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16. Abstract

Studies have shown that motor vehicle noise is a significant national problem in many communities. Construction of traffic noise barriers (sound walls) has been the most often used mechanism to mitigate vehicle noise for residents living next to high density roadways or proposed high density roadways The purpose of this three-phase research project is to develop guidelines and a design guide for analysis, design, and construction of effective noise barrier systems in Texas. This report provides the progress accomplished in phase I, which was a literature review and review of current noise barrier design and construction practices in Texas. The report provides an excellent acoustical background on how noise barriers work, and summarizes the current noise analysis software.

In Texas, each TxDOT district office is responsible for the design of its noise barriers; consequently, many different designs have been successfully used. Designes include small precast concrete panels on precast "Jersey barriers," large precast panels, reinforced masonry, cast-in-place, and barriers with safety-shaped bases. Details are provided from interviews with district design engineers. Additional research is in progress on the possible use of a random jagged top to noise barriers that laboratory experiments show to have a 3-8 dB improvement in insertion loss. Additional research is in progress on finite-element analysis of barriers that might receive vehicle impact.

This research will continue with phase II to study the noise barrier systems in use by other states, the acoustical effectiveness of absorptive noise barriers, and software for noise analysis and aesthetic evaluation. Phase III will study parallel noise barrier systems and will develop a design guide for use by TxDOT district offices.

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Research Report 1471-1

Research Project 0-1471
Effective Noise Barrier Solutions for TxDOT

conducted for the

Texas Department of Transportation
in cooperation with the
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by the

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IMPLEMENTATION STATEMENT

The information presented in this report may be used by district personnel who are required to analyze traffic noise and noise barriers, and by those who are required to design or construct noise barriers. Additional information is available at the Center for Transportation Research.

Future reports will be provided as the research proceeds. The final report will be a design guide with a catalogue of designs for district office use.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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SUMMARY

The NCHRP *181 Synthesis 181*, prepared by Bowlby in 1992, and the report published by the Danish Ministry of Transport, *Noise Barriers—A Catalogue of Ideas*, were found to be excellent reviews of the current design practices and noise barrier technology. These documents and many others are maintained in CTR's library of noise barrier reference material. Meetings with District personnel were held in Austin, San Antonio, Fort Worth, Dallas and Houston. The purposes of the meetings were to inform the districts of the scope of this research project, to provide background on the basic acoustical theory behind noise barriers, and to hear and discuss the experiences of districts that have constructed noise barriers. The five meetings were very successful, and were attended by 67 TxDOT personnel from nine districts. It is expected that FHWA's new computational program (Traffic Noise Model, or TNM), to be released in 1996, will correct the identified deficiencies of STAMINA and OPTIMA, and will permit more accurate and detailed analysis. However, the new TNM will require more powerful computer hardware than the currently used programs. TxDOT has constructed or planned noise barriers in Austin, Dallas, Fort Worth, Houston, Denton, El Paso, San Antonio and College Station. The prefabricated separate post and panel system (using elements of precast concrete) is the most prevalent in Texas. The researchers conducted both face-to-face and telephone interviews with TxDOT noise barrier designers. According to TxDOT designers, structural design of noise barriers is usually governed by the design wind load or by the AASHTO-mandated 45-kN (10-kip) horizontal load simulating the effects of vehicular impact. Design wind pressures varied by district from a high of 30 psf to a low of 20 psf. The performance criteria reported in Chapter 9 are intended to be preliminary. They are proposed as design goals, and constitute a necessary step in the development of the noise barrier design guide. They are submitted for consideration and review by TxDOT. Once these performance criteria are validated and quantified, standardized noise wall designs can be developed that meet them. Phase II will review existing practices in noise barriers in other states and Phase III will produce a recommended guideline for TxDOT district offices to use to analyze, design and construct effective noise barriers.

CHAPTER 1. PROJECT OBJECTIVES AND OVERVIEW

In 1974, a study conducted for the US Environmental Protection Agency (EPA) judged that motor vehicle noise was the single biggest contribution to community noise [1]. As a direct result, approximately 1486 km (929 miles) of noise barriers were constructed with highway funds in the US from 1970 to 1992 at an estimated cost of $816 million [2]. The purpose of this research project is not to propose that the entire state of Texas line its highways with barriers, but rather to prepare statewide answers to the questions of if, why, when, and how a noise barrier should be constructed.

This research project was developed in response to TxDOT district needs: each district is designing different barriers and no statewide standards existed for design, evaluation or construction of noise barriers. The ultimate goal of this three-year study is to develop a design guide for district personnel including a catalog of proven designs for various geometric and topographic situations.

This research project is divided into three phases. The first phase, which concludes with this interim report, is to document and evaluate current TxDOT designs. The second phase is to seek improvements from new materials and concepts, from designs and practices used in other states, and from better acoustical understanding and modeling. The third phase is to implement the new improvements with a design procedure and design guide.

PROJECT OBJECTIVES

The objectives of the Effective Noise Barrier Solutions for TxDOT project are to:

- Evaluate existing noise barrier materials and systems in use by TxDOT with regard to their acoustic performance, visual aesthetics, structural requirements and cost-effectiveness.
- Evaluate existing noise barrier materials and systems in use by other states and the feasibility of new products and materials in comparison to existing TxDOT systems.
- Develop performance criteria for different geometric and terrain conditions that permit the quantification of acoustic performance, aesthetics, structural soundness, and life-cycle cost.
- Develop a methodology for selecting application specific designs based upon the roadway geometry, the surrounding terrain and cultural features, and the environment.
- Develop a model for evaluating parallel reflections of noise barriers and make recommendations as to when it should be used for design.

- Develop improved specific noise barrier system designs, including material specifications, acoustical and structural design methodologies, and construction details.

OVERVIEW OF WORK COMPLETED

We have conducted a thorough literature review of all relevant noise studies and traffic noise barrier reports. **Chapter 2** gives an in-depth analysis of the salient findings of this literature review.

This project began with a meeting of the study's research committee to set the specific objectives of the research team. As a result of this meeting, the team was directed to visit five district offices, and to invite representatives from all districts to attend one of the five meetings.

Meetings with District personnel were held in Austin, San Antonio, Fort Worth, Dallas and Houston. The purposes of the meetings were to inform the districts of the scope of this research project, to provide background on the basic acoustical theory behind noise barriers, and to hear and discuss the experiences of districts that have constructed noise barriers. The five meetings were very successful, and were attended by 67 TxDOT personnel from nine different districts.

In developing the agenda for the district meetings, it became apparent that very few personnel in the district offices had received any formal training on the basic acoustical theory of noise barriers. We were then invited to include in our presentation to the district offices, basic material on "How Noise Barriers Work." That part of our presentation was very well received by the district offices, and is summarized in **Chapter 3**.

Chapter 4 is a review of available noise analysis software programs. From our district meetings we determined that only the FHWA standard programs STAMINA and OPTIMA were used, but widespread dissatisfaction with those programs was noted. Chapter 4 also provides a description of the capabilities of the soon-to-be-released FHWA replacement program for STAMINA and OPTIMA and discusses the advantages of that new Traffic Noise Model (TNM).

In our initial district visits and our follow-up visits, we developed a database of existing noise barriers in Texas constructed by TxDOT. **Chapter 5** provides examples of several of the most common types noise walls. Each district has designed its noise walls differently. Designs include small precast concrete panels on precast "Jersey barriers," large precast panels, reinforced masonry, cast-in-place concrete, and barriers with safety-shaped bases. In that chapter, each is described in more detail, to familiarize the reader with the characteristics and nomenclature associated with the most commonly used wall types.

Chapter 6 presents the results of written and oral interviews with noise wall designers. Using information obtained from those interviews, a database has been developed of fifteen noise barriers constructed in Texas. These barriers have been classified according to particular design features and presented in outline form in this chapter. These data will be used in Phases II and III of this research project to assist in the development of the TxDOT noise barrier design guide. Noise walls exemplifying a particular design feature or wall system will be selected from the database and included in our final design guidelines.

Chapters 7 and 8 are brief descriptions of preliminary acoustical laboratory research and structural computer research. **Chapter 7** describes an laboratory experiment of a scaled noise barrier with a random jagged top edge that may provide an additional 3 to 8 dB of insertion loss compared to an otherwise identical barrier with a smooth top. **Chapter 8** describes a preliminary finite element analysis of a barrier for wind load and vehicle impact. These chapters are preliminary reports of research in progress. Each is expected to lead to a separate technical report in the near future.

Chapter 9 is a draft of a performance criteria for the design and evaluation of noise barriers. The criteria address the acoustical, structural, aesthetic, and life-cycle performance of noise barriers. In June 1995, FHWA released a revised document, "Highway Traffic Noise Analysis and Abatement Policy and Guidance." This document requires that each state highway agency publish by June 1996 a companion guidance and policy document approved by FHWA. The draft performance criteria in Chapter 9 will be revised during Phase II to be compatible with the TxDOT guidance and policy document, and to serve as a commentary to that document.

Chapter 10 is the summary of work completed, and an outline of the work planned for Phases II and III of this research project. Phase II includes the study of noise barriers in other states, and of problems related to the use of sound absorption in barriers. The new noise analysis software will be evaluated. The end result of Phase III will be the development of a TxDOT design guide for noise barriers.

CHAPTER 2. LITERATURE REVIEW

INTRODUCTION

Environmentalists rank noise pollution as one of the foremost environmental problems in the United States. Highway noise pollution has become a top priority issue for transportation planners and designers. Highway noise barriers designed for residential areas must now meet strict legislative noise requirements.

Noise control can be achieved in three ways: control of the source; control along the path; or control at the receiver. In the United States, along-the-path control has emerged as the most commonly used noise control measure, as it does not require modification of a product nor use of hearing protectors by individuals. The primary highway noise control method used by State Highway Agencies (SHA) is a noise barrier. The other method available is to make facilities soundproof, but this is considered only in extreme cases as it is an expensive option. Typically, states are reluctant to reduce vehicle speeds on the roads (control of the source) to reduce noise as large speed reductions are required for significant noise level drops. Source control by restricting vehicle noise emission levels and land use control are also beyond the jurisdiction of SHAs. Faced with these constraints, it is not surprising that noise barrier is the most common way of alleviating highway noise pollution.

A recent study conducted by the Federal Highway Administration (FHWA) has highlighted the following priority areas for noise barrier research [2]:

1. Acoustical Measures for Noise Barrier Performance
   These include theoretical, empirical and computer simulation methods for predicting noise barrier effectiveness.

2. Non-Acoustical Measures of Noise Barrier Performance
   These include criteria such as aesthetics, cost-effectiveness and structural performance of the noise barrier.

3. Parallel Noise Barrier Performance
   This issue concerns the degradation of sound attenuation produced by parallel noise barriers, as a result of multiple reflections from the parallel walls

4. Meteorological Effects on Highway Noise Barrier Performance

As a result of our literature review, a partial discussion is provided for each of these four areas in the following section. In addition, issues such as traffic noise impact and construction trends for highway noise barriers are discussed.

ACOUSTICAL MEASURES FOR NOISE BARRIER PERFORMANCE

Theoretical Method

Using an analytical approach to design a highway noise barrier is difficult because it is not easy to accurately calculate the diffraction of sound around the barrier. The theory of diffraction has its origin in optics. Since sound, like light, is a wave (although with a much longer wavelength than light), diffraction theory has long been applied to acoustical applications. To date, wave diffraction is still one of the most difficult problems in the study of optics and acoustics.

Sommerfield, in 1896, provided the exact solution for the diffraction of a plane wave on a semi-infinite screen [3]. The concept is based on the Huygens-Fresnel principle. Using Kirchoff's diffraction theory for the semi-infinite screen, Sommerfield showed that the sound attenuation by the screen can be approximated by

$$[\mathrm{Att}]_{1/2} = -10\log_{10}\frac{1}{2}\left[\left\{\frac{1}{2}-C_{(v)}\right\}^2+\left\{\frac{1}{2}-S_{(v)}\right\}^2\right]_{\mathrm{dB}} \tag{1}$$

Here $[\mathrm{Att}]_{1/2}$ refers to the diffraction of a semi-infinite open space, $C_{(v)}$ and $S_{(v)}$ are the Fresnel integrals for variable v, and

$$v = H_e\sqrt{\frac{1}{2}\left(\frac{1}{a}+\frac{1}{b}\right)} \tag{2}$$

where H_e is the effective height of the screen, and a and b are the distances from the screen to the source and the receiver respectively. Figure 2.1 shows the values calculated from Eqs. (1) and (2). The point of observation P lies either in the illuminated region or in the shadow zone, depending on whether $v > 0$ or $v < 0$, respectively.

Equation (1), derived from optical diffraction theory, is simple in form and easy to interpret. However, a good approximation in *optical* diffraction does not imply the same accuracy in *acoustical* diffraction. In optics, the wavelength is typically very small compared to the distance between source and obstacle. The reverse is true in acoustics. For this reason, empirical methods are often used for acoustical design of highway noise barriers.

Empirical Method used by FHWA and SHAs for Acoustical Design of Highway Noise Barriers

Since 1976, the FHWA and all SHAs have used the following equation to predict the insertion loss of proposed highway noise barriers:

$$\Delta L = 5\text{dB} + 20\log_{10}\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}\,\text{dB} \tag{3}$$

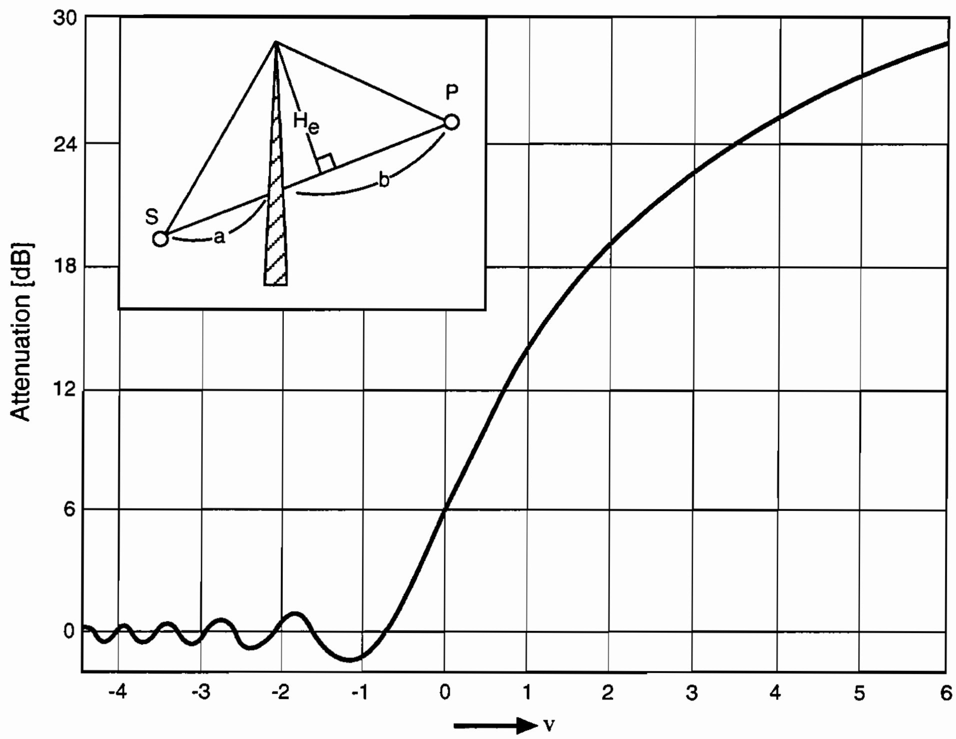


Figure 2.1. Calculation of Insertion Loss Using Kirchhoff's Diffraction Theory

where is the insertion loss of the barrier, which is simply the drop in sound pressure level with the barrier in place. N is the Fresnel number, a frequency-dependent measure of the extra distance the sound must travel as a result of the barrier. It is described by

$$N = 2\frac{\delta}{\lambda} \tag{4}$$

where δ is the path length difference between the direct and over-the-barrier paths of the sound waves, and λ is the wavelength of the source. This empirical formula was developed by Kurze and Anderson [4], who determined it to be a good curve fit to existing data for point sources. Equations (3) and (4) are important because they make it clear that higher barriers are more effective than lower barriers at reducing noise. From Equation (3), it is also clear that 5 dB is the insertion loss achieved when the line of sight between the source and the receiver is just broken, i.e., when N=0. Of the many empirical methods available, Equation (3) is the most simple and reliable for calculating sound attenuation by diffraction, with reasonable accuracy.

It should be noted that the insertion loss in actual field measurements will "saturate" at about 24 dB due to environmental effects like wind, atmospheric absorption and ground impedance effect (i.e., ground reflections). In other words, insertion losses greater than about 24 dB cannot be achieved, regardless of the barrier geometry. Thus, computer programs that use Equations (3) and (4) typically introduce a saturation at 24 dB so that their predictions will agree with this experimental observation.

The results calculated using Equation (3) are generally lower by a few dB than those calculated using Kirchhoff's theory in Equation (2). That is, Equation (3) gives a more conservative estimate of insertion loss. Figure 2.2 is a simple chart comparing the insertion loss calculated using Equations (1) and (3), with experimentally measured data by Maekawa [5].

Insertion Loss from Shaped Barriers

The analyses presented so far have considered barriers that are "thin" compared to the wavelength of the radiation being diffracted. Some practical barriers have a thickness comparable to or larger than a wavelength. For example, buildings, hills, earth berms, and depressed roadways are all thick relative to the wavelengths for typical car and truck noise. Maekawa has proposed that insertion losses for such barriers be calculated by treating them as thin barriers with equivalent dimensions. Several other authors have also addressed the issue of thick or wedge-shaped barriers. Extensive treatment of these barriers can be found in the references.

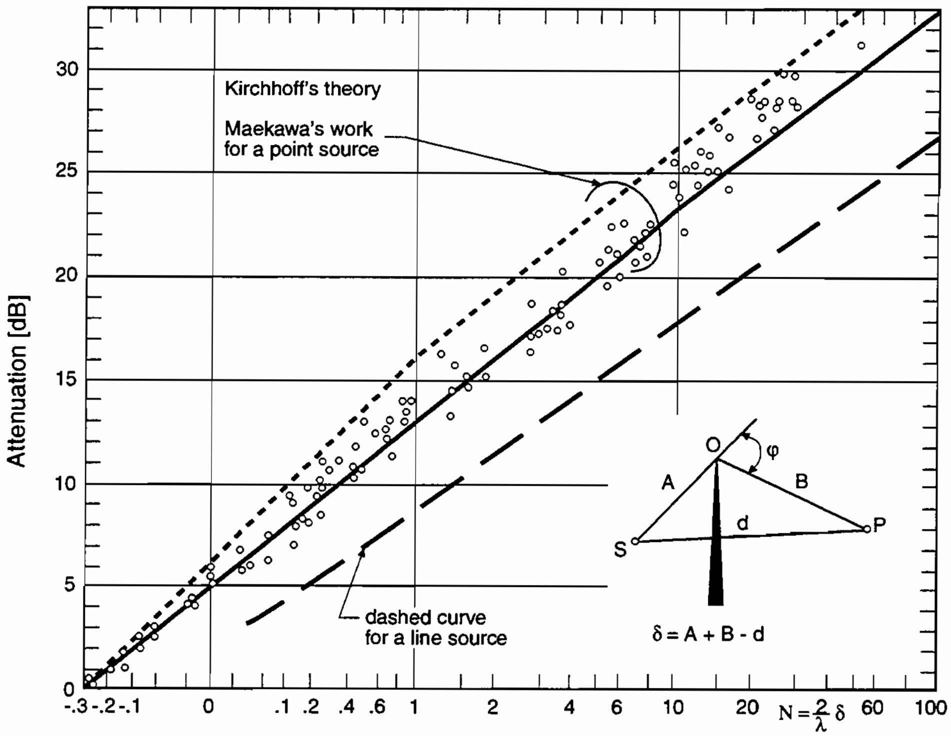


Figure 2.2. Sound Attenuation by a Semi-infinite Screen in Free Space

Use of Foliage as Noise Barriers

Trees and shrubs have been proposed as noise barriers for highway noise control. The Connecticut Department of Transportation has investigated the feasibility of this concept, and has found that to attain a 5- to 10-dBA reduction in noise levels would require a 100-foot wide strip of dense, evergreen vegetation between highway and receiver. This was judged unfeasible [6].

In related research, Hatano and Hendriks [7] found that a 4.5- to 6-m (15- to 20-foot) wide strip of shrubs, 2.5 m (8 feet) high, achieved an average noise reduction of only 1 to 2 dB. They concluded that vegetation is ineffective in reducing highway noise. ROW requirements usually make an earth berm more advisable than foliage barrier.

