Special Noise Barrier Applications

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16. ABSTRACT

This report summarizes an investigation of the technical, aesthetic, and economic feasibilities of incorporating special noise barrier applications into a highway noise control program. The intent of the report is to take as a starting point the thin, vertical, reflective barrier now used in most applications. Special barrier applications are those beyond the thin vertical reflective barrier.

The investigation of technical feasibility relates to the mathematical formulation of the effects of absorptive treatments, slanted tops, T-tops, and other special applications. The economic and aesthetic feasibility investigations examine the value of employing these special applications in lieu of thin, vertical, reflective barriers.

The research reported on herein was performed on behalf of the Washington State Department of Transportation. The intent of the research was for background studies of the effects of special barrier treatments, so the Department could be in a position to implement pilot projects at a later date.

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Final Report

SPECIAL NOISE BARRIER APPLICATIONS

by
Louis F. Cohn, Ph.D., P.E.
Roswell A. Harris, Ph.D., P.E.

Department of Civil Engineering
University of Louisville
Louisville, KY 40292
(502) 588-6276

Submitted to:

Research Office
Planning, Research and Public Transportation Division
Washington State Department of Transportation

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SUMMARY

The problem addressed in this report is the investigation of the technical, aesthetic, and economic feasibilities of incorporating special barrier applications into the WSDOT noise control program. The investigation of technical feasibility will relate to the mathematical formulation of the effects of absorptive treatments, slanted tops, T-tops, and other special applications. In addition, the technical feasibility investigation examines the literature in these areas, and specifies in situ noise measurement studies performed in order to confirm noise reduction performance characteristics.

The economic and aesthetic feasibility investigation examines the value of employing these special applications in lieu of standard vertical, reflective walls. In other words, this investigation specifies those situations where the special barrier applications may be preferential as a result of cost or visual impacts.

Lastly, this project examines the existing highway noise modelling methodology (e.g., the FHWA Model, FHWA-RD-77-108, and STAMINA 2.0/OPTIMA, FHWA-DP-58-1) as it relates to barrier analysis. In its present form this methodology is limited to considering vertical, reflective walls. Methods are suggested to append special barrier analysis to the current methodology, in order to allow for consideration of special barrier treatments with existing tools. In addition, recommendations are made concerning full integration of the special barrier analysis procedures into the noise prediction computer methodology in use by WSDOT.

INTRODUCTION AND RESEARCH APPROACH

Problem Statement

More than 500 linear miles of noise barriers have been constructed in the United States during the last twenty years by state highway agencies. The *vast* majority of these barriers have been vertical, reflective walls made of concrete, wood, or steel. The standard barrier top for these walls is a "knife-edge", providing a single diffraction edge with a reflective diffraction zone.

Clearly, there are many other options for noise barrier shapes than vertical reflective walls with knife-edge diffraction zones. In addition to earth berms, there are options to make barriers absorptive or partially absorptive, to displace the diffraction zone horizontally through the use of a *slanted* section on top, or to provide for a double-diffraction zone through the use of a *T-top* section on the top of the wall.

The problem under study in this project is the technical, economic and aesthetic feasibility of incorporating these special barrier applications into the WSDOT noise control program. The investigation of technical feasibility relates to the mathematical formulation of the effects of absorptive treatments, slanted tops, T-tops, and other special applications. ***This chapter includes a literature review which examines the technical background of these applications.***

Historical Statement

The present methodology for modelling highway noise is **the FHWA Model**, FHWA-RD-77-108, and STAMINA 2.0/OPTIMA, FHWA-DP-58-1. In its present form the FHWA Model is limited to considering vertical, reflective walls.

Chapters in this report will suggest methods to append to the barrier portion of the model, in order to allow for consideration of special barrier treatments with existing tools. In addition, recommendations will be made concerning full integration of the special barrier analysis procedures into the noise prediction computer methodology in use by WSDOT.

The development of computerized highway noise prediction and barrier design tools can be traced to 1963. The FHWA Model is the result of much research and development, as is the STAMINA 2.0/OPTIMA software package. Neither the basic algorithm (77-108) nor the computer package have changed significantly in the past decade, although significant computational enhancements have been produced by the authors. These include REBAR (for parallel barrier analysis), STAMPLOT (for two dimensional plotting), NCAD (for three dimensional plotting), CHINA (an expert system for automated barrier design), and HICNOM (for construction noise prediction).

The effect of enhanced performance by special barrier applications may not be readily apparent until examining the acoustics involved. Essentially, diffraction theory shows that a one foot change in barrier height will result in a one-half decibel change in sound level, as long as line-of-sight with the source remains substantially broken. In other words, if an enhancement in barrier performance due to a special application produces one more decibel of attenuation, the barrier can be made two feet shorter and still produce the same final sound level. A two decibel enhancement would result in a barrier as much as four feet shorter with the same final sound level, as long as line-of-sight remains broken. Considering this one-half decibel per foot performance gain, it is obvious that enhanced performance due to special barrier application could save significant amounts in barrier construction. Shorter barriers would mean less aesthetic impact and less loss of view.

The first prediction model used extensively was that found in NCHRP Report 117 (*Highway Noise, A Design Guide for Highway Engineers*, 1971). The model utilized a statistical approach, in that L_x values (L_{50} and L_{10}) were the only descriptors found in the calculations. The noise source data base upon which the model was founded was quite small and did not adequately represent actual conditions. For example, the model assumed that all vehicles on a highway could be classified as either automobiles or trucks, with the following source emission levels.

$$L = 16+30\log S^{*} \text{ dBA} \quad \text{(automobiles)}$$

$$L = 82 \text{ dBA} \quad \text{(trucks)}$$

*S is speed in mph

Thus, the model assumed that automobile emission levels had a speed dependency of 9 dBA per doubling of speed and that truck emission levels were independent of speed. Both of these assumptions were proved to be incorrect by later studies.

Further research sponsored by NCHRP produced Report 174 (*Highway Noise, A Design Guide for Prediction and Control*, 1976). Included in Report 174 was the **Revised Design Guide** (RDG) which incorporated the medium-truck concept, replaced the L_x initial descriptor with L_{eq}, and generally laid the foundation for the new generation of models.

The RDG had some similarities with another model which was developed independently of the NCHRP effort. In 1972, the Transportation Systems Center (TSC) of the USDOT published its *Manual for Highway Noise Prediction*, popularly know as the TSC Model. This model was L_{eq}-based, but included only two types of vehicles: automobiles and trucks.

While the TSC Model was perhaps more technically sound than the NCHRP 117 model, it never gained wide acceptance by the state highway agencies because of its tendency to overpredict noise levels.

As a way of summarizing the experiences gained in the prediction of highway noise, the following needs were generally recognized as essential in the development of the new generation of models.

- A large data base for source emission levels.
- A mechanism to eliminate variable spatial decay rates as a function of traffic flow density.
- A means to consider excess attenuation by absorptive ground covers.
- An L_{eq}-based descriptor system to reduce statistical dependencies.
- A fully defined and validated theoretical equation for noise emission and propagation.

Realizing that several of these needs had not been met by the research efforts sponsored by NCHRP, FHWA undertook the task of developing the new generation of models as an in-house program. The result was the publication of Report FHWA-RD-77-108, *FHWA Highway Traffic Noise Prediction Model*, which is commonly referred to as the FHWA Model.

The FHWA Model, like several other prediction models, arrives at a predicted L_{eq} through a series of adjustments to a reference sound level. In the

FHWA model, the reference level is the energy mean emission level. Adjustments are then made to the reference energy mean emission level to account for traffic flows, for varying distances from the roadway, for finite length roadways, and for shielding. All of these variables are related by the following equation:

$$L_{eq}(h)_i = (L_o)_{Ei} + 10\log\left(\frac{N_i \pi D_0}{S_i T}\right) + 10\log\left(\frac{D_0}{D}\right)^{1+\alpha} + 10\log\left(\frac{\psi_\alpha(\phi_1,\phi_2)}{\pi}\right) + \Delta_s$$

where

$L_{eq}(h)_i$ is the hourly equivalent sound level of the *i*th class of vehicles.

$(L_o)_{Ei}$ is the reference energy mean emission level of the ith class of vehicles.

N_i is the number of vehicles in the *i*th class passing a specified point during some specified time period (1 hour).

D is the perpendicular distance, in meters, from the centerline of the traffic lane to the observer.

D_o is the reference distance at which the emission levels are measured. In the FHWA model, D_o is 15 meters. D_o is a special case of D.

S_i is the average speed of the *i*th class of vehicles and is measured in kilometers per hour (km/h).

T is the time period over which the equivalent sound level is computed (1 hour).

α is a site parameter whose values depend upon site conditions.

ψ is a symbol representing a function used for segment adjustments, i.e., an adjustment for finite length roadways.

ϕ_1,ϕ_2 are roadway angles of acoustic influence which assist in locating roadway segments spatially.

Δ_s is the attenuation, in dBA, provided by some type of shielding such as barriers, rows of houses, densely wooded areas, etc.

When sequentially added, these parameters produce an hourly L_{eq} value for the *i*th vehicle class. In practice, this means an L_{eq} value for automobiles, medium trucks, and heavy trucks. The overall L_{eq} for the traffic mix, L_{eqTOT}, is then obtained by decibel, or logarithmic, addition.

In order to meet the need to have a large data base available for source emission level determination, FHWA performed an extensive measurement program in four states spread across the country. This measurement program was instrumental in modifying the direction in which highway noise prediction methodologies were heading. The concept of a mean emission level was introduced, which provided the mechanism to eliminate the variable spatial decay rate as a function of traffic density (flow rate). Up until this point the previous models had utilized maximum (passby) emission levels for individual vehicles. Individual vehicles act as a point source, but as the flow rate increases the traffic stream becomes a line source. The spacial decay rate of a point source is 6 dB per distance doubling, while the spacial decay rate of a line source is 3 dB per distance doubling. In practice, most traffic streams are somewhere between a point source and a line source, with some models (NCHRP 117) assuming a modified line source (4 to 4.5 dB). The issue of variability in decay rate had consistently been a problem in overall model accuracy and flexibility.

This problem was solved through the replacement of the maximum emission level with the energy mean emission level. This replacement meant that instead of developing the vehicle emission level **L** by measuring a series of maximum passby noise levels, energy mean emission levels L_E were developed, thereby producing an equivalent sound level (L_{eq}). The spatial decay rate of L_{eq} values is always 3 dB per distance doubling, regardless of traffic density.

The adjustment factors for volume, distance, ground absorption, and so on, are not critical to this literature review, but are discussed in detail in the FHWA 77-108 report. The adjustment factors for shielding and barrier performance, however, are critical, and are discussed below.

Shielding (Δ) The placement of an obstruction between the highway and the observer will shield the observer and therefore lower the sound level. Shielding may take the form of densely wooded vegetative strips, which, according to the models, will ordinarily yield attenuation values of 5 dBA per 100 feet of depth, up to a maximum of 10 dBA. To obtain this attenuation, the density must be such that there is no line of sight possible through the woods, and the trees must be at least 15 feet high.

More recent work on this topic has been completed by the authors. In the paper "Use of Vegetation for Abatement of Highway Traffic Noise", Harris and Cohn have determined that a 2 to 3 dB decrease in noise levels is possible with a narrow (30 feet) belt of vegetation [Harris, 1985]. This research indicates that an even further reduction may be possible with a barrier planted and maintained in such a way as to encourage maximum density growth. This solution may prove to be economically reasonable in cases where a substantial amount of attenuation is not required.

In addition to vegetative screening, it is also possible for buildings to reduce L_{eq} values. A row of houses or other buildings that provide at least 60 percent coverage will yield a reduction of 5 dBA at the first row, according to the FHWA Model.

Barrier Performance The primary concern of this project is what effect will noise barriers have on the values of L_{eq}. In most instances where the shielding adjustment is used, solid barriers or walls are involved. The acoustic phenomenon governing barrier attenuation is known as *Fresnel diffraction*, which analytically defines the amount of acoustic energy loss encountered when sound rays are required to travel over and around a barrier. Figure 1 illustrates the concept of *path length difference*, δ (δ = A + B - C), which is the extra distance the sound travels as a result of the barrier.

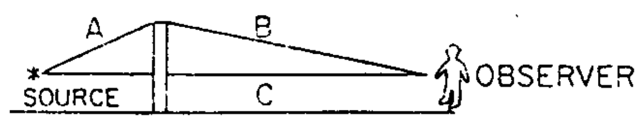


Figure 1 Path Length Difference

Once δ is known, Fresnel diffraction, N, is then mathematically defined as:

$$N=2(\frac{\delta}{\lambda})$$

From the Fresnel number, N, barrier attenuation may then be determined. This is accomplished through integration of the following equations (once each for automobiles, medium trucks, and heavy trucks):

$$\Delta_{B_i}=10\log[\frac{1}{\phi_R-\phi_L}\int_{\phi_L}^{\phi_R}10^{-\Delta/10}d\phi] \qquad (1)$$

where:

$$
\Delta_i = \begin{cases} 0 & N_i \leqslant -0.1916 - 0.0635\epsilon \\[2ex] 5(1+0.6\epsilon) + 20\log \dfrac{\sqrt{2\pi |N_o|_i}\cos\phi}{\tan\sqrt{2\pi |N_o|_i}\cos\phi} & (-0.1916 - 0.0635\epsilon) \leqslant N_i \leqslant 0 \\[2ex] 5(1+0.6\epsilon) + 20\log \dfrac{\sqrt{2\pi (N_o)_i}\cos\phi}{\tanh\sqrt{2\pi (N_o)_i}\cos\phi} & 0 \leqslant N_i \leqslant 5.03 \\[2ex] 20(1+0.15\epsilon) & N_i \geqslant 5.03 \end{cases} \qquad (2)
$$

where Δ_i is the point source attenuation for the ith class of vehicles.

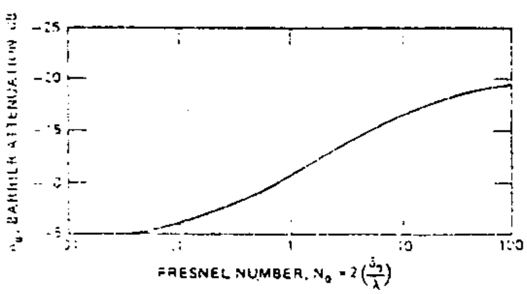
$N_i = (N_o)_i \cos\phi$

ϵ is a barrier shape parameter, 0 for a freestanding wall and 1 for an earth berm.

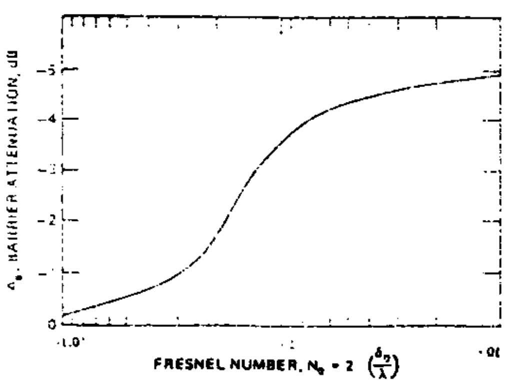
N_o is the Fresnel number determined along the perpendicular line between the source and receiver.

N_{o_i} is the Fresnel number of the ith class of vehicles determined along the perpendicular line between the source and receiver.

Solutions of Equations (1) and (2) yield the following curves:



(a)



(b)

Curves a and b illustrate barrier attenuation versus positive and negative Fresnel Number, respectively, for infinitely long barriers. Given the Fresnel Number, the barrier attenuation may be deduced.

Highway traffic noise is broadband; that is, it contains energy in the frequency bands throughout the audible range. As shown above, the Fresnel number will vary according to the dominant frequency chosen. The dominant frequency for highway traffic is usually taken to be 500 hertz.

The limitations of Fresnel diffraction as defined and used by the FHWA Model include:

- knife-edge barrier top (i.e., thin diffraction plane), and
- reflective barrier surface

The remainder of this chapter contains a literature review, which explores options beyond reflective, knife-edge barriers to enhance barrier performance.

Literature Review

SHAPED BARRIERS

Barrier performance can generally be improved by increasing the height, but studies have shown that the benefit/cost ratio generally peaks at a height of about 13 feet. For this reason, for aesthetics, and to extend knowledge and widen design options in this field, May and Osman performed research to find other ways to increase barrier performance. [May, 1980-1]

In their paper the results of 1/16 scale model studies of a number of barrier types are presented. The many barrier types that were investigated in this study are shown in Figure 2. Among the barrier types studied by May and Osman are:

traditional vertical "knife-edge" barriers, inclined barriers, and thnadner (special shape) barriers.

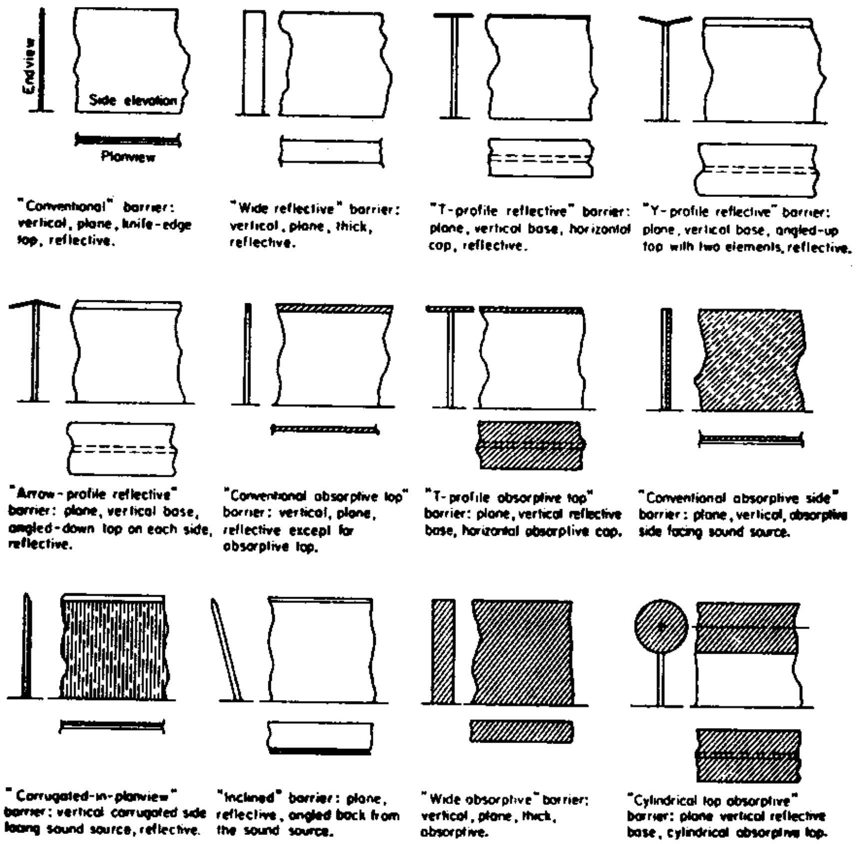


Figure 2 Barrier types investigated by May and Osman

Conventional Barriers

A conventional noise barrier is the reference barrier against which most other barriers are judged. This is the vertical "knife-edge" barrier used in the FHWA Model. As mentioned above, May and Osman concluded that the benefit/cost ratio of the conventional barrier peaks at heights of 13 feet, with taller barriers being less cost effective. Fresnel diffraction calculations leads to the conclusion that, for typical highway noise spectra (dominant frequency 500 hertz) and conventional barriers, **one dBA insertion loss is gained for each two feet in height** once line of sight is broken. At the line of sight break, Fresnel diffraction provides five dBA insertion loss. Using these two rules of thumb, a fifteen feet tall barrier is likely to produce a ten dBA insertion loss.

