The attenuation due to spreading, A_s, is therefore approximated by

$$A_s = C \lg(r/r_0) \text{ (dB)} \tag{5}$$

where r is the distance from the source center in metres and r_0 is a reference distance of 1 metre. For a point source $C = 20$ and for a line source $C = 10$.

Air Absorption

As sound propagates through the atmosphere its energy is gradually absorbed by a number of energy-exchange processes in the air. The amount of absorption depends strongly on frequency and relative humidity, and less strongly on temperature. It also depends slightly on the ambient pressure, sufficiently to require consideration with large changes of altitude (thousands of metres).

In most conditions, dry air can produce high attenuation of sound at high frequencies. Therefore, in the case of a predominantly high-frequency source, measurements made under dry conditions can differ considerably from measurements made under more humid conditions.

Details on attenuation by air absorption are given in American National Standard "Method for the Calculation of the Absorption of Sound by the Atmosphere" (ANSI S1.26-1978 (R1995)) or International Standard ISO 9613-1 "Acoustics—Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere."

Effects of the Environment

There are two main environmental factors which can influence sound propagation:
*   The ground effect—including surface properties, source and receiver heights;
*   Meteorological conditions—including wind velocity gradients, temperature gradients, and turbulence.

The propagation of sound close to the ground for horizontal distances less than a few tens of metres is essentially independent of meteorological conditions; for this case the atmosphere can be regarded as homogeneous and the sound paths (see Fig. 2) approximated by straight lines. The attenuation due to the effects of the environment (A_e) is then that due to the ground alone. For greater distances, meteorologi-

cal conditions usually become a major factor. These factors are refraction by wind and temperature gradients, and atmospheric turbulence. The meteorological effects then modify the ground attenuation to produce the total attenuation due to the environment.

When the sound source is located above a ground surface, sound waves which reflect from the ground will constructively or destructively interfere with those propagating directly from the source (see Fig. 2). Since most grounds are partially reflecting, the reflected wave is also modified in amplitude and phase by its interaction with the ground surface. The amount of attenuation attributable to this ground interaction, and its variation with frequency depends on the surface type and the source/receiver heights and their separation. The effects of the ground are largest for intermediate frequencies (around 500 Hz) when the source is above the ground (1 m or more). If the source is close to the ground all frequencies above 500 Hz display large attenuations.

The main effect of meteorological conditions is refraction, a change in direction of the sound wave propagation, produced by vertical gradients of wind and temperature. Sound refracts (bends) upward, as shown in Fig. 3(a), when the propagation is upwind. Refraction upward often produces a shadow zone near the ground, as shown in the figure, resulting in an excessive attenuation that often reaches 20 dB or more. Sound refracts downward, as shown in Fig. 3(b), when the propagation is downwind. Such downward refracting conditions are favourable for propagation, producing a minimum of attenuation due to the effects of the environment.

During the late morning and afternoon on sunny days, the air temperature usually decreases steadily with increasing height above the ground, a condition known as temperature lapse; sound refracts upward resulting in a shadow zone near the ground [Fig. 3(a)]. In contrast, at night the temperature often increases with increasing height (due to radiation cooling of the ground surface), a condition known as temperature inversion, which may extend to one hundred metres or more above the ground late at night. In a temperature inversion, sound refracts downward, producing a minimum of attenuation due to the environment [Fig. 3(b)].
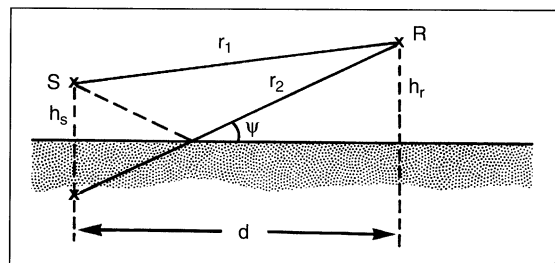

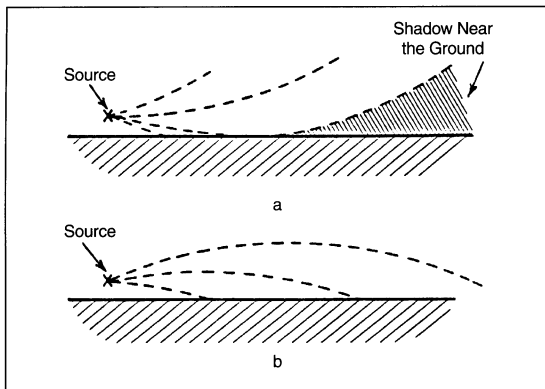*Fig. 2. Direct path r_1 and reflected path r_2 between source S and receiver R.*

Fig. 3. (a) Sound refracts upward when the propagation is upwind or during sunny days. (b) Sound refracts downward when the propagation is downwind or during a temperature inversion.

The atmosphere is an unsteady medium with random variations in temperature, wind velocity, pressure, and density. In practice, only the temperature, wind direction, and wind velocity variations significantly affect sound waves over a short time period. When sound waves propagate through the atmosphere, atmospheric turbulence scatters the sound energy resulting in random fluctuations in measured sound pressure levels. Many acoustical phenomena are strongly and directly affected by atmospheric turbulence. For example, the scattering of sound energy increases the time-average sound levels behind a noise barrier, thus limiting the attenuation that can be provided by a barrier.

Physical Phenomena Associated with the Noise Wall

Numerous physical features[2-22] associated with the noise wall can influence its insertion loss:

- Barrier height and proximity of source/receiver to the barrier;
- Sound absorbing material in the case of a single wall;
- Sound absorbing material to reduce multiple reflections due to parallel reflecting walls;
- Atmospheric effects;
- Effects associated with the surface of the source;
- Time related effects;
- Transmission loss.

A thin barrier is one in which diffraction occurs at a single edge, as shown in Fig. 4(a). A solid fence, of the type usually constructed to be a noise barrier, and a free standing wall are examples of a thin barrier. A thick barrier is one in which diffraction occurs at two edges, i.e., another diffraction point is provided as shown in Fig. 4(b). A building or an earth berm with a wide flat top are examples of a thick barrier. Typically, if the barrier thickness is greater than 3 m, a barrier is regarded as thick for sound components of all frequencies. If the thickness t is less than 3 m, the

barrier is still regarded as thick for sound components of wavelength less than $t/5$.

Barrier Height and Proximity of Source/Receiver to the Barrier

Barrier height and proximity of source and receiver to the wall are of fundamental importance to the attenuation provided by a barrier. In countries around the world, typical barrier heights range between 2 and 6 m. In some countries heights of 8 to 10 m are common and heights as low as 1 m are also found. Barrier protection is greatest for the first row of housing (closest proximity) while reduced protection results for further rows of housing. The most common values for insertion loss range between about 5 and 12 dB, but values between 3 and 25 dB are also measured.

The highest insertion loss is found in the case of rail traffic noise due to the proximity of the source to the barrier. For example, the normal barrier height for the Shinkansen Railway (high speed railway) is only 1.5 to 2 m, while in Europe typical rail barriers are only slightly higher, yet these barriers are found to be quite effective. Intermediate values of insertion loss are characteristic for road traffic noise. For example, in the US highway barrier heights of 6 m and 7 m are very common. In Japan the normal barrier height for highways is 3 m and measured B.N.R. ranges between 15 dB to 23 dB, but barriers tend to reach a height of 8 m to achieve B.N.R.s of 25 to 30 dB in the suburbs of Tokyo. Barrier heights of 5 to 6 m are now common in Australia. Measured insertion losses for barriers 3 to 6 m high are typically between 5 and 12 dB. The smallest insertion loss is obtained in the case of ground-based airport opera-
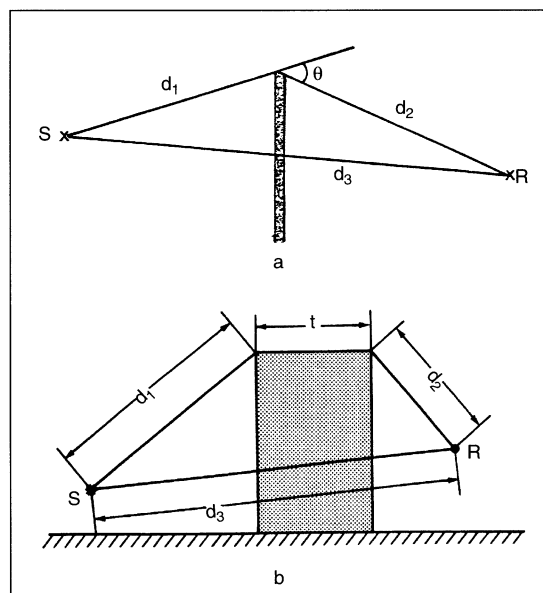

Fig. 4. (a) Diffraction at a single edge. (b) Diffraction occurs at two edges with a thick barrier.

tions due to the larger source/receiver distances and greater source height. For example, barriers 10 m high are common for runup enclosures at US airports, with propagation distances up to 2000 m.