NON-ACOUSTICAL MEASURES OF NOISE BARRIER PERFORMANCE

In addition to acoustical criteria, other factors to be considered in designing a noise barrier include cost-effectiveness, aesthetics, maintenance, construction and structural performance. These are discussed at length in Chapter 6 of this report. Because the cost-effectiveness of a barrier in part determines whether a barrier will be constructed, it is discussed briefly here.

Although states use different means to determine the cost-effectiveness of a barrier, the most commonly used approach is to divide the estimated construction cost of each barrier by the number of residences adjacent to the barrier. A highway noise barrier is usually deemed feasible if it can reduce the noise level by about 5 dB for "impacted receivers" (those closest to the barrier) [8]. The barrier is generally considered cost-effective if it costs no more than $25,000 for each benefited receiver [8]. In most states, a noise barrier is considered cost-effective if it costs no more than $5,000 per receiver per dB reduction. In California, noise barriers costing less than $30,000 per resident unit are considered cost-effective [2]. As an example, a 11.6-km noise barrier on I-440 in Tennessee cost an average of $18,000 per residence [9].

Noise Barrier Aesthetics

The issue of noise barrier aesthetics is problematical, both because of its subjective aspects, and because it represents a potential dilemma for district designers. While those exposed to noise barriers can usually reach general agreement about which barriers are good-looking and which are ugly, reactions are far from unanimous, and reactions to existing noise barriers are sometimes difficult to extrapolate to new ones. While the general public would probably be strongly in favor of good-looking noise barriers, others involved in the noise barrier design process might not make aesthetics a high priority.

Little literature is available on the subject of noise barrier aesthetics. Research is in progress at Pennsylvania State and Texas A&M Universities. Researchers at Penn State have shown slides of different wooden noise barriers to many typical residents, and have asked them to rate the aesthetic appeal of each. Researchers at Texas A&M are concluding a two-year study, prepared for the Dallas District, in which all 50 states were sent a comprehensive written survey on noise barriers and aesthetic treatments.

In 1991, the Danish Ministry of Transport published Report 81, *Noise Barriers - A Catalogue of Ideas* [10]. This report contains a comprehensive picture database of the different type of noise walls constructed in Denmark and other neighboring countries. In addition, it discusses in qualitative terms the factors and methodology used in planning and designing a noise wall.

In 1976, The Federal Highway Administration published a manual for visual quality in noise barrier design which is still applicable today. [11] The manual is a guide to the basic principles which affect visual perception and their application to highway noise barrier design. The manual is not intended to provide design solutions for noise abatement, but rather to illustrate and emphasize the need for visual quality as part of the design process. The manual should be used as a supplement to technical informaiton concerning noise abatement, in an effort to produce highway noise barriers which are functional, attractive and visually related to the surrounding environment.

The aesthetics of noise barriers is not confined simply to the surface appearance of the barrier material. Noise barriers tend to be massive, and can easily become landmarks (good or bad), significantly contributing (again, positively or negatively) to the character of a neighborhood. For this reason, states such as New Jersey have campaigned to have noise barriers designed by architects or landscape architects. Houston is planning a new expressway with a single architectural theme. The new expressway's bridges, overpasses and noise barriers will all be designed to conform to this theme.

Noise barrier aesthetics is also related to residential acceptance and perception. For example, tilted noise barriers (discussed later in this report) are better acoustically than vertical barriers, in situations involving parallel barriers. However, tilted noise barriers are historically less acceptable to nearby residents. Although a noise barrier with a 10-15° outward tilt may be pleasing to motorists, residents on the other side complain because the barrier looks ready to fall on them.

Another aesthetic issue related to noise barriers concerns their opacity. Most barriers in the United States are of opaque materials such as concrete, masonry, or wood. Opaque barriers can block the view of motorists and make driving monotonous. One way to overcome this problem and at the same time achieve a better aesthetic result is to use transparent materials for barriers. A wide variety of transparent materials has been promoted for use in highway noise barriers. The most common are thermo-setting acrylic polymers, known by such trade names as "Plexiglas," "Butacite," "Surlyn," and "Lexan.

The primary advantage of transparent materials over traditional materials in noise barriers is aesthetics. However, many transparent plastics become brittle or discolored in the presence of ultraviolet radiation and ozone. Because their transparency is degraded by highway dirt, they may require periodic cleaning. In addition, the perceived aesthetic advantage of transparent barriers for motorists are often countered by the perceived aesthetic disadvantage for residents, who may not want an unobstructed view of nearby traffic. Formal and informal research studies have indicated a connection between how opaque noise barriers block the view of traffic, and how they are perceived to block noise. For example, although a wooden privacy fence maybe measurably ineffective as a noise barrier, it is nevertheless usually perceived by residents as effective, because it blocks their view of traffic. In this sense, transparent noise barriers may be perceived as acoustically less effective by residents, because of their transparency.

Construction and Maintenance of Noise Barriers

Of all the highway noise barrier issues covered in this literature review, construction and maintenance issues are apparently among the least investigated by the states. The following barrier construction problems are often reported by the states:

1. Efflorescence (crystallization of water-borne alkaline salts on the surface of the concrete, giving a chalky, stained appearance);
2. Inferior quality of the pre-cast concrete;
3. Inadequate curing; and
4. Inadequate construction supervision during barrier construction.

Although information on the maintenance cost of noise barriers is very difficult to obtain from the states, the following maintenance problems have been reported [2]:

1. Wooden barriers: aging, warping, cracking, shrinking and rotting;
2. Concrete barriers: stains, fading and peeling;
3. Graffiti; and
4. The need to preserve space for maintenance access between the ROW line and the barrier.

Problems with graffiti can be reduced by using a rough barrier surface [2]. However, maintenance in general is a major component of the life-cycle cost of noise barriers. Maintenance includes mowing of grass or weeds near the barrier, snow removal and storage, repair of damaged barrier sections, removal of graffiti, and repair of other acts of vandalism. It is difficult to preserve space for maintenance access between the ROW line and the barrier unless there is an easement between the residence property line and the barrier.

PERFORMANCE OF PARALLEL NOISE BARRIERS

Many noise barriers are intended to protect residences on both sides of a highway, using two essentially parallel walls. Such configurations are known as "parallel noise barriers." Several FHWA/SHA projects have investigated the effectiveness of parallel highway noise barriers.

As discussed previously in this section, mathematical calculations predict significant degradation in the performance of parallel noise barriers, compared to single barriers [12]. Experimental studies have also demonstrated that the effectiveness of a barrier can be significantly reduced or even nullified by the presence of a parallel barrier on the opposite side of the highway [13]. However, full-scale field measurements have not provided sufficient information to confirm this predicted reduction in barrier effectiveness. Although most noise barrier specialists agree that some reduction in effectiveness does occur when parallel barriers are built, there is no consensus over the significance of this reduction. There is a need for well-documented sound attenuation measurements of parallel barriers: before construction; after construction of one barrier; and after construction of both barriers.

Several research projects have attempted to address the parallel barrier issue. These are described below.

Dulles Noise Barrier Project

At a highway noise test site near Virginia's Dulles Airport, it was found that adding absorptive material to the roadside faces of two 4.25 m (14-foot) tall vertical barriers gave an improvement of 2 to 6 dB in barrier insertion loss [14]. Tilting the barriers was also effective in compensating for the multiple-reflection effects that degraded barrier effectiveness. For the Dulles test site geometry, tilting either or both barriers 15° from the vertical gave slightly better barrier effectiveness than a 7° tilt angle. The effectiveness of each barrier tilt angle was found to depend on the distance between the two parallel barriers, and on the height of each barrier. It was concluded that a specific tilt angle alone cannot substitute for absorptive treatment in counteracting multiple-reflection effects in parallel barriers.

The highway traffic noise program "Barrier 2.1" was used to predict the insertion loss in the Dulles project. The insertion loss values predicted by Barrier 2.1 were about 3 to 5 dB lower than the measured data. Reference 9 does not recommend a specific solution for multiple-reflection problems in parallel noise barriers.

Field Evaluation of Acoustical Performance of Parallel Highway Barriers Along Route 99 in Sacramento, California

Another experimental study of parallel noise walls was conducted in California, along Route 99 [12]. To prevent significant degradation in the performance of parallel reflective noise barriers, it was recommended that the ratio of the "canyon width" (distance between parallel barriers) to the average barrier height be at least 10:1. Three suggestions were made for mitigating multiple-reflection problems. Each, unfortunately, is expected to substantially increase the cost of parallel barriers:

1. Construct higher barriers to compensate for degradation.
2. Apply noise-absorptive material to one barrier.
3. Tilt the barriers a few degrees outward from the vertical.

The Sacramento project has also recommended that no noise mitigation arising from parallel noise barriers be carried out in California until the actual cause of performance degradation had been confirmed via future research.

Iowa Study on Effectiveness of Parallel Noise Barriers

In Iowa a study was conducted on parallel noise barriers in 1987 under the sponsorship of the FHWA [13]. The following observations were reported:

1. There is a tendency for increased noise levels under the parallel-wall condition as compared to the single wall.
2. The parallel barrier effect is generally more identifiable in the higher frequency components of the noise source vehicles such as a pickup truck (frequency range is not specified in report).
3. For a typical hour, at 30 m (100 feet) from the wall, the L_{eq} for the parallel-wall site was 0.7 dBA higher than for the single-wall site.
4. At 15 m (50 feet) from the wall, L_{eq} for the parallel-wall site averaged 1.5 dBA higher than for the single-wall site.

These observations support the theoretical predictions of degradation in barrier performance as a result of multiple reflection effects from opposite parallel walls.

Other Studies of Parallel Highway Noise Barriers

Using analytical models, Pejaver and Shadley reported in a 1976 FHWA study that degradation in single wall performance due to parallel walls can be as much as 12 to 13 dB [15]. To validate their results, they also conducted scale model testing, and found good agreement (within ± 0.5 dB) with the mathematical model.

In contrast to the demonstrated effectiveness of sound-absorbing materials for parallel barrier situations, field testing conducted in 1976 by the US DOT Transportation System Center (TSC) had concluded that applying absorptive materials to a single barrier gave additional insertion losses of less than 1 dB [16]. It was concluded that sound-absorbing materials were not cost-effective for single noise barriers.

In 1978, Menge used scale models to study the effects of tilted and sound-absorbing parallel highway noise barriers for a planned extension of the Baltimore Harbor Tunnel Thruway [17]. For 4.9-m (16-foot) high vertical walls, he found an insertion loss of 4 dB (at 500 Hz) for reflective walls and 11.5 dB for absorptive walls. For 5.2-m (18-foot) high walls, the insertion losses were 5 dB and 13.5 dB respectively. When the walls were inclined outward 10°, insertion losses were about 10 dB for both reflective and absorptive 4.9 m (16-foot) walls, and about 12 dB for 5.2 m (18-foot) walls. Menge's results were consistent with the Dulles measurements: using absorptive material and tilting the walls helped to compensate for degradation of attenuation due to multiple reflections. That study made no recommendation for solving the multiple-reflection problem in parallel noise barriers.

In 1978, Legillon of the East Paris Regional Laboratory showed that when the ratio of parallel barrier height to canyon width (the space between the barriers) is less than 1/20, multiple reflections can be neglected [18]. If the ratio is increased to between 1/20 and 1/10, it is better to tilt the walls than to use absorptive material. Further, if the ratio is above 1/10 and the single wall attenuation is less than 12 dB, it is better to tilt the wall. However, if the ratio is above 1/10 and the single wall attenuation is greater than 12 dB, use of absorptive material is preferred. Legillon also reported that multiple reflections can degrade insertion loss by as much as 8 dB.

In 1978, May and Osman of the Ontario Ministry of Transportation and Communication evaluated the effectiveness of different barrier shapes placed in parallel-barrier configurations, using a point-source, scale-modeling method [19]. They reported that degradation appeared to increase with increasing receiver distance from the barrier for both absorptive and reflective cases. The parallel barrier degradation was about 2 dB for near lanes, and only about 1 dB for far lanes. Their results indicated that placing sound-absorbing material on a conventional single barrier increased the insertion loss by a mere 1 dB. This is similar to the result reported by the TSC researchers at the US DOT [16].

Summary of Results from Parallel-Barrier Studies

To summarize, the above reports seem to agree in the following areas:

1. Multiple reflections do degrade the effectiveness of parallel noise barriers, but there is no agreement as to the amount of degradation.
2. Adding absorptive materials to a single barrier does not significantly increase the insertion loss of the barrier. Studies showed at best a 1 dB improvement in insertion loss by adding absorptive treatment to a single barrier. Researchers do not generally recommend absorptive treatment on single barriers, as it is not cost-effective.

The above reports seem to disagree in the following areas:

1. The amount of degradation in performance with parallel noise barriers. Pejaver and Shadley [16] reported as much as 12 to 13 dB degradation, whereas May and Osman [20] reported a reduction of only 1 to 2 dB.
2. The ratio of barrier height to canyon width required to make multiple reflection effects negligible. The Sacramento project [12] recommended a height-to width ratio of less than 1/10, whereas Legillon [18] proposed a ratio of less than 1/20.
3. In contrast to Legillon, other researchers who studied the effect of tilted or absorptive parallel barriers did not recommend any preferred method to solve the problem of multiple reflections.

METEOROLOGICAL EFFECTS ON HIGHWAY NOISE BARRIERS

Meteorological effects on highway noise barrier performance are poorly understood and insufficiently researched. Hatano showed that 60 m (200 feet) behind the nearest of two parallel barriers, noise level differences of 4 dBA can be attributed to wind shifts [12]. Wind effects also increased, though not linearly, with source distance. Construction of a noise barrier between a source and a receiver actually tended to make the effect of wind more pronounced. Without a barrier, wind effects decreased rapidly with height. Thus, higher dwellings located downwind from a highway could experience increased noise levels if a barrier were constructed between them and the highway.

FEDERAL AND STATE POLICIES FOR EVALUATING TRAFFIC NOISE IMPACT

According to FHWA policy, traffic noise impact is defined as occurring when predicted traffic noise levels approach or exceed noise abatement criteria, or substantially exceed existing noise levels [20]. The FHWA has established noise abatement criterion for residences of 67 dBA $L_{eq}(h)$. SHAs typically define a "substantial increase" in highway noise as a 10 or 15 dBA increase over existing noise levels. The noise abatement criteria is the sound levels where abatement must be considered. Noise abatement should be designed to achieve a substantial reduction — not the noise abatement criteria.

A 3 dBA change is commonly accepted as the smallest change that most human ears can readily perceive. A 5 dBA reduction is obtained when a noise barrier breaks the line of sight between the noise source and the receiver. Most SHAs will not install a noise barrier unless it is predicted to reduce noise by 10 dBA or more; however, some use 5 dBA as the minimum acceptable reduction.

A detailed traffic noise analysis generally requires that the following procedures be carried out for each alternative [21]:

1. Identify existing activities, developed lands, and undeveloped lands for which development is planned, designed and programmed, which may be affected by noise from the highway;
2. Estimate traffic noise levels;
3. Determine existing noise levels;
4. Determine traffic noise impacts; and
5. Examine and evaluate alternative noise control measures for reducing or eliminating the noise impacts.

TxDOT POLICIES FOR EVALUATING TRAFFIC NOISE IMPACT

In Texas, noise analysis is required for the following highway projects [8]:

1. Projects that move a travel lane closer to the ROW, regardless of the classification of environmental assessment required;
2. Projects in which traffic lanes are moved closer to receivers;
3. Almost all projects for which an Environmental Assessment is required; and
4. All projects for which an Environmental Impact Statement is required.

TxDOT's new Noise Guidelines (June 1996) will state that noise analyses are required for the following Type I highway projects, as defined by the FHWA:

- construction on a new location, or
- physical alteration of an existing highway that substantially changes either the horizontal or vertical alignment, or
- increase in the number of through-traffic lanes.

STATISTICAL TRENDS IN HIGHWAY NOISE BARRIER CONSTRUCTION

The range of SHA responses to highway noise is evident from the fact that some states have built many noise barriers while others have built none. From 1972 to 1992, forty states have constructed over 1,486 linear kilometers of barriers, at a cost of $816 million ($875 million in 1992 dollars) [22]. Noise barrier construction and cost by year are shown in Figure 2.3.

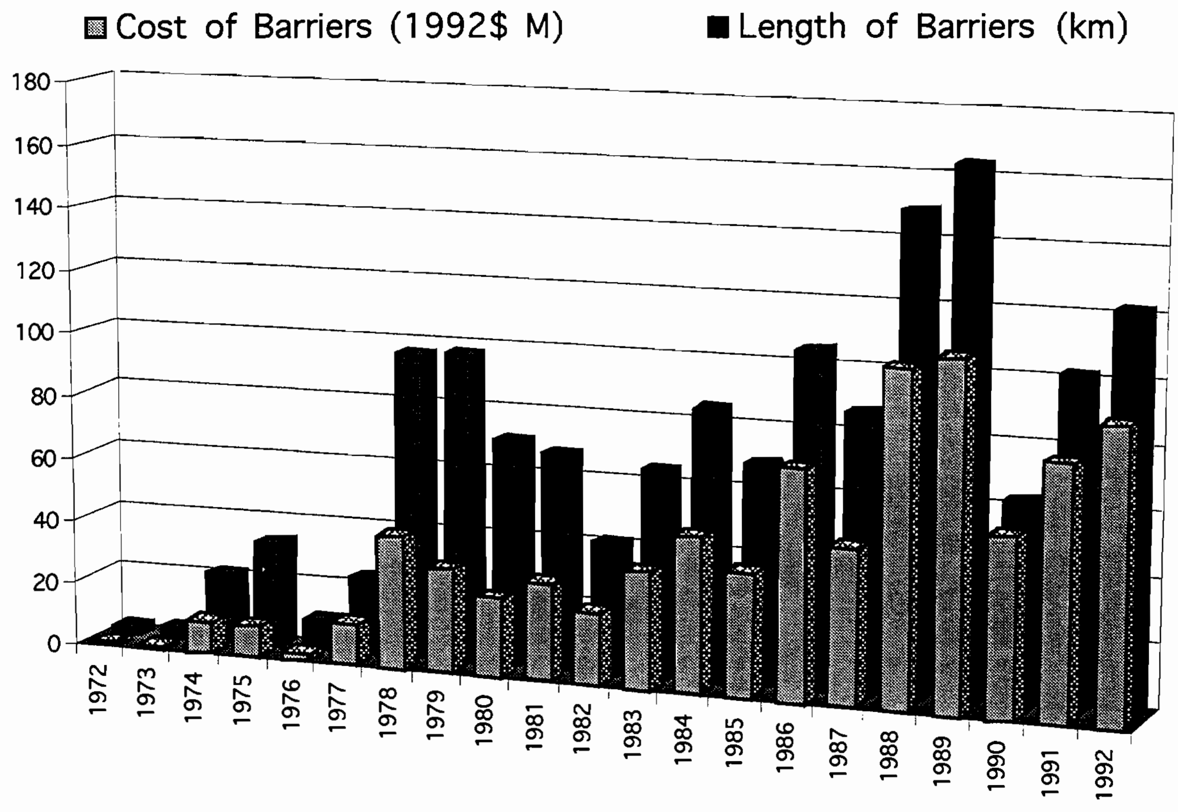


Figure 2.3. Yearly Noise Barrier Construction in the US

Studies of the comparative popularity of different barrier configurations have indicated that the free-standing, thin wall is the most commonly constructed barrier type [23]. A wide range of materials appear to satisfy the public. As shown in Table 2.1, from the period 1972 to 1992, concrete has been most widely used for barrier construction, because of its reasonable cost, low maintenance, durability, versatility of surface aesthetic treatments, and acoustical values.

Other studies have found that communities widely prefer the use of earth berms as highway noise barriers [20]. These have excellent noise reduction capability, and their effectiveness is enhanced when they are covered with dense vegetation. Earth berms are a low-cost alternative to a concrete wall when the ROW is wide enough.

In the 1972-1992 study, wood was the third most popular barrier material. Wood was found to have low initial cost, to be easy to construct, to be naturally appealing, and to be readily available. However, it was also found to have problems with shrinkage deterioration, warpage, high moisture content, poor quality control by contractors, and discoloration around fasteners.

In the 1972-1992 study [22], concrete or clay masonry was the fourth most popular barrier material. Masonry was perceived as having good aesthetic qualities and excellent acoustical performance. Its perceived disadvantages were its higher construction and replacement costs.

The most obvious highway traffic noise barrier trend is a dramatic increase in construction since 1988. Most barriers have been made from concrete or concrete block masonry, have ranged from 3 to 5 meters high, and have averaged $150 to $180 per square meter in cost.