A study by Hutchins, *et al.*, compares the performance of a conventional barrier in the presence of grass and asphalt groundcovers. While May and Osman presented their data in terms of dBA, Hutchins defined insertion loss as a function of frequency, to investigate the underlying propagation phenomena [Hutchins, 1984-1].

Hutchins notes that Fresnel diffraction and thus barrier insertion loss are less at lower frequencies (around 500 Hz). Conversely, the excess attenuation of the ground surface in each case (asphalt and grass) is a maximum centered around the same frequency. This increased attenuation due to the ground arises from destructive interference between direct and reflected rays. Prior to the barrier's placement, an attenuation in excess of free-field propagation exists due to the presence of the ground. However, when the barrier is inserted, the reflected wave between source, ground, and receiver is eliminated, and the destructive interference observed is removed. The barrier attenuates sound due to the fact that the direct wave must diffract over the barrier (Fresnel diffraction), but this effect is diminished by the removal of a beneficial excess attenuation centered about 500 Hz. The result is a decrease in insertion loss centered about this frequency. Hutchins examined several scale model case studies relating barrier performance in the presence of grass and asphalt. Case study results were then compared to outdoor measurements.

The first case considered asphalt on both sides of the 16 feet tall barrier.

In this case (40 feet behind the barrier), the excess attenuation of the ground surface in the barrier's absence peaked at 7 dB at 500 Hz; as a result, use of the barrier does not cause too serious a deterioration in performance with the removal of an initial destructive interference.

In the second case, grass, the situation becomes more complex. The excess attenuation of the ground surface in barrier's absence has a distinct maximum at about 450 Hz of about 20 dB. Thus the placement of a barrier would be expected to result in a diminished insertion loss with a minimum at this frequency, due to the removal of the reflected ray.

Sloped Barriers

May and Osman also studied the performance of an inclined barrier [May 1980-1]. They concluded that overall, no significant additional insertion loss was found with this type of barrier. A sloped barrier has the effect of moving the diffraction edge slightly closer to the receiver or roadway (depending on direction of the slope). Fresnel diffraction is a function of path length difference δ; since such a movement of the diffraction edge will not significantly change δ, Fresnel diffraction and insertion loss will not be significantly altered.

Menge, however, did find some benefit to sloping barriers when used in parallel barrier situations, in a scale model study performed for the Maryland DOT [Menge, 1980]. For a 16 feet tall vertical, parallel barrier case, Menge showed a 4 dBA insertion loss. This minimal performance was a result of the multiple reflections and images created by the parallel barriers. (Parallel barriers are discussed in detail later in this report.) By sloping the barriers back 10 degrees, insertion loss increased to 10 dBA. The enhanced performance was due to the elimination of all but the first reflection. Menge found that the 10 degree angle of slope was optimum.

Thnadner Barriers

Other barrier designs have attempted to enhance barrier performance by shaping the top of a thin barrier to enhance desirable diffraction effects. These are *Thnadner* barriers, Figure 3, in which an attempt is made to deepen shadow regions by deliberately introducing degrees of transparency or phase velocity gradients near the top. Thnadner barriers are barriers that have a shaped edge (see Figure 3).

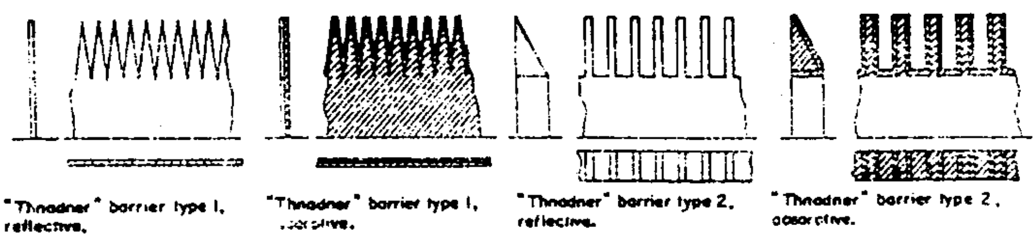


Figure 3 Thnadner barrier shapes

Hutchins, *et al.*, investigated the design of Thnadner barriers, and the design of a barrier with a horizontal segment missing [Hutchins, 1985]. In this study, the Thnadner barriers actually *reduced* insertion loss values compared to the plain barrier, when grass was present. The flat-top (F) and sawtooth designs, Figure 4, were even less effective than the Thnadner barrier with the horizontal segment missing. Intuitively this would be expected, as sound levels increased as more material was removed from the barrier. However, the horizontal (H) design had the same amount of material removed as the sawtooth (S) configuration, but exhibited a poorer performance. This indicates that there is some merit to the Thnadner design, not necessarily in improving the overall performance compared to a barrier, but in attempting to obtain the best performance with a lesser amount of barrier material. As an example, the flat-top design was only slightly worse than the plain (conventional) barrier, and yet in practice would use 87.5% of the material required for a plain barrier.

Figure 4 Thnadner barriers, Sawtooth (S) with 50% open, Flat-top (F) with 25% open, & H design.

BARRIER TOPS

Increasing the effective width of the barrier may be achieved by either increasing the width of the top by various means, or by making the entire barrier thicker. In either case, the result is **double diffraction.** The following section is a review of five promising barrier top modifications. The five modifications discussed are the T-top, Arrow-top, Y-top, Slanted-top, and Cylindrical-top.

T-Top Barriers

The concept of T-top barriers has been studied extensively in Canada. May and Osman first reported in a 1979 1/16 scale model study the possible advantages of a T-top barrier [May, 1980-1]. T-tops of a standard thickness but varying widths were tested under the scenario of a single barrier with a protected receiver (i.e., a receiver behind the barrier). Figure 5 shows the insertion loss for T-top barriers of various cap widths, compared with a conventional knife-edge barrier. Cap thickness was, in all cases, essentially zero.

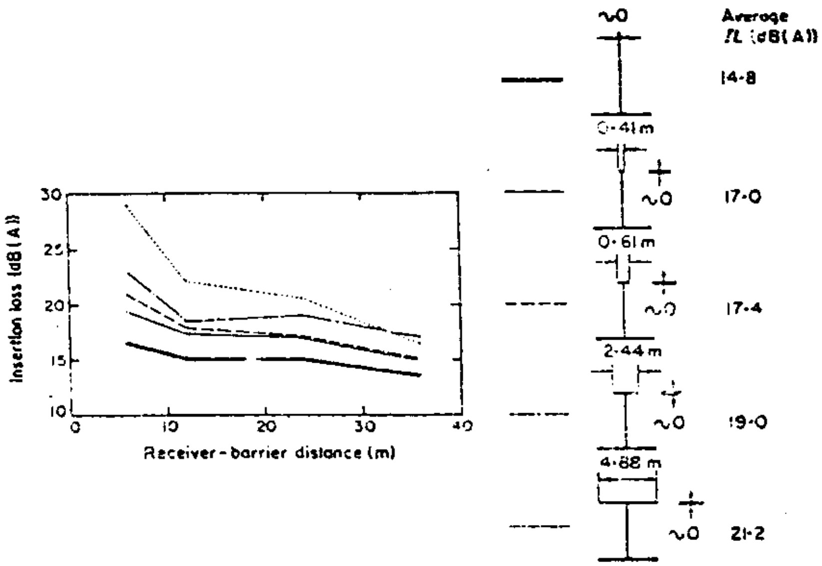


Figure 5. Insertion loss for T-top reflective barriers of various cap widths, compared with a conventional knife-edge top barrier. [May, 1980-1]

Figure 5 shows an increase in insertion loss of 2.2 dBA for a cap width of 1.33 feet, which is 2.1 dBA more than that found for a knife-edge reflective barrier. The greater increase with the T-top barrier was due to double diffraction. It should be noted that if the 1.33 feet wide T-top were stood on its end, thus adding height to the barrier, insertion loss would be increased by about 0.7 dBA. This is based upon the rule of thumb that insertion loss increases one dBA for every two feet of height beyond the line of sight break. This demonstrates the significant potential offered by T-top barriers.

May and Osman also studied the possibility of an absorptive treatment on the top of a reflective T-top barrier [May, 1980-1]. In this study, two frequency bands (500 and 1000 Hz) were considered as well as the A-weighted spectrum. Three levels of absorption were used: NRC values of 0.52, 0.57, and 0.74. Table 1 shows the measure in insertion loss as NRC increases, taking as reference the insertion loss for the lowest quality absorptive material. A direct comparison is made between the insertion loss of the reflective and absorptive T-tops in Figure 6. A review of Figure 6 shows that the absorptive treatment increased insertion loss. For the realistic cap width of 2 feet, the absorptive top produced an additional 1.9 dBA of attenuation when compared to the same width reflective T-top. Again, it should be noted that the absorptive top functions better at higher frequency sound levels because the shorter sound wavelengths have more opportunity to be affected while diffracting across the barrier top.

In addition to their scale model testing, May and Osman conducted a full scale test on an existing highway noise barrier built in Toronto in 1978 [May, 1980-1]. The 13 feet high barrier was tested first with an absorptive side, second with a reflective side, and finally with a thirty inch T-top. Although they found no statistically significant difference between the noise reductions produced by the absorptive and reflective barriers, sound measurements in the residential community behind the barrier showed the T-top barrier produced a 1 to 1.5 dBA **greater** noise reduction than the other two configurations. This is less than would be expected from adding 30 inches of height to the barrier; however, May and Osman noted that high background noise in the area likely reduced insertion loss measurements. Consequently, they felt that their measurements understated the T-top effects.

Table 1

Insertion Loss for Various Absorptive Materials*(dB)

1/3 Octave Band Center Frequency (Hz)	Barrier Height (Ft.)	Noise Reduction Coeff. 0.52	0.57	0.74
500	ALL**	0	1.2	1.5
1000	ALL	0	1.4	3.4
ALL**	10,12	0	1.2	2.1
ALL	14,16	0	1.3	2.7
ALL	ALL	0	1.3	2.4

* Average insertion loss. Reference zero is for material with NRC = 0.52.
** "All" barrier heights or frequencies are those shown in the table.

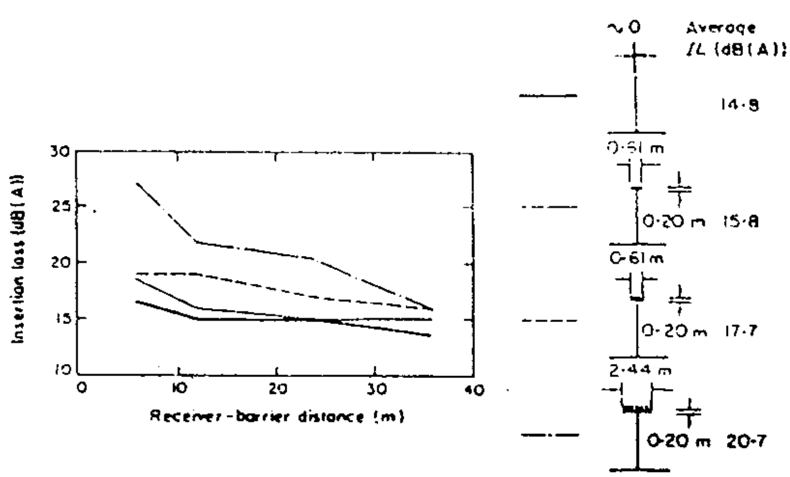


Figure 6. Insertion loss of T-top absorptive and T-top reflective barriers, of the same cap thickness, compared with a conventional knife-edge top barrier.
[May, 1980-1]

Another set of scale modeling experiments were conducted in Canada in 1983 at the Technical University of Nova Scotia [Hutchins, 1984-2]. Hutchins, Jones, and Russell conducted the modeling experiments which investigated the frequency dependence of barrier insertion loss for various noise barrier designs. The effect of ground surfaces were studied, treating both grass-covered ground and asphaltic surfaces. In both cases, the T-top barrier produced larger insertion losses when compared to a standard thin barrier.

In summary, the T-top barrier will provide acoustical performance comparable to a knife-edge barrier, when the difference in height is equal to the width of the T-top. On the positive side for T-top barriers is that the shorter height will result in reduced wind loads, and therefore smaller foundation requirements. Also, since T-top barriers are shorter, they will have less of an aesthetic impact. On the negative side, T-top barriers may cause problems with snow accumulations in some climates. This problem could be solved by slightly sloping the T-top.

Arrow-top Barriers

In their scale modeling tests, May and Osman described an "arrow-top" barrier, in which the cap of the T-top slopes down 14 degrees on each side. The arrow-top barrier was considered in scale testing as an alternative to the T-top and Y-top types. May and Osman found that the average insertion loss for a reflective arrow-top barrier to be 1.8 dBA higher than that of the conventional knife-edge barrier. This is illustrated in Figure 7. The insertion loss provided by the arrow top barrier was, however, lower than those of both the Y-top and T-top barriers of equal 8 feet span. (Y-top barriers are discussed in the next section.) This fact prompted the conclusion that only where the receiver is close enough for the path of the sound wave to graze the barrier does the shape function well. Presumably this applies also

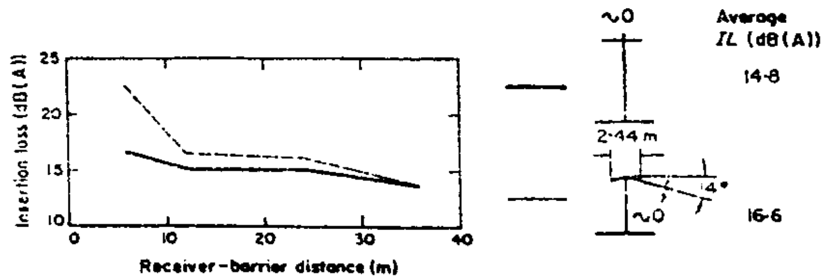


Figure 7. Insertion loss of the arrow-top reflective barrier, compared with a conventional knife-edge top barrier. [May, 1980-1]

to the position of the source. For situations in which source and/or receiver are discretely located (i.e., are localized and fixed relative to the barrier) it might be possible to tailor the slopes of the arrowhead to maximize attenuation. For less defined positions of source and receiver, May and Osman concluded that the arrow-top barrier does not seem to work as well as the Y-top or T-top. Obviously, this is because there is no pronounced double diffraction activity with the arrow-top barrier.

Hutchins, *et al.* also tested arrow-top barriers in their scale model studies [Hutchins, 1984-2]. Their results agreed with the theoretical finding of May and Osman, that arrow-tops were superior to knife-edge barriers, but inferior in performance to T-top and Y-top barriers.

Y-Top Barriers

Y-top barriers were also studied by both Hutchins and May and Osman, to see whether, for an equivalent height and overall width, they had an insertion loss equal to that of the T-top barrier. Such a finding would have suggested that the good performance of the T-barrier is independent of the interaction of its flat top and the grazing wave. This would open the way to considering barriers similar in their diffractive effects to the Y-top barriers, but which present fewer snow clearance and drainage problems.

In their scale model study, May and Osman found that the Y-top barrier gave a 3.5 dBA higher insertion loss than a conventional knife-edge barrier [May, 1980-1]. However, the insertion loss was 0.7 dBA lower than that of the T-top barrier with an equivalent 8 feet span. Figure 8 illustrates the insertion loss of the Y-top reflective barrier.

Hutchins found the Y-top barrier also provided a greater insertion loss than a standard knife-edge barrier [Hutchins, 1984-2]. However, in this study the T-top barrier once again surpassed the Y-top barrier in performance by slightly less than 1 dBA. This slight difference may be due to the fact that the T-top yields a continuous flat surface which provides interference with the propagating wavefront from the first diffraction in the double diffraction activity. The top edges of the Y-top function as two separate barrier edges like two conventional knife-edge

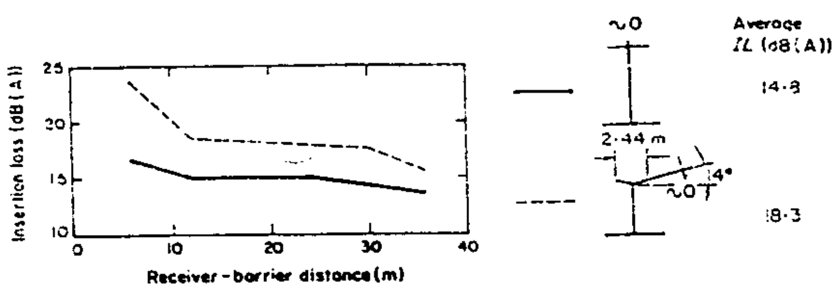


Figure 8. Insertion loss of the Y-top reflective barrier, compared with a conventional knife-edge barrier. [May, 1980-1]

barriers placed close together. This complex question regarding the diffraction zone of each barrier top will be investigated further in the *mathematical formulation.*

Although Y-top barriers provide slightly less attenuation than T-top barriers, they are superior to knife-edge barriers, and warrant further examination. Along with T-top barriers, they may be useful to WSDOT in certain situations.

Slanted-top Barriers

Slanted top noise barriers are used extensively in Japan. In a 1982 publication, Cohn discussed the possible advantages of slanted barrier tops [Cohn, 1982-1]. These advantages were observed during research conducted on barrier materials and shapes he conducted in the Laboratory of the Japan Highway Public Corporation.

It is common to see noise walls in Japan with the upper one-third of height slanted toward the traffic at a 30 to 45 degree angle. The result is that the slanted tops displace the location of the diffraction edge, and can contribute to **slightly** increased barrier attenuation (in a way similar to fully slanted barriers discussed earlier).

Cylindrical-top Barriers

The concept of cylindrical-top absorptive barriers was discussed by May and Osman in their scale model tests of different barrier shapes [May, 1980-1]. In their 1979 study, a cylindrical top absorptive barrier (cylinder diameter of 8 feet) produced a 2.5 dBA higher insertion loss than was found for a conventional knife edge reflective barrier [May, 1980-1]. This is not a significant improvement over the knife-edge for this unrealistic shape. Given that the cylinder will not induce double diffraction, it is logical that it would not greatly outperform other shapes, including the knife-edge barrier.

A more recent study of the sound shielding efficiency of a cylindrical top barrier was reported in 1991 by Fujiwara and Furuta [Fujiwara, 1991]. These authors examined two types of cylinders, namely a perfectly hard reflective cylinder and a perfectly absorptive cylinder. The effects produced by the cylinders for the case of an incident spherical sound wave were measured in an anechoic chamber. A traditional reflective knife-edge barrier was used as a test barrier to obtain the excess attenuation produced by a thin hard barrier without a cylinder. Initial scale models indicated that the effect of the hard cylinder was not significant in the practical shadow region; therefore, a full scale test was not initiated for the reflective cylinder. However, the effect of the absorptive cylinder was much better, with excess attenuation over the knife-edge barrier of 7 to 8 dBA in the practical shadow region. This scale model result prompted Fujiwara and Furuta to develop a new absorptive cylinder for full scale testing and practical use.

An absorptive cylinder was designed for attachment to an existing highway noise barrier. A fiberglass pipe was used as the absorptive material, and it was covered with a very thin polyvinyl film and a perforated aluminum thin plate for protection against rain and wind. A final covering of stainless steel grill was added for protection against traffic accidents. A thin, vertical steel plate was placed inside the fiberglass pipe along the centerline to provide a reflective surface for any penetrating incident sound waves. The cylinder produced a sound absorption coefficient of 0.7.