Sound Absorbing Material— Single Walls

Given a thin vertical reflecting noise barrier that obstructs the source-receiver path, an added device, material, or shape may be used to improve its performance. However, such modifications must not be used to reduce the height of such a barrier below the source-receiver direct paths.

There is a body of evidence[10,16,20-22,28,48] to suggest that the use of absorbing materials can enhance barrier performance. The information is based on the effects of absorbers on single barriers and parallel barriers. As with all barrier problems it is very difficult to give a simple description of a particular effect since so many other parameters are involved. Nonetheless, the general principles can be described. Placing absorptive material on a single barrier has theoretically two advantages (see Fig. 5). One is to reduce diffracted sound into the shadow zone. The second is to minimize sound reflection between the source and the barrier surface, thus avoiding the build up of the sound level.

The effectiveness of absorbing surfaces depends upon the efficiencies of the absorbing material. The effectiveness of a porous absorber usually decreases as the frequency decreases. Resonators usually have a maximum of absorption around their resonance frequency. Theoretical and experimental results indicate that the increase in insertion loss of a barrier due to the introduction of absorber on one side is related to the angle θ between the absorbing barrier surface and the ray from the source or receiver to the top of the barrier. When θ is 90° the effect is negligible. The increase in insertion loss rises to approximately 2 dB when θ is 45° and may reach 10 dB for very low angles. If both sides are absorbing the effect is approximately additive. Thus it is necessary for the source or receiver to be close to the barrier for this effect to be significant. For example, a source 1 m above the ground would need to be 4 m from a 3 m high barrier for an absorbing surface on the source side to produce an increase in insertion loss of about 1 dB behind the barrier. The full effect of an absorber on the diffracted path can be achieved by a strip at the top or sides of a barrier which has a width of one wavelength. For a broadband spectrum this means the whole of the side for normal height barriers (e.g. 3.4 m for 100 Hz). Non-flat (struc-

tured) barriers can scatter the sound incident over them in many non-specular directions; this diffusion should not be confused with the phenomenon of absorption.

Sound Absorbing Material—Parallel Barriers

An important application of absorption is in the case of parallel barriers. The attenuation provided by the barrier on one side of the source is degraded[3,4] due to reflections from the reflective barrier on the opposite side [see Fig. 6(a)]. In the case of road traffic noise, results show that the degradation typically ranges from about 2 to as much as 7 dB. A more complete discussion of the degradation in insertion loss from parallel rigid barriers is given in the applications section under road traffic noise. Application of absorption over the road-facing side of the barrier restores the performance with a progressive improvement depending on the area covered. The performance can also be restored by sloping[17] the barrier, as shown in Fig. 6(b). The required angle will depend on the separation of the barriers. This may not be an optimum solution that should be encouraged, as the reflected sound could cause problems elsewhere. If the sloping surface has dimensions less than the wavelength of the sound, a scattering rather than a reflection process occurs. Unlike absorption, which dissipates acoustic energy, scattered sound may lead to increased sound levels elsewhere.

Atmospheric Effects

Barrier performance is disturbed by other factors such as the atmosphere. Upward-curving sound paths, as in propagation upwind or during the temperature lapse characteristics of sunny days, do not reduce the acoustic performance of a barrier. However, it is generally recognized that downward-curving sound paths, as in propagation downwind or during the temperature inversions that are common at night, do reduce the insertion loss of a barrier. This reduction varies with wind speed, frequency and propagation distance. For example, in Japan, road traffic noise measured behind various barrier sites was analysed to examine the relationship be-
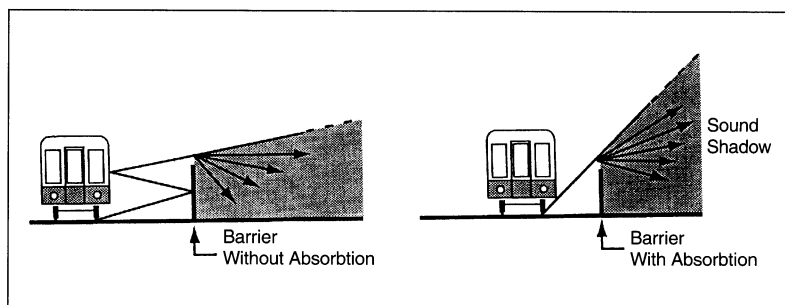

Fig. 5. The effects of placing absorptive material on a single barrier.

tween barrier noise reduction and vector wind. The results showed a wide scatter for vector winds in the range ± 2.0 m/s, indicating no systematic dependence. However, downwind data obtained on one site when the vector wind was greater than 2 m/s showed a decrease in barrier noise reduction.

Atmospheric turbulence scatters[7] sound energy into the acoustic shadow behind a barrier. Therefore, turbulence is responsible for setting an upper limit to the amount of insertion loss that can be obtained from a given barrier configuration. For example, when the barrier noise reduction values obtained from the study in Japan are averaged and plotted against the design chart, close agreement is obtained until the predicted values exceed 20 dB. The measured barrier noise reduction tends to level off at around 20 to 25 dB.

Effects Associated with the Surface of the Source

For sources which have significant bulk, such as trucks or trains, multiple reflections[14] between the barrier and the surface of the source could be expected to degrade the performance of the barrier particularly when the source and barrier are in close proximity (see Fig. 7). There are two distinct cases; one in which the vehicle side with the major noise sources is visible over the top of the barrier, the other when it is not. Computer simulation results show a progressive degradation of the insertion loss as the height of the vehicle is increased, with an approximately constant degradation of about 5 dB when the vehicle is visible. This number is dependent on many other parameters. Using a sound intensity technique to measure the sound radiation characteristics from Shinkansen trains[13], it was found that the apparent height of the noise source is changed by the effect of the noise barrier.

Time-Related Effects

The assumption that traffic can be described by a series of fixed sources can lead to problems[5,15] in the derivation of some noise quantities. These arise because the vehicles are actually moving reflecting bodies, and also because practical barriers have a finite length. As a result, the effectiveness of the barrier changes with the vehicle position, which is also related to any effects of multiple reflections that occur between the barrier and the body of the vehicle.

A fundamental descriptor of noise from a road, or a railway, is the function of sound pressure level versus time at a given receiver point for the passby of a single vehicle. This descriptor can then be used to derive the noise assessment indices L_{Ai}, L_{AeqT}, etc.

In the case when the interaction between the vehicle body and the barrier can be neglected, the time function is still required in order to derive the statisti-
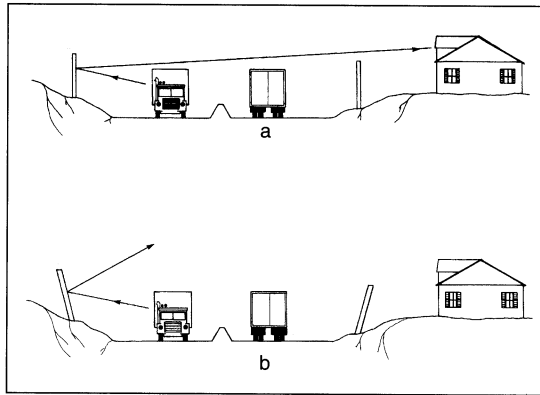

Fig. 6. (a) The attenuation provided by the barrier on one side of the source is degraded due to reflections from the reflective barrier on the opposite side. Application of absorption restores the performance. (b) The performance can also be restored by sloping the barrier.
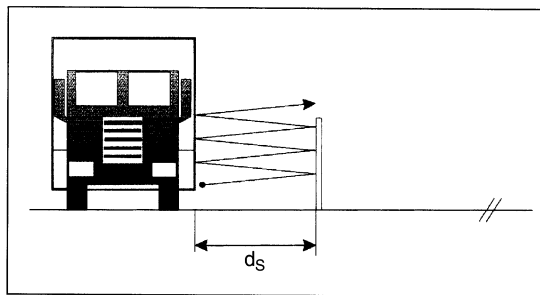

Fig. 7. How multiple reflections can cause a degradation of performance for noise barriers.

cal indices. However, in this specific case, the L_{AeqT} can be calculated accurately assuming a series of fixed noise sources. In cases where high sided vehicles are close to barriers with a reflecting surface on the roadway side, multiple reflections can occur, which can degrade the performance of these barriers.

Transmission Loss

Theoretically, the sound transmission loss of noise barriers must be accounted for in determining the insertion loss, since the sound transmitted through the barrier makes some contribution to the sound level at the receiver. However, for practical purposes, barriers are often constructed of materials that have sufficiently high transmission loss such that the contribution from transmission is negligible. To ensure that this is true, and to avoid the need to compute the contribution from sound transmitted through the barrier, the transmission loss should be at least 10 dB more than the desired insertion loss. An important consideration is that laboratory-measured transmission loss may be significantly higher than *in-situ* transmission loss if substantial gaps are present between barrier panels, between panels and support columns, or between panels and the ground. If gaps are present, calculations to estimate *in-situ* transmission loss can assist in determining net barrier insertion loss.