SUMMARY

From this review of technical literature related to highway noise barriers, it is clear that construction and maintenance issues have not been adequately studied. This is partly because most SHAs have found it difficult to collect construction and maintenance information. With maintenance cost constituting a substantial portion of the barrier life-cycle cost, it becomes a top priority to design a barrier with low maintenance cost. Designers have to consider acoustical, structural, aesthetic, and maintainability criteria in noise barrier design. This issue is not adequately addressed in the literature, and it should be studied further.

TABLE 2.1. NOISE BARRIER CONSTRUCTION IN MATERIALS FOR DIFFERENT HEIGHT RANGES [22].

	Material (1,000 Square Meters)							
Height Range	Concrete	Block	Wood	Metal	Combination	Berm	Brick	All Material
>9.9 m	7	-	-	-	-	4	-	11
9-9.9 m	29	-	-	-	16	4	-	49
8-8.9 m	25	-	4	-	12	-	-	41
7-7.9 m	192	-	87	7	45	26	-	357
6-6.9 m	227	29	134	28	225	12	-	655
5-5.9 m	306	3	89	6	62	4	16	488
4-4.9 m	879	579	279	114	338	50	18	2,298
3-3.9 m	338	543	172	61	221	127	14	489
2-2.9 m	137	134	70	10	86	36	12	489
< 2 M	10	6	16	1	1	9	-	43
Total	2,150	1,294	851	227	1,006	272	60	5,916

Note: There are 56,000 square meters of noise barriers constructed with other materials.

Despite the many research projects carried out on parallel noise barriers using computer simulation models, scale-model experiments, and full-scale field measurements, the effect of multiple reflections on barrier insertion loss is still not well understood. Researchers have differing opinions. Although most agree that multiple reflections degrade the effectiveness of the parallel noise barrier, the amount of degradation is not agreed upon. There is also no consensus regarding the best method to overcome multiple-reflection effects. Hence, this area should continue to be a priority research topic for noise barrier researchers.

Another relatively neglected area concerns meteorological effects on barrier performance. Information in this area is sparse. More needs to be done in this area, especially to investigate the role of wind effects and atmospheric absorption on barrier performance.

Many states have avoided building highway noise barriers because of concerns over their aesthetic impact. However, as more and more states become urbanized, more highway noise barriers are expected to be built. It has been estimated that Texas alone has the potential to build $20 - $100 million in noise barriers over the next 10 to 15 years. Building noise barriers drains financial resources of the states. Thus, the task of the barrier designer is to design a highway noise barrier that fits with its surroundings, and performs its intended acoustical and structural function at a reasonable life-cycle cost.

CHAPTER 3. HOW NOISE BARRIERS WORK

HOW HIGHWAY NOISE BARRIERS WORK

This section of the report is intended to be a primer on highway noise barriers. It explains the fundamental mechanisms through which noise barriers attenuate sound, and the basis of computer codes such as STAMINA that are used for the design of noise barriers. This primer is based on material previously presented at meetings with TxDOT district personnel. The material presented is divided into four major topics: the properties of sound, sound striking a barrier, diffraction around barriers, and other effects of interest.

Properties of Sound

To fully appreciate how highway noise barriers attenuate sound, it is necessary to understand some attributes of sound. Sound is typically characterized in terms of two main properties: frequency and intensity. The *frequency* of a sound is the objective measure of its *pitch* (subjective measure). The range of human hearing is about 20 Hz to 20,000 Hz. Cars produce noise in the range of 20 to 2,000 Hz. Trucks produce noise in the range of 10 to 1,000 Hz. In both cases the typical sound has a broad peak at about 125 Hz, but this number is misleading because the ability of humans to hear sounds is not uniform throughout the audible frequency range. As a result of the skewing of the sound by our hearing system, typical car and truck noise has a broad perceptual peak at about 500 Hz. Since speech is concentrated from about 300 to 3,300 Hz, car and truck noise is quite effective at intruding on speech, a fact of which we are all painfully aware.

The *intensity* of a sound is the objective measure of its *loudness* (subjective measure). Intensity is a measure of the sound energy. Humans have an ability to perceive a wide range of sound intensities. Indeed, our hearing range is significantly broader than that of any of our other senses. Partly as a result of this, we use a logarithmic scale for intensity. The specific scale employed is the decibel or dB, named after Alexander Graham Bell. It is defined as $dB = 10 \log_{10} (W/W_{ref})$, where W is the sound energy or a quantity proportional to energy (such as intensity or pressure squared), and W_{ref} is a reference sound energy (or intensity or pressure squared) defined as the standard for comparison. The dB measure is termed a *level.* If the quantity used is energy, the result is the sound energy level; if the quantity in the logarithm is intensity it is the sound intensity level; if the quantity is pressure squared, the result is the sound pressure level.

Given this definition, a doubling in the intensity of a sound corresponds to an increase of 3 dB in the sound level. However, we do not generally perceive a doubling of intensity as a doubling in loudness. The general rule of thumb is that a doubling of loudness (in the speech range) corresponds to a 10 dB increase in intensity, i.e., to an increase in the energy by an order of magnitude. Figure 3.1 below shows the sound pressure levels associated with a variety of situations and sources. The levels are presented in terms of dBA. Here the "A" indicates that "A-weighting" was used to account for the human hearing variations as a function of frequency. The dBA scale is accepted worldwide as the best predictor of human response to sound. Note that the figure shows that the range of hearing spans 14 orders of magnitude of intensity. The federally mandated levels at which noise mitigation for residences should be considered are also shown in the figure.

An important property of sound that plays a key role in noise barrier operation is called *geometrical spreading*. Geometrical spreading refers to the fact that sound, very much like light, reduces in intensity as it propagates from a source. One can determine the attenuation produced by geometrical spreading by noting that sound energy is approximately conserved as the sound spreads from the source. For a source concentrated at a point in space (a point source), such as shown in Figure 3.2, the sound spreads uniformly on the surface of a spherical wave front. The total energy can be found by multiplying the intensity at a set distance from the source by the area over which that intensity is distributed. Because the surface area of a sphere increases in proportion to the square of the distance from the center, the energy is proportional to intensity at a point, multiplied by the square of the distance from the source to that point. Since total energy is conserved, doubling the distance from d to 2d, must result in a drop in intensity by a factor of four (6 dB). While most sound sources are not point sources, one can approximate cars and trucks as point sources which move. Hence, for road noise sources, it is reasonable to assume that a doubling of the distance from source to receiver will result in roughly a 6 dB drop in the sound level. Geometrical spreading thus explains one of the mechanisms by which highway noise barriers attenuate sound—namely, by making it travel farther so that its intensity and perceived loudness drop.

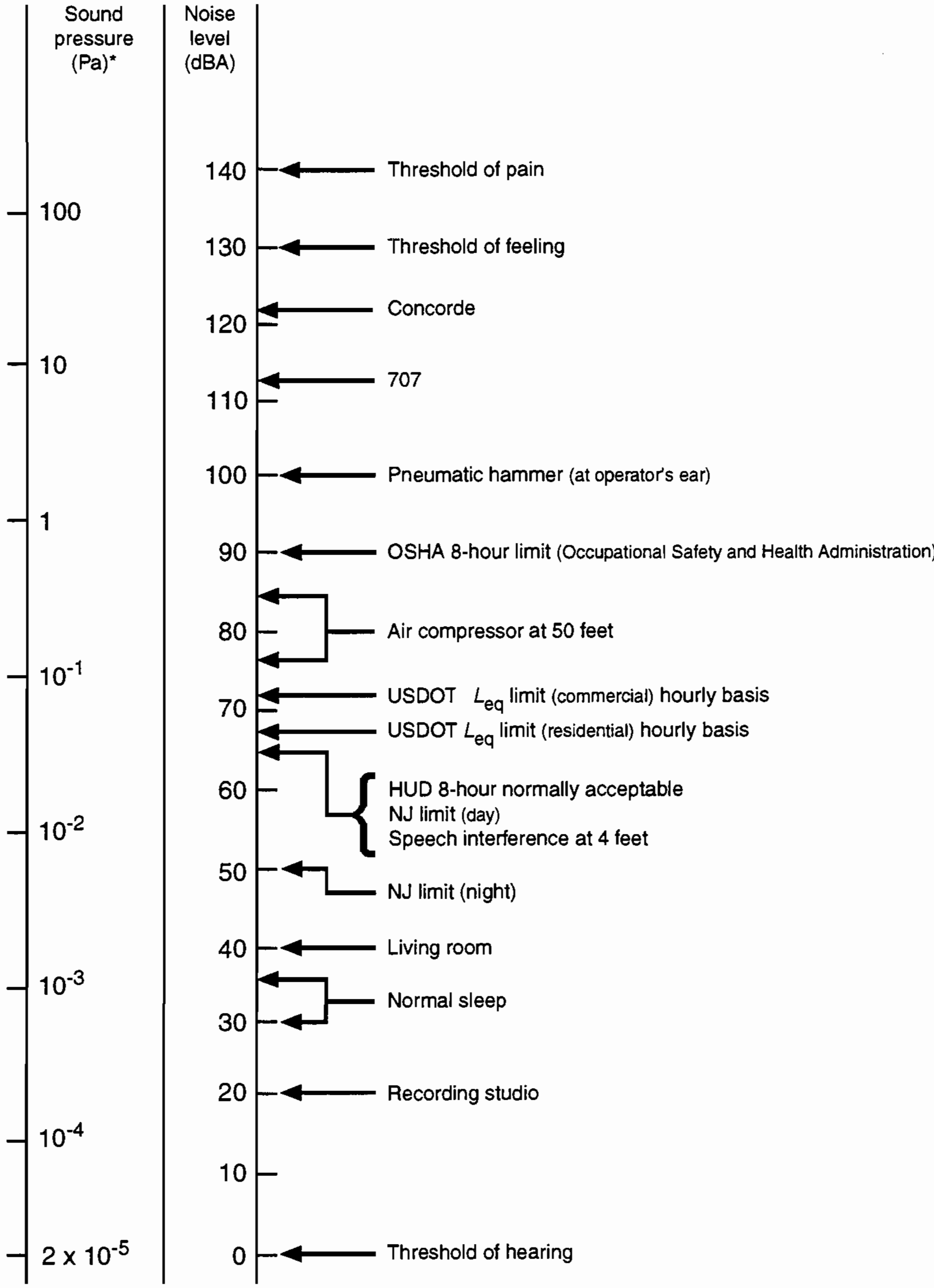


Figure 3.1. Typical sound pressure levels in dBA.

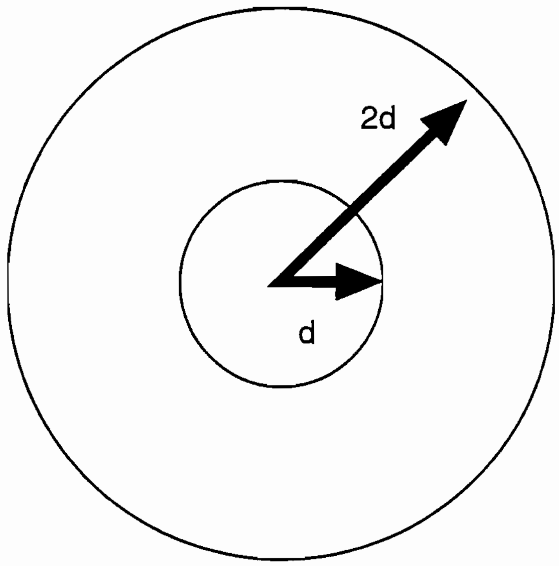


Figure 3.2. Geometrical spreading of sound from a point source.

Sound Striking a Barrier

Now consider what happens when noise generated by a vehicle on a road strikes a barrier. Figure 3.3 shows that tire noise, radiated in many directions, can miss the barrier entirely by being on a largely upward trajectory (region I), strike the barrier along its edge (region II), or strike the body of the barrier (region III). Each of these three regions has distinctive sound attenuation mechanisms.

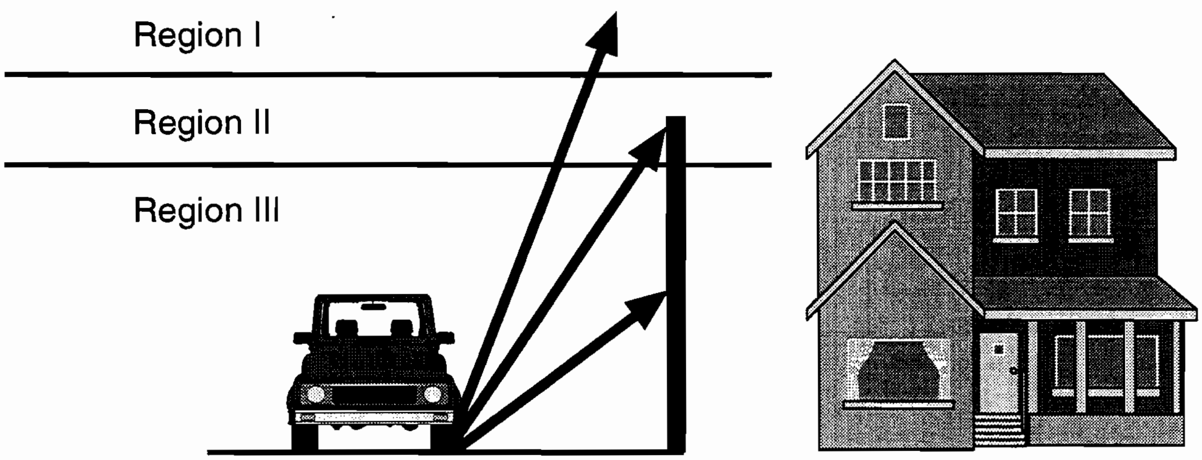


Figure 3.3. Sound striking a barrier.

REGION I: SOUND MISSING THE BARRIER

First consider sound that misses the barrier entirely because of being on a predominantly upward path. This sound is unaffected by the barrier, but would not have reached a receiver on the opposite side of the barrier anyway. Hence, the sound in Region I is not relevant to the discussion of barrier operation.

REGION III: SOUND STRIKING THE BARRIER

Sound striking the barrier has three possible paths, indicated in Figure 3.4 it can reflect, it can be transmitted through the barrier, or it can be absorbed through conversion of the sound energy to heat. Each of these phenomena deserves some attention.

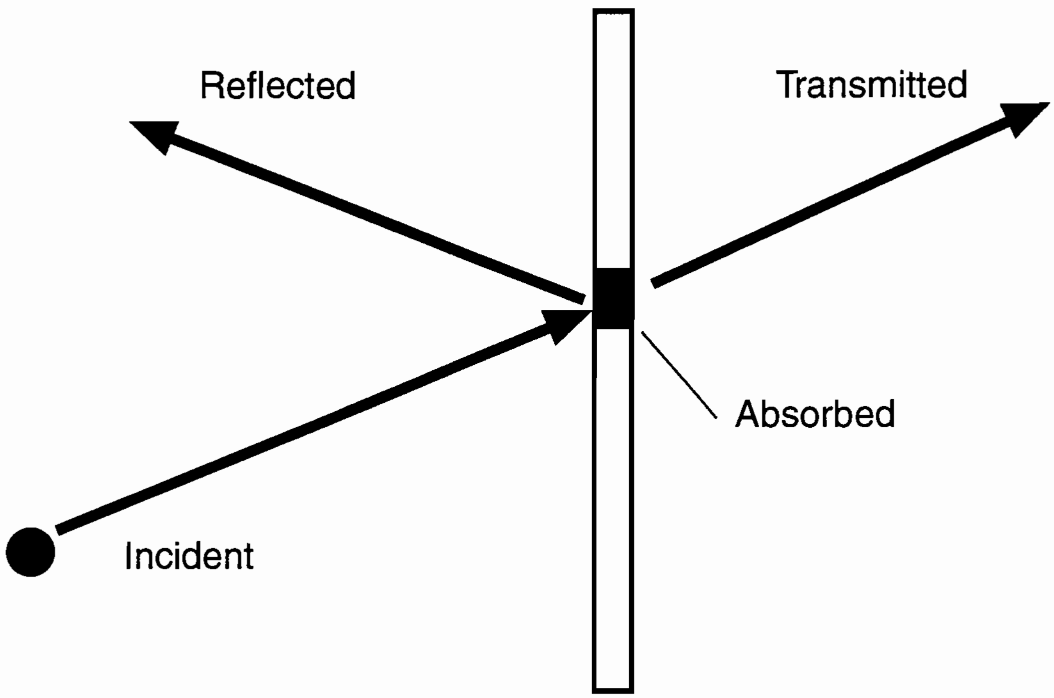


Figure 3.4. Sound striking the main body of a barrier.

If the sound striking the barrier is reflected, it will certainly not travel to the other side of the wall, and thus it will not be heard by a receiver whom the barrier is intended to protect. Hence, from the perspective of the population it is intended to help, reflection of sound from the barrier is desirable.

If the sound is transmitted through the wall, then the wall behaves as a less than perfect obstacle between the sound source and the receiver. To prevent significant amounts of sound from being transmitted through the barrier, wall design guides usually set a minimum acceptable transmission loss. The transmission loss (TL) is defined as the drop in sound energy (in dB) as sound goes from one side of a wall to the other. A minimum TL of 20 dB means that at most 1 percent of the incident sound energy goes through the wall. A minimum TL of 30 dB means that at most 0.1 percent of the sound energy goes through the wall. Typical design guides use a minimum acceptable TL of 20-35 dB. The most important factors in determining the TL through a wall are the product of its mass density ρ and its thickness h, and the frequency of the sound. The larger the ρh product and the higher the frequency, the greater the TL. This rule is known as the *mass law of transmission*. Figure 3.5 shows TL versus frequency for mass law transmission. Note that a doubling of the frequency increases the TL by 6 dB. Similarly, a doubling of the ρh product increases the TL by 6 dB. Table 3.1 shows the thicknesses of various materials that would be required to obtain a TL of 30 dB at 100 Hz and at 500 Hz.

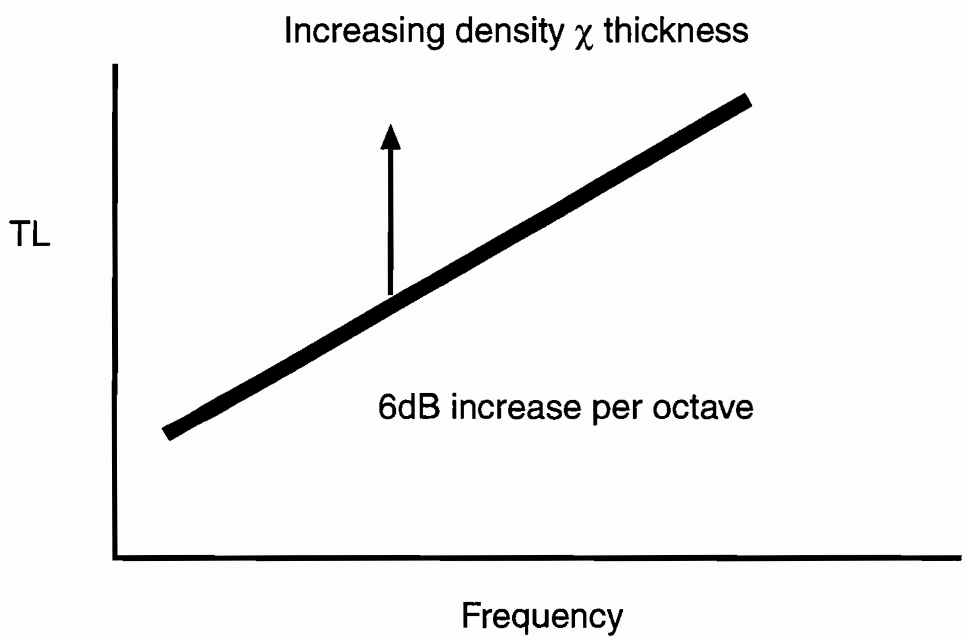


Figure 3.5. Mass law transmission of sound through walls.

A recent trend in noise barrier design has been the introduction of the absorptive noise wall. Consider the role of absorption for sound striking the main body of a barrier. When sound strikes an absorbing surface, a fraction of its energy is converted to heat. This fraction is indicated by the absorption coefficient of the material. A familiar example of sound-absorbing material is the acoustical tile common on ceilings of buildings. For typical acoustical tile, the absorption coefficient ranges from about 0.15 for low frequencies to 0.80 for high frequencies. This corresponds to attenuation of the sound pressure level by 0.7 dB (low frequencies) to 7.0 dB (high frequencies). Of course, acoustical tile is not designed for outdoor use, so it is not appropriate for highway noise barriers. Hence, one consideration is the selection of absorptive materials for noise walls. One popular choice is aerated concrete (a low-density concrete with high pore volume). Such material can offer an absorption coefficient of about 0.2 to 0.6 in the important frequency range for traffic noise. This corresponds to an attenuation of 1-4 dB. A more important consideration for absorptive walls, however, is determination of the circumstances under which they are likely to offer an improvement in the barrier performance.