The cylinder (approximately 20 inch diameter) was attached to a 0.1 mile section of an existing 10 feet high noise barrier along an expressway. The plane in which the measurements were made was perpendicular to the barrier and was located at the middle point of the cylinder installation. The noise level difference (L_{eq}) before and after the installation of the cylinder was found to be 2-3 dBA, **for a measurement location deep in the shadow zone**. This is a significant amount of excess attenuation, with the result being that a cylinder-top barrier could provide an equal amount of insertion loss as a knife-edge barrier, but with 4-6 feet less height. Unfortunately, this effect would quickly diminish as the receiver moves out of the deeper parts of shadow zone. Most sensitive receptors of highway noise are not in the deeper parts of the shadow zone. However, the potential for enhanced barrier performance with absorptive cylinders has been demonstrated in this study; absorptive cylinders will be further examined later in this report.

SINGLE WALL ABSORPTIVE BARRIERS

Absorptive noise barriers have been extensively studied for many years. However, a review of the literature on this subject shows that there are still many uncertainties about the usefulness of covering barriers with absorptive material. For example, Maekawa carried out experiments on the diffraction of an absorptive barrier, but he discarded his experimental results because of their significant deviations from theory [Maekawa, 1965]. Later, Butler remarked that those experimental results were probably accurate [Butler, 1976].

Later, Jonasson [Jonasson, 1972] proposed combining the propagation theory of Ingard [Ingard, 1951] with the diffraction solution of Bowman *et al.*

[Bowman, 1969] in order to calculate and compare the insertion loss provided by a depressed road and an absorptive barrier.

At about the same time, Rawlins published theoretical studies on the diffraction of sound by an absorptive wedge [Rawlins, 1976]. He showed that a strip, one wavelength wide, of an absorptive material at the top edge of a barrier led to the same diffracted field as that provided by a totally covered barrier. However, Rawlins did not consider the effect of placing this absorptive strip only on the source side or on the receiver side or on both sides of the barrier.

In 1977, Fujiwara presented a study that specifically dealt with the excess attenuation provided by an absorptive material placed on the surfaces of a barrier [Fujiwara, 1977]. His results suggest that an absorptive cover can increase the free-field attenuation of a barrier by more than 6 dBA. Later, Isei presented a method for calculating the insertion loss of an absorptive barrier on a finite impedance ground using a diffraction solution [Isei, 1980]. In contradiction to Fujiwara, the theoretical and experimental results obtained by Isei showed that the absorptive properties of the barrier do not significantly change its insertion loss.

Koers recently suggested a solution for calculating the diffracted field over an absorptive barrier [Koers, 1983]. This solution is derived from the diffraction solution of Pierce and Hadden [Pierce, 1975]; additional terms are introduced to take into account the specific impedance of each side of the wedge. Unlike the other diffraction model, this solution has the advantage of respecting the reciprocity condition. Unfortunately, Koers did not extend his solution to calculation of the insertion loss provided by an absorptive barrier, as he did not study the real benefit of covering the barrier with an absorptive material.

In 1989, L'Esperance, Nicolas, and Daigle published a method for calculating the insertion loss of a thin barrier covered with absorptive material, either on the source side, on the receiver side, or on both sides [L'Esperance, 1989]. The method used combined a classical theory for the propagation of sound over ground with the approximate solution for diffraction over an absorptive wedge proposed by Koers, which can take into account the specific impedance of each side of the barrier. The validity of the method was confirmed by comparing theoretical results with experimental measurements for various geometrical configurations and barrier boundary conditions. The results showed that, when the angles of diffraction are significant, the insertion loss of a hard barrier can be substantially increased by covering one of its surfaces with an absorptive material. This absorptive layer must be placed on the surface of the barrier associated with the greatest angle of the diffracted rays paths (source top-edge or receiver top-edge). When these angles are about the same on each side of the barrier, the increase will be the same if the absorptive material is placed on the source or on the receiver side. In this case, it was found that by covering both sides of the barrier, the increase of the insertion loss due to the absorptive material will double compared to a single covering.

Another aspect of absorptive treatment is the question of the durability of the absorptive material. When sound absorptive materials are used indoors, they have to comply with requirements related more to the danger of fire than to durability. For outdoor applications this situation is reversed. In highway applications, for example, these materials must be resistant to (a) weather conditions, which are particularly severe when there are freeze-thaw cycles, (b) acts of vandalism, (c) impacts from vehicles, even though barriers are usually protected by guide rails, and (d) the presence of chlorides from snow plowing operations and spray. From an acoustical point of view a relatively high sound absorption would be desired in the range of 500 to 2000 Hz, where traffic noise contains much of its energy.

In 1980, Behar and May published the results of a study of the durability and sound absorptive properties of the available sound absorbing materials for highway noise barrier applications at that time [Behar, 1980]. Seven materials of various compositions were tested, as well as one "absorption system".

Several different tests were applied:

(1) the samples were attached for 9 months (through winter) to a wooden noise barrier erected just behind the guide rail of the Queensway freeway in Ottawa, Canada;

(2) the sound absorption coefficients of most of the materials were measured before and after the above-mentioned weather exposure, in order to see if there were any significant changes in their values;

(3) four accelerated durability tests were run in the laboratory.

Behar and May concluded, in general, that absorptive materials can behave in three ways depending on whether they are (a) mounted freely without a backing, (b) mounted on a hard surface (such as steel or concrete) without an air gap, or (c) mounted on a hard surface, but with an intervening air gap. With the first mounting, they saw that absorption coefficients are usually very low at low frequencies but rise steadily as frequency increases. Therefore they may absorb high frequency noise better than low frequency noise. The second of these mountings often results in an absorptive peak in the mid-frequency range which improves the overall behavior of the material. With the third mounting, it is sometimes possible to shift the resonance peak towards the lower end of the frequency range by increasing the air gap, thus increasing absorption at traffic noise frequencies. Furthermore, if mechanical protection such as a perforated metallic covering is provided, more changes are likely to occur in the absorption coefficient such as an increase in the middle frequency range and a decrease at high frequencies.

These were the general trends in the behavior of absorptive materials that Behar and May observed in their study. They used standing wave tube measurements as a means to compare the absorption of some classes of the materials on a common basis, and to assess the change in absorption coefficient (α) with time. However, they stated that the actual sound absorption of a material mounted in a particular way could only be found by a proper measurement of a test sample mounted in the same way it will be mounted *in situ*.

In a 1988 study, the Federal Highway Administration, in conjunction with the Maryland Department of Transportation State Highway Administration, conducted an experiment to determine the resistance of absorptive sound barriers to repeated cycles of freezing and thawing [Lane, 1989]. The experimentation was intended to help determine the acceptability of the sound barrier samples; it was not intended to provide a quantitative measure of the service life of a particular product. Testing was performed on two absorptive sound barrier samples, each 2 feet by 3 feet. The 4 inch thick samples consisted of 2 inch thick porous concrete on one side of the panel and 2 inch thick normal concrete on the other side of the panel. Embedded in the surface of the porous concrete were 1 inch smooth aggregate pieces. The two concretes differed in such properties as strength, mix proportions, and density.

The testing conformed to procedures described in the "Interim Method of Test for Resistance of Porous Concrete to Freezing and Thawing" which was developed internally by the FHWA. The samples were exposed to regular cycles of freezing and thawing. Thawing took place for 4 to 6 hours during the day; samples were then stored in a freezer each night. During the testing, the specimens were situated randomly in both the freezer and the moist room so as to negate any location-specific effects. The initial saturated weights and the condition of the specimens were recorded. Both specimen were weighed and evaluated after 50, 95, 158, and 200 cycles respectively. The normal concrete showed no signs of deterioration; however, the porous concrete surface of both specimens were severely deteriorated, with both losing approximately 60 percent of the surface. Therefore, these porous concrete samples were determined to be unsuitable as absorptive sound barriers in situations where they will be subjected to repeated freeze/thaw cycles.

The issue of durability has been successfully addressed by the proprietary product *Durisol*, a concrete based material with wood chips pressed into the mix. Durisol is able to achieve <u>and maintain</u> a noise reduction coefficient of about 0.6. This product has been used extensively in Canada and Europe for more than 10 years.

In summary, absorptive barriers offer potential for enhancement of insertion loss performance over reflective knife-edge barriers, even for single wall systems. The upper limit of this enhancement is likely to be on the order of two dBA. Certainly single wall absorptive barriers will be examined more closely later in this report.

SPECIAL BARRIER APPLICATIONS

Parallel Barriers

Of major concern for barrier performance is the situation where barriers are needed on both sides of a highway. Multiple reflections between parallel traffic noise barriers can seriously degrade the acoustical performance, or insertion loss, expected from each wall. This section of the report will analyze the pertinent domestic and foreign literature on this subject.

The problem of multiple reflections between parallel traffic noise barriers with the receiver outside the noise "canyon" is of great interest. Much of the work on this subject has been sponsored by government transportation agencies in France, Germany, England, Japan, Canada, and the U.S. Of particular interest is the importance of specular multiple reflections in degrading barrier insertion loss, the value of sound absorption in controlling the problem, and the relatively small contribution of sound scattering.

West German researchers have also been addressing the parallel barrier problem for many years through a combination of mathematical and scale modeling and field measurement work. In an early study, Reinhold and Burger computed multiple reflection effects as functions of wall height and receiver height [Reinhold, 1971]. Average sound level differences ranged from 3 to 4 dBA for a 10 feet high receiver, and from 0 to 12 dBA for a 40 feet high receiver.

Ullrich has studied multiple reflections from both depressed highway sections and tunnels [Ullrich, 1974]. His calculations, which included scattering and specular reflection, showed a maximum 3 dBA increase if both the source and the far wall reflection point were visible to the observer. However, at a field site with a tall factory wall opposite the road from an earth berm, the measured degradation behind the berm ranged from 4 to 7 dBA depending on the receiver height. Ullrich attributed this large effect to reflections off the factory wall in the 500 to 2000 Hz range. He also reported difficulties in finding good field study sites, concluding that nearly ideal sites were needed for studying diffuse and specular reflections and the effects of absorptive surfaces. One comparison for vertical retaining walls showed 3 to 6 dBA differences in average sound level between measurements for reflective walls and predictions for absorptive walls, depending on receiver distance.

In another study, through both mathematical and scale modeling, Ullrich examined cantilevered horizontal sections partly covering a depressed highway [Ullrich,1978]. Degradation was found to be a function of the wall reflection coefficients, the single wall insertion loss, cut depth and width, and receiver height and distance. For a 15 feet deep and 60 feet wide depressed section, Ullrich found that reflective partial coverings with 6 feet high reflective barriers at their edges would result in insertion losses of 1 to 8 dBA, depending upon receiver position. Covering the surfaces with absorptive material (with a 50 to 60 percent sound absorption capability) typically increased insertion losses by 2 to 3 dBA as the "reflection potential" decreased from 0.9 to 0.4.

In a more recent study, Ullrich presented additional modeling and field results, concluding that depressing roads with reflective vertical retaining walls was not a suitable means of noise abatement [Ullrich, 1983]. Audible sound level reductions could only be achieved if the walls of the cut section were made sound-absorbing, in combination with overhangs (and noise barriers for high insertion loss situations). For low insertion loss situations, a depressed highway with vertical walls could actually produce levels up to 2 dBA higher than an unshielded at-grade highway.

Figure 9 shows measured and calculated results from Ullrich for a highway consisting of a 70 feet wide cut of 25 feet depth with 11 feet wide overhangs. Insertion losses ranged from 2.0 to 6.0 dBA for reflective walls, 1.6 to 9.5 dBA for absorptive walls, and 4.5 to 12 dBA when five feet walls were added at the edges of the overhangs. Thus, absorptive treatment increased insertion loss by 3.5 to 4.5 dBA.

Beyer published results for a major noise barrier research project [Beyer, 1982]. Scale modeling studies done by his group at the French CSTB facilities examined propagation from elevated and depressed highways for a variety of parallel barrier treatments and cross-sectional shapes. The elevated highway was modeled as 40 feet above the ground, with parallel 20 feet high barriers set 50 feet apart. Broadband A-weighted insertion loss contours were produced for reflective and absorptive walls. Typical insertion loss differences were 3 to 5 dBA for receiver heights of 0 to 15 feet and receiver distances of 75 to 150 feet.

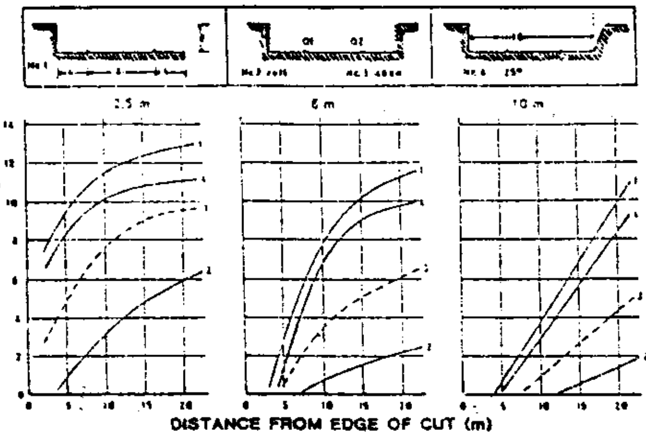


Figure 9. Scale-modeled insertion loss for a depressed highway as a function of receiver distance from edge of near retaining wall, for receiver heights of 2.5, 6.0, and 10.0 m. 1) reflective vertical near wall only; 2) reflective vertical near and far walls; 3) absorptive vertical near and far walls; 4) reflective vertical near wall and reflective inclined far wall. [Ullrich, 1983]

For the depressed highway, Beyer studied two basic cross-sections: (1) 15 feet depth, 50 feet width, and (2) 20 feet depth, 100 feet width. Addition of absorption material ($\alpha = 0.6$) increased insertion loss by a range of 0 to 8 dBA for the narrower highway section, and 0 to 4 dBA for the larger section.

Beyer also presented field data for a depressed highway in Dusseldorf, where the cut depth ranged from 10 to 30 feet. As shown in Table 2, the sound level remained relatively constant at a given receiver distance and height as the depth of cut increased. Thus, as the diffraction angle increased, the multiple reflection degradation also increased.

Table 2

Average Sound Levels For Depressed Highways
Of Varying Depths In Dusseldorf,
As Measured By Beyer

Receiver/ Wall Distance (m)	Receiver Height (m)	Average Sound Level(dB)		
		3 m depth	6 m depth	9 m depth
0.0	1.5	74	73	73
0.0	8.0	75	74	74
10.0	1.5	63	63	63
10.0	8.0	72	71	71
40.0	1.5	57	61	61
40.0	8.0	62	64	63

Finally, Beyer presented scale model data for two special designs: (1) parallel barriers faced with overlapping louvered panels inclined upward 15 degrees, and (2) parallel walls supporting an open grid over the highway, where the flanges of the grid varied in depth, spacing, and absorptive coverage. The former performed similarly to the absorptive vertical walls ($\alpha = 0.67$), while the latter showed mixed results. A properly designed grid appeared to offer as much as 12 dBA **additional** insertion loss compared to vertical reflective walls without the grid, while an improperly designed grid could actually increase levels.

Much of the Canadian work on multiple reflections and absorptive design has been done by researchers in the Ontario Ministry of Transportation and Communications (OMTC). Studies have included field tests of material durability, scale modeling, computer modeling, and field investigations.

May and Osman of OMTC evaluated different barrier shapes using a point source scale modeling technique for three scenarios: single barrier, single barrier on opposite side of highway from receiver, and parallel barriers [May, 1980-1]. For the parallel barrier situation, both four and six lane highways were examined, with sources located in the near lane for each travel direction.

The scale model results, presented in Table 3, showed parallel barrier degradations of 1 to 2 dBA for the near-lane source and up to 6.2 dBA for the far-lane source. When the barriers were made absorptive (NRC of 0.75), the degradation was minimal for the near-lane source but still as much as 4.9 dBA for the far-lane source. Thus, absorption appeared to reduce degradation by about 2 to 3 dBA. The authors indicated that degradation appeared to increase with increasing receiver distance from the barrier for both the absorptive and reflective cases. For inclined walls, not shown in Table 3, the insertion loss degradation for near lanes was about 2 dBA, while being only about 1 dBA for far lanes.

In a field study by Hajek and Blaney, along a six lane highway, the barriers were 16 feet high, and only 125 feet apart with two-lane two-way service roads on the community side of each wall [Hajek, 1984]. Each barrier had sound absorbing panels (NRC of 0.6) on the upper four-fifths of both sides, and a three feet wide sound absorptive "cap" mounted on top to give a T-top. Absorptive treatment was included on the residential sides to minimize reflections from the service road traffic.

Hajek and Blaney measured levels at several locations, including a single barrier area. Comparisons were made with scale model results and with STAMINA 2.0 predictions with manually-added image sources. There were two sites studied,

Table 3
Point Source Parallel Barrier Insertion Loss
Degradations, As Scale-Modeled
By May And Osman*

# of Lanes	Receiver/ Wall Distance (m)	Receiver Height (m)	Insertion Loss Degradation (dB)			
			Reflective Walls		Absorptive Walls	
			Near Lane Source	Far Lane Source	Near Lane Source	Far Lane Source
4	16.2	1.2	0.5	3.5	3.0	1.5
	32.2	1.2	2.5	4.0	1.5	1.5
	32.2	2.0	2.0	6.0	2.0	4.0
	32.2	4.0	2.0	6.0	0.5	3.5
	32.2	6.1	3.0	6.0	0.5	3.0
	40.5	1.2	3.5	6.0	1.5	2.5
6	16.2	1.2	0.6	4.2	0.0	2.5
	32.2	1.2	0.9	3.9	1.2	2.5
	32.2	2.0	1.2	6.2	0.2	4.9
	32.2	4.0	1.5	5.5	0.4	3.4
	32.2	6.1	1.7	4.4	1.8	2.8
	40.5	1.2	1.7	5.5	0.0	0.8

* [May,1980-1]

one in an absorptive parallel barrier situation and the other in a single wall situation. Table 4 presents the results at the two sites. For first floor receivers, the data show a 2.0 dBA measured decrease in insertion loss from the single to parallel barrier cases, in contrast to a 1.3 dBA predicted decrease.

Hajek and Blaney found good agreement between measured levels and the STAMINA 2.0 results, and found that adding the three feet absorptive cap reduced levels by about the same amount (1 dBA) as increasing the barrier height by 3 feet.

Table 4

Comparison of Insertion Losses Measured And Predicted
By Hajek And Blaney on the Queen Elizabeth Way (QEW) in Toronto

Case	Receiver Height (m)	Insertion Loss(dB)	
		Measured	Predicted
Parallel Walls	1.2	4.7	4.6
Parallel Walls	3.5	6.1	3.9
Single Wall	1.2	6.7	5.9
Single Wall	3.5	7.5	6.7

Additional research has been performed in Canada outside the Ontario MTC. For example, Hutchins and Pitcarn have used a laser point source between two 1:60 scale parallel barriers to locate specular reflections paths for different parallel barrier configurations, including vertical and inclined walls, and T-, Y-, and arrow-tops [Hutchins, 1983]. Once these paths were located, intensity levels at the barrier top were calculated based on the image propagation distances. They concluded, for a typical highway geometry, that the multiple reflection intensity levels were similar for all of the configurations except the inclined walls. When the walls were inclined toward the source, the multiple reflection level increased by 1.1 dBA over the vertical wall case; inclination away from the source decreased this level by 1.5 dBA.

In another study, Balachandran *et al.* measured levels from a 6-lane expressway with no barriers, with one barrier on the opposite side of the highway, and with parallel barriers (11 feet high and 130 feet apart) [Balachandran, 1984].