Barrier Shapes

Results in the literature[23-38] have identified a wide range of noise barrier systems, some of which appear to be more effective in terms of acoustic performance than the simple plane reflective barrier widely used. There are two distinct cases; one case is that of a single barrier of different shapes, the other is the case of multiple edge barriers. Many of these systems incorporate absorbing surfaces. Resonant cavities have been used to produce "soft" surfaces and some configurations are designed to promote destructive interference between waves following two different paths. A problem that needs to be overcome with these designs is the narrow band of frequencies for which they are usually effective. Studies have included computer modelling, laboratory experiments, and field measurements. The average improvement in insertion loss for the various designs 2 m high compared with simple plane reflective barriers of identical height ranges from 0.5 to 3.5 dB depending on detailed design.

Single-Shape Noise Barriers

Single-shape noise barriers include wedge-shaped barriers, berms of various kinds, T- shaped and Y-shaped barriers, and arrow-profile barriers. In Japan, barriers in which the upper section is angled or curved over part of the roadway are common. Numerical modelling of the efficiency of single noise barriers of various shapes confirms that barrier height (i.e., the path length difference effect) is of fundamental importance to the attenuation produced by a barrier. Also, the type of ground cover has a large effect upon the calculated insertion loss.

For barriers with hard reflecting surfaces, those with vertical or nearly vertical sides perform significantly better than those with shallow sloping sides. For example, there is general agreement that the insertion loss for the hard-surface wedge is lower than for a vertical barrier, but no consensus exist as to the magnitude of this effect. Further, for wedge shaped barriers, a progressive reduction in insertion loss is observed with increasing wedge angle. T-shaped barriers give consistent improvements in insertion loss over a wide area compared with a simple plane reflective barrier of the same height. However, when the T-profile is modified to an arrow-profile, a significant reduction in insertion loss is observed.

Application of absorbent material to the upper surface of a T-profile barrier increases the insertion loss by an amount depending upon the width of the cap and the efficiency of the absorber. When the T-shaped barrier with strongly absorbing upper surfaces is modified to an arrow or Y-shape there is a significant reduction in insertion loss. Field data published in Japan show the effects of placing an absorbing cap or modified cylindrical shape on top of a thin hard barrier. By measuring the sound pressure levels from traffic noise before and after the installation of the absorbent material they find that barrier performance is improved by approximately 2 to 3 dB. An attenuation of 2 dB corresponds to the increase in the barrier height of about 2 m. However, this much improvement is only achieved for relatively large diffraction angles, where source and receiver are close to high barriers. The improvement reduces to about 0.5 dB for typical geometries along suburban highways.

Calculations show that when the wall becomes a broad wedge or a berm, an absorbing surface can become very important. When an absorbent surface is introduced to shallow-sided forms of barrier, some improvement in insertion loss is found that is associated with increased attenuation at high frequencies. Some evidence shows that a grass covered wedge is less efficient than a rigid wall of the same height if the wedge angle is more than about 45 degrees. On the other hand for geometries encountered in practice, a flat topped grass covered berm generally performs similarly to a wall of the same height at the same location. Further, when source and/or receiver are very close to the berm there is usually an increase in insertion loss, again mostly associated with increased attenuation at high frequencies. Walls on top of berms are becoming a common approach to noise abatement. Mounting a thin-wall atop an absorptive-topped berm does not initially increase the insertion loss, since the beneficial effect of the absorptive top is lost and is not fully recovered by the increase in the total barrier height. However, as the height of the thin-wall increases, the performance is recovered. The wall/berm combination has the advantage of not requiring as much land as a full berm.

Multiple-Edge Barriers

Multiple-edge barriers can be of two different kinds. There are multiple-edge barriers with a single foundation and there are those comprised of several parallel barriers on the same side of the road. Studies show that multiple-edge barriers give consistent improvements in insertion loss over a wide area compared with simple plane reflective barriers. A benefit of this type of barrier is that an extra edge could be incorporated onto existing noise barriers. The number of possible multiple-edge designs is large, and studies of different configurations are on-going.

Double barriers represent the second type of multiple-edge barriers. They can be efficient in attenuating noise, in comparison with a vertical screen of the same effective height. Double barriers can provide large gains where significant diffraction occurs at

the upper edge of both screens. The attenuation improves as the distance between the barriers increases beyond a few wavelengths but also depends on the absorption between the barriers and/or ground absorption (spacing must be much greater than a wavelength and absorbers present to effect substantial improvements). As further barriers are added the efficiency increases, although if working within a limited ground space, there may be a trade-off between the addition of another barrier and the subsequent reduction in barrier spacing. It is noted that the benefits from multiple barriers occur throughout the spectrum, even at low frequencies.

Models

Accurate prediction of barrier insertion loss must somehow simultaneously account for all of the physical phenomena discussed above. Although this goal is still beyond current capabilities, developments[39-79] in our ability to predict sound propagation through the atmosphere has increased dramatically during recent years. Models can be separated to two main categories; *empirical* models and *theoretical* models. Both types of models include the attenuation due to geometrical spreading. Where the empirical models differ from theoretical models is in the incorporation of the other attenuation mechanisms. The empirical models tend to rely on general tendencies found in experimental data bases. They often work well as long as the specific situation of interest falls within the bounds of the databases. Theoretical models on the other hand rely on our mathematical ability to describe real-life situations.

The incorporation of the effects of the ground[48,51,68] is now fairly widespread in the theoretical models. Only a very limited number of models include the effects of curved sound paths due to refraction. However, refraction is most important at longer ranges where barriers generally begin to lose their effectiveness. Only a very limited number of models include the degradation due to scattering by atmospheric turbulence, but the limiting insertion loss due to this phenomenon is generally known through the empirical databases. Often the calculation involves propagation from traffic located on a paved road surface to a receiver on grass covered ground. There are few theoretical models[39] that account for the effect of the hard/soft transition and this effect is most often ignored. There are virtually no theoretical models that incorporate more complex topographical features, and most often a ray tracing approach is used. However, these effects are included in most empirical models.

It is very important to recognize the limitations of the models being used for prediction or design purposes. The Working Party recommends comparison of various models when designing a barrier. It is also important to appreciate how to enter data and to be confident in these inputs. It is the collective experience of the Working Party that inexperienced users cannot use models as effectively as experts, largely due to inadequate documentation on the protocol to follow in using models and insufficient appreciation of their limitations.

Computation of barrier insertion loss is done in two parts according to Eq. (1). First, sound levels in the absence of the barrier are calculated followed by sound levels calculated in the presence of the barrier. The techniques[59] available to calculate sound levels in the absence of the barrier include empirical codes, analytical solutions for propagation above a flat porous ground, analytical solutions for selected atmospheric profiles, ray tracing techniques which include interaction with the ground and meteorological conditions, and more sophisticated numerical solutions to the full wave equation: the fast field program (FFP) and the parabolic equation (PE). There is also an International Standard[80] covering prediction of levels from a source. The attenuation that can exist due to natural features, particularly absorbing ground cover, before the construction of a barrier is often not appreciated. For this reason the measured insertion loss of a barrier when constructed is not as large as predicted from the barrier diffraction attenuation and can sometimes result in negative values in certain regions of the spectrum. Approximations in models can also lead to calculations indicating negative insertion loss.

The presence of the barrier imposes an additional challenge for computational techniques. Most of the theoretical methods which have been developed to calculate the attenuation of barriers are semi-empirical and based on ray tracing and geometrical acoustics. These methods fall into two categories: those in which only the amplitude of the sound field is predicted; and those in which the phase of the sound field is estimated so that interference effects can be studied.

Empirical
In the first category the most influential early studies were those of Maekawa[61] and Kurze and Anderson[57]. These researchers predicted the sound attenuation due to a reflecting knife-edge in terms of the Fresnel number. These prediction methods have been applied to predict the insertion loss of a vertical rigid barrier located on the ground, and form the basis of the current road and railway traffic noise barrier prediction method in many countries. In some countries barrier height is determined by other specific design charts.

In its simplest form, the attenuation provided by a thin barrier represented by an infinite half-plane

is calculated as a function of Fresnel number N defined as

$$N = (2/\lambda)(d_1 + d_2 - d_3) \qquad (6)$$

(see Fig. 4(a); λ is the wavelength of the sound). The curve in Fig. 8 is the attenuation provided by a thin barrier as a function of Fresnel number and forms the basis for the well-known chart developed by Maekawa. Maekawa empirically corrected the curve in Fig. 8 to account for the presence of the ground. The remarkable agreement, on average, with a large body of measured field data and its simplicity of use has led to the widespread engineering use of the chart.

Theoretical

In the second category of theoretical methods some form of a geometrical theory of diffraction[40,48,71] is used, coupled with an approximation for the spherical wave reflection coefficient at an impedance plane, to account for ground reflections. The sound field behind the barrier is determined by the sum of the terms associated with the four paths shown in Fig. 9 and a complex interference spectrum is formed. Mostly these methods have been restricted to a thin vertical barrier on a reflecting or finite impedance ground.