TABLE 3.1. THICKNESSES (h) OF DIFFERENT MATERIALS REQUIRED FOR A TRANSMISSION LOSS OF 30 dB AT 100 HZ AND 500 HZ.

Material	h for TL=30 dB at 100HZ	h for TL=30 dB at 500HZ
Steel	5.3 mm (0.21 in.)	1 mm (0.04 in.)
Concrete	16 (0.63)	3.3 (0.13)
Glass	18 (0.72)	3.6 (0.14)
Rubber	32 (1.24)	6.4 (0.25)
Plexiglas	46 (1.81)	9.1 (0.36)
Pine	93 (3.66)	19 (0.73)

If our discussion is limited to the situation shown in Figure 3.3, in which there is a house with people in residence on the opposite side of a noise wall from the roadway, then absorption has nothing to offer in terms of barrier acoustical performance. This is because the energy striking the main body of the barrier is presumably reflected away from the house. Hence, for the population that the noise wall was specifically designed to protect, absorptive walls are no better than reflective walls. Now let us broaden our consideration of absorption to other barrier geometries which often occur. For instance, consider the situation shown in Figure 3.6, in which there are homes on both sides of a highway, but a noise barrier is located only on one side. In this circumstance, the sound reflecting from the noise wall could be redirected toward the homes on the side of the road with no barrier. In other words, the barrier could improve the noise situation for some of the residents,

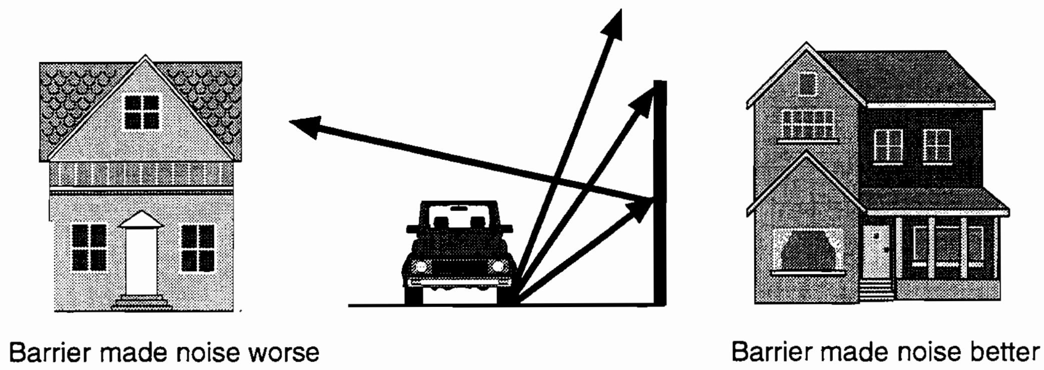


Figure 3.6. One situation in which a barrier with an absorbing surface would be useful.

while making it distinctly worse for others. One means of preventing this problem is to make sure that the sound reflected back toward unprotected homes is of much lower intensity than the incident sound on the barrier. A reasonable way to accomplish this is to use an absorbing material on the side of the barrier facing the road. Another situation in which one might wish to consider absorptive wall surfaces is shown in Figure 3.7; it involves barriers on both sides of a highway. As a result, significant sound energy is trapped between the barriers and the sound pressure level heard by drivers can be quite high. Absorptive wall surfaces facing the highway will lower these sound levels. Furthermore, in this case some of the sound reflected from one barrier will strike the edge of the other barrier (Region II). As discussed below, this sound scatters from the edge, with some of the sound energy being redirected into the area behind the barrier. By introducing absorption on the noise barrier surfaces, one can reduce the intensity of the sound reaching the opposite barrier's edge and scattering. It should be noted, however, that the amount of improvement offered would be quite small, since the absorption would not effect the sound taking the shortest path directly from the noise source to the barrier edge.

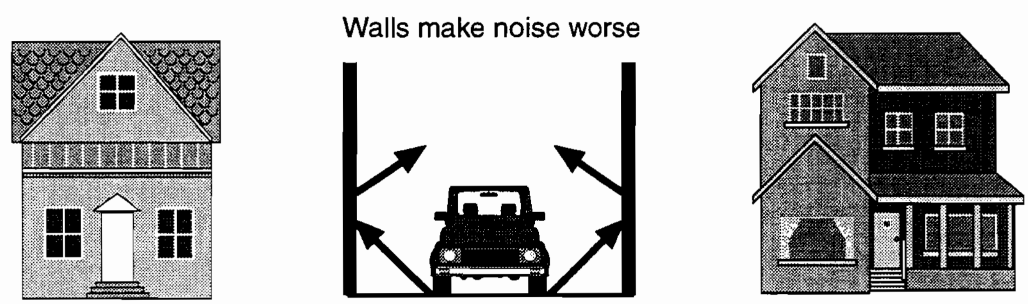


Figure 3.7. Another situation in which one might choose to use absorbing barriers.

REGION III: SOUND STRIKING THE BARRIER EDGE

Finally, consider sound striking the edge of the barrier. Indeed, from the perspective of the receiver located on the opposite side of the barrier from the highway, this sound controls the amount of attenuation offered by the noise wall.

Consider a sound source as shown in Figure 3.8. The source radiates sound in many directions. Some of the sound strikes the barrier edge. If sound were precisely like light, one could define a *shadow zone* (or, in the case of sound, a *quiet zone*). This quiet zone would be the region bounded by straight lines leaving the source and just grazing the wall edge. This is shown in Figure 3.8. A receiver in the shadow zone would be totally protected from noise. Unfortunately, sound is not exactly like light. Because it has a much longer wavelength (distance for sound at a given frequency to start repeating its pattern), sound has a far greater likelihood of going around wall edges, in a process called *diffraction*.

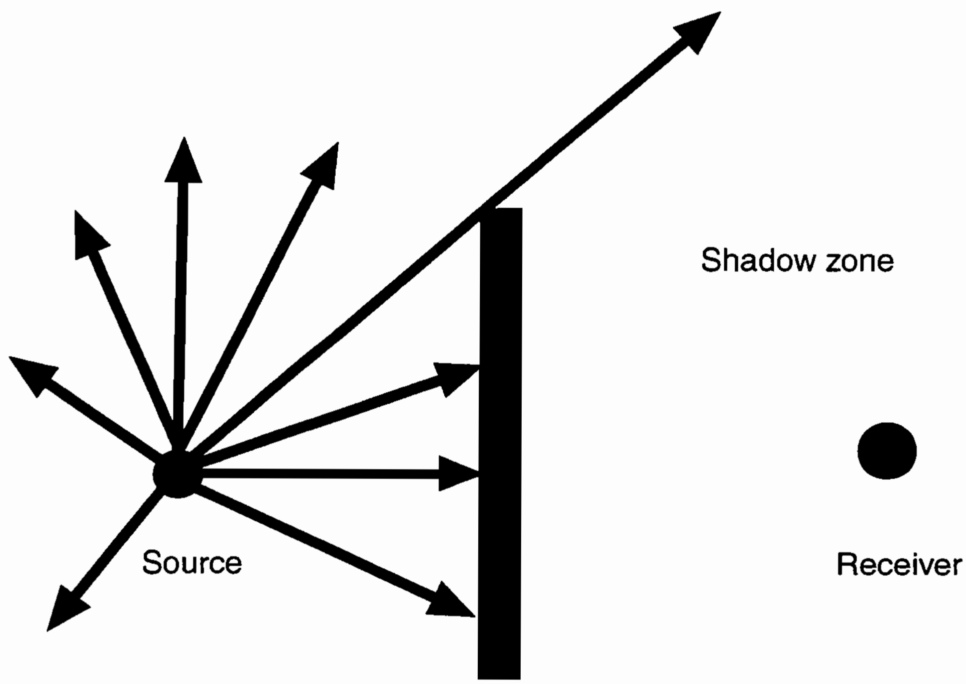


Figure 3.8. Sound striking the edge of a barrier, defining a shadow zone.

Diffraction can be explained in the following way. The sound that strikes the edge of the barrier scatters and behaves like a secondary point source, radiating in all directions. This is shown in Figure 3.9. As a result, some of the sound that was travelling on an upward path is redirected into the quiet zone. The net effect is to make the quiet imperfect -- that is, some sound enters the quiet region. One would still expect a noise reduction compared to the situation without a barrier; because the sound has now been made to travel a longer path, geometrical spreading decreases its intensity.

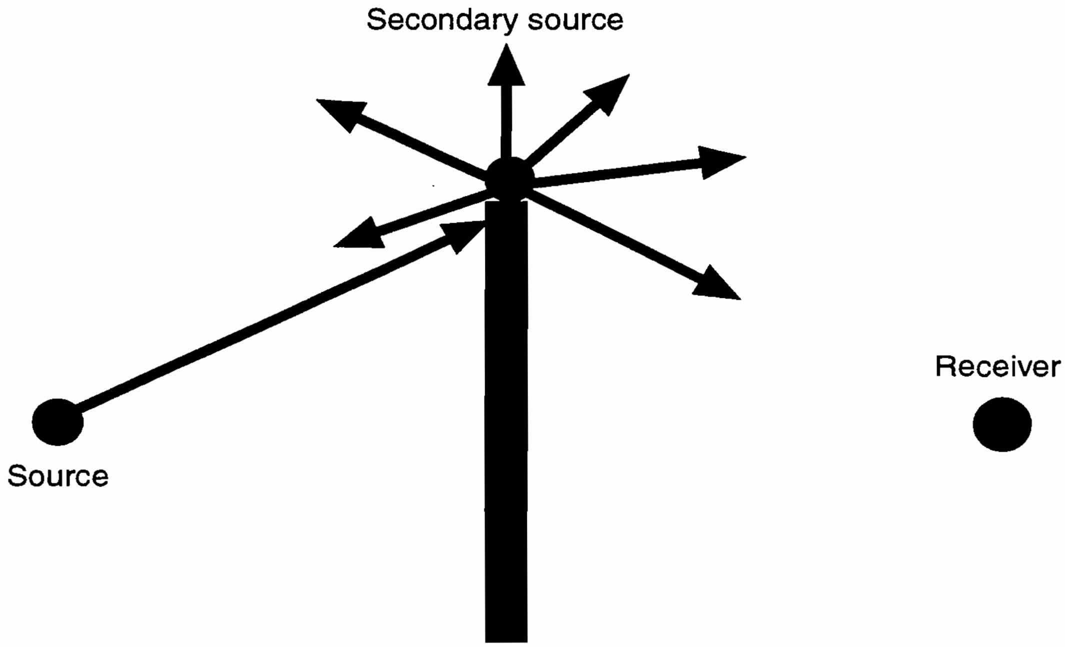


Figure 3.9. Sound scattering at a barrier edge.

It is possible to calculate the amount of sound which reaches the region behind the barrier, and this is done in the computer models used for barrier design. The result is usually presented as an *insertion loss*, i.e. a decibel measure of the change in the sound pressure level with and without the barrier in place. To estimate the insertion loss, IL, one first calculates the *Fresnel number*, a nondimensional measure of how much farther the sound must travel as a result of the barrier. Figure 3.10 shows this concept. The normalization factor is the wavelength of the sound, which can be expressed in terms of its frequency and the speed of sound propagation. The Fresnel number, N, is defined as

$$N = \frac{2(a+b-\ell)f}{C_0} \qquad (1)$$

where f is the sound frequency in Hz, C_0 is the speed of sound propagation in air (about 343 m/s (1100 ft/s)) and a, b, ℓ and are distances as indicated in the figure.

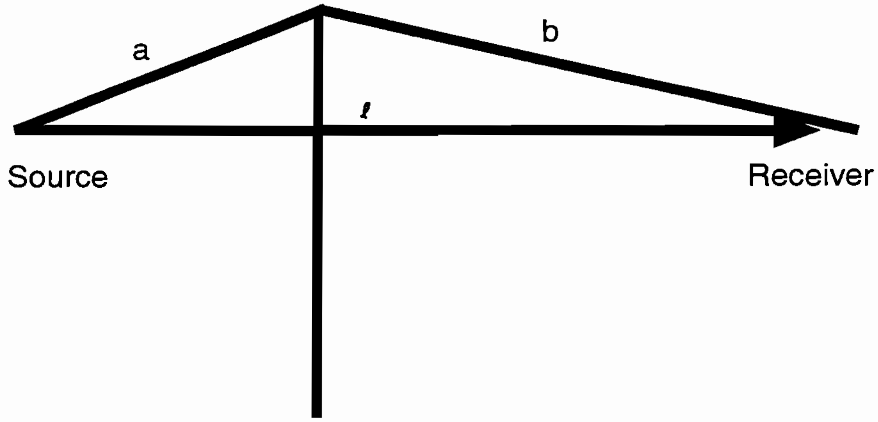


Figure 3.10. Barrier geometry with distances defined.

Using the Fresnel number, a model has been developed for predicting the IL as a function of N. This model, developed by Kurze and Anderson [4], is the result of compiling data of many researchers onto a single plot and developing a curve fit for a point source. The result is:

$$IL = 5\text{ dB} + 20\log_{10}\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}} \quad \text{for } N \leq 12.5$$

$$IL = 24\text{ dB} \quad \text{for } N > 12.5 \qquad (2)$$

Figure 3.11 shows a plot of this result.

A noise wall is 4 m away from the nearest tire, and is 4 m tall. A house is 5 m beyond the barrier an dhas a window at a height of 1 m. From these dimensions, the direct path length (ℓ) is equal to the square root of 81 + 1 = 9.05 m. Similarly, the path length a = 5.66 m and b = 5.83 m. Hence (a + b - ℓ) - 2.44 m. The Fresnel number at 100 Hz is given by Equation 1 as 4.88 x 100/343 = 1.42. From the plot in Figure 3.11 (in Equaton 2), the predicted IL is 15 dB at this freuqncy. At 500 Hz, N = 7.11 and the predicted IL is 22 dB.

While the above calculation may seem extremely simple-minded, it is precisely the computation conducted for computer-aided noise models used to predict the effectiveness of noise barriers. In these models, such as STAMINA, the traffic volume information is used to determine the location of vehicles of various types on roadways. The major noise sources associated with each vehicle are then identified, and the noise at specified locations is determined using geometrical spreading and the barrier model above. The total noise at any location is found by simply adding the noise from each source.

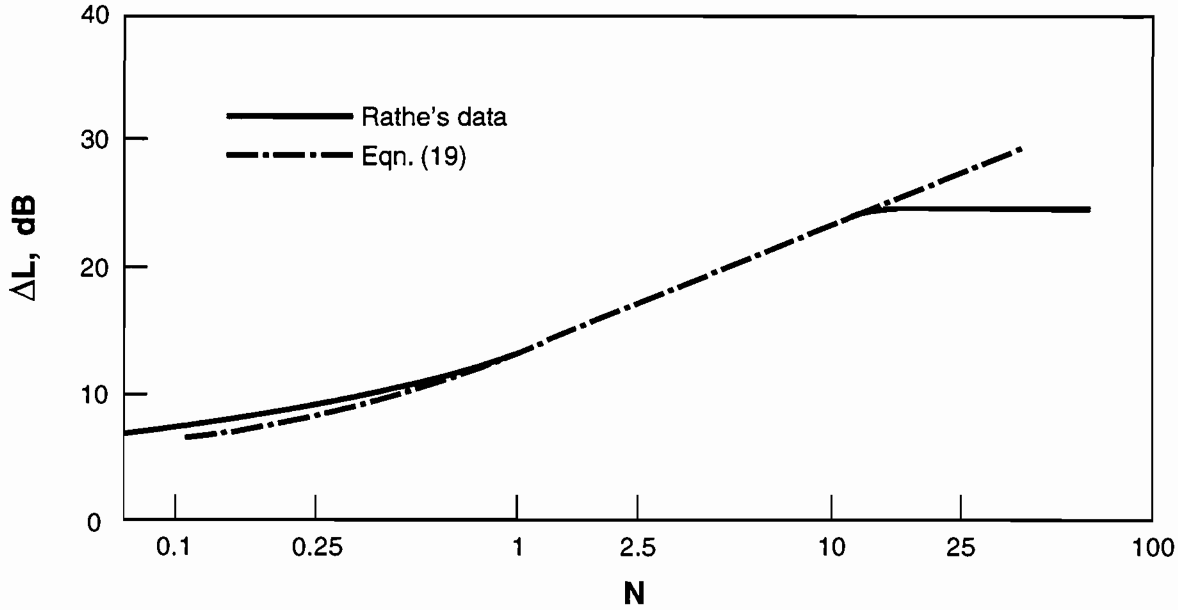


Figure 3.11. Insertion Loss versus Fresnel number from Kurze and Anderson [4].

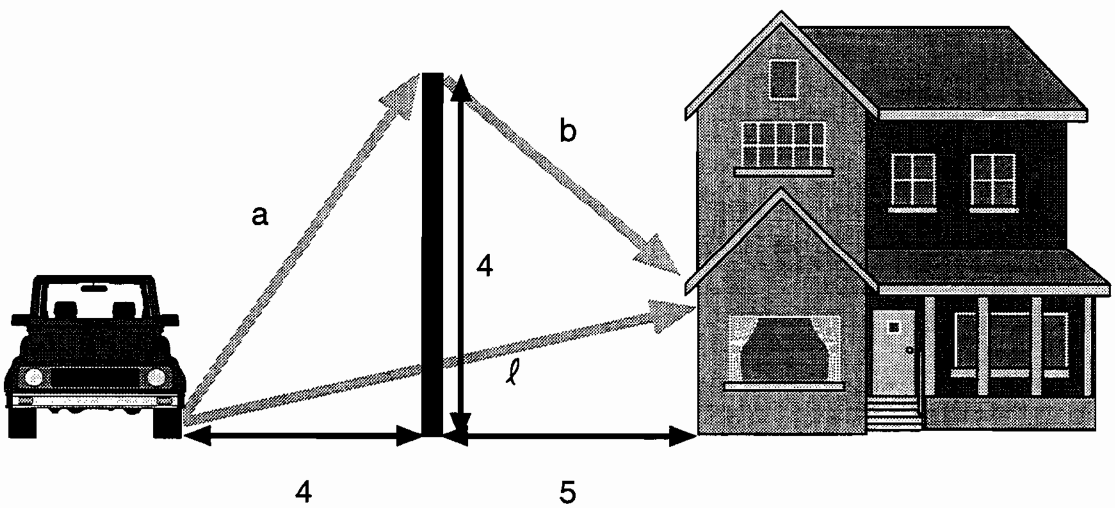


Figure 3.12. Example scenario.

What is clear from the experimental results and the model based on them, is that the acoustical effectiveness of a barrier is determined by its Fresnel number. The aim should be to make N as high as possible to the limiting value of 12.5, beyond which no further improvement occurs. For a fixed frequency or set of frequencies at which the noise sources emit sound, this can be accomplished by maximizing the difference between the modified and the original source-receiver distances. This is done either by (1) raising the barrier height, or (2) placing the barrier closer to the receiver or to the roadway.

Other Barrier Effects

The material presented above describes the fundamental mechanisms by which noise barriers mitigate road noise. This section discusses additional items of interest to highway noise barrier designers: the barrier as a line source of sound, the effect of gaps in the noise wall, and the length required for effectiveness.

From the discussion above, it should be clear that most sound reaching receivers located on the side of a noise barrier opposite from a highway is the result of diffraction of sound at the barrier top edge. To this point, the discussion here has treated the diffraction of sound at a barrier edge as a one-dimensional problem. Of course, the edge of a barrier is not a point in space, but a line. A sound source radiating in all directions has a range of angles (or paths) along which the sound will strike the barrier edge. At each point along the edge, the sound scatters. Hence, the barrier edge resembles a line of point sources radiating sound in all directions. If we consider the case of a single point source, all secondary sources at the barrier edge are related to each other (since they were all generated by the same initial source). Generally, this is situation should be avoided in noise control, because related (coherent) sound sources can reinforce each other to produce more sound energy than if they were independent sound sources. Several methods are available for preventing the barrier edge from acting as a line of coherent sources. Our approach has been to study the effect of superimposing a small variation in the barrier height about the average value. The visual effect is to produce a barrier with a jagged edge. Preliminary results show that the acoustical effect is substantially greater sound reduction (3-8 dB) compared to a uniform-edged barrier of the same average height.