They concluded that the average sound levels increased by 0.6 to 4.3 dBA after the single wall was erected on the opposite side of the highway. Although no single wall insertion loss data were collected, they also concluded that the parallel barrier multiple reflections degradation was as much as 2 dBA.

Finally, Hutchins *et al.* have presented 1/80 scale model results for single and parallel barriers of various cross-sectional shapes [Hutchins, 1985]. Ground surfaces were modeled as asphalt or grass. The noise barriers were modeled as being 16 feet high and 115 feet apart. Two point sources (ultrasonic whistles with scaled frequencies from 125 to 2250 Hz) simulated "near" and "far" lane positions 35 feet from each wall, at a height of three feet above the ground. An array of 4 receivers was studied at scaled distances of 40 and 80 feet from the near wall and at heights of 3 and 10 feet.

The results were presented as sound pressure level insertion loss spectra for each barrier shape for each source/receiver pair. A-weighted levels were not computed. Insertion loss was shown to vary markedly with frequency, a consequence of ground surfaces of varying flow resistivities. Source and receiver position were also important parameters.

Table 5 summarizes their results over the full frequency spectrum. For thin vertical walls, degradations were typically small. In general, the larger degradations were at frequencies below 500 Hz, while negative degradations (increased insertion loss) were in the 500 to 1000 Hz range. The result for the "grass" covered triangular section, simulating a berm, are particularly surprising: the presence of the second berm caused large degradations in certain frequency ranges, generally centered on

500 and 1000 Hz. Substantial degradations at certain frequencies may also be observed for the inclined wall, the 8 foot thick wall, and the T-top for the case of the low receiver and far source. The researchers concluded that, in most cases, the insertion loss degradation was small.

Table 5

Insertion Loss Degradations Modeled By Hutchins et al. For Various Geometries And Barrier Shapes

Source/ Near Wall Distance (m)	Receiver/ Near Wall Distance (m)	Receiver Height (m)	Barrier Shape	Degradation (dB)
10.6	12.2	1	Berm	0 to 10
10.6	12.2	1	Others	0 to 1
10.6	12.2	3	Berm	0 to 10
10.6	12.2	3	Others	0 to 1
10.6	24.4	1	Thin vertical	0 to 1
10.6	24.4	1	Others	not tested
10.6	24.4	3	Thin vertical	-1 to 3.5
10.6	24.4	3	Others	not tested
24.4	12.2	1	Thin vertical	-2 to 2.5
24.4	12.2	1	Berm	0 to 10
24.4	12.2	1	Inclined	-2 to 2.5
24.4	12.2	1	2.4m thick	0 to 7
24.4	12.2	1	T-top	1 to 6.5
24.4	12.2	1	Others	0 to 1
24.4	12.2	3	Thin vertical	-1 to 5
24.4	12.2	3	Others	not tested

Pejaver and Shadley studied parallel barrier insertion loss degradation theoretically and with scale models in the 1970s [Pejaver, 1976]. In their initial calculations, they represented traffic by a eight feet high point source in the center of the canyon, used Sabine absorption coefficients (independent of the angle of incidence), and assumed equal absorption coefficients for each wall, equal wall heights, no scattering and specular reflection.

Figure 10 shows degradations for point source scale modeling simulating a 70 foot wide canyon with nine foot high walls and a source-receiver distance of 100 feet. Insertion loss degradation ranged from 3 to 6 dBA for $\alpha = 0.05$ (left graph) and 2.5 to 4.5 dBA for $\alpha = 0.2$ (right graph), in both cases increasing with increasing receiver height.

Pejaver and Shadley also calculated line source insertion loss degradations for several canyon widths and barrier heights. Figure 11 presents degradation as a function of receiver height for four scenarios. Among other items, the results showed: degradation could be as much as 12 to 13 dBA (in some cases resulting in negative insertion losses); the depressed roadway cross-section was most sensitive to degradation; absorptive treatment provided substantial improvements; degradation increased as receiver distance increased, as canyon width decreased and as barrier heights increased; ground reflections could be ignored when more than 10 wall reflections affected the level at receiver; and geometrical acoustics was workable and straightforward.

Simpson developed a parallel barrier insertion loss degradation nomograph based on the Pejaver/Shadley assumptions and results [Simpson, 1976]. Input data

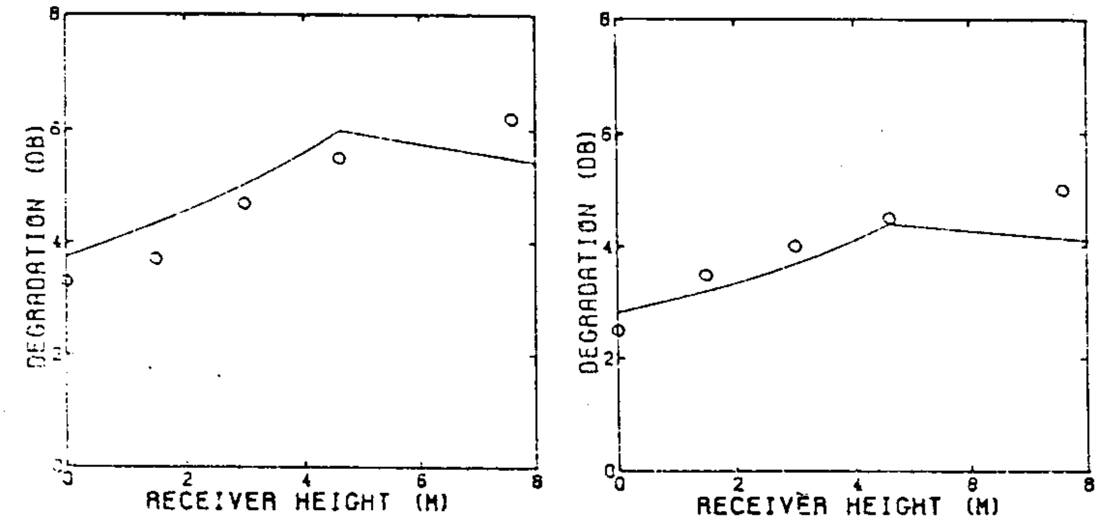


Figure 10. Parallel barrier insertion loss degradation as a function of receiver height for barrier surface absorption coefficients (α) of 0.05(left) and 0.2(right). 0: scale model; _: calculated. Height of barriers = 4.6 m; barrier separation = 21.9 m; receiver distance to near barrier = 30.2 m. [Pejaver,1976]

for the nomograph include single wall attenuation (for a receiver at the height of the roadway), canyon width, actual receiver height, and noise reduction coefficient. The nomograph is a simplified FHWA parallel barrier analysis tool. Knauer used it to predict a 5 to 6 dBA insertion loss degradation for a highway project, leading to the installation of sound absorptive panels on one wall [Knauer, 1980]. Limited noise measurements at the site after barrier construction, but prior to addition of the absorptive panels, showed levels at the barrier top to be 3 dBA higher than single wall predictions, and 5 dBA higher behind the barrier. However, beyond the barrier end, the predictions closely matched the measurements, implying the existence of multiple reflection effects in the parallel wall area.

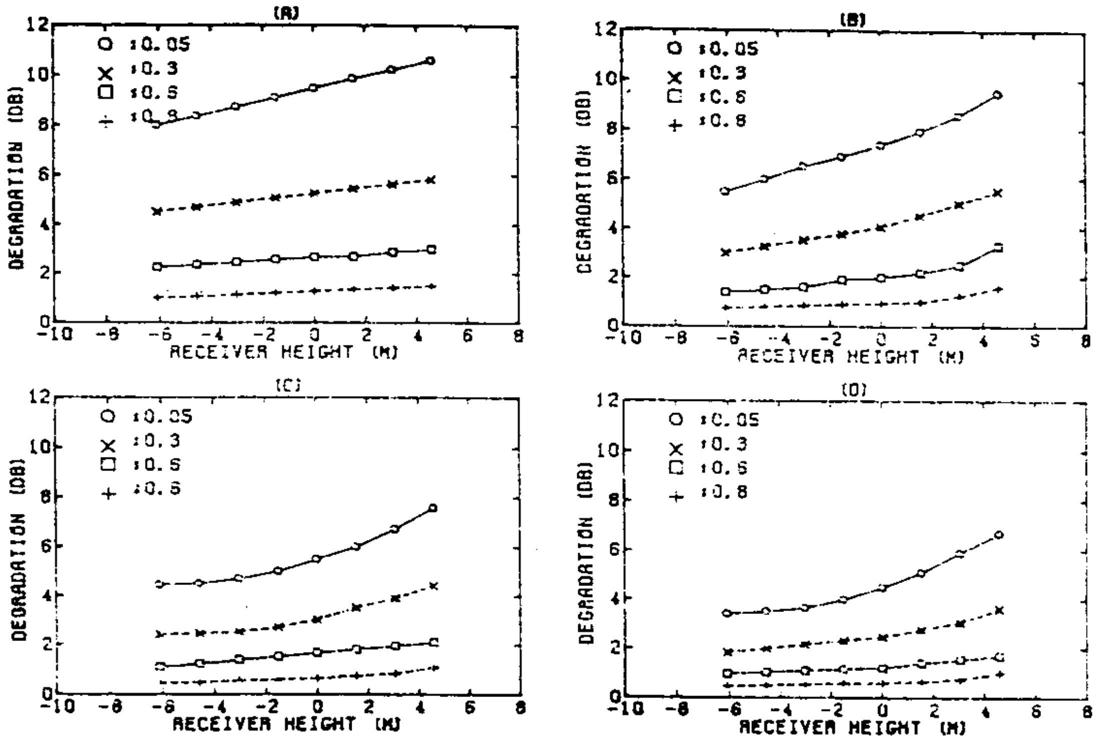


Figure 11. Parallel barrier insertion loss degradation as a function of receiver height above road (H_R) and barrier surface absorption coefficient (α). Height of barriers = 4.6 m, barrier separation = 21.9 m. Receiver distances: (a) 152.4 m., (b) 61.0 m, (c) 30.5 m, and (d) 15.2 m.[Pejaver, 1976]

Menge studied inclined and absorptive parallel highway noise barriers with scale modeling [Menge, 1980]. Figure 12 shows some results. For 16 feet high vertical walls, insertion losses at 500 Hz were 11.5 dBA and 4 dBA, for absorptive and reflective walls, respectively, thus resulting in an insertion loss degradation of 7.5 dBA. When the walls were sloped back by 10 degrees, the insertion loss degradation disappeared.

In another study, Bowlby and Cohn developed a highly flexible algorithm and computer program to predict parallel barrier insertion loss degradation [Bowlby, 1983]. Their IMAGE3 program combined the emission, propagation, and barrier

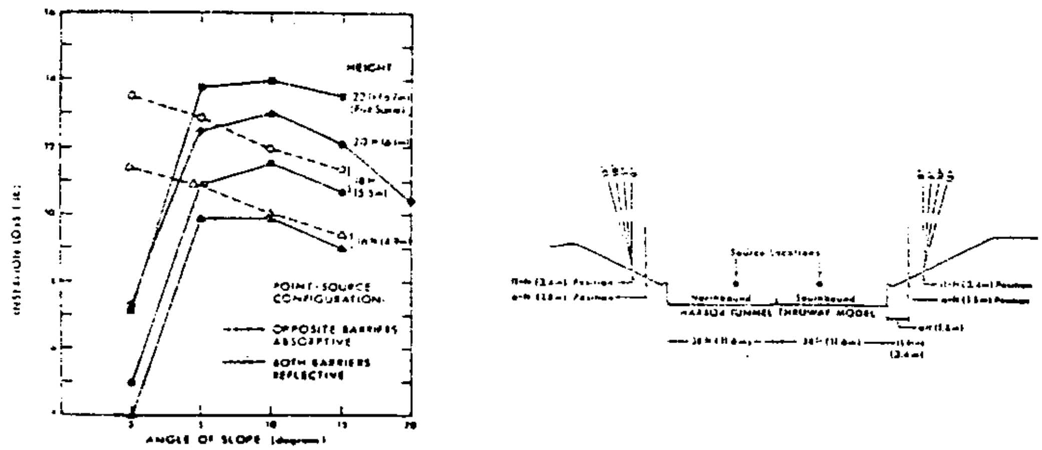


Figure 12. Insertion loss as a function of angle of slope of barriers for absorptive (---) and reflective (___) parallel barriers of heights between 4.9 and 6.7 m. [Menge, 1980]

attenuation features of the FHWA highway traffic noise prediction model with a specular multiple reflections algorithm. Features include variable source and receiver positions, variable source spectra, and independently variable wall heights and sound absorption coefficients.

Harris and Cohn have done further work on the parallel barrier algorithm, with the result being the computer program REBAR. This program yields realistic parallel barrier insertion loss degradation values for a variety of scenarios. The REBAR results have been validated through the application of measured data on the Route 24 project in Summit, New Jersey. Basically, this validation showed that actual measured degradation values are typically less than those predicted with IMAGE3.

The use of a simplified geometrical acoustics, representing specular reflection, has led to the overestimation of parallel barrier insertion degradation.

Several important factors are not considered in the geometric acoustics approach. These are sound scattering by the medium (air); diffusion of the very large sound wave fronts of the later image sources; and vehicle shielding within the canyon.

These factors diminish the likelihood of parallel barrier insertion loss degradation. Generally, the problem should only have potential for significance when the following conditions exist:

- Canyon width less than 200 feet;
- Barrier height at least 10 feet;
- Canyon width to barrier height ratio less than 20:1
- Barriers perfectly parallel with top elevations the same.

INNOVATIVE BARRIER FACES AND TEXTURES

Fresnel diffraction as applied by the FHWA Model to knife edge barriers assumes smooth, perfectly reflective barrier faces. A legitimate question to ask is "Would surface texturing or some other treatment provide additional insertion loss for the same path-length-difference δ ?" The answer is potentially yes.

A basic surface roughening is not likely to add any insertion loss. By the time a wave front from a highway source reaches even a shoulder barrier, its radius is at least 15 feet. In addition, the dominant wavelength of the highway noise spectrum is between two and three feet, depending on the truck mix. Consequently, sound energy from highway traffic is not significantly affected by small changes in surface texture. For example, a barrier with split face concrete blocks will provide essentially the same insertion loss as smooth concrete blocks. To the approaching sound wave, these surfaces appear to be smooth and completely reflective. The introduction of absorptive materials, as discussed earlier, may make a difference, by capturing some of the diffracting energy, to yield up to a 2 dBA insertion loss enhancement well inside the shadow zone.

Since normal masonry concrete blocks do not contain any absorbing materials, they are essentially fully reflective. It is possible to make such blocks absorptive in two ways. First, an absorbing material such as *Durisol* can be used in the block making process. As discussed earlier, Durisol is a concrete based material which utilizes fibrous wood chips as an absorbing agent. The second way is to use a product like *Soundblox*, which is a resonator masonry block. Soundblox are actually helmholtz resonators, since each block is slit in the middle, thus producing two chambers which absorb sound energy in the frequency range of highway noise. A Noise Reduction Coefficient (NRC) of about 0.6 can be obtained with a system such as Soundblox. An NRC of 0.6 indicates that approximately 60% of the audible acoustic energy has been absorbed.

This literature review did, however, provide information on a barrier surface modification technique that could enhance insertion loss. That technique, Phase Reversal, is discussed below.

Phase Reversal Barriers

The efficiency of conventional barriers for noise control decreases as the wavelengths of sound increase to become comparable to the dimensions of the barrier. In order to improve the low-frequency performance of noise barriers there has been some interest in modifying conventional barriers to include a waveguide filter. The waveguide consists of an open network of rigid strips which filters sound energy in both low and high frequencies. Figure 13 shows a schematic cross-section view of the phase reversal barrier. The improved performance of the barrier is a result of interference behind the barrier between the diffracted field and the field propagating through the waveguide. In an initial study, the refractive properties of a waveguide network and theories which are likely to predict the first stop band frequency were evaluated in order to obtain the optimum tuning of the waveguide. More recently, some experiments and theory have been described which study the interference effects between diffracted and waveguide fields. In addition, the behavior of the device as a function of angle of incidence has been investigated.

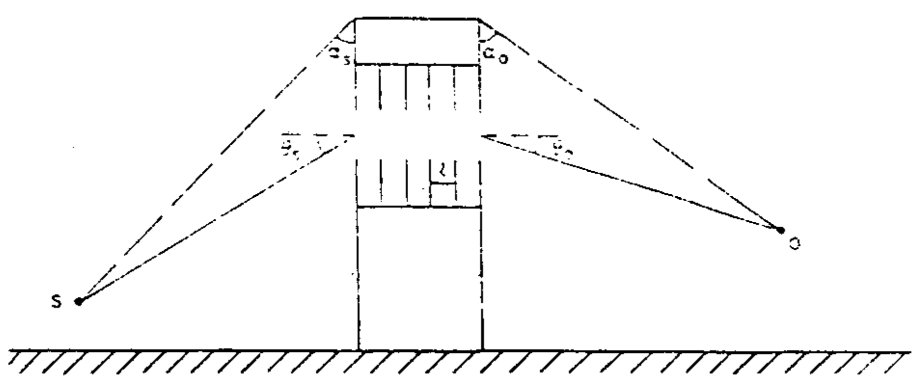


Figure 13. Schematic cross-section of the phase reversal barrier [Nicolas, 1986]

Nicolas and Daigle conducted a scale model study of a slow-waveguide barrier on finite impedance ground in 1986 [Nicolas, 1986]. In this study, limitations in the waveguide model were removed and the theory was extended to allow for reflections due to the presence of the ground. The experimental results were systematically compared to the predictions of the theory and to the performance of a conventional noise barrier.

In the low-pass region of the waveguide at low frequencies the barrier was found to provide additional noise reduction in a limited band of frequencies where destructive interference between the diffracted and waveguide fields occur. However, this was usually at the expense of increased levels in adjacent bands where constructive interference occurs. Measurements also showed that at higher frequencies, the transmission through the waveguide becomes very complex and sometimes resulted in a degradation of the noise reduction. Nicolas and Daigle therefore concluded that the waveguide would possibly be useful when a unique and dominant pure tone was present at low frequencies. Unfortunately, highway traffic sources are typically broadbanded in nature.

A similar study was published in 1986 by Amram, Chvojka, and Droin [Amram, 1987]. The study was conducted on a 1/20 scale model and was performed on a large impedance ground in the laboratory of the Centre Scientifique et Technique du Batiment de Grenoble, France. A subsequent comparison with preliminary field measurements on a full scale prototype was also completed.

The study concluded that the waveguide filter demonstrated better control of low frequency noise than a solid barrier of equivalent shape. Destructive interferences occurred between the diffracted part of the incident noise and the retarded part transmitted through the sound transparent device, which accounted for the better performance of the phase reversal barrier. Measurements in the field, on a real prototype, have shown trends similar to those found in the laboratory: better low frequency control (up to 5 dBA at 125 Hz) for the phase reversal barrier when compared to the solid one, this mainly in the vicinity of the shadow line.

Both studies on the phase reversal barrier and the concept of "destructive interference" drew similar conclusions. This type of barrier could possibly be beneficial where a dominant low frequency exists. It will certainly be examined in more detail in the next chapter of this report.