To produce predictions for configurations which are more complicated in terms of barrier shape and absorptive treatment, the use of the boundary element method has been investigated[48,75]. This method has

Fig. 8. Attenuation provided by a thin barrier as a function of Fresnel number according to the chart developed by Maekawa.

important advantages over the methods based on a geometrical theory of diffraction approach. A main advantage is its flexibility, in that, by positioning the boundary elements appropriately, arbitrary shapes and surface acoustic properties can be accurately represented. Secondly, it has the advantage of accuracy in that, provided that the boundary elements are made a small enough fraction of a wavelength, a solution of the governing wave equations of acoustics can be produced that is correct to any required accuracy. The disadvantage of the boundary element method is that large computing times and storage can be required, especially for barrier designs which vary along the length as well as in cross-section. A further limitation which it shares with the other methods described above, is that atmospheric effects are not considered, so that only predictions for a neutral quiescent atmosphere are obtained.

Application of the Models

International Standard ISO 9613-2 Acoustics—"Attenuation of sound during propagation outdoors—Part 2: General method[80] of calculation"—specifies an engineering method for calculating the attenuation of sound during propagation outdoors in order to predict the levels of noise at a distance from a variety of sources. It aims to determine the average time-interval equivalent continuous A-weighted sound pressure levels under meteorological conditions favourable to propagation from sources of known sound emission above natural ground surfaces. These conditions are for downwind propagation, or equivalently, propagation under a well developed moderate ground-based temperature inversion, such as commonly occurs at night.

It also aims to determine a long-term average A-weighted sound pressure level. The duration of the long-term interval is much longer than that required for specifying the average equivalent continuous A-weighted sound pressure level for downwind propagation described above, and encompasses a wide variety of meteorological conditions.

The method consists specifically of octave band algorithms (with nominal midband frequencies from 63 Hz to 8 kHz) for calculating the attenuation of sound which originated from a point source, or an assembly of point sources. The source may be moving or stationary. The method is applicable in practice to a great variety of noise sources. It is applicable, directly or indirectly, to most situations concerning road or rail traffic, and many other ground-based noise sources. Specific terms are provided in the algorithms for a variety of physical effects, including screening by noise barriers.

The formulas to be used are for the attenuation of sound from point sources. Extended noise sources,
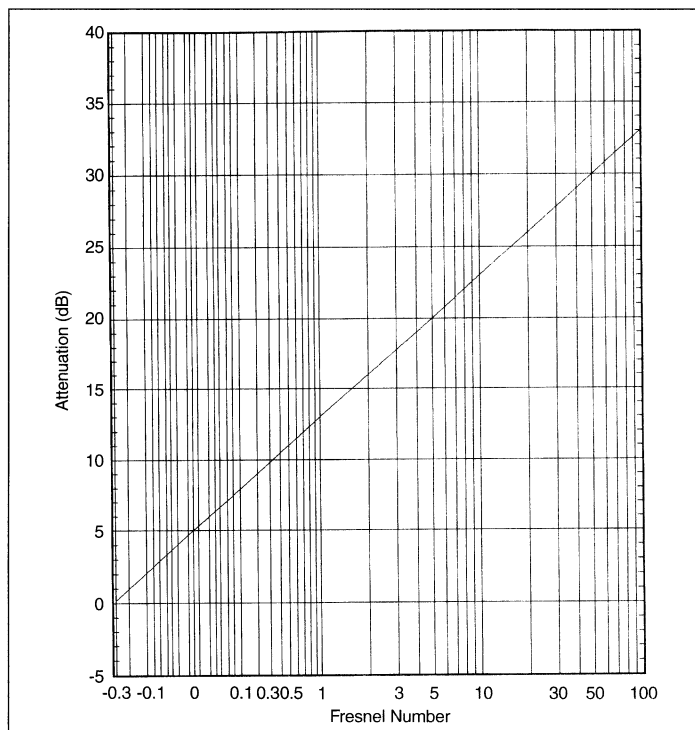
therefore, such as road and rail traffic are represented by a set of sections, each having a certain sound power and directivity. A line source may be divided into line sections, an area source into area sections, each represented by a point source at its centre.

The International Standard calculates diffraction over the top edge and around a vertical edge of a barrier. Double diffraction over thick barriers can also be calculated. (The Working Party notes, however, that the formulas for calculating double diffraction yields a discontinuity in the solution when passing from single diffraction to double diffraction). The screening attenuation is not taken to be greater than 20 dB in the case of single diffraction from thin screens, and 25 dB in the case of double diffraction by thick screens. The screening attenuation for two screens is calculated as in the case for double diffraction.

Each country[81-103] has usually adopted its own specific method for predicting the performance of barriers for specific transport noise sources. For example in the UK[84], calculation of the attenuation of road traffic noise by a barrier is performed using a chart in terms of path length difference. In Japan, barrier height is determined by a design chart[79] such as Maekawa's or other specific design charts using a representative spectrum of road traffic noise. In Lithuania the decrease in A-weighted noise level due to a noise wall is estimated in decibels using a design chart which assumes that the wall is 3 m from the edge of the road. When walls in city streets are used as barriers, they must be sound absorbing. The frequency dependence of sound absorption is chosen in accordance with the typical spectrum of noise for the transportation source. In the USA, STAMINA/OPTIMA has been the official highway noise prediction and barrier design model[92,93].

The US Department of Transportation's Federal Highway Administration (FHWA) is developing the next generation of highway noise prediction computer code[82] called the Traffic Noise Model (TNM). In addition, the new model has the potential for standardizing and improving rail and transit noise prediction in the USA. The only significant sound propagation components that have not been included in the TNM are those due to atmospheric effects such as wind and temperature gradients; the model assumes a neutral atmosphere. This decision was motivated by FHWA's purpose that propagation over relatively short distances (less than about 200 m) is most important. The expected increases in development cost, computation time, and user input complexity associated with including such atmospheric algorithms would be quite significant.
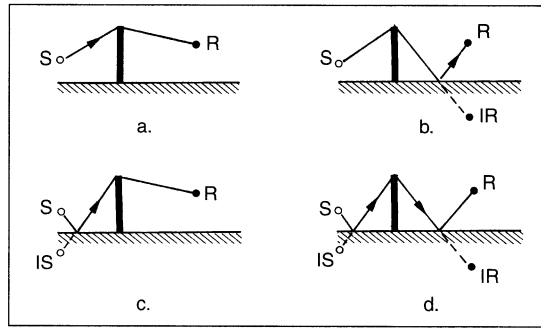
Many models such as the TNM and the Dutch

Fig. 9. The sound field behind a barrier is determined by the sum of four paths.

model calculate all important sound propagation paths from the source to the receiver, including reflection and diffraction, at one-third octave or octave band centre frequencies. The TNM model includes diffraction from ground impedance discontinuities, such as the edge of the pavement adjacent to a highway. Ground lines and earth berms are included, so that the exact terrain between source and receiver can be entered. Special reflective barriers can be coded which generate an image of the roadway to account for reflection at the barrier surface. Only single reflections are supported in the three dimensional portion of the TNM. (A two dimensional ray-tracing module is included for analysis of multiple reflections.) Multiple diffraction is included. The model computes the cumulative effects of diffraction from various points in the geometry, if they are significant contributors to the total sound level at the receiver. Perturbable barrier and berm heights are included, so that a matrix of results for several barrier heights at once can be constructed for rapid barrier design decisions later. Rows of buildings can be included, and require the user to specify the percentage of area that the buildings block in each row. Tree zones are included, and incorporate the ISO values for attenuation due to dense foliage. Sound level descriptors include L_{Aeq1h} and L_{dn}. Traffic data input tables allow traffic input for both descriptors.

The US Army Construction Engineering and Research Laboratory (USA-CERL) has developed a long-distance sound propagation model[78] called SoundProp that incorporates the effects of atmospheric conditions. It is a point-to-point model that operates in 1/3 octave bands and computes the propagation of sound in the atmosphere above the ground and in the presence of a barrier if one exists. The propagation mathematics are based on a fast field program that was exercised many times on a supercomputer to generate a large database of results under various conditions of atmospherics, ground type, and geometry (source and receiver height and range).

Products and Materials

Barrier materials are briefly described here[104]. Different products have their own characteristics apart from their acoustical performance, including cost, durability, safety and aesthetics.

There are a range of traditional building materials commonly used for noise barriers, This is being supplemented by innovative, proprietary products developed for specific barrier applications. All of these barriers can be categorized as either reflective or absorptive.

Reflective Barriers

Reflective barriers are constructed using all of the common building materials and include:

- concrete—precast panels, masonry blocks, and purpose-designed masonry units
- lightweight concrete - fibrous cement, purpose-designed elements
- metal sheeting
- plastics
- glass
- wood
- other materials

The use of these various products tends to be regionalized, obviously dependent on relative economies of the different materials in different areas and other factors mentioned above.