Another consideration is the effect of gaps in the noise wall. Frequently, noise barriers are considered in areas where existing driveways, local roads, or entrance and exit ramps would require sizable gaps in the barrier structure. Under such circumstances it is reasonable to question barrier effectiveness in mitigating noise. Indeed, gaps that are large compared to the sound wavelength (about 0.6 m at 500 Hz), strongly degrade performance. Significant amounts of sound travel directly through the wall opening without experiencing any attenuation, thus rendering the remainder of the structure nearly useless. As a result, some jurisdictions nationwide have adopted parallel barrier structures at exit and entrance ramps. These parallel walls make it possible to eliminate "holes," although they add to the wall cost. Such treatments generally are not possible on access roads with driveway access. Under these circumstances, noise barriers are not likely to be a good sound control option, and other approaches should be sought.

Many noise walls have small gaps. For example, a small hole (about 200 by 200 mm) might be required near a joint. Because these holes are small compared to the dominant sound wavelength in traffic noise, they have little effect on wall effectiveness, provided that they comprise less than 1 percent of the total wall area.

Finally, a common question is how long a barrier must be in order to be effective. To answer that question, one need only know that the analysis presented above for diffraction applies whether the barrier edge is horizontal or vertical. This means that a highway noise wall is most effective if it is sufficiently long that sound diffracting around the beginning and end of the barrier contributes negligibly to the noise at the receiver locations. For this to be the case, barriers must extend beyond the boundaries of the homes being protected, so that the distance from the end of the barrier to the receiver is at least as long as the distance from the top edge of the barrier to the receiver. In other words, the wall must extent beyond the home boundary by a distance at least equal the height of the barrier.

CHAPTER 4. NOISE ANALYSIS SOFTWARE

COMPUTER SIMULATION MODELS FOR HIGHWAY NOISE BARRIERS

Field measurements can provide very accurate sound data for the time period monitored. However, unless measurements are repeated many times at each site, it is difficult to determine whether the recorded noise levels are representative. This is because environmental conditions such as wind and temperature gradients can significantly alter sound levels. Recorded noise levels also can be influenced by typical urban noises that are not traffic-related, such as aircraft flyovers, fire sirens, or construction activities. It is possible to avoid these non-traffic related noises; the trade-off is that the duration of monitoring must be substantially increased, and some of the recorded data may be invalidated.

In summary, field measurements are very costly and labor-intensive. Computer simulation models can overcome these disadvantages. Several such models have been developed for predicting the effectiveness of highway noise barriers. Typical of these computer models are STAMINA 2.0 and OPTIMA, Image 3-0, Barrier 2.1, TPBP, SoundPLAN and TrafficNoiseCAD. In this chapter, these models are briefly discussed. Their basic principles are reviewed, their most common applications are discussed, and their capabilities and limitations are noted.

STAMINA 2.0

STAMINA 2.0 is the most commonly used model for predicting highway noise attenuation by a barrier. It was developed for the FHWA by the acoustical consulting firm of Bolt, Beranek and Newman. It is designed to model 20 roadways, 10 barriers, and 20 receivers in a single run. It creates a data file for use by another program, called OPTIMA, which determines the most effective barrier heights and lengths for the specified geometry. As many as eight barrier heights can be modeled in each OPTIMA run.

STAMINA is the traffic noise prediction program most commonly used by state highway agencies, including TxDOT. Many states, including Texas, have developed input modules to make STAMINA easier to use. In fact, so many input modules have been developed and widely distributed that even the FHWA does not have any original versions of the program.

The major limitation of the STAMINA program stems from the limitations of computer hardware that prevailed at the time of its development. STAMINA was initially developed for use on mainframe computers, because those were the only ones available with the necessary computational power. Because mainframe computer time was expensive, STAMINA was written to use only a single frequency of 500 Hz for analysis of noise, rather than a 1/3-octave band analysis.

Highway traffic produces a range of noise within the human hearing spectrum from 100 to 10,000 Hz. Trucks produce a different noise frequency spectrum than do passengers cars. As reported in Chapter 3, the attenuation of sound and the perceived annoyance of sound are frequency dependent. The choice (for STAMINA) of the single 500-Hz frequency is a good compromise between the most dominant traffic noise frequencies, and the more-annoying, slower-attenuating, lower-frequency noise. However, a single-frequency analysis has limitations in analyzing specific situations.

Traffic volumes in STAMINA 2.0 are based on design hourly volume (DHV). Usually, Level of Service C traffic volumes and associated running speeds are used to predict the worst-case scenario. From this information, STAMINA 2.0 calculates the equivalent sound pressure level L_{eq} (the constant sound level that would deliver the same sound energy as the given time-varying signal).

The current version of STAMINA 2.0 is a single-screen model that is independent of ground impedance. It uses an incoherent line barrier algorithm based on the work of Kurze and Anderson [4], and a single wall design curve for point sources from Maekawa's work. Noise attenuation is first calculated for a point source, and then expanded to a line source via integration over the barrier length.

Three types of barriers can be modeled in STAMINA 2.0: absorptive, reflective and structural. Other factors considered used by the model are "alpha factors" and "shielding factors." Alpha factors describe the effect of hard or soft ground on noise propagation from the source to the receiver. Shielding factors account for additional noise attenuation due to buildings, trees or terrain features. The default alpha factor of STAMINA 2.0 corresponds to "hard ground." When an earth berm is used, the predicted attenuation is increased by 3 dB because of these soft-ground propagation effects.

An evaluation by Hatano indicated that STAMINA 2.0 tends to overpredict before-barrier noise levels by an average of 2.9 dBA, and after-barrier noise levels by 3.8 dBA [24].

The following rules of thumb are often used to check results of computer simulations:

1. If the traffic volume is doubled and the roadway geometry does not change, the noise level will increase by 3 dB. If the traffic volume is increased 10 times, the noise level will increase by 10 dB.

2. If average vehicle speed increases by 8 kph (5 mph), and the percentages of cars, medium trucks, and heavy trucks do not change, the noise level will increase by 1 dB.
3. If one traffic lane is added, the noise level will increase by 1 dB.
4. If the distance from the roadway to the receiver is doubled, the noise level will decrease by 4.5 dB for soft ground and 3dB for hard ground. Conversely, halving the distance will increase the noise level by 3-4.5 dB depending on the ground hardness.

When estimating the noise attenuation by a barrier, STAMINA 2.0 uses source heights of 0 , 0.7 m and 2.4 m for automobiles, medium trucks and heavy trucks respectively.

IMAGE-3

Another computer simulation program, known as Image-3, was developed by Bowlby and Cohn [25]. It is designed to predict the degradation of insertion loss for parallel highway noise barriers. The model calculates the degradation in single-barrier attenuation due to the presence of the far barrier.

Image-3 is designed to model 3 vehicle types, up to 6 roadways (arbitrarily located between 2 vertical barriers of variable height), and separation and absorption properties. The main features in Image-3 are:

1. Each barrier height can be varied.
2. All three vehicle types used in STAMINA 2.0 can be analyzed.
3. Up to six line sources can be modeled.
4. Up to five receivers can be studied simultaneously.
5. Noise Reduction Coefficients (NRC) for octave bands centered on 250, 500, 1,000 and 2,000 Hz are used for each barrier.
6. Each wall can be divided into three horizontal zones with distinct absorption coefficients.

Image-3 was calibrated using data from mathematical models, acoustical scale models and field measurements.

The reported shortcomings of this computer simulation model are:

1. The barriers and roadway sources must be parallel to each other.
2. The elevations of the barrier tops and roadways must be uniform (but not necessarily equal to each other).
3. Noise coming from beyond the ends of a barrier is not addressed.

4. Propagation is based on a 3 dB reduction as distance is doubled; the model, like STAMINA 2.0, assumes an acoustically "hard" surface.
5. Modeling of tilted barriers is not addressed.

BARRIER 2.1

This traffic noise prediction model was developed for the FHWA to predict parallel barrier effectiveness in the Dulles Noise Barrier Project [14]. The model addresses barrier inclination, barrier reflection, ground impedance and source heights. It has several limitations, which are reportedly being corrected:

1. It does not accept ground elevations below a fixed road grade elevation of zero feet.
2. While the program considers ground reflections in the equivalent site, it does not account for ground reflections at the barrier site.
3. The program cannot address travel lanes with zero traffic volume.

TILTED PARALLEL BARRIER PROGRAM

As noted previously, the current version of STAMINA 2.0 is a single-screen type model independent of ground impedance. The Tilted Parallel Barrier Program is intended as an investigative tool to study the complex problem of parallel tilted barriers on segmented impedance boundaries [26].

In addition to accounting for multiple-reflection effects due to parallel barriers, TPBP can also model ground impedance effects. Results obtained from TPBP suggest that:

1. Increasing barrier height is not always an effective means of compensating for multiple-reflection effects.
2. Application of materials with a high absorption coefficient (0.9) in the 500 to 1,000 Hz range could significantly reduce the degradation of insertion loss caused by parallel barriers.

TrafficNoiseCAD

TrafficNoiseCAD is a complete software package that performs the combined functions of STAMINA and OPTIMA. It was developed by William Bowlby of Vanderbilt University, and has been available commercially for about five years. It is used by SHAs in New Jersey, Pennsylvania and Nevada [27]. It is compatible with STAMINA input files; it uses the graphical interface from AutoCAD or MicroStation to show plan, elevation, and three-dimensional views of the noise barrier, receiver locations, and noise levels. It is general perceived as more userfriendly than the combination of STAMINA and OPTIMA, and it permits better visualization of the results of multiple analyses.

Although TrafficNoiseCAD is widely regarded as a significant improvement over STAMINA and OPTIMA, we cannot recommend its adoption by TxDOT at this time, for the following reason: by the end of 1995, the new TNM is expected to far exceed the capabilities of TrafficNoiseCAD. If TNM is successfully released, there will apparently be no need to purchase TrafficNoiseCAD. However, if TNM should be further delayed or have major problems, serious consideration should be given to the acquisition of TrafficNoiseCAD as a working alternative to TNM.

SoundPLAN

SoundPLAN is a noise analysis software system developed in Germany. SoundPLAN has an analysis system that can provide a comparison of each of the different noise analysis procedures and standards from the United States, Germany, Austria, Great Britain and Scandinavia.

The current version of SoundPLAN is less than 2 years old and supports color graphical output. One of its most attractive features is the ability to produce color maps of noise contours. Another unique feature of SoundPLAN is its ability to analyze road, rail and air traffic noise. It can also perform air pollution studies of vehicle emissions. SoundPLAN requires more computing capability (at least an 80386 microprocessor) than STAMINA or OPTIMA [28].

TxDOT NOISE ANALYSIS SOFTWARE

Based on our visits to several TxDOT district offices, only the FHWA developed STAMINA and OPTIMA programs are used in Texas. Prior to the announcement of the new FHWA model, the Houston District (which designs more noise barriers than all the other districts) had expressed interest in using a more comprehensive model such as SoundPLAN or TrafficNoiseCAD.

In a typical district office, the Environmental Affairs or Special Projects office performs a STAMINA analysis based upon forecast traffic and receiver locations, and then uses OPTIMA to determine the optimum barrier height and location. A design engineer finally designs a barrier to meet those height and location requirements. In most districts we visited, the design engineer is either chosen randomly, or is the highway designer responsible for that construction segment of the roadway. The Houston District, however, has enough noise wall projects to allow a specific engineer to specialize in their design.

According to TxDOT district offices, OPTIMA is usually conservative by 2-3 dB in calculating the insertion loss (IL). In many cases, post-construction measurements have indicated that noise barriers were 2-3 dB more effective then calculated when based upon actual traffic levels at the time of construction (rather than forecast traffic levels for a 20-year design life).

The Houston District raised another concern: when the typical concrete pavements constructed in heavy-traffic areas there are evaluated with STAMINA, actual noise levels are 5 dB higher than calculated. The reason given for this problem is that contractors have a construction option on how the pavement surface is textured; the surface of choice (for high skid resistance) is transverse tining. Unfortunately, this surface is known to produce higher noise levels than the conventional pavement modeled in STAMINA. This surface provides high skid resistance in wet conditions, but also causes higher-than-normal traffic noise. When the barrier is optimized in height with the OPTIMA program using the STAMINA traffic noise levels, the actual constructed noise barrier does not meet expected noise levels at the receiver locations.

Another potential problem with the STAMINA/OPTIMA combination involves cases where noise barrier walls have gaps for driveways and street openings. Anecdotal evidence from the districts indicates that OPTIMA permits openings that generally result in inefficient noise barriers. Finally, OPTIMA cannot analyze situations involving reflection between parallel walls.

TRAFFIC NOISE MODEL (TNM)

The FHWA has evidently also recognized that STAMINA and OPTIMA do not fulfill the needs of the states. Using a pooled-funds study under the direction of the National Transportation System Center, the FHWA has spent the last several years developing a new traffic noise model for highway traffic, which the FHWA has named "Traffic Noise Model" (TNM).

The new Traffic Noise Model is intended to replace STAMINA and OPTIMA. Nearly all the features developed in TrafficNoiseCAD have been incorporated into the TNM. However, this widely heralded and much-needed program comes at a price. It is much more computationally intensive than STAMINA and OPTIMA, mostly because it performs a full 1/3 octave band analysis of the traffic noise source and the performance of the barrier. Many new features have been added to the modeling of barrier performance.

Acoustical Modeling Improvements of the TNM

The TNM will have significant improvements in both the characterization of the traffic noise and the accuracy of calculating barrier performance. While the STAMINA program uses a single frequency to estimate noise levels and barrier performance, the TNM will use 1/3-octave bands for those calculations.

Whereas STAMINA calculates the source noise level from the design hourly volume of traffic and the percentage of trucks, TNM will permit customizing of the traffic stream to model the actual situation. It will have a database of several standard vehicles, and will permit composite vehicle types. Each vehicle will have sub-source heights for the individual components of the vehicle's noise emissions. Variables modeled may include constant- versus interrupted-flow traffic, and level terrain versus hills. This last modeling capability is significant, because trucks tend to produce annoying low-frequency sound when climbing hills.

Different pavement types have been shown to produce significantly different sound levels. Researchers in South Africa have achieved source noise reductions exceeding 8 dB using open-graded asphalt pavements [29]. This level of noise reduction is equivalent to halving the traffic level. Because of the effects of different pavement types, the TNM will also provide the user with a choice of three types of pavement surfaces: open- and dense-graded asphalt pavements, and concrete pavements. Data for these pavement types have been field-collected in several states in 1994 [30].

Because the input data can be characterized much more accurately and more computational power is available to support the 1/3 octave band analysis, TNM is being developed with new analytical algorithms. TNM will consider more sound paths from the source to the receiver than are possible in STAMINA. Therefore, the results should besignificantly more accurate. As an option, transmission loss or reflection can be selected as variables in the analysis. Finally, the TNM is being designed specifically to analyze the problem of reflected sound from parallel noise barriers.

New Features of the TNM

Many of the features that have made TrafficNoiseCAD so popular are being incorporated into the TNM. Most important of these is the ability to obtain input information from CAD drawings. Most new highway design plans are drawn in CAD software; direct import of those files into TNM will save resources. TNM will be able to import AutoCAD and MicroStation files, and also older STAMINA files. In the Windows operating environment, it will support the use of a digitizer for building an input file from paper plans. It will also allow data to be imported from spreadsheet programs.

The TNM will support many new graphic options such as plan views, vertical and perspective views, roadway profiles and barrier elevations. In addition, contours can be calculated and displayed for sound level, insertion loss, and noise attenuation level. These contours can be saved, permitting graphical comparison of the results of different noise mitigation options.

Once the TNM's output has been calculated, the results will be able to be plotted. The FWHA choice of plotting program is the Air Force-developed NMPLOT (also the FAA choice for plotting INM Version 5.0, the new FAA program for predicting airport noise). However, export to DXF file format will also be supported, permitting subsequent importation to MicroStation or AutoCAD.

Hardware Requirements for the TNM Program

The FHWA has released the following minimum hardware requirements for the TNM Program:

- IBM Compatible Computer with 486/ 66 MHz CPU
- 8 Megabyte Random Access Memory (RAM)
- 300 Megabyte Hard Disk
- SVGA Video Monitor (must support 1024 x 768 resolution with small fonts)
- Microsoft Windows 3.1
- Windows-Compatible Digitizer

While the TNM program has not been released for testing, its efficient operation will probably require hardware exceeding these minima. By the time of its release, however, the typical entry-level home or office computer will probably far exceed these minima Based on experience with similar programs, we believe that the following minimum hardware will be required to efficiently run the new Traffic Noise Model for noise barrier analysis:

- IBM Compatible Computer with 586 (Pentium) Processor or equivalent
- 16 Megabyte Random Access Memory (RAM) (32 megabyte if using Windows NT)
- 500 Megabyte Hard Disk (1 Gigabyte preferred)

- SVGA Video Monitor (suggest 17 inch screen to view the 1024 x 768 pixel resolution)
- Video Graphics Accelerator Card with 2 Megabytes RAM
- Microsoft Windows 3.1 (Windows NT)
- Windows Compatible Digitizer
- CD-ROM
- Network Card or method of transferring files greater than 1.44 Megabyte (Zip Drive, Cartridge Hard Drive or Tape Backup)

If computer-generated renderings of noise barriers are required for public presentations, additional software (such as "ModelView for MicroStation") should be considered for purchase as well.

CHAPTER 5. COMMON TXDOT NOISE BARRIERS

INTRODUCTION

As noted in Chapter 1, the research team held 5 informational meetings in early 1995, meeting with TxDOT personnel in Austin, San Antonio, Fort Worth, Dallas and Houston. One purpose of those meetings was to gather information about the state of the art in noise barrier design in Texas.

After each informational meeting, our research team visited, studied and photographed examples of the different types of noise barriers found in the host district. The photographs were assembled into a slide database, and also incorporated into a file containing information on each typical barrier. The purpose of this chapter is to present information from that file in narrative form, and thereby review the different types of noise barriers most commonly found in Texas today.

HIGHWAY NOISE BARRIER SYSTEMS USED IN TEXAS

Because highway noise barriers that are distinct in appearance may actually be quite similar in function, it is useful to assign them to particular "systems." This classification is not definitive nor unique, and is adopted primarily for convenience. For purposes of this report, noise barrier systems used in Texas are classified as follows:

- Noise Barriers Not Intended to Resist Vehicular Impact
    - prefabricated separate post and panel system
    - prefabricated integral post and panel system
    - constructed-in-place post and panel system
    - fan wall system
    - reinforced earth berms
- Noise Barriers Intended to Resist Vehicular Impact
    - prefabricated, barrier-mounted post and panel system
    - prefabricated safety-shape wall system

In the remainder of this chapter, each system is described, and is illustrated by photographs of example walls.

NOISE BARRIERS NOT INTENDED TO RESIST VEHICULAR IMPACT

Prefabricated, Separate Post and Panel System

The prefabricated separate post and panel system is the most common system used for noise barriers in Texas. This system consists of prefabricated panels, placed between posts. The system is shown schematically in Figure 5.1. The panels are usually of precast concrete, but can also be of other materials.The space between the posts can be filled either with a single panel, or with several shorter panels, stacked vertically. The posts are usually of either concrete or steel. Figure 5.2 shows a typical prefabricated, separate post and panel wall, made of full-height, precast concrete panels placed between steel posts, constructed in the Houston District. Figure 5.3 (a close-up view of the same noise barrier) shows the precast concrete fascia plate, intended to provide an aesthetic cover for the steel column and the joint between the panel and the column.