CONCLUSION

Several *Special Noise Barrier Applications* that have potential for improving barrier performance have been discussed in this literature review. These applications will be further studied in the next chapters of this report regarding their mathematical formulations, and technical and economic feasibility for use by WSDOT. Among the applications that will receive further study are:

- Absorptive barriers (single and parallel barrier systems)
- T-top and Y-top barriers
- Cylindrical-top barriers
- Sloped and slanted-top barriers
- Phase reversal barriers
- *Thnadner* barriers

FINDINGS

Mathematical Formulation

INTRODUCTION

Highway noise predictions methodologies are a combination of theoretical considerations and empirical data. For example, the FHWA Model (FHWA Report 77-108) combines known propagation rates across ground and over barriers with reference energy mean emission levels obtained from extensive field measurements to produce highly accurate L_{eq} values.

The FHWA Model, as well as all other highway noise prediction tools, is structured to follow the traditional noise analysis pedagogy of *source, path, and receiver*. This project, **SPECIAL NOISE BARRIER APPLICATIONS**, is concerned only with the path component of the issue. The path represents the propagation element of highway noise prediction.

In order to predict propagation adequately, FHWA has identified six characteristics of the path that must be properly accounted for in the mathematics [FHWA, 1979]. These characteristics represent different acoustical processes that occur between the source and the receiver. They are:

- **Unobstructed propagation** through a calm atmosphere,
- **Diffraction** over tops of noise barriers and around the side edges of large buildings,
- **Refraction** of sound, due to wind velocity and temperature gradients in the atmosphere,
- **Transmission** through solid structures such as noise barriers and residential walls,

- **Specular reflection** from building facades and from the ground, including any resulting absorption of sound energy, and
- **Scattering** from uneven facade surfaces, from trees, from roadway vehicles, and even from atmospheric turbulence.

This report concerns all of these six characteristics except the first, unobstructed propagation. The remaining five in some way or another affect highway noise barrier performance (diffraction, refraction, transmission, specular reflection, and scattering).

The literature review (Chapter 1) identified six potential special noise barrier applications that warranted further study in the mathematics formulation chapter of the report. These are:

- Absorptive barriers (single and parallel barrier systems)
- T-top and Y-top barriers
- Cylindrical-top barriers
- Sloped and slanted top barriers
- Phase reversal barriers
- *Thnadner* barriers

These six potential applications use as a starting point the *conventional, vertical knife-edge reflective barrier*. Fresnel diffraction is the method utilized in the FHWA Model to account for the performance of vertical knife-edge reflective barriers. The mathematics for basic Fresnel diffraction was discussed in detail in the literature review of this report. The mathematics involved with shaped barriers and barrier tops will be discussed in this chapter. These include sloped barriers, Thnadner barriers, T-top, Y-top, Slanted top, and Cylindrical top barriers. Lastly, those potential applications that address barrier surface treatments will be discussed. These include single and parallel absorptive barriers and phase reversal barriers. Based upon the findings of this mathematical formulation, the most promising of the potential special barrier applications will be prioritized. The applications on this priority list will be studied in greater detail later in this report. These further studies will address technical and economic feasibility for use by WSDOT on actual projects.

CONVENTIONAL REFLECTIVE BARRIERS

A conventional noise barrier is generally the reference barrier against which most other barriers are judged. This is the vertical, "knife-edge" reflective barrier used in the FHWA Model; it is based upon Fresnel diffraction. Numerous studies have investigated the performance characteristics of these barriers, and were discussed in the literature review.

The limitations of Fresnel diffraction as defined and used in the FHWA Model include:

- knife-edge barrier top (i.e., thin diffraction plane)
- reflective barrier surface

The remainder of this mathematical formulation explores options beyond vertical reflective knife-edge barriers to enhance barrier performance.

SHAPED BARRIERS

Thnadner Barriers

There have been various studies performed to evaluate the performance of noise barriers containing perforations or openings. One such type of barrier is the

Thnadner barrier. Thnadner barriers operate on the principle of deepening the shadow zone by shaping the barrier edge to give amplitude or phase gradients that refract the sound upwards [Wirt, 1979]. In Wirt's indoor measurements, Thnadner barriers produced enhancements of a few dBA over unmodified barriers, but ground effects were not discussed and detailed frequency data were not presented.

Another study performed by Hutchins *et al.* investigated the interference processes which occur for different propagation paths depending upon the ground surface present [Hutchins, 1984-2]. The Thnadner designs studied in this experiment were shown previously in Figure 4.

Hutchins *et al.* found that the Thnadner designs studied performed **less effectively** than a solid barrier in the presence of a grass covered ground (Figure 14) [Hutchins, 1984-2]. Similar results were obtained with asphalt covered ground, as shown in Figure 15.

Hutchins *et al.* concluded that the Thnadner barriers appear to cause an upward shift in the dominant frequency of the insertion loss compared to a solid barrier, when grass was present (Figure 15) [Hutchins, 1984-2]. The flat-top (F) design, performed slightly less effectively than the solid barrier, while the sawtooth (S) design performance was even worse. Intuitively this would be expected, since sound levels increased as more material was removed from the barrier. However, the horizontal (H) design had the same amount of material removed as the sawtooth (S) configuration, but exhibited a poorer performance.

In summary, Thnadner barriers will not improve insertion loss performance. However, the research conducted by Hutchins *et al.* illustrates that there may be

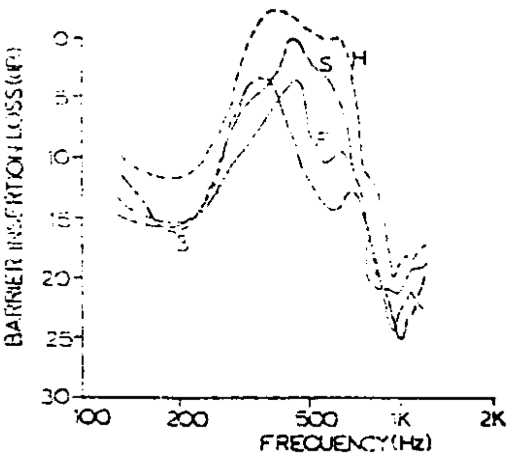


Figure 14. Insertion loss data for Thnadner barriers compared to the insertion loss data for a thin reflective barrier (B). Grass-covered ground was present.

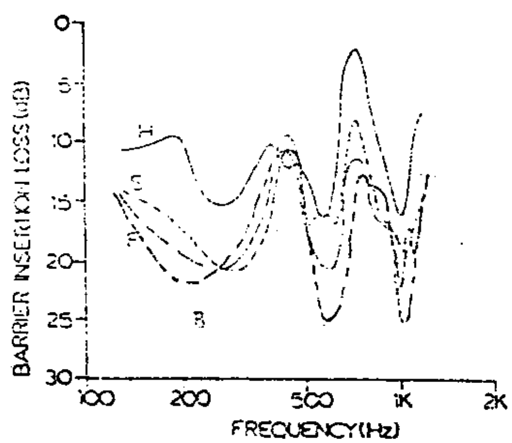


Figure 15. Insertion loss data for Thnadner barriers compared to the insertion loss data for a thin reflective barrier (B). An asphalt covered ground was present.

some merit to the Thnadner design. Only in a special case where barrier performance may be slightly sacrificed should a Thnadner barrier be considered as a possible alternative. This possible advantage of a Thnadner barrier would be purely economical, in that an adequate performance **may** be obtained with a smaller amount of barrier material. From a practical standpoint, WSDOT is not likely to see a situation where the Thnadner design is the best approach to a barrier solution.

T-Top Barriers

T-top barriers have been the subject of a limited number of previous studies, encompassing either acoustical scale modelling, direct field measurements, or both. In general, these studies have shown that T-top barriers achieve a significant increase in insertion loss over a conventional barrier of the same height. This is primarily due to the opportunity for **double diffraction** to occur on the continuous flat surface of the top of the barrier. There are currently two methods of describing the phenomenon of double diffraction, namely a *Geometrical Theory of Diffraction (GTD)* and the *boundary element method.* These methods are discussed below. There is, however, currently no exact solution for the double diffraction problem.

To predict the effectiveness of a barrier design, an analytic model for the diffracted acoustic energy is often used. The total pressure field p at a receiver point is calculated from:

$$p = p_i + p_r + p_d$$

where

p_i =	The pressure at the receiver due to a point source located along a line of sight in free field
p_r =	The reflected pressure
p_d =	The diffracted pressure

The incident field, p_i, is calculated for a point source whose strength is equivalent to the power generated from a segment of an incoherent line source. The reflected pressure, p_r, is calculated by use of reflection coefficients. The very important diffracted pressure, p_d, is calculated either from an analytic model, or in many practical cases by use of Keller's Geometric Theory of Diffraction (GTD) [Keller, 1962].

Even though there is no exact solution for double diffraction, reasonable models can be derived based upon Keller's GTD [Hayek, 1990]. T-top barriers are a typical example of double diffraction (Figure 16). The incident ray, originating at the source, impinges on the first edge of the T at point Q. The diffracted ray emerges from the first edge and travels the width of the top and strikes at the point P. The doubly diffracted ray then travels from P to the receiver. The width of the top of the T is denoted as r. Using GTD, the double diffracted pressure is given by:

$$p_d = p_i(Q)D(\phi,\phi_0,\beta)D(\phi',\phi_0',\beta)A(R_1,R_2,R_3)e^{-ik(R_2+R_3)}$$

where

β = the acute angle between z_o and R_1 (Figure 16)
$p_i(Q)$ = the incident pressure at Q
$D(\phi, \phi_o, \beta)$ = the diffraction by the first edge of the T
$D(\phi', \phi_o', \beta)$ = the diffraction by the second edge of the T
$A(R_1, R_2, R_3)$ = the geometrical spreading factor

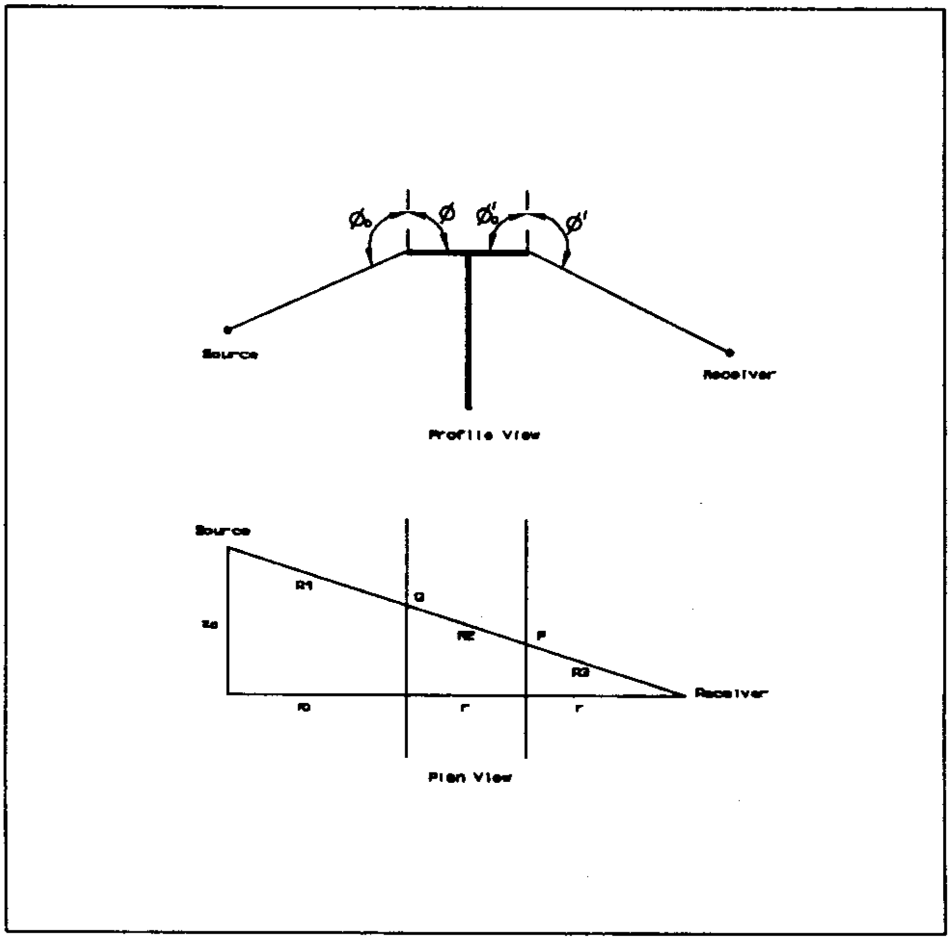


Figure 16. Geometry for double diffraction from a T-top barrier.

The exponential term represents the phase from Q to P to the receiver. The geometrical spreading factor is given by:

$$A(R_1,R_2,R_3)=\sqrt{R_1/(R_2R_3R)}$$

where

$$R=R_1+R_2+R_3=\sqrt{(r_0+r+r')^2+z_0^2}$$

$$\sin\beta = (r_0+r+r')/R$$

$$R_1 = r_0/\sin\beta \qquad R_2 = r/\sin\beta \qquad R_3 = r'/\sin\beta$$

In normal highway noise prediction language, geometrical spreading is a consequence of 3 dB/distance doubling.

To simulate the noise from a line of highway traffic, the line is represented by a finite number of equally spaced incoherent point sources of equal source strength. The contribution of each point is found and the line source is approximated by the summation of these individual points. Once the total acoustic energy from the line of incoherent point sources is found, the insertion loss of the barrier can be computed as

$$IL=-10\log_{10}\{|p|^2/|\overline{p_g}|^2\}$$

where

p = the total diffracted acoustic energy at the receiver
p_g = the total acoustic energy from the line source

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 by Seznec [Seznec, 1980]. The advantages and disadvantages of this method as compared to the geometrical theory of diffraction (GTD) approach were discussed by Hothersall *et al.* [Hothersall, 1991-2]. 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, provided the boundary elements are made a small enough fraction of a wavelength. 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 GTD is that atmospheric effects are not considered.

The boundary element method is quite complex and rather cumbersome; therefore, the numerous equations governing this method will not be presented. However, it should be stated that results from this method are most often obtained by applying numerical solution methods to boundary integral equations describing the barrier configuration in question. The performance of T-top barriers has been investigated using this numerical model by Hothersall *et al.* and the results of this study will be discussed.

The equations in the boundary element method are solved as a two-dimensional problem, mainly due to the fact that the more realistic three-dimensional problem is much more computationally extensive to solve. However, it has been proven in the literature that by modelling the problem as two-dimensional, useful predictions can be made [Hothersall 1991-2].

Hothersall *et al.* recently conducted scale model experiments utilizing the boundary element method [Hothersall, 1991-1]. Interesting results were found on the performance of an absorptive T-top barrier. Figure 17 illustrates the insertion loss spectra for three barrier forms: vertical reflective, vertical absorptive, and absorptive T-top.

In the study, Hothersall reported that the spectrum for a T-top barrier of the dimensions shown in Figure 17, but with a reflecting upper surface, followed a similar trend to that shown for the vertical wall, but with an increase in insertion loss of approximately 0.5 dB. The absorptive T-top performed substantially better at higher frequencies. This performance can be attributed to the increased opportunity for sound absorption due to the shorter wavelengths of sound at high frequencies. Although the insertion loss values in Figure 17 are reported in dB, the A weighted L_{eq} for the values can be calculated. In that case, the absorptive T-top barrier provides approximately 3.5 dBA more insertion loss than the conventional reflective barrier. This excellent performance has been observed in model experiments, but has not been tested in full scale trials.

A study of the acoustic field surrounding a T-top barrier was also conducted by Hothersall *et al.* [Hothersall 1991-1]. In this study, the boundary element method of solution was used to find the pressure at certain points on the surface of the barrier. The points selected were at intervals of λ/5 along the segments, where λ is the wavelength of the source. The pressure at a receiver point in or above the ground surface was obtained from an integral equation. Results were presented in terms of insertion loss, defined by:

$$IL = 20\log_{10}\left(\frac{P_g}{P_b}\right) dB$$

where

P_g = the acoustic pressure at the receiver
P_b = the acoustic pressure when the barrier is introduced

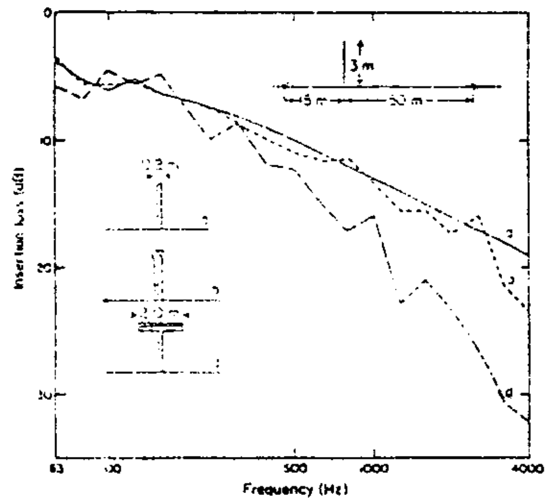


Figure 17. Insertion loss spectra for three barrier types: (a) vertical reflective, (b) vertical absorptive, and (c) absorptive T-top.

Broad-band insertion loss values near three barriers (each ten feet (2.96 m) in height) were calculated for A-weighted traffic noise spectrum between 63 Hz and 3.16 kHz . These values are shown in Figure 18 [Hothersall, 1991-1]. Hothersall *et al.* considered points between 14 and 16 m from the source, which therefore held P_g roughly constant. Thus, the magnitude of the change in insertion loss from one point to another in Figure 18 is the same as the change in the sound pressure level, to within a maximum of 1 dB over the range of points. An insertion loss of zero dB indicates no change upon introducing the barrier. For the vertical wall, figures near to this value are observed close to the upper surface. The insertion loss changes to -3 dB close to the front surface due to reflection. In Figure 18 (b) results are presented for a T-top barrier with a 0.5 m wide and 0.01 m thick cap. Low values of insertion loss (and hence, high values of pressure) were observed below the cap on the source side. Close to the upper surface a smaller change than might have been expected occurred across the width, from 0 to 1 dB. When an absorbing cap was used (Figure 18 (a)) the change

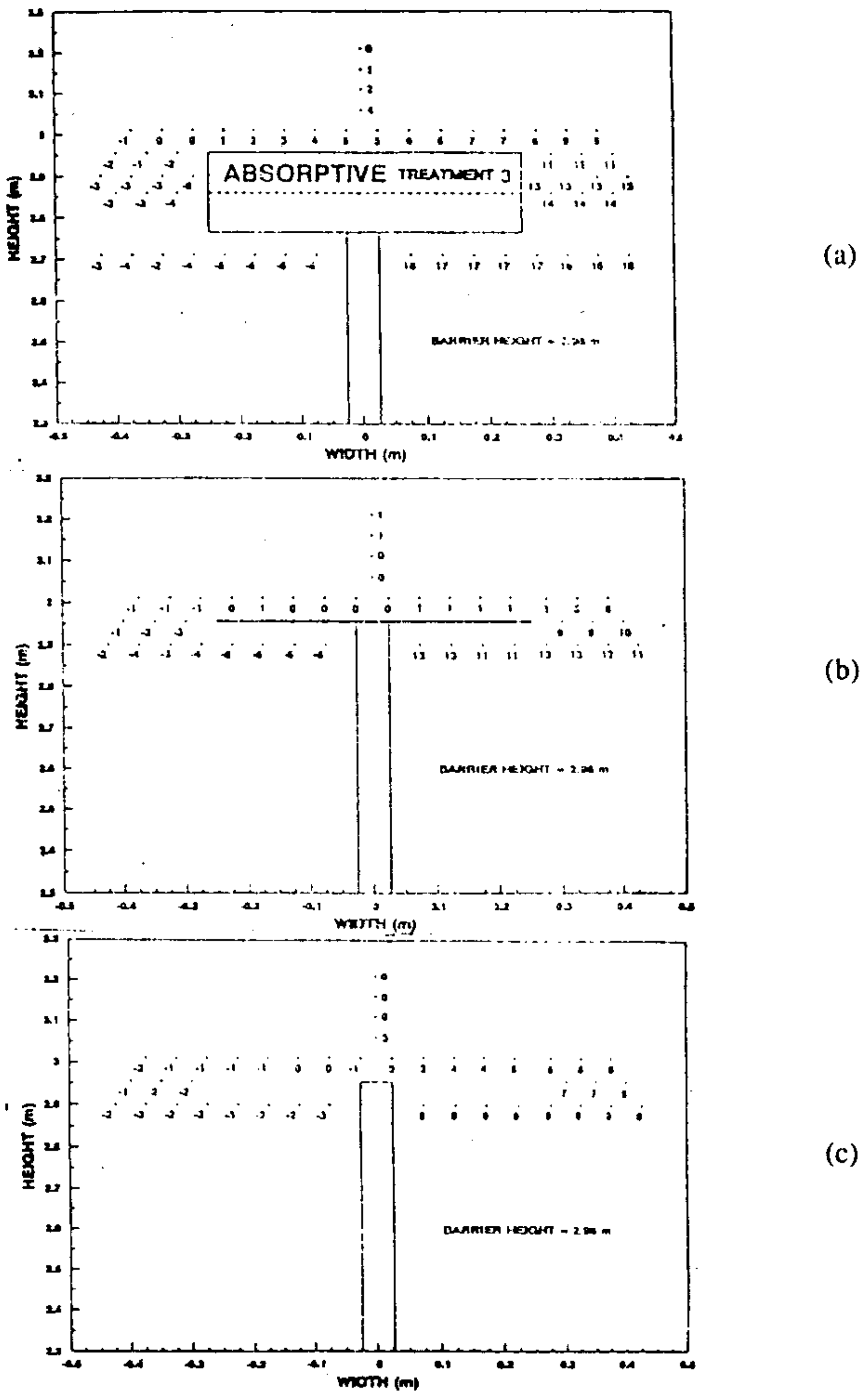


Figure 18. Insertion loss in the upper region of three barriers. (a) Absorptive T-top, (b) Reflective T-top, (c) Reflective vertical wall.

in insertion loss over the width of the cap was greatly increased (from 1 to 7 dB).