Concrete walls are common reflective barriers. They are usually made up of stacked panels 3 to 5 m long and 0.5 to 1.8 m high. The thickness is 90 to 200 mm and the surface density of this type is 200 to 400 kg/m^2. There are also barriers designed with elements that consist of combinations of flower boxes on different heights on the barrier. In this case a luxuriant vegetation can be obtained and the barrier becomes more or less absorptive.

Lightweight concrete and other fibrous cement can also be used for barriers. In most cases the low density is not a problem since the transmission loss of the barrier is not the critical parameter.

Metal sheeting is also used for barriers. Commonly used is steel and aluminium that is sea water resistant. Mostly thin sheets from 1 to 2 mm are being used. These materials are often combined with mineral fibres giving an absorptive barrier. With metal barriers, care must be given to ensure that they are thick enough to give a high enough transmission loss, particularly at low frequencies. Also metal sheet barriers are combined with vegetation (fast growing trees or shrubs) in front of and behind the barrier to obtain a "green" barrier.

Plastic elements are also used for barriers. Sometimes they are made of recycled materials. The surface density averages around 10 to 20 kg/m^2. Plastic elements are used more in absorptive barriers.

Glass and other transparent plastic elements are coming into use for barriers. They are made of glass, of acrylic or polycarbonate resin of 5 mm to 8 mm thickness, or polymethylmethacrylate of 15 to 20 mm thickness. The surface density averages around 10 to 20 kg/m^2. The advantage of this material is that drivers and passengers can see the landscape through the barrier and residents can see the road or railway line. This can be important when barriers are erected in front of dwellings. Problems are visual reflections on the barriers (as a mirror) and the cleaning of the barrier, but these can be solved by inclining the construction.

Wooden barrier materials are commonly used in the UK, the US, The Netherlands and in Austria. Timber is also widely used in Northern Europe, Scandinavia, Australia and Canada.

Other materials or combination of materials can be used as well. For example, metal sheeting or plastic elements in combination with glass and other transparent plastic elements can be employed. Also combinations with absorptive elements, glass and other transparent plastic elements can be very practical. Architects can make some attractive designs by combining different materials with special shapes. There are many examples of interesting shapes and material combinations in France, Germany and The Netherlands.

Absorptive Barriers

Absorptive barriers are a fairly recent innovation and their use is not as widespread as reflective barriers. Absorptive barriers include:

- composites—using traditional acoustical techniques such as commercial mineral fibres behind a perforated facing, wooden network, perforated plastics, porous concrete, etc.
- ceramics
- sintered metals
- cement-bonded wood-wool or wood chips
- aerated concrete

There are two general types of systems that are used to create absorbing surfaces of barriers.

Systems with Cavities Incorporating Absorbing Materials

The most common systems of this type are perforated metal boxes containing fibrous materials. An example of this is the standard absorptive panel design specified by the Public Highway Corporation of Japan since the early 1970s. The barrier panel consists of a glass fibre sheet 50 mm in thickness, wrapped with polyvinyl fluoride film of 21 μm thickness. This fibre sheet is inserted in a metal box with a back air space of 33 mm thickness. The front

surface of the box is made from an aluminum panel with slits and the back side of the panel is made of steel sheet of 1.6 mm thickness. The absorption coefficients (measured in a reverberation chamber) are greater than 0.7 and 0.8 for 400 Hz and 1000 Hz respectively. This type of material is widely applied to barriers used for inter-city highways.

A second type is a construction of cement or baked clay blocks with internal cavities. The traffic-facing side of the block contains holes or slots. Sound is absorbed at the resonance frequencies of the cavities and the range of frequencies absorbed is extended by the inclusion of fibrous or foam fillers.

Systems with Panels of Open Textured Porous Materials

Absorption within the material is achieved by inertial and frictional losses. These materials are usually incorporated with a hard backing to prevent sound being transmitted through the panel. If the panel is directly mounted on the backing a thickness of 50 to 100 mm is required to provide good absorption characteristics at the lower frequencies. The front faces are often profiled rather than flat. If an air gap is introduced between the panel and the backing, the thickness can be reduced and the low frequency performance retained.

Materials used in this category are porous cement and concrete, wood chips in a cement matrix and small particles in an epoxy matrix. Ceramic sound absorbers are made from particles of a hard porcelain and are formed into a porous board of 10 mm to 50 mm in thickness. This material has thermal resistance and resistance to chemical substances in exhaust gases from heavy trucks and cars. However, it is not as resistant to physical impact such as the impact resulting from a collision with a car. A common absorptive material used adjacent to highways and railways in the US and Canada is made from wood fibres bonded together with portland cement of 50 to 100 mm thickness and backed with a solid concrete panel.

Vegetative barriers are constructed from vegetation that is rooted in a soil mound or in specially-constructed panels. The insertion loss of these constructions is determined primarily by the dimensions of the earth bank or solid structure. For artificial, steep-sided structures, some form of irrigation is necessary to retain viable plants.

Measurements

It is the collective experience of the Working Party that well conceived and documented experimental measurements are the only reliable way to verify the effectiveness of road and rail noise barriers. Measurements can be of two types; verification of the field insertion loss and laboratory measurements on sample constructions. Field measurements verify how the design is performing. A program of in-situ field measurements[105-108] shows how assembled components age and also how movement of a barrier with time affects the insertion loss and/or transmission loss. Sample constructions can be tested in the laboratory and include methods to measure the absorption and transmission loss. However, intrinsic properties of the individual components may not necessarily reflect the in-situ performance and as a result it is important to test sample constructions.

Standards for Measuring Barrier Insertion Loss

American National Standard "Methods for determination of insertion loss of outdoor noise barriers" (ANSI S12.8-1987) covers insertion loss determination by measurement or by measurement and prediction for outdoor noise barriers of all types. The standard adopts insertion loss as the basis for determining effectiveness of a barrier. The standard recommends use of the A-weighted sound exposure level or time-averaged sound level or octave band sound pressure level, but does not preclude use of other noise descriptors. It provides methods for determining the insertion loss of outdoor noise barriers at receiver locations of interest under conditions of interest. In addition, the standard presents requirements for the documentation of the procedures and results to permit interpretation and independent evaluation of the results. It may be used for routine barrier performance checking, or engineering or diagnostic evaluation, and may be used in situations where the barrier is to be installed, or has already been installed. Three methods are presented. The recommended method is the "direct measured" method where the user measures levels at the reference and receiver positions both before and after barrier installation. The same receiver and reference positions are used in both the "before" and "after" case. It may be used only if the barrier has not yet been installed or can be removed for the "before" measurements.

Alternative methods are an "indirect measured" method and an "indirect predicted" method. If the barrier has been installed prior to any direct "before" measurement and it cannot be readily removed to permit such measurements, the user may simulate the "before" condition by measuring at a site that is equivalent to the study site minus the barrier. If it is not possible either to make actual before measurements or to make substitute "before" measurements at an equivalent site, then "before" predictions may be possible. When predictions are used, errors inherent in the chosen prediction method further decrease the precision of the resulting insertion loss.

Draft International Standard ISO/DIS 10847 Acoustics—"*In-situ* determination of insertion loss of outdoor noise barriers of all types"—also specifies methods for the determination of insertion loss of outdoor noise barrier intended to shield various kinds of noise sources. The International Standard only specifies two methods for the determination of insertion loss of outdoor noise barriers. The recommended method is the direct measurement method discussed above. The alternative method is the indirect measurement method also discussed above using measured "before" levels at an equivalent site. The International Standard does not include the indirect predicted method.

Applications

This section discusses three main application areas[109] where barriers are used: road traffic noise, railroad noise, and ground based aircraft operations.

Road

Road traffic[110-113] is the most widespread source of noise in all countries and the primary reason for annoyance and interference with human activities. Figure 10 shows the typical profile of a road noise barrier installed between four lanes of traffic and residential dwellings. Several factors affect the performance of the barrier and most of these have been discussed in general terms above. The height of the barrier is of fundamental importance to the attenuation of road traffic noise. In many countries, typical highway barrier heights range between 2 and 3 m, while in other countries heights range between 3 to 6 m and barriers up to 8 m high can also be found. Proximity of source to barrier is an important factor in determining the attenuation. For example, in Fig. 10, the barrier provides less attenuation for the westbound traffic than for the eastbound traffic. A very important issue in the case of road traffic noise barriers is the degradation in performance of a barrier on one side of the road by the presence of a second parallel barrier on the other side of the road.