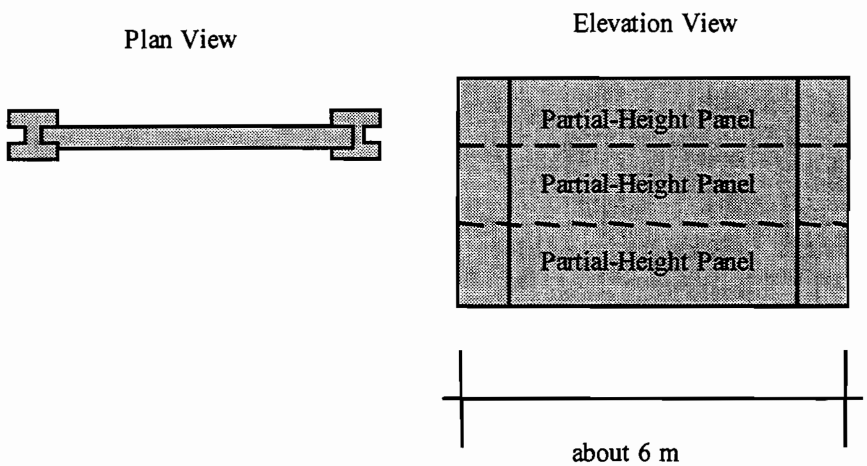


Figure 5.1. Schematic Illustration of Prefabricated, Separate Post and Panel System for Highway Noise Barriers

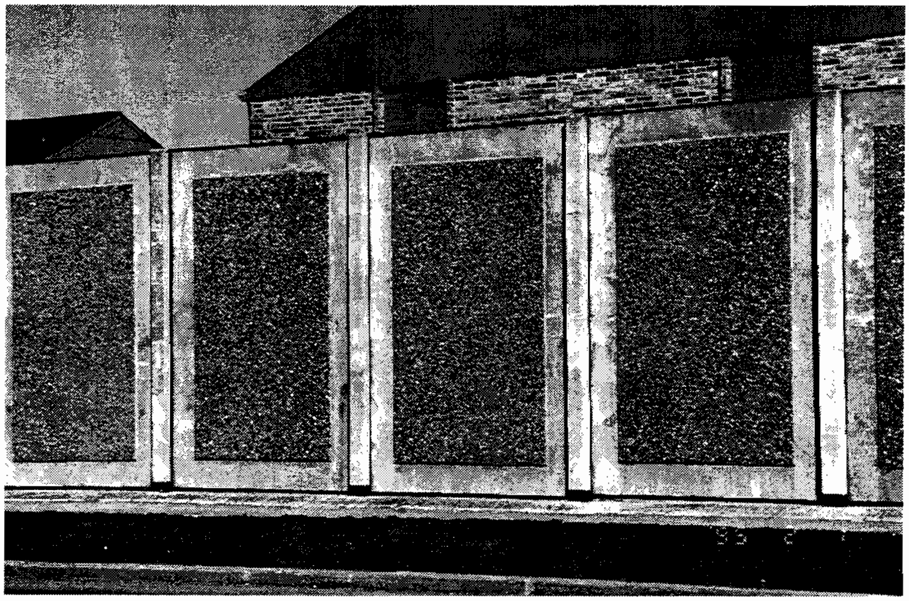


Figure 5.2. Example of Prefabricated, Separate Post and Panel Noise Barrier (Houston District, precast concrete panels, steel columns with concrete fascia panels)

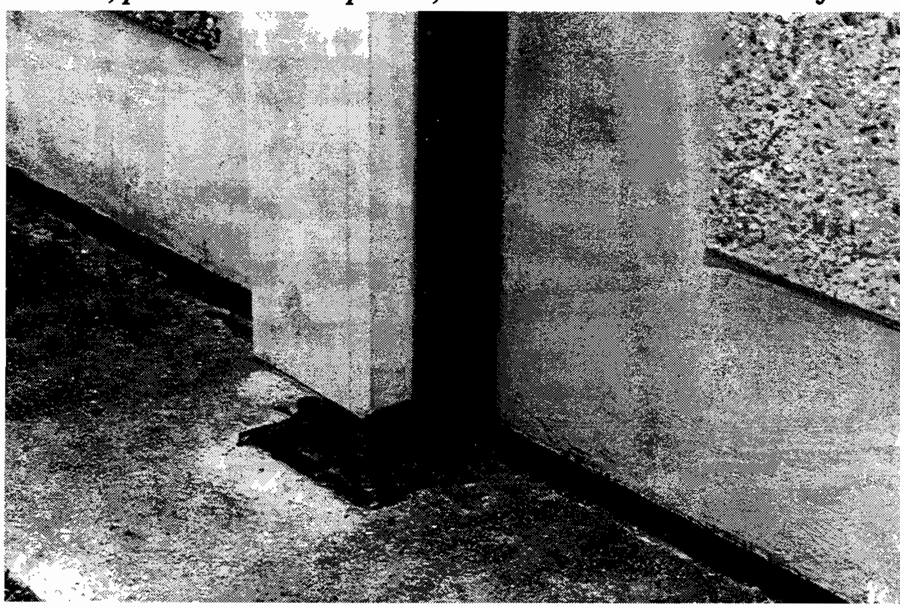


Figure 5.3. Close-up View of Column on Noise Barrier of Figure 5.2

In this system, there is no grade beam. The panels span between the posts, whose spacing is often dictated by the type and layout of the foundation used. As discussed further in the chapter dealing with performance criteria, the post spacing ranges from 3.0 to 7.5 m (10 to 25 feet). Drilled shafts without grade beams are the standard foundation type for all noise barriers in the Houston District. The precast panels are typically of reinforced concrete, and are “flown” into place between the columns using an overhead crane.

The prefabricated, separate post and panel system has several advantages:

- It is versatile, lending itself to a wide range of construction materials, panel heights, and aesthetic treatments. For example, since the choice of post material (concrete, steel, or other) is a contractor option, several noise barriers, such as the one shown in Figure 5.4, have concrete posts. If the presence of overhead utilities or restrictions on crane operation so dictate, the required lifting height or panel weight can be reduced by using multiple, partial-height panels, rather than a single large panel. The panels can have a wide variety of surface textures and colors.
- It is easily constructible, requiring relatively little disruption of traffic.
- It is relatively easy to repair, by removing and replacing the damaged component.

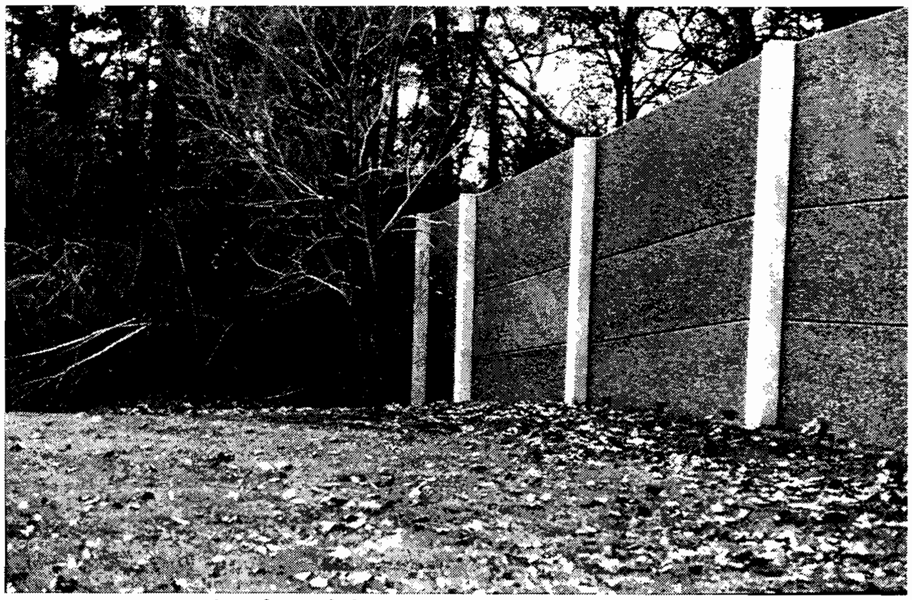


Figure 5.4. Example of Prefabricated, Separate Noise Barrier System (Houston District, precast concrete posts and precast concrete panels)

Prefabricated, Integral Post and Panel System

The prefabricated, integral post and panel system is a slight variation of the prefabricated, separate post and panel system discussed above. It offers the same advantages. The difference is that instead of being free-standing, the posts are integral with the panels. This system is illustrated schematically in Figure 5.5. After the monolithic panel-and-post elements are placed, the post end of the panels are most often bolted from the top panel to the drilled shaft foundation or post-tensioned using a cable embedded in to the drilled shaft and threaded thru the panel or panels as they are lowered into place.

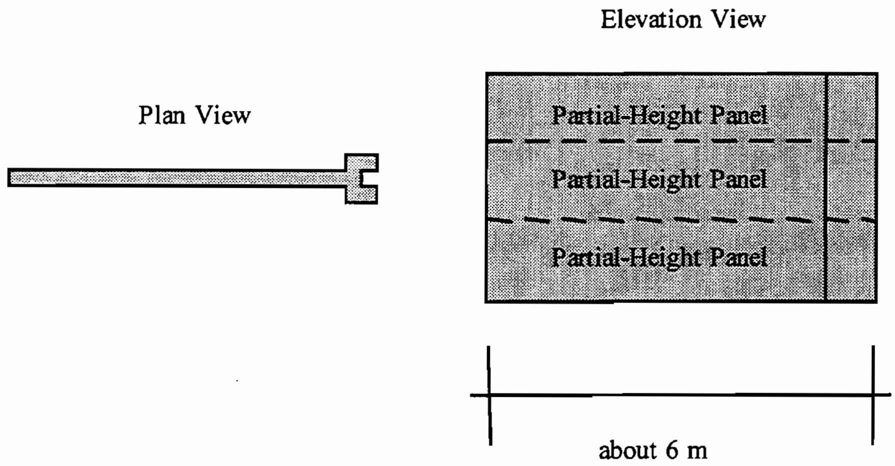


Figure 5.5. Schematic Illustration of Prefabricated Monolithic System for Highway Noise Barriers

Constructed-in-Place Post and Panel System

This system is superficially similar to the prefabricated post and panel systems discussed above. However, the posts and panels are constructed in place, using reinforced concrete or reinforced masonry. The panels must either be constructed using self-supporting formwork, or on top of shoring or a grade beam. A grade beam increases the cost of the foundation. The principal disadvantage of this system is the potential disruption of traffic associated with construction. This is not always critical. Figure 5.6 shows an example of this system, constructed in reinforced masonry in the Austin District. The San Antonio District has a nearly identical design.

Although constructed-in-place concrete barriers are possible, our research team has not identified any barriers of this type in Texas. One wall in Dallas, however, has a cast-in-place base topped by precast panels. This barrier is unique in several respects. It separates an exclusive residential neighborhood from the LBJ Freeway. As a result of negotiations, the neighborhood gave TxDOT the ROW for the freeway widening, and TxDOT was required to retain an architect acceptable to the neighborhood, for the design of the noise barrier.

Figure 5.6. Constructed-in-Place Post and Panel System in Austin (reinforced masonry posts and panels)

The result is an architecturally pleasing but very massive noise barrier that cost about $42 per square foot, more than twice the statewide average. The architectural treatment includes small areas of decorative tile cemented into recesses in the precast concrete panels, and a contrasting white decorative cap placed on top of the panels. It is TxDOT's position that this barrier is an anomaly that will not be repeated.

Fan Wall System

A fan wall system is generally composed of full-height, precast panels placed in a zigzag configuration in plan and inter-connected using bolts or cables. This zigzag configuration provides overturning stability, permitting the elimination of posts. In certain areas with very good soil conditions, the foundation can consist only of a compacted base. This system has the potential advantage of low cost, due to the elimination of posts and foundation. However, its zigzag footprint requires more right-of-way than a straight wall. A fan wall system can be constructed with less concern for disturbing buried utilities. However, it can make subsequent access to such utilities more difficult, because its overturning stability can be endangered if it is necessary to dig along a significant length of the wall. The fan wall system construction in the Austin District and shown in Figure 5.7 was specifically chosen due to the presence of buried utilities.

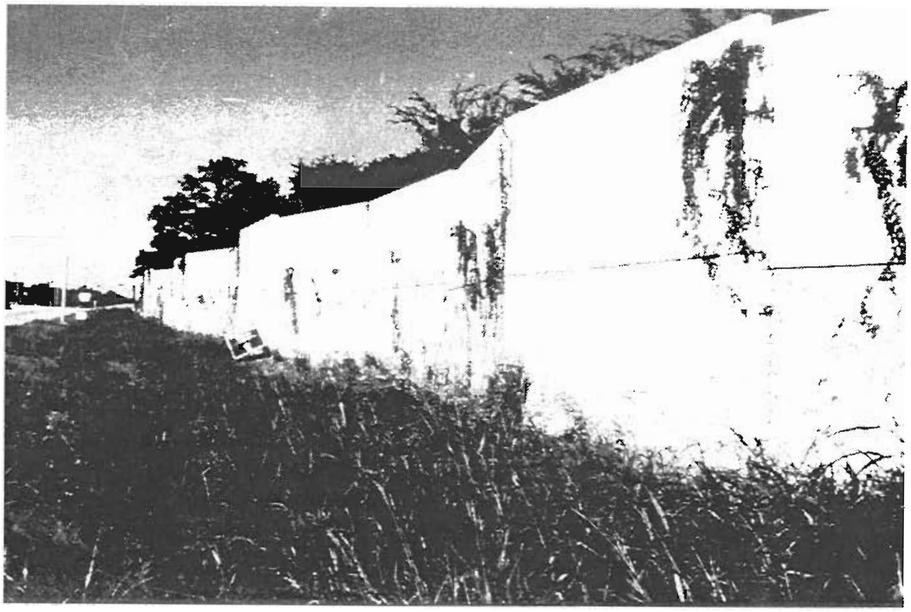


Figure 5.7. Example of Fan Wall System
(Austin District, precast panels interlocked with steel cables)

The Houston District has constructed examples of the fan wall system (Figure 5.8). The fan wall system used in Houston differs from that of the Austin footprint. The Houston system is wider, requiring more ROW. Eventhough this wall has no drilled shaft foundations the Houston District now requires drilled shafts under all future walls because of the possibility of overturning due to trench excavation. The Houston District has noted that the irregular shape of the fan wall makes it difficult to mow next to the wall, and can provide criminals with places for concealment.

The staggered noise barrier system alternates straight wall and angled wall sections while incorporating the use of stackable post and panel construction. The staggered barrier is interrupted at regular intervals with a short section perpendicular to the roadway. As shown in Figure 5.9, a staggered wall is less monotonous than a straight one. Its footprint provides some inherent lateral stability. This footprint is usually used with the prefabricated post and panel system, but it could be used with other systems as well.

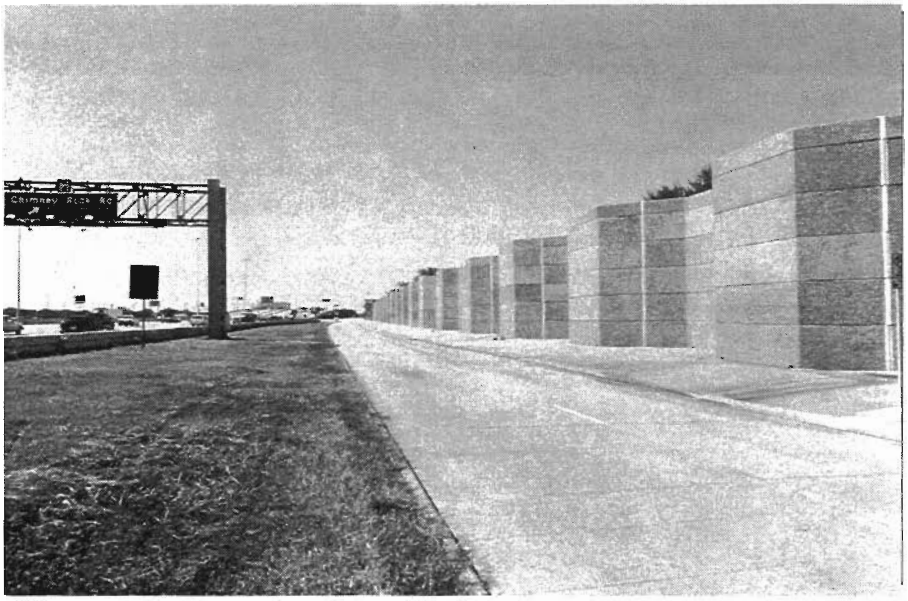


Figure 5.8. Example of Fan Wall Noise Barrier (Houston District)

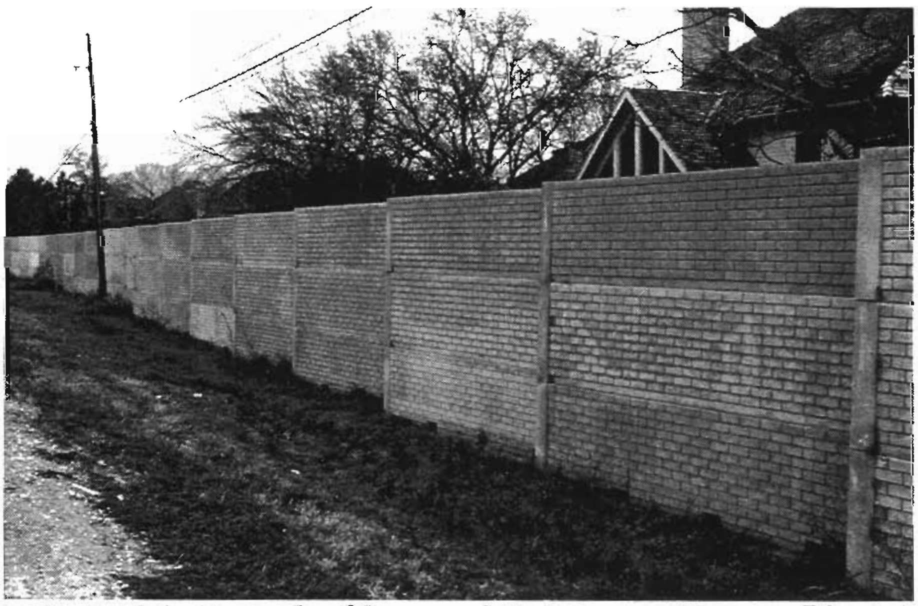


Figure 5.9. Example of Staggered Wall System (Houston District)

Earth Berms

The earth berm system is simply a hill of earth. In some instances, the center of the berm is filled with alternate materials (such as recycled tires) to reduce costs. Earth berms have the aesthetic advantages of being less imposing and more natural in appearance than noise barriers of other materials. Vegetation on the berm can enhance this aesthetic appeal. However, trees planted on an earth berm noise barrier can reduce the barrier's acoustical effectiveness by scattering noise to the receivers that otherwise would have been directed over them. The main disadvantage of earth berm noise barriers is the ROW they require. Earth berms are really an ideal solution if space is available. The Fort Worth District has one such barrier.

NOISE BARRIERS INTENDED TO RESIST VEHICULAR IMPACT

Prefabricated, Barrier-Mounted Post and Panel System

The prefabricated, barrier-mounted post and panel system is another variation of the post and panel system, involving structural steel posts anchored atop a TxDOT T501 traffic barrier ("Jersey barrier"). The traffic barrier is used to reduce potential hazards during vehicular impact, while supporting the post and panel elements intended to achieve the desired sound attenuation. This system is very popular in the Fort Worth District, and has also been adopted by the Texas Turnpike Authority for the North Dallas Tollway. Figure 5.10 shows a typical Fort Worth District noise barrier, constructed using this system. In the Fort Worth District, the precast panels are constructed either with exposed aggregate or smooth-finished concrete.

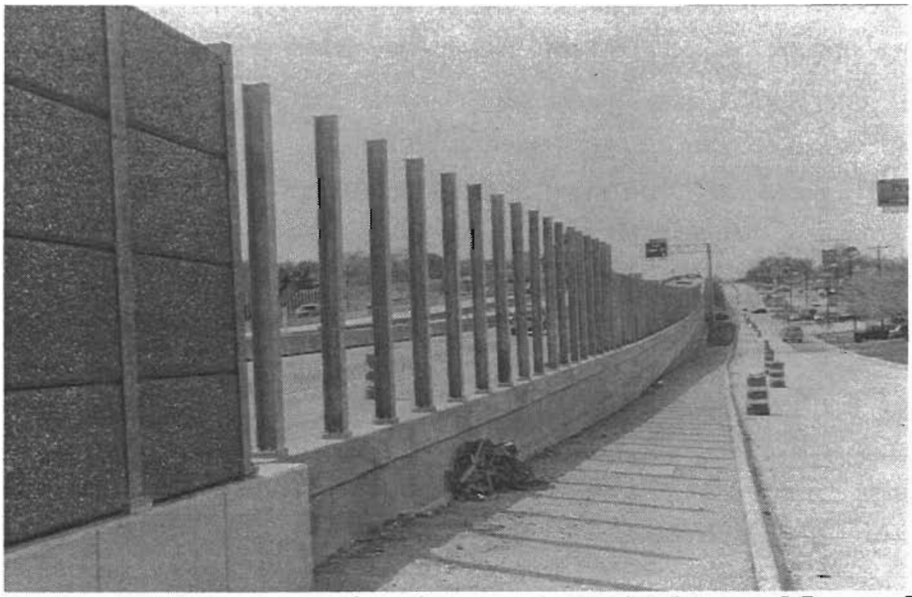


Figure 5.10. Example of Prefabricated, Barrier-Mounted Post and Panel System (Fort Worth)

The posts are typically attached to the impact barrier using a base plate and embedded anchor bolts. This connection is often difficult and costly to construct in the field due to the tight tolerances resulting from the narrow barrier top (only 150 mm (6 inches) wide). Because the barrier top is so narrow, the base plate is also narrow, and the overturning resistance of the post is low. As a result, the post spacing must be close—Fort Worth uses a spacing of only 1.5 m (5 feet). The panels must therefore be short. While more panels are required than if the posts were farther apart, the smaller panels are easier to disassemble if necessary. The short panel length and exposed steel posts have resulted in a poor aesthetic rating for this design.