Because the receiver positions are unrealistically close to the barrier, the insertion loss values in Figure 18 are not of any practical value. They do, however, present interesting information about the acoustic energy field near the barrier tops. As previously stated, the higher the value of insertion loss reported, the lower the acoustic pressure at that point. In the case of the reflective T-top, the low insertion loss at the top of the barrier indicates that pressure doubling on the top is most likely occurring. This information confirms the belief of May and Osman that a reflective T-top increases the chance of pressure doubling on the flat top. In the case of the absorptive T-top, the higher value of insertion loss indicates lower acoustic pressure on the barrier top. The lower pressure values clearly indicate that more acoustic energy is being absorbed by the barrier top, and thus less energy is being transferred to the receivers. The increased efficiency of absorbing caps can be attributed to this fact. **Consequently, absorptive T-top barriers appear to have much more promise than reflective T-top barriers.**

Two contrasting ways to model double diffraction have been discussed, and both have proven that excess attenuation can be obtained through the use of T-top barriers. It is clear that the good performance of the T-top barrier is dependent upon the interaction of its flat top and the grazing sound wave. This performance is significantly increased when the T-top includes an absorptive treatment. In summary, T-top barrier performance can be approximated as follows: *The increased performance resulting from the absorptive T-top is <u>at least</u> equivalent to that which would result if the T-top section were stood on its end and added to the height of the vertical section of the barrier.* Certainly absorptive T-top barriers should be a strong candidate for further consideration by WSDOT for Phase II Research. This is especially important since the literature does not definitely address the double diffraction effect in real world highway noise barrier situations.

Y-Top Barriers

Y and T-top barriers of equivalent height and width have been studied to see whether they had similar insertion loss characteristics, because they both benefit from the double diffraction phenomenon. The Y-top, however, has consistently performed slightly poorer (about 1 dB) than its reflective T shaped counterpart. This is primarily due to the fact that the Y-top lacks a continuous flat surface to provide interference with the propagating wavefront from the first diffraction in the double diffraction activity.

The top edges of the Y-top function as two separate barrier edges like two conventional knife-edge barriers placed close together. The potential insertion loss of this Y shape can be found by utilizing either the geometrical theory of diffraction (GTD) or the boundary element method. Both of these modelling methods have been discussed in the previous section, and therefore, the mathematics describing them will not be included again here.

While not quite as effective as T-top barriers, the Y-top is superior in performance to conventional barriers. In a previously cited study, Hothersall *et al.* found the Y-top to be about 1 dB less effective, which corresponds to a two foot shorter barrier when using the T-top over the Y-top. However, the Y-top may prove useful to WSDOT in certain situations.

Sloped Barriers

Sloped barriers have been studied as a possible alternative to conventional vertical knife-edged reflective barriers. May and Osman investigated this type of inclined barrier and concluded that overall, no significant additional insertion loss was found for this barrier type [May, 1980-1]. This conclusion is reasonable when considering the mathematics involved, which is Fresnel diffraction.

A sloped barrier has the effect of moving the diffraction edge slightly closer to the source or receiver (depending upon the direction of the slope). As discussed previously, Fresnel diffraction is a function of path length difference, δ. Intuitively, it is logical to conclude that such a movement of the diffraction edge will not significantly change δ; thus, Fresnel diffraction and insertion loss will not be significantly altered. Consequently, single sloped barriers do not significantly increase insertion loss compared to conventional barriers.

Sloped barriers may still be a viable option in the special case of parallel noise barriers. The possibility of barrier tilt as an effective method of counteracting the degradation of insertion loss due to multiple reflections will be discussed later in this chapter under the special application of parallel noise barriers.

Slanted Top Barriers

The use of slanted top noise barriers in other countries, especially Japan, was discussed in the literature review. It is common to see noise barriers in Japan with the upper one-third of height slanted toward the source at a 30 to 45 degree angle [Cohn, 1982-1].

Just as with the fully sloped barrier discussed above, a slanted top barrier top has the effect of moving the diffraction edge slightly closer to the receiver or source (depending on the direction of the slope). This movement of the diffraction edge is equivalent to the construction of a vertical, knife-edge reflective barrier located at the same distance from the source as the horizontal distance between the source and the apex of the sloped top.

Since Fresnel diffraction governs slanted top barriers in the same way as it does with fully sloped barriers, there is no significant additional insertion loss than that which results from the sloped barrier. However, there is a visual benefit to be gained when the slanted top is in the direction of the traffic. Exceptionally tall barriers can have the appearance of "going away" from the receivers, while providing the same insertion loss as the vertical barrier. As a result they may appear to be shorter, and may actually provide better light and less screening of view.

Cylindrical Top Barriers

The literature review produced a relatively new concept of placing an absorptive cylinder on top of existing noise barriers. In a 1991 publication, "Sound Shielding Efficiency of a Barrier with a Cylinder at the Edge", Fujiwara and Furuta discussed the possible advantages of this shaped barrier top [Fujiwara, 1991]. In order to fully comprehend and evaluate the cylindrical top, the mathematical procedures governing it are discussed below.

The theoretical analysis of the sound diffraction by a thin barrier with a cylinder at the edge was first reported by Keller in the early 1960's [Keller, 1962]. This analysis considered two specific boundary conditions, namely perfectly hard and perfectly soft (fully absorptive). However, the solution for a perfectly absorptive barrier with a perfectly absorptive cylinder was not derived explicitly. Keller did discuss ways to derive a solution for the diffraction at a barrier with a round edge, but he concluded that it would be extremely complicated to get the solution given an absorptive barrier surface. Due to this complication, Fujiwara approximated the solution for the perfectly absorptive barrier by adding together the solutions for the hard and the soft conditions and dividing the result by two, thus yielding an average value. This is the same assumption made by Rawlins, who studied the case of an absorptive barrier without a cylinder in the mid 1970's [Rawlins, 1976].

The diffraction problem by a half plane surface with a cylinder at the edge has been solved by Keller for a two-dimensional sound field. As previously mentioned, the effects of hard and absorptive cylinders were defined for the case of an incident cylindrical wave (two-dimensional sound field).

In their study, Fujiwara *et al.* used the terms [EHC] and [EAC], to be *Effect of Hard Cylinder* [EHC] and *Effect of Absorptive Cylinder* [EAC]. Some numerical examples of [EHC] and [EAC] are shown in Figure 19 (a) - (c). The ordinate shows the excess attenuation of the cylinder, and the abscissa gives the size of the cylinder relative to the wavelength. The dashed curves show the values of [EHC] and the solid curves show the values of [EAC]. The positions of the source, receiver, and barrier, are shown in each figure. Figure 19 illustrates the greater attenuation obtained by the absorptive cylinder as compared to the reflective cylinder. Due to the poor performance of the reflective cylinder, Fujiwara discarded it from further consideration as a viable barrier top. However, a prototype absorptive cylinder top was developed for practical use with an existing highway noise barrier. The performance of this absorptive cylinder top was discussed previously in the literature review of this report.

The very complex mathematics for the absorptive cylinder top need not be

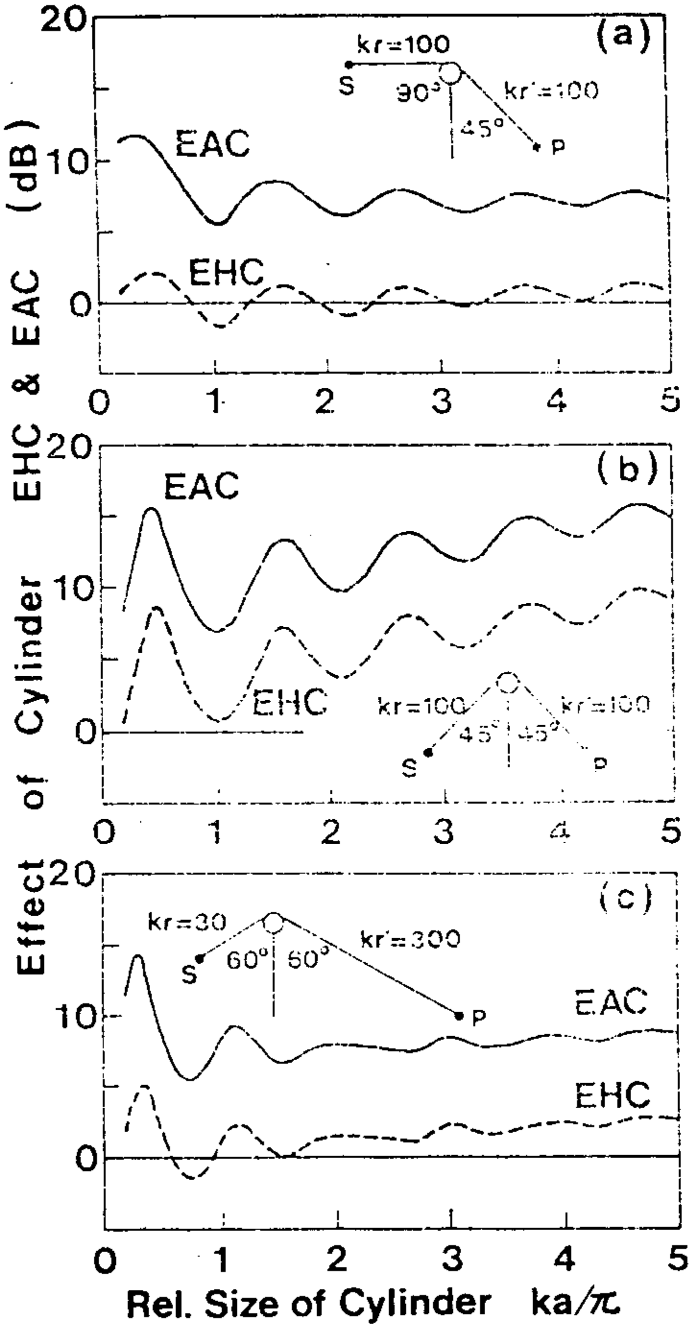


Figure 19. Effects of hard and absorptive cylinders [EHC] and [EAC]. Solid curves and dashed curves show the values of [EAC] and [EHC] respectively. Source and receiver locations are shown in each figure.

re-stated here. The study completed by Fujiwara and Furuta does, however, contain a persistent limitation, which is the location of the receivers in their study. The noise level difference (L_{eq}) before and after the installation of the cylinder was found to be 2-3 dBA, for a measurement location deep in the shadow zone. Although this is a significant amount of excess attenuation, this effect quickly diminishes as the receiver moves out of the deeper parts of the shadow zone. Most sensitive receptors of highway noise are not in the deeper parts of the shadow zone; therefore, the excess attenuation measurements in this study are somewhat deceiving. Consequently, the absorptive cylindrical top is not a high priority for additional study in later stages of this project, although it may have sufficient potential to be studied more in the future.

POTENTIAL BARRIER SURFACE TREATMENTS

Parallel Barriers

The situation where barriers are required on both sides of a highway is of major concern in barrier performance. The acoustical performance (insertion loss) of parallel noise barriers can be seriously degraded by the occurrence of multiple reflections of sound in the noise "canyon". The mathematics involved in recent studies is the subject of this section of the report.

Cohn and Bowlby conducted research to develop and validate an algorithm for the prediction of insertion loss degradation in parallel barrier situations [Cohn, 1986]. They began the algorithm development in a series of steps. First, the FHWA highway traffic noise prediction model equation for the hourly average sound level from a class of vehicles moving along a straight level roadway was converted into a form convenient for multiple reflection calculations [Barry, 1978]. Second, expressions were developed for determining the distance from each image source to a receiver, and the angles at the receiver subtended by the image roadway segments. Third, an expression was developed for determining the acoustic energy reaching a receiver from an arbitrary position along each image source. This expression accounts for absorption of energy upon each reflection off each barrier. Then, the expression was expanded to include the entire length of the image line source.

Cohn and Bowlby expanded the FHWA model barrier diffraction equations to include image sources by making an adjustment for atmospheric attenuation. They also developed expressions to determine whether or not a reflection would strike both barriers or pass over their tops. Finally the contributions from each image source were summed to obtain the total level for each vehicle class, for each roadway, and for each receiver.

The following assumptions were made in this model development:

- Geometrical ray acoustics, or image theory, could be used, allowing wall reflections to be modeled as specular.
- Sound scattering does not appreciably affect final levels for receivers outside the canyon formed by the parallel barriers.
- Reflections off the ground within the canyon do not significantly affect parallel barrier insertion loss degradation.
- For prediction of degradation, sound propagation over the near barrier may be based on a 3 dB reduction in the hourly average sound level per doubling of distance from the roadway.

Cohn and Bowlby's parallel barrier algorithm represents an expansion of the basic FHWA model to address multiple reflections. In the FHWA model, the hourly average sound level (L_{eq}) from a class of vehicles on a straight level roadway for an acoustically hard site is given as:

$$L_{eq} = (\overline{L_0})_E + 10\log(Vd_0\pi/1000S) + 10\log(d_0/d) + 10\log[(\phi_2 - \phi_1)/\pi] - \Delta_B \quad \text{Eq. (1)}$$

where

$(\overline{L_0})_E$ is the reference energy mean emission level in dB
V is the hourly flow rate of vehicles (vehicles/hr)
S is the average operating speed of the vehicles (mi/hr)
d_0 is the reference distance of 15.2 m
d is the perpendicular distance in feet from the receiver to the roadway.
ϕ_1, ϕ_2 are horizontal angles in radians
Δ_B is the attenuation in dB of the noise level of this source by a barrier.

Cohn and Bowlby introduced a new variable, I_{eq}, to represent the *unshielded* acoustic energy of a vehicle class. Thus

$$L_{eq} = 10\log(I_{eq}) - \Delta_B \quad \text{Eq. (2)}$$

where I_{eq} is given as

$$I_{eq} = [I_L\ Vd_0^2\pi(\phi_2 - \phi_1)]/(1000Sd\pi) \quad \text{Eq. (3)}$$

and where I_L is $10^{(Lo)E/10}$. Noting that d_0 equals 15.2m, the I_{eq} relationship may be rewritten as:

$$I_{eq} = (0.231 I_L V/S)[(\phi_2 - \phi_1)/d] \quad \text{Eq. (4)}$$

and I_L, N, and S will remain constant for all image sources for a given vehicle class for a given roadway. They then generalized this equation for the *i*th image source for this vehicle class on this roadway as

$$(I_{eq})_i = (0.231 I_L V/S)\{[(\phi_2)_i - (\phi_1)_i]/d_i\} \quad \text{Eq. (5)}$$

where $(I_{eq})_i$ is the direct energy representation from the *i*th image source, $(\phi_2)_i$ is

ϕ_2 for the *i*th source, $(\phi_1)_i$ is ϕ_1 for the *i*th source, and d_i is the perpendicular distance to the centerline of the *i*th source.

Values for *di*, $(\phi_2)_i$, and $(\phi_1)_i$ are taken from Figures 20 & 21.

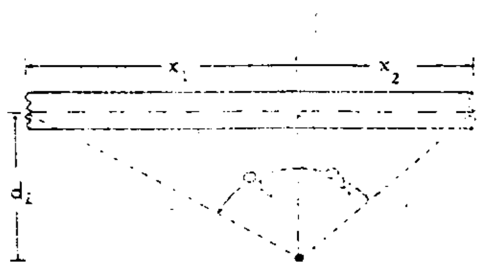


Figure 20. Plan view of a roadway section illustrating angles used in traffic noise predictions.

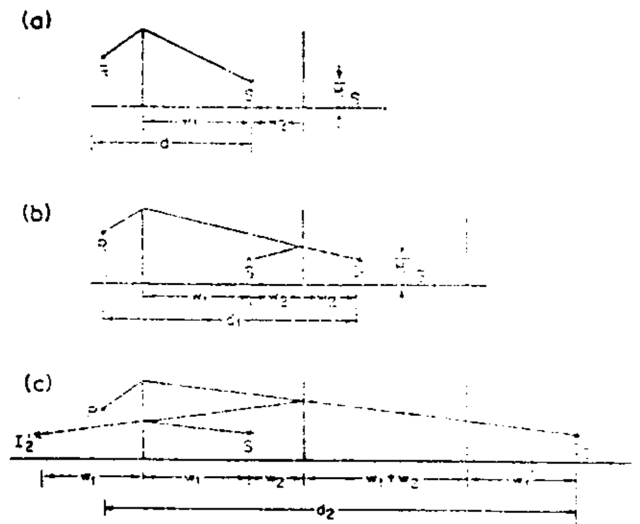


Figure 21. Section views of parallel noise barriers illustrating distance parameters.

Figure 21 (a) shows that in a parallel barrier canyon of width *w*, the actual source is located at w_1 from the wall nearest the receiver and at w_2 from the far wall, where

$$w = w_1 + w_2 \qquad \text{Eq. (6)}$$

Based upon distances from the first image source $\mathbf{I}_1$, in Figure 21 (b), and the second image source $\mathbf{I}_2$, in Figure 21 (c), a generalized expression for the distance to the *i*th image can be determined:

$$d_i = d + aw_1 + bw_2 \qquad \text{Eq. (7)}$$

where *a* and *b* are coefficients such that when *i* is odd, *a*=*i*-1 and *b*=*i*+1, and when *i* is even, *a*=*b*=*i*.