The effects of multiple reflections between two barriers placed on both sides of a highway because noise reduction is needed on both sides, has been the subject of much debate and some research. Research shows that under various circumstances, the degradation (reduction) in barrier insertion loss (A-weighted) can be as high as several decibels when normal reflective walls are used. Since some models do not compute this degradation, many users are ignorant of the potential compromise of their barrier designs by this effect. Several models have been developed to attempt to compute the effect, but measurements have shown less degradation than the models have predicted. (Partly as a result, the FHWA in the US has not taken an official stand or recommended a procedure to deal with multiple reflections.) Consequently, some barriers are being constructed without this effect having been computed or accounted for in the acoustical design. In many cases, these barriers are not providing the expected insertion loss. The FHWA's new Traffic Noise Model will include a two-dimensional multiple-reflection module that is calibrated to match measurements.

Studies[3,91] in the US going back into the 1970s have shown that degradation of single-barrier performance does occur when parallel reflective walls are used. The studies showed that as much as 7 dB degradation of insertion loss could be expected with certain highway geometries. Measurements of insertion loss degradation outdoors at a full scale test roadway have been performed at Dulles International Airport and along highways in California and Maryland. It was found that the measured degradation is a function of the ratio of the distance between the two barriers (W) and the barrier height (H). Table I shows the highest measured insertion loss degradation for A-weighted traffic noise from each of the three studies, along with the W/H ratio of the measured geometry.

In Japan, measured results from a parallel barrier site were analysed and the results show that the dif-
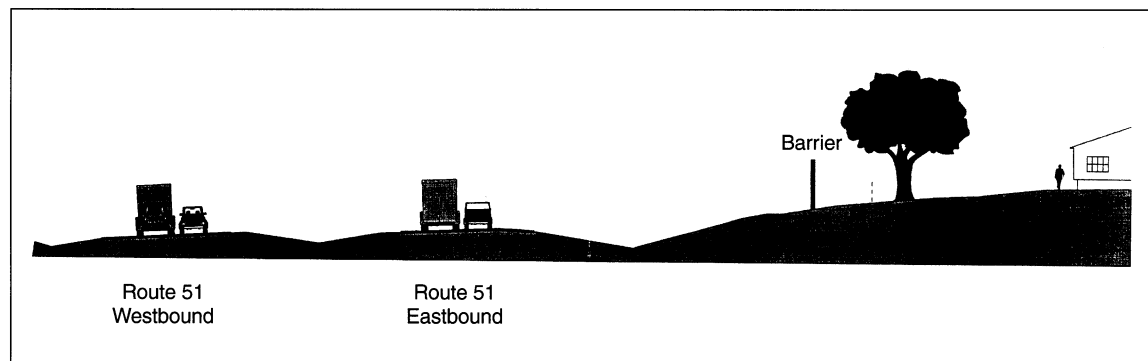

Fig. 10. Proximity of source to barrier is an important factor in determining attenuation. The barrier provides less attenuation for the westbound traffic than for the eastbound traffic.

ference in barrier efficiency between single and parallel barrier is less than 1.5 dB for barriers of 3 m height at roads with 24 m to 30 m width (*W/H* ratio between 8 and 10). Experimental results are summarized in Table 1.

There is a body of literature evaluating the improvement in parallel barrier insertion loss by the use of absorbers. In Japan, measurements[21] were made of the insertion loss for parallel barriers at a test field where all conditions except meteorological factors were artificially controlled. The test was carried out under calm wind conditions. The results showed that the absorptive treatment of the wall surface was important and the improvement of barrier efficiency was 2 dB to 5 dB for parallel barriers 3 m high with a separation of 15 m (a width-to-height ratio, or *W/H*, of 5). When the separation of the barriers is 45 m, the increase is 4 dB. In Canada, field measurements in the Toronto area[111,112] showed no significant change in site results when parallel 3 m barriers 74 m apart were treated with absorbers. These results are summarized in Table 2.

Trees and bushes are very poor road noise barriers; they provide very little attenuation as a result of shielding. Their roots do provide some ground attenuation by keeping the soil porous. Therefore, the principal contribution of vegetation is not to barrier attenuation but instead to ground attenuation, which is inherent in the calculation for A_e. However, if the foliage is dense enough to completely obstruct the view, and if it also intercepts the path of sound propagation, and if it is also deep enough, there may be some additional attenuation caused by propagation through the foliage. A hedge, a row of bushes, a strip of vegetation left to grow naturally, or a forest may all be examples of dense foliage. There is little or no attenuation from bare branches or trunks of trees at frequencies of interest. Nonetheless, aesthetic consideration should not be ignored. If noise barriers are made to appear more attractive visually, by incorporating vegetation in the design, they may reduce annoyance further than would be predicted from the actual acoustic attenuation provided.

Elevated roads or viaducts are common in urban areas, and without noise barriers they present the worst case for noise propagation, as compared with at-grade roads and depressed roads (roads in cuttings). Elevating the noise sources allows sound to propagate at higher levels to larger distances from the road, because the noise-reduction benefits of building shielding and ground-effect attenuation are reduced or eliminated [Fig. 11(a)]. However, adding noise barriers to elevated roadways provides more efficient noise reduction than barriers for at-grade and depressed roadways.

Table 1. Highest measured insertion loss degradation for A-weighted traffic noise from five studies, along with the *W/H* ratio of the measured geometries.

Study	Max. IL degradation (dB)	W/H
Dulles	6.2	6
Maryland	2.8	9
California	1.4	15
Japan	1.5	8 to 10
Canada	0	25

There are two reasons for this. One reason is that the path length difference is greater for elevated roads. The other reason is that since little noise shielding is present at distant receivers, the introduction of a barrier on an elevated road can make a significant improvement; whereas barriers along at-grade and depressed roads provide little or no benefit to distant receivers, since they represent little *additional* shielding over the substantial amount that already exists.

However, building barriers on viaducts or embankments is not always easy: one must often limit their height for specific reasons (foundations, weight, aesthetics, safety...). Meanwhile, barriers below 2 m cannot be really effective for the traffic on the farthest lanes: the use of a "central" barrier can solve the problem [Fig. 11(b)]. The close position of these barriers to the vehicles gives high interactions between these (see the related paragraph). The use of high absorptive (one side lateral, double sided central) barriers is necessary to get the real benefit of this screening design.

Rail

The use of barriers to control railway noise[114-120] is most common in the European countries. They are considered easier to design. In general railway noise barriers are lower than road noise barriers; except in Australia where there are barriers up to 8 m high. The main source of noise at speeds less than 270 km/h is due to the wheel/rail interaction. At greater speeds, aerodynamic noise tends to dominate. For

Table 2. Improvement in parallel barrier insertion loss by the use of absorbers.

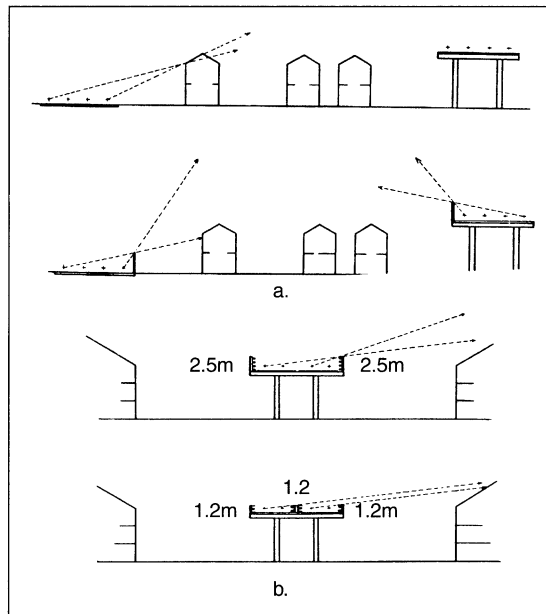| Study	Inprovement (dB)	W/H
US	6	4
Japan	2 to 5	5
Canada	0	25

Fig. 11. (a) Comparison of the sound propagation with a road and with a viaduct. Adding a barrier to elevated roadways provides more efficient noise reduction than bariers for at-grade roadways. (b) Ways to reduce barrier height on a viaduct.

trains, vehicles are longer and more reflective than road traffic and the directivity patterns are different and must be accounted for.

A survey[120] of fourteen models (see Table 3) for the prediction of the effectiveness of a noise barrier along a railway line has recently been completed. The models are compared with each other and to some measurements. The main objective of the investigation is to gain insight into the rules of calculation used in order to determine the acoustic effect of barriers. The calculation methods show differences in the acoustical and geometrical characterization of the noise source or noise sources. A wide range of source locations is specified and also the calculation of the attenuation of a barrier and the calculation of the effect of the ground absorption gives a variety of mathematical formulas. The computed insertion loss of an absorptive barrier of 2 m high, along a two track railway, varies between approximately 7 and 12 dB. For the nearest track the result varies between 8 and 15 dB.

Figure 12 gives an overview of the various source locations. The most frequently used location of the source is at the head of the nearest rail and at a height of 0 m. With the exception of the model from Japan, all other source locations are, seen from the top of the barrier, at a higher position. We note that the model for the Channel tunnel calculates the effect of a barrier for the two tracks together. The highest source location is found in the French Mithra-fer model. This model is mostly used for TGV trains where, at high running speeds, the noise sources from air turbulence especially on the top of

the train becomes important. Due to the fact that there are various source locations, every model will yield a different path difference, but the models also use different relationships between the path difference and the barrier attenuation.