Wind loads restrict the height of this barrier system. Although the T-501 barrier alone has been designed for vehicle impact, the combination of impact barrier and mounted noise wall system has not been designed for vehicle impact.

Prefabricated "Safety Shape" Barrier Systems

The "safety shape" noise barrier system, conceived in the Houston District, combines the potential vehicular impact resistance of the mounted post and panel system with the aesthetic advantages of prefabricated, separate or integral systems. This system, shown in Figure 5.11, consists of a full-height precast panel and integral column, anchored to a lower portion that is trapezoidal in cross-section.The panel and lower portion of the wall are locked together with anchor keys cast into the panels and grouted in place as the panel is lowered onto the lower panel (trapezoidal). The final connection to the drilled shaft is made with a long bolt introduced from the top and screwed into an insert that is cast in the drilled shaft.

The safety shape system is intended to reduce the hazards of a vehicular impact. However, neither the Fort Worth barrier-mounted post and panel system nor the safety shape system is designed to a specific vehicular impact standard. Houston District designs the bottom panel to withstand a 10 kip concentrated load, simulating a vehicle impact.

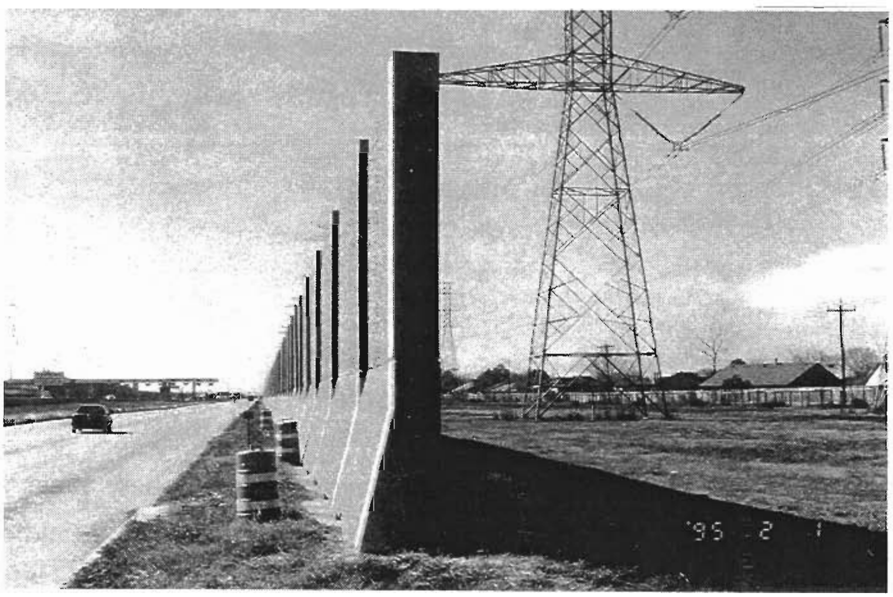


Figure 5.11. Example of Safety Shape Noise Barrier System (Houston District)

SUMMARY

Many different noise barrier systems are used in Texas. They can be classified as in this chapter. Other states and countries use noise barrier systems not addressed in this chapter. The following Chapter describes the results of our questionnaires and interviews with engineers responsible for the design and construction of each noise barrier system.

CHAPTER 6. TxDOT EXPERIENCE WITH NOISE BARRIERS

TxDOT EXPERIENCE WITH NOISE BARRIERS

Over the past decade, the Texas Department of Transportation (TxDOT) has constructed noise barriers of various types and materials. The lessons learned from each of these projects represent a storehouse of knowledge pertaining to noise barrier design. By gathering and documenting this information, a useful design reference can be produced and made available to TxDOT personnel to use when designing a noise barrier. To accomplish this goal, phone interviews were conducted with district personnel regarding their experience with noise barrier design. In addition, data were collected on selected noise barriers throughout the state via a mail survey. This chapter summarizes and presents the information gathered from the districts.

SUMMARY OF PHONE INTERVIEWS WITH TxDOT DISTRICT PERSONNEL (11/94 - 5/95)

The primary objective of the phone interviews was to assist our research team in evaluating the current processes used in noise barrier design throughout the state of Texas. Since the Texas Department of Transportation does not endorse standardized noise barrier design guidelines, each district's method of selecting and designing a noise barrier differs. The interview focused on the structural considerations in the design process, such as foundation design and material selection. The questions are listed in the Appendix.

The phone conversations were conducted with structural engineers from the five districts that currently have designed and constructed at least one noise barrier. These five districts are the Dallas, Fort Worth, Austin, San Antonio, and Houston districts, and the contacts' names and addresses are listed in the Appendix. In talking with each engineer, the need for a standardized design guideline became evident.

The interviews focused on three major topics: the material and barrier type selection process; the structural design procedure; and the major problems encountered. Each district had different procedures for handling each step of the design process.

Design Process for Noise Barriers

The first questions for each survey recipient dealt with the structural design process, i.e., design of the barrier whose existence, height and length have already been determined by acoustical considerations. All districts were familiar with the AASHTO *Structural Design*

Specifications for Noise Barriers [31], and used it as a first reference. Several other references were cited:

- TEK Manual published by the National Concrete Masonry Association [32]
- *Uniform Building Code* [33]
- AASHTO Bridge Specifications [34]
- LRFD Design Manual [35], ACI 318 [36], and other material codes
- Other applicable codes such as the Structural Welding Code [37]

Some districts noted that the above references did not address some important design parameters, and did not consider all design conditions. In particular, the need for guidelines on the minimum thickness of a free-standing barrier, on deflection limits (serviceability), and on vehicular impact requirements was identified.

In all districts, the structural engineer was responsible for selecting, developing numerical design parameters, and applying the design. For the Houston district, the most common noise barriers are proprietary systems. In these cases, the owner and contractors involved in the noise barrier selection ultimately responsible for the design and called upon manufacturers or TxDOT personnel (using in-house standards) for assistance. However, the district engineer still must approve each project.

Factors Influencing Design of Noise Barriers

The primary factors influencing the design of a noise barrier are the parameters necessary to achieve the most effective noise reduction. These parameters are dictated by acoustical requirements and determined by the environmental engineer. Once these parameters have been specified, the physical noise barrier is designed .

The application of the noise barrier design process was controlled by the following principal factors: aesthetics; cost; maintenance; local influences; and structural constraints. Although important in each noise barrier design, cost was not the controlling factor for most designs and selection processes. In Austin and San Antonio, aesthetic considerations controlled. In Fort Worth, design was dictated by structural constraints due to the placement of the barriers on traffic barriers (mounted barriers). In Houston, local influences dictate that the barriers be built of concrete, the primary building material for the region. Overall, the primary factors that determined the final noise barrier design varied from project to project and district to district, making the standard design process difficult to describe.

In addition to the structural factors mentioned above, several other factors influence the final design of noise barriers. These include drainage, landscape, road access, vehicular impact, foundations, environmental impact, community impact, sight distance, R.O.W. width, and soil conditions. Several of these factors are discussed in a later section. Consideration of these factors depends highly on the situation and conditions in which the noise barrier is to be placed, and will be discussed in more detail in the finished design guideline of this research project.

Currently, four of the five Texas districts polled have no personnel assigned specifically to the design of noise barriers. Houston has had the most experience with noise barriers, and has assigned a permanent staff member (Mark Anthony) to noise barrier study and plan preparation. Most projects are handled by the Special Task Department, and are usually a cooperative effort between the Environment and Structural Engineering divisions.

Contracting Process for Noise Barriers

Most noise barrier projects were let, and the contractor selected, on a bid basis. Some districts used prequalified contractors on projects, and did not allow the project to be bid. In most cases, alternates were allowed to be bid by the contractors. In such cases, requirements were defined for the alternates. As with the design criteria, the alternate designs were required to satisfy the most important design parameters discussed above.

Special Details for Noise Barriers

Provisions for Openings. In all districts except one, no doors were placed in the constructed noise barriers. In one location in San Antonio, a metal door was placed to allow the utility company access to telephone pole located behind the barrier.

Maintenance. For maintenance purposes, the barrier in San Antonio was coated with an anti-graffiti finish. In most districts, the exterior zones and adjacent strip are maintained by the state or by the adjacent landowners.

Provision for Vehicular Impact. In most districts, vehicular impact is considered for noise barriers placed adjacent to the right of way (ROW), although a few engineers expressed concern over these provisions. In the Houston district, noise barriers are designed according to the AASHTO Bridge Specification [34]. The Fort Worth district uses mounted noise barriers. For the mounted barrier system, only the T501 barriers were designed for vehicular impact according to the AASHTO Bridge Specification [34]. In Dallas, the structural engineer imposed extra live and dead load in order to account for impact, although no formal requirements were specified.

Drainage, Flood Control. In many districts, drainage and flood control were not critical. Most districts provided drainage holes or rip-rap at the base of the noise barrier or traffic barrier. In Houston, one barrier was constructed with an error in the drainage hole size. The opening was made too tall which raised several concerns, including child safety. An additional concern is obstruction of drain holes by garbage or debris.

Foundations of Noise Barriers. In most cases, drilled-shaft foundations were used. Some exceptions were noted. In Fort Worth, noise barriers are mounted on traffic barriers. Therefore, standard traffic barriers were constructed, and embedded anchor bolts were used as panel foundations (see Additional Concerns). For the masonry barrier in Austin, buried utilities dictated shallow foundations, and a spread footing was selected.

Service Life Performance of Noise Barriers

Several cases of minor cracking, spalling, and joint degradation have been observed. These problems were attributed to improper detailing and to inexperience with noise barrier design. In addition to design oversights, several barriers have experienced a vehicular impact which resulted in cosmetic damage to the barrier. In only four cases reported did vehicular impact cause severe damage to a noise barrier. All of these were located in the Houston district.

In one case, a truck impacted a noise barrier causing fragments to scatter into a nearby recreational area. In another case, a car impacted a noise barrier at the center of a panel. The impact cracked the bottom noise barrier panel vertically along its centerline and the leading edge of the car was reported to penetrate the noise barrier. All noise barriers have been repaired by replacing the panels which were damaged and there are no post-impact effects remaining such as post tilting or cracking in adjacent panels.

Additional Concerns Regarding Noise Barriers

Some problems were noted regarding the mounted barrier system. The most serious occurred when the T501 traffic barriers were cast by slip-forming, which prohibits the placement of anchor bolts extending above the barrier top. A mechanical coupling system must therefore be used to attach the anchor bolts with an embedded bar. This procedure is very costly, and presented some construction problems when embedded bars were cast improperly at a small angle. Due to the narrow top surface of the traffic barrier, the tolerances allowed in the posts were small, and field alterations had to be made to align the bolts. A more serious problem arose when the cage or anchor bolts were struck by the form during construction. If the anchor bolt couplers are shifted forward or backward, the moment arm between the tension bolt and the compression concrete is reduced in one direction. This reduction in moment arm causes a reduction in the moment capacity of the post connection. This could result in potential structural problems.

Comments Regarding Phone Interviews

From these surveys, the need for a TxDOT design standard for noise barriers is apparent. Although the structural design of a noise barrier is relatively simple, each project in the different districts is being approached separately. This leads to inefficient use of time, and to incomplete consideration of the various design options and design criteria. In addition, it was noted that currently available technical literature does not adequately address such structural factors as vehicular impact, repair, deflections, and limitations on barrier dimensions.

SUMMARY OF NOISE BARRIER SURVEYS

As mentioned earlier, phone interviews were conducted with district structural engineers to assess and evaluate the current processes used in noise barrier design. In addition, each of the engineers was asked to complete a mail survey pertaining to individual noise barriers constructed in their district. The survey asked for the completion of an information sheet on each noise barrier, and the inclusion of any specifications and plans that exist.

The noise barrier file is a synthesis of the results obtained from the mail surveys completed by the Texas districts. The primary objectives of the noise barrier file were to assist our research team in evaluating the design criteria currently used for noise barrier design throughout Texas, and to create a database to be included in the final design guidelines as a reference for TxDOT personnel in selecting noise barriers. To provide a usable database, information was gathered on several examples of different types of noise barriers constructed throughout Texas. Currently, the noise barrier file contains an information sheet on 15 TxDOT noise barriers, as well as district standards, plans, and specifications (if available). A sample information sheet is located in the Appendix.

Contents of Noise Barrier

In total, information was received for 15 different noise barriers from five districts: Austin, Dallas, Fort Worth, Houston, and San Antonio. These 15 noise barriers comprise a complete database of different barrier systems with which TxDOT personnel has had experience. A description of these systems are provided in Chapter 5. The dastabase contains the following items:

- A list of noise barriers (district, location, description)
- An information sheet on each noise barrier
- A picture or slide of each noise barrier
- Structural plans for at least one noise barrier in each district

- Complete set of plans and specifications for two Austin and one Dallas noise barriers

Each district also sent a set of structural plans corresponding to the most common type of noise barrier built in their district.

Noise Barrier Classifications

The noise barriers were classified according to various parameters such as material type; the results are presented here in outline form.

Material and Systems. For the 15 noise barriers, only three materials were reported: concrete, masonry, and earth. The most common material is concrete, used for 12 barriers. The systems most often used in Texas are constructed using a pre-cast concrete panel system. This system is preferred due to its fast installation time and its ability to be replaced or removed easily. Reinforced masonry block has been used in two barriers and only one earth berm barrier has been constructed.

Foundations. As noted from the phone interviews, pier and beam foundations were the most common. Overall, 9 of the 15 noise barriers used some form of pier and beam foundation. Several other foundation types were reported, including fan-barrier systems, earth embankments, spread footings, and embedded anchor bolts (used in mounted noise barriers on T501 barriers).

Adjacent Utilities. The presence of electric, water, gas, telephone and other utilities adjacent to the noise barrier is of concern when selecting a foundation. This is exemplified by the masonry noise barrier project located in the Austin District on Parmer Lane (designed by Joe Tejidor, Austin District). Overall, five noise barriers were reported as having buried utilities, five with overhead utilities, and three without the utilities crossing the line of the barrier. For two noise barriers, this information was not available.

Aesthetic Finishes. The most common aesthetic finish was a textured surface with an exposed aggregate or fractured rock style. In total, 10 of the 15 noise barriers were reported with this type of finish; three barriers were either painted or left plain; and one barrier had tile inserts.

Drainage. Seven barriers were reported to have drainage holes placed at their bases; six barriers had no provision for drainage; and only one barrier had landscaping (earth contouring) to provide additional drainage. As a result of the telephone interviews, it was concluded that, drainage and flood control were considered but were not critical issues in most projects.

Vehicular Impact Considerations. In only five cases was vehicular impact considered in the design. This was most commonly achieved by mounting the noise barriers atop a T501 barrier, or by shaping and designing the lower portion of the noise barriers to enhance safety in the event of a vehicular impact. The latter is referred to as a "safety-shaped barrier." Overall, 9 of the

15 noise barriers were reported not to have addressed vehicular impact. In most such instances, the barrier was placed beyond the clear distance from the right-of-way. In the remaining few cases where vehicular impact was not explicitly considered, the district engineers were noted to have independently provided and/or analyzed for vehicular impact. However, they were concerned about the adequacy of their provisions.

Maximum Design Wind Load. In the Houston district, the maximum design wind speed was 160 kph (100 mph) 146 kg/m^2 (30 psf). In all other cases except one, the maximum design wind speed was 144 kph (90 mph) 122 kg/m^2 (25 psf). For that remaining noise barrier, a design wind load of 128 kph (80 mph) 98 kg/m^2 (20 psf) was used. The wind speed was selected based on the 50-year mean recurrence interval as suggested in the AASHTO Specifications for Structural Design of Sound Barriers.

Height and Length. Noise barriers varied tremendously in length. Their heights varied from 2.9 m to 6.9 m (9 feet 6 inches to 22 feet). Most barriers had an average height of 3.6 to 4.9 m (12 to 16 feet).

Cost. Costs were reported for seven noise barriers. The cost per square meter of barrier ranged from $118 to $269. The Fort Worth district reported barriers ranging from $118 to $172 per square meter; they were primarily 3 m to 3.6 m (10 feet to 12 feet) tall, concrete panel noise barriers mounted atop T501 barriers (not included in the cost figures). The most expensive noise barrier reported was a 4.5 m (15-foot) tall, concrete panel barrier located in Dallas. One earthen noise barrier was reported to have a cost of $1.82 per cubic meter.

Comments Regarding Noise Barrier Classifications

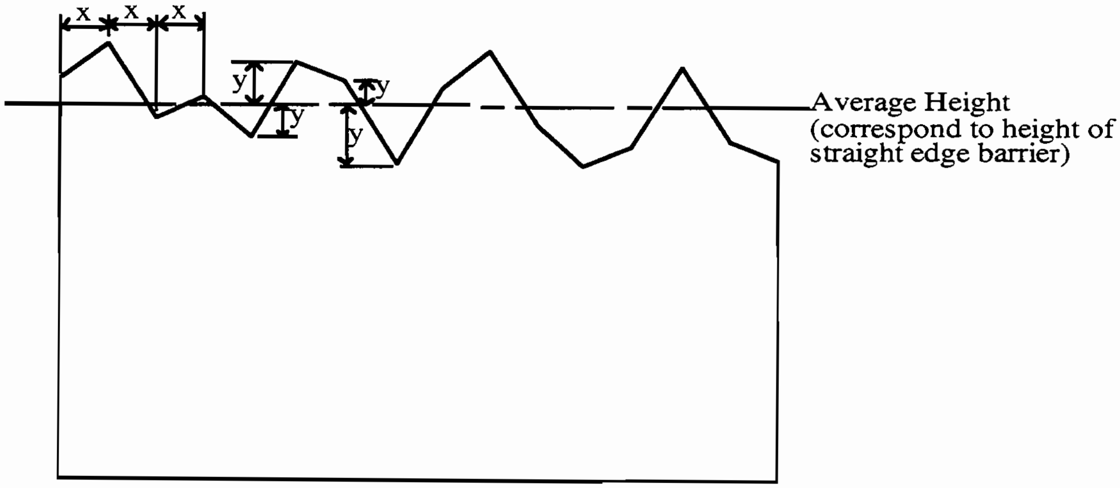
Examination of the information gathered in the noise barrier file reveals several similarities in design choices among districts. However, there is little consistency among districts, and even among designs produced by each district. This suggests either that external factors such as material availability or public involvement influence the design process, or that the design process and design criteria should be standardized. In either case, the availability of a database from which district engineers and planners could select standardized and approved noise barrier systems would greatly reduce the design time necessary for each new barrier, and would increase the cost effectiveness of the noise barriers.

CHAPTER 7. ACOUSTICAL RESEARCH

PRELIMINARY RESULTS FROM A SCALE-MODEL EXPERIMENT ON NOISE BARRIERS WITH A RANDOM TOP EDGE

As stated earlier in this report, sound from an omni-directional noise source, diffracted by a barrier edge, behaves as though the barrier edge were a line of coherent (in-phase) secondary point sources. As a result, the total sound energy reaching a receiver on the opposite side of the barrier could be greater than the sum of the diffracted energy of each secondary source.

The authors have considered the approach that this coherent addition of point sources at the barrier edge can be prevented by making the top edge of the barrier *jagged* instead of straight. The model used is a random variation of the barrier height about an average height corresponding to the height of a straight-edge barrier. The horizontal spacing between neighboring peaks and troughs is chosen to be constant. A sketch of this random top edge noise barrier profile is shown in Figure 7.1. Note that x is a constant while y varies.



Note: (1) x is the horizontal spacing between neighboring peak/trough
(2) y is the random height variation of the peak/trough from the average height

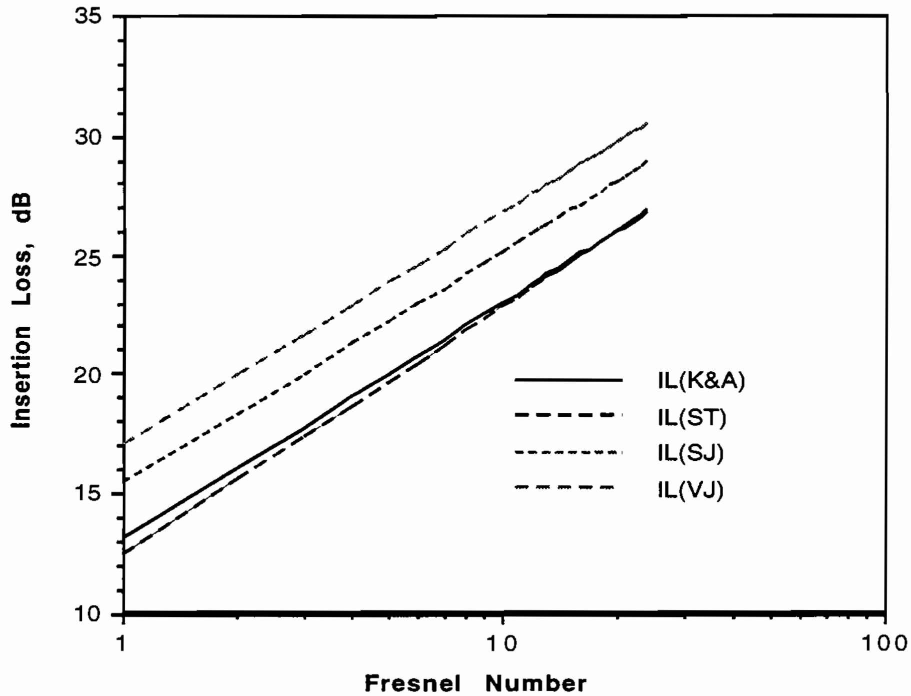
Figure 7.1. Sketch of Random Top Edge Barrier Profile

A 3-level full factorial experiment was carried out using 4 independent variables: Fresnel number; source frequency; horizontal spacing of peaks; maximum height variation of peaks from the average. The latter two variables define the jaggedness of the barrier top edge. The random height variation was found by using a random number generator scaled to the specified maximum.