End angles $(\phi_2)_i$ and $(\phi_1)_i$ are determined by:

$$(\phi_2)_i = \arctan(x_1/d_i) \qquad \text{Eq. (8a)}$$

$$(\phi_1)_i = \arctan(x_2/d_i) \qquad \text{Eq. (8b)}$$

This research took into account the situation where the reflected image never strikes the far wall for return across the canyon, thus not adding to the total level at the receiver. Figure 22 (a) illustrates where the image source will not occur for receiver $\mathbf{R}_1$ because the far wall is too low, while Figure 22 (b) shows a situation for receiver $\mathbf{R}_1$ where a reflection will indeed strike the far wall. The determination is straightforward: the image source is located, and the elevation of the ray from the image to the top of the barrier (or to the receiver if it is in view of the image source) is computed and compared to the elevation of the top of the far wall. If the ray elevation exceeds the far wall elevation, the image will not exist.

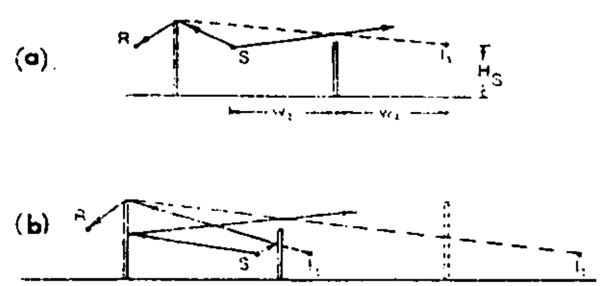


Figure 22. Section views illustrating how the presence of an image source depends on far wall height. (a) Image source I_1 does not exist for source S; (b) image source I_1 (off far wall) exists, but image source I_2 does not exist.

Cohn and Bowlby have taken into consideration that a receiver **R** may be located at a position such that the reflected ray will not diffract over the top of the near barrier, but will propagate directly to the receiver, Figure 23. They concluded that in this situation the calculation of the elevation of the ray at the far wall plane must be done using the line between image source and *receiver*, not image source and near wall top. For a given image source, the intensity of the sound is reduced due to partial absorption upon each reflection off each wall, Figure 24.

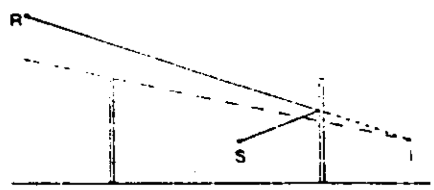


Figure 23. Section view of parallel barriers where reflected ray (-) from source S does not diffract over top of near wall to reach receiver R.

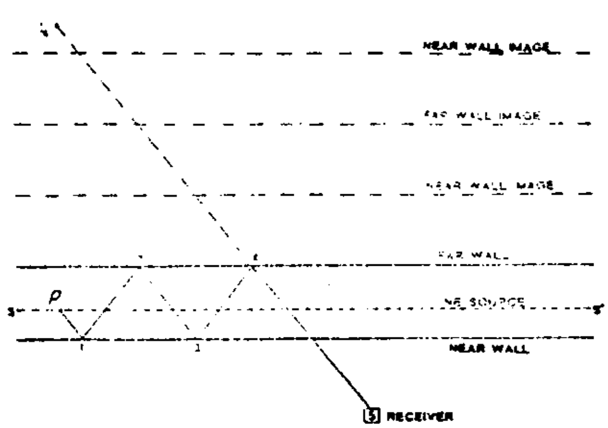


Figure 24. Plan view of parallel barriers illustrating fourth image source (I_4) for a source *p* located along line S-S′. Numbers 1-4 are reflection points referred to in text.

Cohn and Bowlby have shown that the decrease in point source sound intensity from one point to another is a function of the square of the ratio of the distances from the source to each point. Thus the incident intensity at the *i*th image, relative to a reference point at distance d_0, is

$$I_{(i+1),J} = I_0(d_0/r_i)^2 \times[(1 - \alpha_N)^{(i-c)/2}][(1 - \alpha_F)^{(i+c)/2}] \qquad \text{Eq. (9)}$$

where α_N is the absorption coefficient of the near wall, α_F is the absorption coefficient of the far wall, and c equals 0 if i is even and c equals 1 if i is odd.

The two terms in square brackets in Eq. (9) are constant for any point along a given image line source. If this expression is integrated to represent the equivalent intensity $[(I_{eq})_i]$ of the point source moving along line S-S′ (Figure 24), then the equivalent intensity would also be multiplied by these two constant terms. Therefore, by applying the *i*th image to Eq. (5):

$$(I_{eq})_i = (0.231 I_L V/S)\{[(\phi_2)_i - (\phi_1)_i]/d_i\}$$
$$\times[(1-\alpha_N)^{(i-c)/2}][(1-\alpha_F)^{(i+c)/2}] \qquad \text{Eq. (10)}$$

The coefficient α_k is the absorption coefficient for the kth reflection off either wall for the *i*th image. Thus,

$$(I_{eq})_i = \left(\frac{0.231 I_L V}{S}\right)\left(\frac{[(\phi_2)_i - (\phi_1)_i]}{d_i}\right) X\left(\prod_{k-1}^{i-1}(1-\alpha_k)\right) \qquad \text{Eq. (11)}$$

This expression represents the equivalent acoustic energy at a receiver from the *i*th image line source, including wall absorption; it does not include attenuation due to atmospheric absorption or diffraction over the near barrier. Atmospheric attenuation is addressed by deriving an atmospheric attenuation factor Δ_a. Beranek presents such a factor for outdoor noise propagation from a point source as [Beranek, 1971]:

$$\Delta_a = (7.4 f^2 r/h) \times 10^{-8}, \text{ in dB}, \qquad \text{Eq. (12)}$$

where f is frequency in hertz, r is distance in meters, and h is relative humidity in percent.

Conversion to a line source function for incorporation into Cohn and Bowlby's parallel barrier algorithm is based on the fact, for "hard" site propagation, that equal angular segments of a line source (as viewed by the receiver) contribute equal amounts of sound energy to the total average sound level. Thus a line source of arbitrary angular size is divided into ten equal parts, each contributing one-tenth of the total energy $(I_{eq})_i$ at the receiver, or $0.1(I_{eq})_i$. A value for $(\Delta_a)_j$, the atmospheric attenuation for the jth segment, is obtained by using Beranek's expression for outdoor noise propagation (Eq. (12)). Letting

$$(\alpha_a)_j = 10^{[(\Delta_a)_j/10]} \qquad \text{Eq. (13)}$$

the intensity ratio of each segment $(I_{eq})_j$ adjusted for atmospheric attenuation is

$$[(I_{eq})]_{adj} = \frac{(I_{eq})_j}{(\alpha_a)_j} \qquad \text{Eq. (14)}$$

The total adjusted intensity ratio for the ith image $[(I_{eq})_i]_{adj}$ is then

$$[(I_{eq})_i]_{adj} = \sum_{j=1}^{10} [(I_{eq})_j]_{adj} \qquad \text{Eq. (15)}$$

Thus,

$$[(I_{eq})_i]_{adj} = [0.1[(\frac{0.231 I_L V}{S})(\frac{[(\phi_2)_i - (\phi_1)_i]}{d_i})] \times (\prod_{k=1}^{i-1} (1-\alpha_k))][\sum_{j=1}^{10} (\frac{1}{(\alpha_a)_j})] \qquad \text{Eq. (16)}$$

This equation includes all components of the calculation except barrier attenuation.

Cohn and Bowlby addressed barrier attenuation by the use of Fresnel diffraction, which was discussed in previous sections of this report. They determined the point source barrier attenuation (Δ) by using notation that was based on the Kurze-Anderson formulation, where

$$\Delta = \begin{cases} 0 & \text{for } N \leq -0.1916, \\ 5+20\log[(\sqrt{2\pi |N|})/\tan(\sqrt{2\pi |N|})], & \text{for } -0.1916 < N \leq 0, \\ 5+20\log[(\sqrt{2\pi |N|})/\tanh(\sqrt{2\pi |N|})], & \text{for } 0 < N \leq 5.03, \\ 20 & \text{for } N > 5.03 \end{cases} \qquad \text{Eq. (17)}$$

The attenuation Δ is integrated over the length of the line source shielded by the barrier. The barrier attenuation for an image line source $(\Delta_B)_i$ is

$$(\Delta_B)_i = 10\log[(\frac{1}{[(\phi_R)_i - (\phi_L)_i]}) X(\int_{(\phi_L)_i}^{(\phi_R)_i} (10^{(\Delta/10)}) d\phi] \qquad \text{Eq. (18)}$$

where $(\phi_L)_i$ and $(\phi_R)_i$ are the angles at the receiver between the normal line to the barrier and the left and right endpoints of the barrier, respectively (as viewed from the receiver), and Δ_i is the point source attenuation at any point *i* along the line, which may be obtained by rewriting Eq. (17), substituting $N_0\cos\phi$ for *N*.

Cohn and Bowlby concluded that the L_{eq} contributions of the *i*th image source to the total average sound level (for a given vehicle class) may be given as

$$(L_{eq})_i = 10\log(0.1[(\frac{0.231 I_L V}{S})(\frac{[(\phi_2)_i - (\phi_1)_i]}{d_i})] \times (\prod_{k=1}^{i-1}(1-\alpha_k))[\sum_{j=1}^{10}(\frac{1}{(\alpha_a)_j})]) - (\Delta_B)_i \qquad \text{Eq. (19)}$$

They then show that the total L_{eq} at the receiver from all of the image sources for a given vehicle class on a given roadway is the logarithmic combination of the $(L_{eq})_i$ contributions:

$$L_{eq} = 10\log\sum_{i=1}^{n}(10^{(L_{eq})_i/10}) \qquad \text{Eq. (20)}$$

where n is the number of image sources.

This parallel barrier algorithm has been computerized to provide practical analysis tools. The first program, IMAGE-3, was used to show that very large insertion loss degradation values could be obtained for situations where reflective barriers were tall and close together. The insertion loss degradation values obtained from IMAGE-3 were often nearly as large as the single barrier IL values. For example, a single barrier designed to produce a 10 dB reduction could see its IL reduced to 2-3 dB with the introduction of a barrier in the opposite side of the highway, for an IL degradation of 7-8 dB. A newer program REBAR, shows that this IL degradation is likely not so large, being on the order of 2-4 dB. In either case, the multiple reflection problem resulting from parallel reflective barriers is in many cases serious. Rules of thumb have been developed by the authors (Cohn and Bowlby) to assess this potential seriousness, including:

- Barriers must be within 200 feet of each other and parallel;
- Barrier height must be at least 10 feet;
- Barrier top elevations must be approximately equal.

In other work in this area, Slutsky and Bertoni performed research to account for the effect of barrier tilt. They concluded that barrier tilt is an effective method of counteracting the degradation due to multiple reflections caused by parallel barriers. Tilt angles as small as 3 degrees were found to be effective for wide roadways (150 ft between barriers), and larger values (10 to 15 degrees) are needed for narrow roadways (60 ft between barriers) [Slutsky, 1988]. Menge also performed work in the area of tilted barriers. He concluded that an outward tilt angle of 10 degrees was the most efficient [Menge, 1980].

The most effective method to solve the multiple reflections problem is to use an absorptive treatment on the barriers. Both IMAGE-3 and REBAR can account for absorptive material use. Basically, they demonstrate that an NRC (Noise Reduction Coefficient) of 0.60 or greater is adequate.

Given the potential for significant parallel barrier IL degradation in urban corridors of Washington State, this should be a high potential area for further study in Phase II research.

Single Wall Absorptive Barriers

The possible advantages of single wall absorptive noise barriers have been the subject of several studies throughout the past two decades. However, the literature review of this report revealed that many uncertainties still exist about the usefulness of covering barriers with absorptive material. The mathematics involved in the phenomenon of diffraction over absorptive barriers is quite complex, and has not yet been fully defined in the literature.

Laboratory scale model measurements, however, have shown that up to 2 dB additional IL can be gained in certain situations when using absorptive treatments on single barriers. These unpublished results were obtained by Cohn as part of a parallel barrier study using the laboratory of the Japan Highway Public Corporation in 1982. This maximum of 2 dB is obtainable when the barrier protrudes well past the line of sight break and the diffraction angle is large (i.e., deep in the shadow zone). This requirement of steep diffraction angles was confirmed in a study by Nicolas *et al.* [Nicolas, 1989] which combined an approximate diffraction solution with a well-known theory for sound propagation over the ground [Embleton, 1976] in order to calculate the insertion loss of a thin absorptive barrier.

In certain cases, single wall absorptive barriers may be useful to WSDOT. The cases include those where the receivers are very close to and below tall barriers.

Phase Reversal Barriers

The efficiency of conventional barriers for noise control decreases as the wavelengths of sound increase to become comparable to the dimensions of the barrier. In order to improve the low-frequency performance of noise barriers, there has been some interest in modifying conventional barriers to include a slow-waveguide filter.

The boundaries of the waveguide filter (Figure 25) are arranged with a series of slots, along which the sound waves propagate more slowly than in free air. This creates refraction with an index n_r larger than the one in the frequency band of interest [Amram, 1981]:

$$n_r = c_a/c_b \qquad \text{Eq. (21)}$$

where c_a is the sound speed in free space(air) and c_b is the sound speed in the waveguide. From theory that was originally developed for microwaves the n_r can be obtained from [Amram, 1983]:

$$n_r = (\lambda/\pi l)\tan^{-1}(-B_{oe}/B_{ce})^{1/2} \qquad \text{Eq. (22)}$$

where

λ = the wavelength
l = defined in Figure 25

The two quantities B_{oe} and B_{ce} in Eq. (22) stem from microwave theory, and represent complex impedances to the propagating sound through the waveguide. They are calculated as follows:

$$B_{oe} = \tan\frac{\pi l}{\lambda} + \frac{2b}{\lambda}\ln\left(\frac{1}{\sin(\pi\delta/2)}\right) + \frac{2b}{\lambda}\sum_{m=1}^{\infty}\left(\frac{\tanh(n\pi l/b)F'}{F'} - 1\right)\frac{\sin^2\pi n\delta}{n(\pi n\delta)^2} \qquad \text{Eq. (23)}$$

$$B_{ce} = -\cot\frac{\pi l}{\lambda} + \frac{2b}{\lambda}\ln\left(\frac{1}{\sin(\pi\delta/2)}\right) + \frac{2b}{\lambda}\sum_{m=1}^{\infty}\left(\frac{\coth(n\pi l/b)F'}{F'} - 1\right)\frac{\sin^2\pi n\delta}{n(\pi n\delta)^2} \qquad \text{Eq. (24)}$$

where

$\delta = b'/b$
$F' = [1-(b/n\lambda)^2]^{1/2}$

Note: Eqs. (23) and (24) are only valid for l/b and b/λ when less than 0.9.

Nicolas and Daigle show that, along with the greater index of refraction, the waveguide behaves as a filter at specific low and high frequencies [Nicolas, 1986]. The specific frequencies are related to the geometry of the barrier cross section.

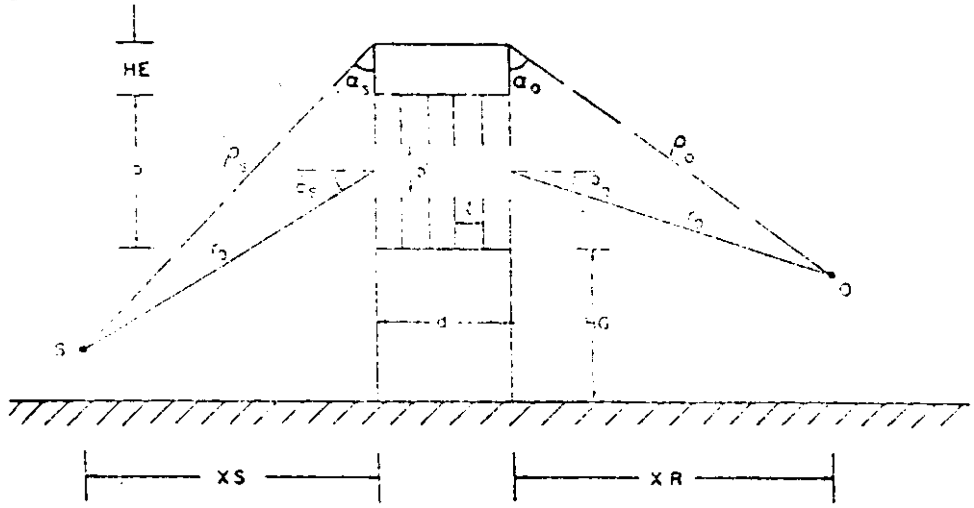


Figure 25. The boundaries of the waveguide filter.

Nicolas and Daigle concluded that, at specific frequencies where significant destructive interference occurs between the diffracted field and the field transmitted through the waveguide, there is an enhanced noise reduction. However, at adjacent frequencies there is constructive interference which can degrade the performance of the barrier. At frequencies between 200 Hz and about 1 kHz the barrier waveguide provides less attenuation than the standard barrier because of the additional waveguide field adding in phase to the diffracted field. When the diffracted and waveguide fields interfere destructively just above 1 kHz, an additional attenuation of several dB is obtained in a restrictive frequency band. In the region above 1.5 kHz the measured results indicate that, on the whole, the barrier alone performs better. The performance of the waveguide device between 200 and 1000 Hz improves for greater source and receiver distances to become comparable to the performance of a barrier alone. However, this is at the expense of a degradation of barrier-waveguide attenuation in the region of the destructive interference.

From these results it can be implied that waveguide filters would only be useful when a unique and dominant pure tone is present at low frequencies. Since highway noise is broadband in frequency, this type of barrier application would not be feasible. *Consequently, phase reversal barriers are not recommended as a major area of further study.*

CONCLUSIONS

Several potential promising special noise barrier applications have been presented. Upon reviewing both the literature and mathematical formulations behind these applications, the following applications should be used in the technical, aesthetic, and economic feasibility studies in the next section of the report.

1) Absorptive T-top Barriers
2) Single Wall Absorptive Barriers
3) Slanted-top Barriers
4) Absorptive Parallel Barriers
5) Y-top Barriers

INTERPRETATION, APPRAISAL, AND APPLICATION

Aesthetic and Economic Feasibility

INTRODUCTION

Highway noise control has been practiced in the United States for the last two decades. Highway noise barriers, while providing important noise reduction, are often perceived negatively by the public. This negative perception results from two basic issues: visual incompatibility and excessive cost. These two issues are the subject of the final phase of this project, **SPECIAL NOISE BARRIER APPLICATIONS**.

The mathematical formulation (Task II) identified five potential special noise barrier applications that warranted further study in the aesthetic and economic feasibility phase of the project. These are:

- Absorptive T-top Barriers
- Single Wall Absorptive Barriers
- Slanted-top Barriers
- Parallel Barriers
- Y-top Barriers

These five potential applications will be addressed in this report with regard to both aesthetic and economic feasibility. First, a general overview of aesthetic and economic impacts will be discussed. Next, the feasibility of shaped barrier tops will be analyzed. These include absorptive T-top barriers, slanted-top barriers, and Y-top barriers. Lastly, those potential applications that address barrier surface treatments will be discussed. These include single wall absorptive single barriers and parallel barriers.

NOISE BARRIER IMPACTS

Aesthetic Impacts

The principal that guides a noise barrier design to minimize negative aesthetic impacts is *compatibility*. The barrier should integrate into the highway environment in such a way as not to draw attention to itself. Several concepts were identified in the preparation of Synthesis Report 87, "Highway Noise Barriers," for the National Cooperative Highway Research Program of the Transportation Research Board [Cohn, 1981]. These include:

- Size and mass
- Material selection and color
- Landscaping
- Citizen Involvement

The question of the optimum barrier size and mass is of concern to the noise control engineer. Increasing the height of barriers can improve performance, but studies have shown that the benefit/cost ratio generally peaks at a height of about 13 feet. For this reason, and for aesthetics the question of special noise barrier applications is of vital interest.