In Fig. 13, an overview is given for the measured effect of the barrier and the calculated insertion loss of a barrier with a height of 2 m above the railhead along a two track railway and 4.5 m from the centre line of the nearest track. The overview is given for acoustically absorptive barriers. If one compares the insertion loss of an absorptive barrier for the nearest track (Track 1), the result of the calculations for the standard situation (a barrier of 2 m) with the different calculation models varies between 8.0 and 15 dB.

Differences of Barrier Effectiveness between Roads and Railways

Beyond the fact that the diversity of vehicles is much higher with road traffic than with trains, some important differences play a big role in the way a barrier can be effective. These differences should be taken into account in order to assess the real effectiveness of a barrier either along a highway or along a railway.

Location of Vehicles/Barriers

While the location of road vehicles is "free" on the width of the roadway, trains are normally well localized on the tracks. Moreover, the width of a railway is much narrower than that of a highway. Finally, for road safety reasons, it is not possible to erect barriers too close to a highway, while barriers can usually be place quite close to trains. For these reasons, noise barriers are generally more effective along railways than along highways.

Need for Absorption

The large size of the railway vehicle allows multiple reflections between the side of the train and the barrier, which may be located quite close to the train. Therefore, absorptive materials are often required on the side of the barrier facing the train, to reduce reflected sound energy and retain desired insertion loss. For highways, absorptive materials may only be needed to prevent multiple reflections with an opposite-side barrier or large vehicles if they are very close to the barrier, or if reflections could cause unwanted sound-level increases on the opposite side of the highway.

Directivity Patterns

The performance of a noise barrier will be affected by the directivity of the source and this should be taken into account in the design. Single road vehicles can be approximated as monopole sources, but the rail-wheel noise source from railways is strongly directional with high intensity in the horizontal direction.

Table 3. Survey of fourteen models for the prediction of the effectiveness of a noise barrier along a railway line.

	Calculation in dB(A) and spectra	Type of model	Reflective and/or adsprptive barriers	Barrier attenuation calculation method	Source location		Ground absorption	
					Horizontal	Height (m)	Without barrier	With barrier
Nordic model	dB(A)	complete	both	straight line path diff.	track center line	0.50	yes	yes
British Rail	dB(A)	barrier	both	straight line path diff.	railhead	0.00	no	no
Channel Tunnel	dB(A)	complete	both	straight line path diff.	railway center line	0.50	yes	0 dB(A)
TRL model	dB(A)	complete	both	straight line path diff.	railhead	0.00/(4.00)	yes	0 dB(A)
The Netherlands	spectra	complete	absorptive	curved line path diff.	railhead	0.00/0.50	yes	yes
German Schall 03	dB(A)	complete	absorptive	straight line path diff.	track center line	0.00	yes	0 dB(A)*
TV7630 Rheda model	dB(A)	barrier	both	straight line path diff.	railhed	0.00	no	no
German 1980	dB(A)	barrier	absorptive	straight line path diff.	railhead	0.00	no	no
Japanese method**	dB(A)	barrier	both	straight line path diff.	near the rail	0.00	0 dB(A)	0 dB(A)
French Cetur model	dB(A)	complete	absorptive	monogram	railhead	0.65	no	no
French Mithra-fer	spectra	complete	both	straight line path diff.	railhead	0.80	yes	yes
Swiss Semibel	dB(A)	complete	absorptive	straight line path diff.	railhead	0.50	yes	same as without
Austrian ÖAL 30 simple	dB(A)	complete	absorptive	straight line path diff.	track center line	0.30	no	no
Austrian ÖAL 28/30	spectra	complete	absorptive	curved line path diff.	track center line	0.30	yes	yes

* For short distances from the track

** There are other Japanese methods with the source at the track center line and at 0.0 m height.

Ground-Based Air Operation

There is sometimes a need to control noise from certain specific ground-based airport operations[121]. Barriers are often used for this purpose, but it is recognized that this is not a big market.

Barriers for Aircraft Runups

"Runups" are aircraft engine tests that are performed by mechanics to ensure that the engines they have serviced are ready for carrying passengers. Runups are frequently conducted at night and often at relatively high power settings. Unlike aircraft takeoffs and landings, runups do not follow a predictable time pattern; the duration can be from a few seconds to many minutes. This indeterminate duration of runups adds to the annoyance factor and the usual noise impact criteria are not always appropriate.

Since the noise emissions from jet engines are quite directional, the orientation of the aircraft during a runup has a significant influence on the sound levels radiated into the surrounding community. Where airports have residential land use within a kilometre or so of the runup area, and where the options for orienting the aircraft are limited, many airports have constructed noise barriers or runup "enclosures" to reduce the radiated noise. Barriers or enclosures are located as close to the aircraft as is practical, to increase noise reduction and to minimize cost. In the U.S. the minimum distance between source and barrier is about 6 m, and typical distances range from 10 m to 40 m, depending on aircraft size and engine location. Ordinarily, the barriers are designed to provide 10 to 15 dB of noise reduction. Where wide body jets such as the DC-10 and L-1011 must use the runup area, the barriers must be up to 10 m high to block the propagation for the high tail-mounted engine.

Multiple sound reflections within the runup area must be controlled in order to maximize the barrier effectiveness. In some cases, sound-absorptive material is used or sloped sides are used to eliminate multiple reflections. Long propagation distances give rise to issues that need to be considered in the acoustical design of barriers used to control runup noise. The primary issues are atmospheric effects and ground effects. Many times, noise problems from runups occur at night when winds are light and do not affect barrier performance substantially. However, in areas where prevailing winds or temperature inversions are common, reduced barrier effectiveness due to curved propagation paths should be considered. If there is soft ground in the vicinity of the runup area, barrier insertion loss may be reduced due to loss of ground-effect attenuation.

Barriers for Start of Takeoff Roll

Jet aircraft create high noise levels especially to the side and behind them during their takeoff roll down the runway. Many airports are located in areas where only a few hundred meters separates the planes from the nearest homes. Often, the terrain is flat and unobstructed. A-weighted sound levels of around 90 dB have been measured at homes 300 m from the runways during the start of the takeoff roll.

Since areas around runways must be clear of obstruction, barriers cannot be located near the aircraft for safety reasons. In the U.S., the Federal Aviation Administration imposes restrictions that prevent useful barriers from being located within about 200 m of a runway. This means that barriers for start of takeoff roll noise must be constructed near the receivers to be effective.

Because aircraft are generally assigned to use runways so that they take off into the wind, there is frequently a wind component in the source-to-receiver
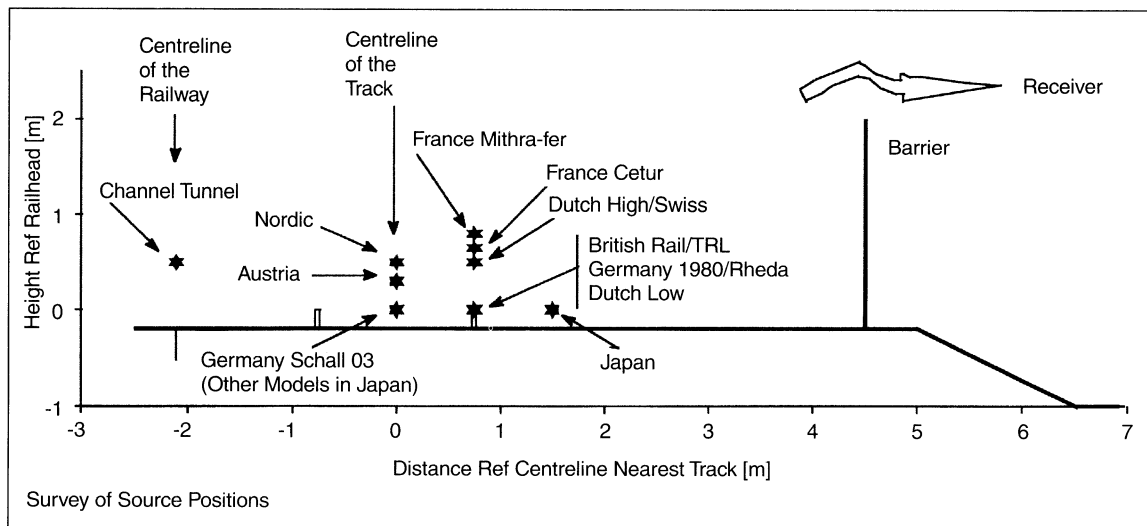

Fig. 12. Overview of the various source locations.

direction during takeoff. This tends to reduce the effectiveness of the barrier, however, a study in the U.S. has shown that even fairly strong winds degraded insertion loss to only a minor degree when the barrier was in close proximity to the receiver.