The concept of compatibility should certainly direct the barrier design in the areas of material selection and color. For heavily developed urban and suburban areas, the NCHRP Synthesis study showed that concrete barriers were determined to be preferable, because of the abundance of concrete bridges, retaining walls, and buildings in those settings. An important consideration to note for concrete (and masonry) barriers is that citizens strongly prefer them to be tinted [Cohn, 1984]. California and Nevada, for example, routinely use a light brown pigment in their concrete barriers [Cohn, 1981].

The importance of an effective landscaping plan in achieving compatibility cannot be over-emphasized. Several state highway agencies have reported a strong correlation between perceived acoustic effectiveness and a well received landscaping plan. While the correlation is difficult to quantify, one state claimed it could be up to 7 dBA in excess "psychological" attenuation [Cohn, 1981]. Utilizing widely accepted [White, 1975] principles of psycho-acoustics, this would translate into an enhancement in performance of as much as 75%.

Lastly, it is important to utilize a thorough plan of citizen involvement, as a method to increase acceptance of barrier projects. The Synthesis results in this area were clear in the conclusion that if the public believes that it has played a legitimate role in the barrier development process, it will receive the final design in a more favorable fashion [Cohn, 1981].

Visual quality is unquestionably a major area when one considers ways to reduce the intrusiveness of highway noise barriers. Another area that is of considerable interest is *cost*. The following section summarizes the current state-of-the-art in barrier cost reduction.

Economic Impacts

The concept of barrier cost reduction (BCR) was first introduced as part of a study in Baltimore for the Maryland Department of Transportation [Menge, 1980]. The BCR concept was the first to significantly address the problem of balancing cost against acoustical performance.

The Federal Highway Administration sponsored a major effort to integrate the BCR concept into its basic highway noise prediction procedure, commonly known as the "FHWA Model" (which was discussed in detail in the literature review of this project). This work produced the companion computer programs, STAMINA 2.0 and OPTIMA [Bowlby, 1982], which are currently in wide use throughout the country.

More recently, the authors have produced significant computational enhancements to the STAMINA 2.0/OPTIMA computer software package. These include CHINA (an expert system for automated barrier design) and REBAR (for parallel barrier analysis). Both of these programs can be used to combat the economic feasibility questions arising in barrier design.

Clearly, the current computer software packages available will produce as efficient a noise barrier system as possible within the limits of the programs. This maximum efficiency has positive effects upon barrier intrusion in that both costs and size can be minimized. For urban and suburban situations, however, these gains could be lost as increased heights of conventional barriers are required to alleviate the noise problem.

Special noise barrier applications are an alternative to increased heights of conventional reflective barriers. The remainder of this chapter addresses the aesthetic and economic feasibility of the five previously mentioned potential special noise barrier applications.

SHAPED BARRIER TOPS

Absorptive T-top Barriers

The performance characteristics of T-top barriers has been discussed in the literature review of this project. Absorptive T-top barriers have performed well in past acoustical scale modelling studies. However, full scale modelling and direct field measurements from absorptive T-tops have been extremely limited in past studies. Nevertheless, the possibility of enhanced performance from this barrier top is evident.

The greater complexity of a T-top barrier, as compared with a conventional barrier of equal performance, may be offset by a lower wind loading for its lesser height. Wind loads often dictate the strength requirements of the posts used in most barrier designs, which are a major component of barrier costs. A situation has also been discussed by Hajek and Blaney where foundation design did not favor a further increase in height, thus necessitating the use of a T-top, or similar design, to increase insertion loss [Hajek, 1984]. The T-top design clearly has an economic advantage in these two areas (wind loading and foundation requirements) when compared to increasing the height of a conventional noise barrier.

As previously discussed, the aesthetics of a barrier are also an important factor for nearby residents. A shorter T-top barrier may be received better by citizens than a higher conventional barrier. Knauer has reported of a situation where the demands of residents to retain a full view of their coastal surroundings has led to the erection of barriers having insufficient height to meet "target" noise levels [Knauer, 1980]. This would seem to be an ideal situation to make use of a T-top design. Intuitively, if predicted conventional barrier insertion losses are small, then the increase that may be provided by a T-top barrier may help to justify the barrier in the first place. Experimental studies have shown that absorptive T-top barriers perform well in the laboratory. However, the durability of this absorptive treatment when exposed to seasonal weather conditions has yet to be proven. The question of durability of absorptive side treatments has been discussed in the literature review of this project. (This issue has been successfully addressed by the proprietary products including *Durisol* and *Soundblox*, which will be discussed later in this report.) The placement of absorptive treatment on the **flat top** of a T-shaped barrier will undoubtedly increase the opportunity for liquid infiltration into the absorptive material. Whether this chance for increased exposure proves detrimental to the success of absorptive T-top barriers is yet to be proven by adequate exposure time of full scale prototype models.

In summary, absorptive T-top barrier feasibility can be approximated as follows: Absorptive T-top barriers have both positive economic and aesthetic qualities, and perform accoustically at least equivalent to that which would result if the T-top section were stood on its end and added to the height of the vertical section of the barrier (In order to obtain this acoustical performance, it is necessary that the T-top barrier still maintain a complete line-of-sight break with the receiver.). Certainly absorptive T-top barriers should be a strong candidate for more detailed consideration by WSDOT in Phase II research.

Slanted-top Barriers

Slanted-top barriers have been used extensively in Japan, and were discussed in the literature review [Cohn, 1982-1]. However, the findings of the mathematical formulation indicate that only a slight potential for additional insertion loss (when compared to a conventional barrier) exists. Still, the slanted-top has the quality of a better aesthetic appearance.

In the event a situation requires a relatively tall barrier, a slanted top may prove to be advantageous. Slanting the upper part of a tall reflective barrier towards the source can yield a diminishing appearance from the receivers. This appearance would definitely be more aesthetically pleasing to the residents, while providing the same insertion loss as a vertical barrier of equivalent height. The slanted top may actually appear shorter, and could provide better light and less screening of view for the receivers.

A slight increase in costs due to structural requirements and increased construction times could arise from the selection of a slanted-top barrier. However, the benefits gained from a better public acceptance of this special barrier top may justify its selection. A more detailed economic analysis of actual job data could provide prudent information on the economic feasibility of this special barrier top. Along with absorptive T-top barriers, slanted-top barriers may be useful to WSDOT in special situations.

Y-top Barriers

Y-top barriers, as discussed previously in this project, were initially studied to compare with T-top barriers. Although they have consistently performed slightly poorer (about 1 dB) than an equivalent reflective T-top barrier, the Y-top is still superior in performance to conventional barriers. For this reason, the Y-top was recommended for further study in the project.

The benefits of Y-top barriers are very similar to those of the absorptive T-top discussed earlier in this report. Lower wind loading and lesser foundation requirements due to the decreased height of the Y-top compared to a conventional barrier are very positive aspects of this special barrier top. The decreased height could also prove to be more aesthetically pleasing to the general public.

On the negative side for Y-top barriers could be a potential drainage problem produced by the trough created at the top of the barrier. Although installation of drains along the barrier top may alleviate this problem, it could also increase costs. Drains would also require periodic maintenance to ensure a "debris free" path. This drainage question may render the Y-top less economically feasible than the absorptive T-top barrier. While not as effective as absorptive T-top barriers, Y-top barriers could prove useful to WSDOT in certain situations. Continued research into the Y-top barrier could provide solutions to the potential drainage problem.

POTENTIAL BARRIER SURFACE TREATMENTS

As mentioned previously, barrier performance can generally be improved by the use of absorptive treatments. When sound absorptive materials are used outdoors in highway situations, they must be resistant to (1) weather conditions, which are particularly severe when there are freeze-thaw cycles, (2) acts of vandalism, (3) impacts from vehicles, and (4) the presence of chlorides from snow plowing operations and spray. From an acoustical point of view a relatively high sound absorption would be desired in the range 500 to 2000 Hz, where the A-weighted traffic noise contains much of its energy.

Behar and May performed research on the performance and durability of various types of absorptive materials.[Behar, 1980] This research, along with that of Lane [Lane, 1989], was discussed previously in the literature review and will not be re-stated in this section. Their research indicated that it was possible to achieve increased insertion loss with the use of absorptive materials while at the same time using a material that was durable.

As stated previously, the issue of durability has been successfully addressed by the proprietary products such as *Durisol* and *Soundblox*. The first product, Durisol, is a concrete based material which utilizes wood chips (as an absorbing agent) pressed into the mix. Durisol is able to achieve and maintain a noise reduction coefficient of about 0.6. This product has been used extensively in Canada and Europe for more than 10 years. The second product, Soundblox, is a resonator masonry block. Soundblox are actually helmholtz resonators, since each block is slit in the middle, thus creating two chambers which absorb sound energy in the frequency range of highway noise. A Noise Reduction Coefficient (NRC) of about 0.6 can be obtained with Soundblox.

The improvements in aesthetics from the use of absorptive materials are more in terms of (a) reducing the potential for vandalism by roughening the surface texture, and (b) reducing required height. Smaller barriers (in terms of height) are more aesthetically compatible than taller barriers.

Single Wall Absorptive Barriers

The performance of thin perfectly reflective barriers may be increased with the use of absorptive material. Many studies have been performed to show improved effectiveness by the addition of absorptive materials to the surface of barriers.

The placement of an absorbent strip along the edge of the barrier was the topic of research by Rawlins [Rawlins, 1976]. He showed that a strip, one wavelength wide, of an absorbent material on the top of the barrier led to the same diffracted field as that provided by a totally covered barrier. However, Rawlins did not consider the effect of placing this absorbent strip only on the source side, on the receiver side, or on both sides of the barrier.

L'Esperance *et al.* performed research which dealt with the angles of the diffracted paths (source top-edge and/or receiver top-edge) [L'Esperance, 1989]. This research shows that when the angles of the diffracted paths are sufficiently large, it is possible to increase the insertion loss of a thin perfectly reflecting barrier with the use of absorptive treatment. When the angle of the diffracted paths are greater on one side (source or receiver), it is more efficient to place the absorptive covering on the surface of the barrier associated with this side. When these angles are about the same on both sides of the barrier, which is generally the case when the source and the receiver are located at the same distances from the barrier, an absorptive covering will give the same increase no matter which side it is placed upon. Also, by covering both sides of a barrier, it is possible further to increase its insertion loss, especially when both the receiver and the source are located near the barrier [L'Esperance, 1989].

The use of absorptive materials on single barriers is an effective way to increase the insertion loss of the barrier. The absorptive material is only needed in the upper zone of the barrier, which is the size of the dominant wavelength (generally about 2 feet). As mentioned earlier, the use of absorbent material can also help reduce the height of a barrier in order to achieve the desired insertion loss. Single wall absorptive barriers may provide up to 2 dBA in additional insertion loss for receivers deep in the shadow zone. However, there are currently no analysis methodologies available to quantify the effects of single barrier absorption.

Parallel Barriers

The problem of multiple reflections between parallel noise barriers will have the potential for significant barrier insertion loss degradation when the following conditions exist: the canyon width is less than 200 feet, barrier height at least 10 feet, canyon width to barrier height ratio less than 20:1, and the barriers are perfectly parallel with top elevations the same. If these conditions are met the consequent degradation in insertion loss can be reduced by the use of absorptive treatments.

Cohn *et al.* performed research which indicated that covering the surfaces with absorptive material typically increased insertion losses by 2 to 3 dB as the "reflection potential" decreased from 0.9 to 0.4 [Cohn, 1984]. This research, as well as numerous other studies, all show that absorptive treatments to parallel barriers do help considerably in reducing the number of multiple reflections when conditions warrant.

DESIGN SUMMARY AND MATRIX

A brief summary of the various special noise barrier applications is included in this section of the report. A chart has been constructed (Table 6) to act as a type of quick reference guide to selecting a special barrier type.

As can be seen from the chart, T-Top barriers should be considered when the height of a conventional barrier is to exceed 13 feet. There are numerous advantages to using a T-top barrier, the most important being the reduced height of the barrier. With the reduction in height comes a decrease in windloads, which in turn will enable the designer to use smaller posts in the design of the barrier. This then results in smaller foundation requirements for the T-top barrier. The disadvantages associated with this type of barrier are debris accumulation and the possibility of drainage problems. Debris accumulation may occur on the top of the barrier and may include such things as snow or foliage. This, in turn, may require

TABLE 6

DESIGN MATRIX FOR SPECIAL NOISE BARRIER APPLICATIONS

Barrier Type	T-Top	Y-Top	Slanted Top	Absorptive Single	Absorptive Parallel
Height	>13'	>13'	>13'	All	>10'
Approx. Increased I.L. (dB)	1.5-2.0	1.0-1.5	0.0-0.5	0.0-2.0	2.0-3.0
Approx. Increased Cost (%)	10%	10-20%	10%	25%	20%
ADVANTAGES					
Reduced Height	✓	✓		✓	✓
Reduced Windloads	✓	✓		✓	
Smaller Foundation Requirements	✓	✓		✓	
Aesthetic Appearance	✓		✓		
DISADVANTAGES					
Debris Accumulation	✓	✓			
Drainage Problems	✓	✓			
Increased Foundation Requirements			✓		
Questionable Durability of Material				✓	
Periodic Maintenance	✓	✓		✓	✓

periodic maintenance, for cleaning purposes, of the barrier.

The Y-top barrier, like its T-top counterpart, would also be considered when the height of a conventional barrier exceeds 13 feet. This type of barrier has many of the same advantages of the T-top barrier; excluding the area of aesthetic appearance. Currently, there is not enough research to determine if this barrier type would be aesthetically pleasing to the residents being protected by the barrier. The disadvantages associated with the Y-top barrier is the drainage problems that may occur without periodic maintenance. The inclusion of drainage holes throughout the barrier may alleviate the storm water runoff, but other debris, such as foliage, may hamper the ease of drainage through the barrier.

The slanted top barrier would be considered when the height of a conventional barrier is to exceed 13 feet. One of the advantages of this type of barrier is that it has a diminishing appearance from the receivers if the top is slanted towards the roadway. This, in turn, contributes to the improved aesthetic appearance of the barrier. The disadvantages of this type of barrier are the increased foundation requirements. This is a result of the increase in windloads on the barrier as a result of the slanted top. As a result, the cost of construction would increase as foundation requirements increase.

A conventional barrier with absorptive treatment would be considered when numerous receivers are located deep in the shadow zone (i.e., a large diffraction angle). As the diffraction angle becomes smaller (receivers located farther away from the barrier) the potential advantages of an absorptive barrier will diminish.

When parallel barriers exist, and the conditions previously mentioned are met, the use of absorptive material is a viable way to increase the insertion loss of the barriers. The absorptive material lessons the effect of the various image sources, which were discussed previously in this report. This type of barrier would require periodic maintenance to ensure that the absorptive material has not been damaged.

Computer Applications

NOISE, the current highway noise software used by WSDOT, includes STAMINA 2.0/OPTIMA as the basic means of prediction and barrier design. These programs implement the FHWA Model (FHWA-RD-77-108), thus limiting barrier analysis to reflective knife edge diffraction. Consequently, there is no way to consider the effects of T,Y, or slanted tops, or parallel barriers internally within the existing software. Either additional computer programming is required, or manual techniques must be applied.

The manual techniques would be similar for each special treatment. The first step is to complete the barrier design assuming no special treatment, then use the appropriate rules of thumb to modify barrier height. The rules of thumb include the following:

1) *Absorptive T-top barriers* enhance performance through double diffraction such that a vertical barrier's height can be reduced at a one-to-one ratio to the width of the T-top, as long as adequate line of sight breaks are maintained. The cost of the new design (shorter T-top barrier) can then be calculated and compared to that of the vertical barrier.

2) *Y-top barriers* also enhance performance through the use of double diffraction, although they are not as effective as absorptive T-tops. The literature indicates that as long as the width of the Y is at least one wavelength (at least 2.5 feet), the Y-top barrier will add up to 2 decibels in insertion loss over the vertical barrier. Therefore, a Y-top

barrier's height can be reduced by up to 4 feet, as long as adequate line of sight breaks are maintained. The cost of the new design (shorter Y-top barrier) can then be calculated and compared to that of the vertical barrier.

3) *Slanted top barriers* enhance performance by moving the diffraction edge closer to the source, and therefore slightly increasing the path length difference. While the literature does not quantify these effects, it can be conservatively assumed that a slanted top barrier can add up to one decibel in insertion loss over a similar vertical barrier. Therefore, a slanted top barrier's height can be reduced by up to 2 feet, as long as adequate line of sight breaks are maintained. The cost of the new design (slanted top barrier) can then be calculated and compared to that of the vertical barrier.

4) *Single wall absorptive barriers* enhance performance such that as much as 2 decibels in insertion loss can be gained over a similar reflective barrier, as long as a significant path length difference is still maintained. Therefore, an absorptive barrier's height can be reduced by 3-4 feet as long as adequate line of sight breaks are maintained. The cost of the new design (shorter but absorptive barrier) can then be calculated and compared to that of the vertical barrier.

5) *Parallel barriers* degrade insertion loss by as much as 4 decibels when: barrier tops are approximately the same elevation, canyon width is less than 200 feet, and barrier height to canyon width ratio is 1:20

or less. In order to offset this degradation, parallel barriers should be made absorptive, with Noise Reduction Coefficients (NRC) equal to 0.65 or greater.

Regarding additional programming, the Federal Highway Administration is sponsoring a project that is intended to ultimately produce a new version of STAMINA 2.0/OPTIMA. This new version will likely include the capability to analyze some of these special treatment options.

Conclusions and Recommendations

CONCLUSIONS

The design matrix shown in Table 6 indicates that special applications can increase barrier performance by as much as 3 decibels. Those treatments with the most potential include absorptive T-tops, Y-tops, slanted tops, and absorptive single and parallel barrier systems. With each treatment, however, there is an associated cost increase, which can be as high as 25 percent. It is likely that the cost increase would be warranted, since there is a potential 2 foot height reduction gained for each one decibel insertion loss performance enhancement.

RECOMMENDATIONS

Given this potential, followup research should be initiated to examine the feasibility of applying the treatments to actual WSDOT projects. This proposed research is described below.

Implementation

RECOMMENDATIONS FOR SUGGESTED PHASE II RESEARCH

The primary objective of this research would be to examine the potential for applying results to real projects in Washington State. Several specific applications have been identified which could improve the WSDOT noise program. It is important that these applications be analytically tested on one or more actual projects, in order to gain definitive information on their real potential.

It is expected that most of the special applications identified would show real potential for improving various aspects of the WSDOT noise program. This followup study would have the benefit of clearly demonstrating that potential, and would thus position the department to implement an improved noise control program. In addition, it is hoped that one or more of the special applications would be utilized on the specific highway projects used in this study, since a great deal of analysis would be performed on them. This benefit alone could more than offset the cost of the work proposed herein.

The results from this research would be delivered in report form, and would include summary discussions. Also included would be quantitative information on both the standard barrier design and the modifications resulting from the special barrier treatments. Cost, performance, and aesthetic information would be part of the report.

The outcome of this research would be an implementation strategy for immediate use by WSDOT, making it a highly practical project. In addition to this implementation strategy, it is expected that the specific highway projects used as field laboratories would be able to benefit directly from use of the special treatments.

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