In designing barriers to control start of takeoff roll, ground-effect attenuation must usually be considered to assess properly the expected insertion loss, unless all ground surfaces between source and receiver are acoustically hard. Since propagation distances can be large, accurate prediction of the expected loss of attenuation due to soft ground is difficult, particularly over terrain with variable geometry and impedance. Often the expected loss of ground-effect is determined through measurement at different heights.

Earth berms are sometimes constructed at airports in the U.S. to control start of takeoff roll noise. Berms are often less expensive than walls, they receive wide acceptance for aesthetics, and the necessary land is often available on the airport's property. If walls are used, they are usually in the range of 6 to 10 m high.

Other

The most effective noise control measures are those effected at the source, particularly by quieter designs. Tangible progress[122] has been made in the abatement of motor vehicles noise by quieter engines, better air-intake and exhaust mufflers and quieter tires and road surfaces to reduce the impact of traffic noise in communities along roadways. Also there are many ways of modifying the transmission path to reduce the level of noise at the receiver. At the land use planning stage, the distance between source and receiver can be increased by setting aside sufficiently large areas of land as buffer zones along new roads and around new airports. Valuable land close to new highways or railways which is not suitable for housing development because of noise nuisance may be used for the construction of light industrial or commercial premises where the sensitivity of the occupants would be less. These structures then act as noise barriers. The buildings can be connected by noise walls to provide a continuous screen. It is also possible to erect barrier blocks of single aspect dwellings where the facades of the buildings facing the noise source have a high noise insulation specification and may contain no windows or access points.

A growing number of studies have described the design of specific surfaces to exploit the interaction of the sound field with the ground to obtain noise reduction. In Europe, a new road structure[123] called drainage asphalt has appeared in which discontinuous granular formulation can produce an important void content (porosity) inside the structure. It is possible to obtain a porosity of 20% or more with 0-10 mm aggregates and a 2-6 mm discontinuity. Some results show an overall noise reduction. In Europe and beginning in North America, much research has been conducted on reducing tire/road noise through the use of open-graded or porous road surfaces. Many different types of surfaces have been investigated, with reported reductions of up to about 5 dB. However, the noise reduction realized by such pavements has been found to deteriorate within a few years, as the voids fill or wear down. Also, recent studies have shown that rougher pavements can increase roadside noise levels substantially. Some examples of rough pavements include grooved concrete, chemically-washed concrete and pavement blocks.

In Europe false tunnels have been used when important insertion loss is required rather than the barriers of height greater than 3 m that would be required to achieve the desired attenuation.

Direction for Future Work

The Working Party believes that the issue of the accuracy of noise level estimation calculated with prediction models requires more attention. Calculation of A-weighted levels cannot be as accurate as calculations made per octave frequency band or per 1/3-octave frequency band. If 1/3-octave or octave band levels are known or predicted, this opens up the possibility of using a loudness scale in sones or phons. Sone values relate directly to subjectively perceived loudness which is a major component of noise nuisance. The effects of a barrier could then be more closely gauged in terms of human perception.

Also it is desirable that each source on a vehicle be characterized by a height, position, and sound power level depending on the type of vehicle (road or rail) and on the speed. For example, in the case of passenger cars or light trucks, a first noise source just above the road surface is the corresponding source for the tire-road noise. The other source, slightly higher, corresponds to the engine exhaust, fan, and/or aerodynamic noise. Currently, it is common to perform calculations using normalized traffic flow. In the future, effort should be devoted to the average characteristic of the source(s) of a traffic flow with passenger cars, light trucks and heavy trucks, and for different types of trains such as rim braked passenger trains, discbraked passenger trains, diesel trains and different types of freight trains. It is necessary to define and standardize these characteristics for every type of vehicle separately, so that when a calculation is made with a prediction model the different vehicles can be combined with different speeds to the actual
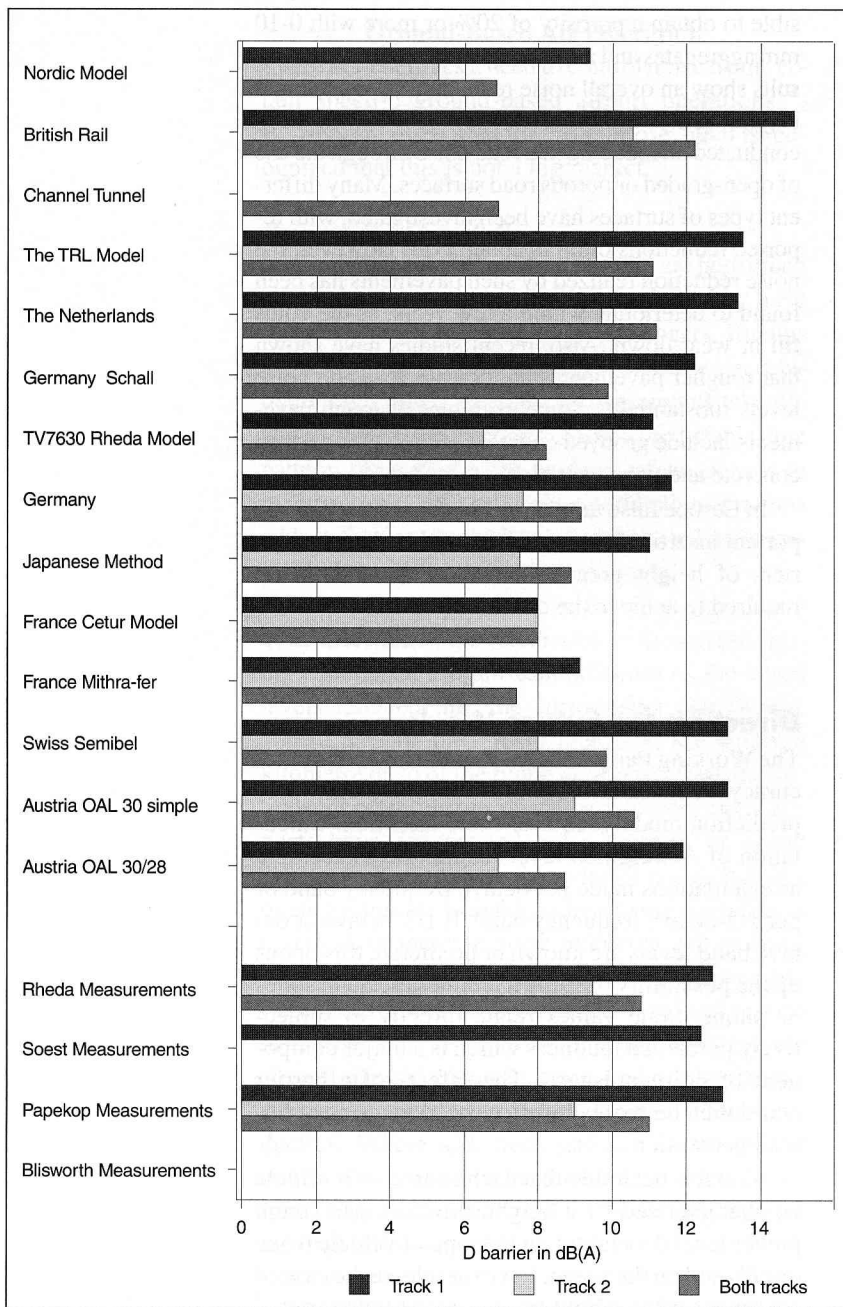
Fig. 13. Comparison of the prediction models with measurements of the effect of absorptive acoustic barriers.

duced by a barrier. In countries around the world typical barrier heights range between 2 and 6 m. It is the collective experience of the Working Party that the most common values for insertion loss range between about 5 and 12 dB, but values between 3 and 25 dB are also often found. There is smaller body of evidence to support the use of absorbing material to improve the performance of barriers. Parallel vertical reflective barriers along both sides of a roadways may degrade performance. The use of absorbing material is particularly important in this type of application. It is the collective opinion of the Working Party that generally documentation on noise walls are difficult to interpret and apply in practice.

The reduction in noise levels provided by barriers can be expressed in other quantitative terms or in terms of psychoacoustical measures of the effects of noise of people. For example, a 12 dB reduction is equivalent to a four fold increase in the source to receiver distance (for "point" sources). Sociological studies have shown a direct relationship between community noise levels and the number of persons highly annoyed in a given population. Although the relationship in not linear, a reduction of 12 dB is roughly expected to reduce the percentage of people highly annoyed by traffic noise in typical circumstances by as much as 20 to 30%. Speech communication is clearly essential in human society. When speech sounds are masked by noise, speech intelligibility is reduced and the quality of communication is impaired. An improved speech-to-noise ratio of 12 dB can improve the percentage of correct words by about 40%.

Acknowledgments

traffic flow in order to get the equivalent sound levels at the receiver.

Further, road side studies of the effectiveness of absorptive treatment on noise barriers should be made where traffic and meteorological factors are strictly quantified.

Conclusion

The Working Party believes that there is strong body of evidence to support the use of barriers as an effective method of abating transportation noise. Barrier height and proximity of source and receiver are of fundamental importance to the attenuation pro-

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