The experiment was conducted using a barrier with 9 different random edge profiles and one straight-edge profile. The random edge barriers were constructed with three discrete increments of 9, 25, and 37 mm for the horizontal spacings and three discrete increments of 5, 11, and 18 mm for the maximum height variation. The straight-edge barrier is used as a baseline against which to compare the effectiveness of the random-edge barriers. The Fresnel numbers used in the experiment were 2, 7, and 20 and the source frequencies were 5, 12, and 21 kHz. Note that these frequencies and dimensions are appropriate for this scale-model experiment, but are not representative of traffic noise which tends to peak at about 500 Hz. These scale models were chosen to permit the experiment to be conducted in the confines of a laboratory in which extraneous noise can be eliminated and still permit extrapolation to full-scale analysis.

Preliminary results show that the insertion loss for a random-edge barrier can be improved by about 5 dB compared to a straight-edge barrier of the same average height. This result is very significant because it suggests that it is possible to get more noise reduction for a given barrier cost, or to reduce the required average height of a barrier (and thus its cost) for a given amount of required insertion loss. Figure 7.2 shows preliminary results for the insertion loss of a straight-edge barrier, a slightly jagged barrier of the same average height, and a very jagged barrier of the same average height. Also shown is the empirical expression for insertion loss proposed by Kurze and Anderson [4].

Based on the results here, it is believed that continued study of jagged-edge barriers is warranted. Funds from sources other than TxDOT are being sought to support continued work in this area.



Note: IL(K&A) - Kurze & Anderson [4]
IL(ST) - Straight Edge
IL(SJ) - Slightly Jagged Random Edge
IL(VJ) - Very Jagged Random Edge

Figure 7.2. Comparison of Insertion Loss for Random Top Edge Barrier and a Straight Edge Barrier of the Same Average Height

CHAPTER 8. STRUCTURAL RESEARCH

STRUCTURAL CONSIDERATIONS FOR NOISE BARRIERS

Like any structure, a noise barrier must be designed to resist the loads that it will experience during its service life. Two primary load cases must be considered: wind loads and vehicular impact loads. By studying the response of noise barriers to design lateral loadings, their behavior can be observed and their performance evaluated.

CURRENT GUIDELINES FOR STRUCTURAL DESIGN OF NOISE BARRIERS

In 1989, AASHTO published a set of recommended guidelines, *AASHTO Noise Barrier Specifications* [31], pertaining to the design of noise barriers. Revised in 1992, the guidelines outline the parameters required for design including loading cases, foundation design, and material detailing requirements. Although these specifications provide a good first reference for design engineers, they do not adequately address several key structural issues. Most notably, issues such as vehicular impact and deflection control are not clearly defined by the AASHTO Specifications, nor by any other technical reference.

LOAD CASES FOR NOISE BARRIERS

Wind Loadings on Noise Barriers

Any structure placed outdoors is subjected to wind loads. In design, wind loadings are modeled as a pressure acting over the vertical face of the barrier. In noise barrier design, the design wind pressure is calculated using Equation 1 of the AASHTO *Specification for the Structural Design of Noise Barriers* [31]

$$P = 0.00256\,(1.3V)^2 C_d C_c \qquad (1)$$

where P is the wind pressure, V is the design wind speed based upon 50-year mean recurrence interval, C_d is the drag coefficient (=1.2 for noise barriers), and C_c is the combined height, exposure and location coefficient. The wind speed is factored by 1.3 to account for the effects of gusts. As evident from this equation, the design wind pressure depends on the height of the barrier and the setting in which it is placed. For instance, a barrier located in the city experiences different wind loads than a barrier located in the country. These factors are incorporated in the coefficient, C_c. A detailed procedure for applying design wind loads to noise barriers is available in the AASHTO *Specifications for the Structural Design of Noise Barriers* [31].

In design, the forces and moments resulting from wind loads on a barrier must be checked against the barrier's lateral load capacity. However, applicable codes and guidelines do not address barrier deflections, nor do they specify deflection limits for noise barriers. Although for most noise barrier systems, the deflections under design wind loads are not a strength or stability concern, large deflections can be detrimental to serviceability (performance as perceived by the public).

Vehicular Impact Loadings on Noise Barriers

In many cases, acoustical requirements and the cost of acquiring the adjacent property to the roadway, dictate that the noise barrier be constructed adjacent to the roadway. Due to the location of noise barriers near roadways, vehicular impact loading must be addressed in the design.

When considering vehicular impact, several solutions can be applied:

- place the noise barrier beyond the right of way
- use landscaping to redirect vehicle before impacting the barrier
- place a traffic barrier in front of the noise barrier to prevent impact
- mount the noise barrier on top of a traffic barrier
- design the noise barrier for vehicular impact

As mentioned above, the available space often dictates which of the above solutions can be used.

Vehicular impact is not only a structural concern, but also a public safety and serviceability issue. In general, vehicular impact barriers such as the T501 traffic barrier are designed either to redirect the incoming vehicle, or to control the post-impact motion of the vehicle. The intent of placing a barrier such as a T501 barrier adjacent to the right-of-way is either to prevent the vehicle from impacting objects behind the barrier (protecting the driver), or to prevent the vehicle from striking a person in the vehicle's path (protecting the public).

When designing a noise barrier to act as a vehicular impact barrier, the design considerations discussed above remain the same, and vehicular impact is added to them. In addition to its effect on the impacting vehicle, the response of the noise barrier itself must also be considered. Vehicular impact has two possible effects on a noise barrier: it excites the noise barrier dynamically; and it causes damage to the noise barrier. One danger is that the dynamic excitation caused by vehicular impact may cause the barrier to become unstable, leading to possible collapse. In addition, as a result of vehicular impact, detached elements or fragments from the noise barrier may penetrate the vehicle or scatter, endangering residents behind the barrier.

Other Load Cases for Noise Barriers

The governing load cases for noise barrier design primarily involve lateral loads. Other load cases may sometimes require consideration. Examples are earthquake loads, snow loads, temperature loads, and water loads from flooding. In Texas, these load cases generally do not govern, and for this reason are not addressed explicitly in this study.

CURRENT STRUCTURAL RESEARCH ON NOISE BARRIERS

The purpose of this research is to investigate the behavior of several typical noise barriers subjected to wind and impact loads. Analytical models will be used to quantify and study the response of several types of noise barrier systems. By examining the performance of each noise barrier system, potential safety hazards can be identified for particular noise barrier designs. From these studies, a performance criteria will be developed by which each barrier can be evaluated under different load cases. The goal of this study is ultimately to develop a simplified analytical method that can be used by design engineers for evaluating the structural performance of new and old designs.

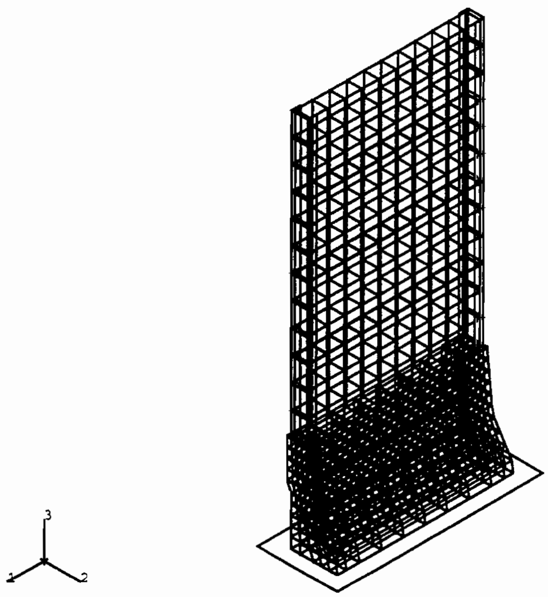
WORK PLAN FOR STRUCTURAL RESEARCH ON VEHICULAR IMPACT EFFECTS

Types of Noise Barriers to be Studied for Vehicular Impact Effects

The first task of the study was to identify the various types of noise barriers currently constructed in the state of Texas. Although several noise barrier systems have been used in the past, two typical noise barriers were selected for the study. The two barrier types were both post and panel systems and are described below:

System 1 - A post and panel type noise barrier mounted atop a T501 traffic barrier. The spacing of the post is 1.5 m (5 feet) and the barrier is 3.8 m (12 feet 7 inches) in total height. The posts are steel I-sections and connected to the traffic barrier by means of an end plate-anchor bolt connection.

System 2 - A post and panel type noise barrier with a safety shape lower panel. The panels were cast monolithically with one post and constructed using "flown-in" techniques. The posts are secured using unbonded threaded reinforcement or bolts placed at the centroid of each post. The spacing of the post is 6 m (20 feet) and the barrier is 6.7 m (22 feet) in total height.



8.1. Plot of ABAQUS– Model

Analytical Approach Used to Study Vehicular Impact Effects

For each barrier, a 3-D finite element model using the commercial software ABAQUS will be developed for the purpose of quantifying the response of the noise barrier during impact and wind loadings. Static and dynamic analyses will be performed using load-time histories obtained from field crash tests presented in NCHRP 230 [38] and *Development of a Limited Slip Portable Concrete Barrier Connection* [39]. The response of each noise barrier will be closely examined, and potential hazards will be identified.

Work To Date on Structural Research

Simplified models based on first principles were used to obtain estimates of the deflection and strength of the noise barrier systems under statically applied wind pressures. The wind pressures were selected based on 160 kph (100 mph) average wind speed, corresponding to hurricane conditions. Currently, the finite element model for System 1 is being refined to ensure that inelastic behavior can be accounted for in the analysis during impact loads. A plot of the model is shown in Figure 8.1.

CHAPTER 9. PERFORMANCE CRITERIA

GENERAL

Before rational and coherent design procedures can be proposed for noise barriers, it is necessary to have a clear understanding of the various functions that such barriers are intended to perform. The purpose of this section is to present those functions as performance criteria, arranged in a logical manner. Each criterion is explained, and relationships among them are emphasized.

The performance criteria can be classified into the following general categories:

- Acoustical requirements
- Aesthetic requirements
- Traffic safety requirements
- Structural requirements

ACOUSTICAL REQUIREMENTS FOR NOISE BARRIERS

The first requirement of a noise barrier is that it serve its acoustical purpose or purposes. One purpose is to reduce the noise level perceived by a receptor located away from the roadway (the source of the traffic noise). Another purpose may be to reduce the noise level perceived by a receptor located on the roadway itself. Because these purposes are associated with quite different performance requirements, they are discussed separately below.

Acoustical Requirements for Receptors Located Off the Roadway

The perceived noise level of sound produced on a roadway, and perceived by a receptor located off that roadway, depends on the loudness and frequency spectrum of the sound, on the distance between the source and the receptor, on the characteristics of the path that the sound must travel between source and receptor, and on the sensitivity of the receptor. Because the first and last of these factors are usually beyond the control of the noise barrier design process, this section emphasizes the role of the source-receptor distance, and of the path characteristics.

Sound produced at the source radiates out in all directions, attenuating with distance. If the path between the source and the receptor is interrupted by a barrier that blocks sound transmission through the barrier, the sound reaching the receptor is reduced to the diffracted sound that travels over or around the barrier. In order to be effective, the noise barrier must block the line of sight between the source and the receptor. From the viewpoint of the receptor located off the roadway, it is irrelevant whether the sound is absorbed by the barrier or reflected back towards the source.

Most conventional wall materials (such as steel, concrete, masonry, or wood) can be used in thicknesses sufficient to block the transmission of sound. For a 30 dB transmission loss (TL) only 0.1 percent of the sound energy is transmitted through the panel. For example, the thicknesses required to produce a 30 dB TL are given below in Table 9.1 for different materials at 100Hz and 500Hz.

TABLE 9.1. THICKNESSES (h) OF DIFFERENT MATERIALS REQUIRED FOR A TRANSMISSION LOSS OF 30 dB AT 100 HZ AND 500 HZ.

Material	h mm (in.) TL = 30 dB at 100 HZ	h mm (in.) TL = 30 dB at 500 HZ
Steel	5.3 mm (0.21 in.)	1 mm (0.04 in.)
Concrete	16 (0.63)	3.3 (0.13)
Glass	18 (0.72)	3.6 (0.14)
Rubber	32 (1.24)	6.4 (0.25)
Plexiglas	46 (1.81)	9.1 (0.36)
Pine	93 (3.66)	19 (0.73)

It is clear that for all materials except perhaps wood, the thickness that would normally be used in noise barriers to achieve structural performance and durability, is sufficient to block sound, and thus to fulfill this acoustical requirement.

The acoustical requirements for a effective noise barrier can be summarized as follows:

1. To achieve good transmission loss of 10 dB above the expected reduction, design the noise barrier with a surface density of at least 20 kg/m^2 [20].
2. To optimize the extra distance which the sound has to travel (the further it has to travel, the less sound energy will arrive at the receiver because of spreading loss), design the noise barrier to be as close to either the souce or the receiver as practically possible.
3. If small holes in the noise barrier cannot be avoided, design the panels such that the total open area due to the holes is less than 3 percent of the panel total area.
4. In cases where driveways, local roads, entrance or exit ramps are present, as a minimum, the barrier must extend 4 times in each direction as the distance from receiver to the barrier [8].

This can be very difficult to achieve on exit and entrance ramps due to sight distance requirements.

5. The noise barrier must at least block the line-of-sight of the source and the receiver at all times. This will achieve a 5 dB reduction in noise level. An additional 1.5 dB reduction in noise level can be achieved for every meter increase in height after the barrier breaks the line-of-sight.
6. Noise barriers are effective for receptors that are located within 65 meters of a roadway.

Acoustical Requirements for Receptors Located on the Roadway

If the barrier is required to reduce the perceived noise level for receptors located on the roadway, additional acoustical requirements are imposed. The barrier can be designed to meet these requirements by reflecting the sound upward, away from the roadway, or by absorbing the sound so that less of it is reflected back to the roadway.

Under certain conditions, sound generated on the roadway can be reflected back to the roadway so that it is in phase with the original sound waves. In other words, the receptor perceives his own sound, and also reflected sound from his vehicle or from other vehicles. In this situation, the perceived sound level is increased because of the noise barrier. This situation is referred to in general as "parallel reflection." In extreme cases, the effect of parallel relfections can be comparable to the sound level increase experienced in tunnels.

AESTHETIC REQUIREMENTS FOR NOISE BARRIERS

The general category of aesthetic requirements includes all aspects of the impact of the noise barrier on their surroundings. These include their physical surroundings, and also their human surroundings. For discussion purposes we have included their impact on drainage and flood control.

Impact of Noise Barriers on Physical Surroundings

By their very presence, noise barriers impact their physical surroundings. This impact depends first on the physical setting in which the barrier is placed. A barrier that would be almost imperceptible in an urban setting could visually dominate a rural or coastal setting. Perception of noise barriers must be approached from the viewpoint of the driver, and also from the viewpoint of the receptor.

The visual impact of the noise barrier on the driver depends on the speed of the vehicle, the height of the barrier, the distance of the barrier from the roadway, and surface texture of the barrier. If vehicles are generally moving rapidly close to the barrier, drivers do not notice the details of the barrier. If the vehicles move more slowly, or if the barrier is farther away, the details of the barrier are noticeable and important. If the barrier is high and close to the driver, and particularly if it is on both sides of the roadway, it may produce a "tunnel effect," in which drivers perceive themselves as being uncomfortably surrounded by the barrier.

The visual impact of the noise barrier on the receptor depends on the barrier height, the distance of the barrier from the receptor, and the surface texture and color of the side of the barrier facing the receptor. This visual impact can be accentuated if the barrier changes the pattern of light and shadow on the receptor's property.

Two design approaches are available to mitigate any undesirable impact that noise barriers may have: In the first approach, the barrier is designed to be "monumental," dominating the landscape. Its materials and details are selected so that it becomes a pleasing part of the landscape. In the second approach, the barrier is designed to blend with the landscape. This approach is best exemplified by the selection of a noise barrier in the form of an earth berm. While right-of-way constraints can make an earth berm impractical, other options are also available. Whichever approach is taken, it is advantageous that the visual appearance of the noise barrier reflect the historical and architectural context of the region in which it is placed. For example, noise barriers in a coastal area can be colored to blend with the sand that surrounds them; and they can be decorated or patterned with symbols that are historically meaningful for the area.

Aesthetic Considerations for Noise Barriers

While there are probably as many different definitions of an "aesthetically pleasing" noise barrier as there are potential viewers of that barrier, general consensus does exist regarding the basic principles governing aesthetic acceptability of noise barriers:

- The barrier must be compatible with its natural surroundings in scale, for (shape), and surface texture.
- The barrier must be compatible with surrounding structures
- The barrier's appearance must not change over time, unless that change is visually pleasing.
- The barrier must conceal, when possible, the marks of vehicular impact.

DRAINAGE AND FLOOD CONTROL REQUIREMENTS FOR NOISE BARRIERS

The first consideration in assessing the drainage and flood control requirements for noise barriers is to note that a formal investigation of such requirements may not always be required. Depending on the size and location of the barrier, the topography and rainfall characteristics of the area where it is located, and the design practices of the agency responsible for its construction, a formal flood modeling analysis may be required.

Overall Planning Issues Related to Drainage

In the preliminary planning phase of a noise barrier, its probable effect on drainage must be considered. Its probable effect depends on its plan length (the greater the length, the greater the effect), and also on its plan location with respect to known characteristics of water flow. Although noise barriers rarely act as dams, barrier height can also be influential in extreme situations. As noted below, barrier details such as drainage holes have implications for drainage. If these details are part of a standardized barrier design, they can be addressed consistently for all noise barriers.

Local Design Issues Related to Drainage

In addition to the overall relationship between barrier design and its impact on drainage, local issues must also be considered. For instance, if a particular barrier section is located so that it obstructs a water flow channel, drainage requirements are clearly more severe than in the general case. Similar considerations apply when adjacent landscaping or other highway features change water flow so that the noise barrier becomes more of a drainage obstruction.

Relation between Acoustical and Drainage Requirements

Holes are typically placed in noise barriers to prevent the barriers from acting as dams. Experience has indicated that holes should be no more than 100 mm (4 inches) tall. If they are shorter than 3 inches, cans and other debris cannot pass through them; if they are taller, children and animals can get stuck in them. Three inches is considered ideal. Acoustical considerations indicate that as long as the total area of the drainage holes is less than 3 percent of the area of the panel, their acoustical effects are negligible. Similar comments also apply to the small gaps that are part of normal construction tolerances in noise barriers.

TRAFFIC SAFETY REQUIREMENTS FOR NOISE BARRIERS

A fundamental requirement for highway noise barriers is that they not decrease the safety of those using the roadway, nor the safety of those adjacent to the roadway. Requirements that relate directly to those safety issues include the following:

Requirements for Visibility and Sight Distance

Noise barriers must be located so that they do not compromise requirements for visibility from vehicle to vehicle, nor requirements for sight distance from vehicle to intersections, signs, and traffic signals. Sight distance can become a problem for barrier design because barriers located closer to the roadway or receiver are acoutically more effective because of higher Fresnel numbers, but barriers located too close to the roadway may not provide adequate sight distance for intersecting streets or driveways.

Requirements for Effects on Light and Shade

If noise barriers create patterns of light and shadow on the roadway, this can be hazardous: Because of the time normally required for the human eye to adjust from bright sunlight to shadow, drivers' ability to detect objects on the roadway can be significantly impaired.

In some climates, shadow zones created by noise barriers can create areas in which ice can form and not melt. This can be extremely hazardous on overpasses and bridges where ice is more likely to form. Because of the light/dark visual adjustment problems of shadow zones, the ice can be difficult for drivers to detect, thereby increasing its potential hazard.

Finally, sunlight from highly reflective noise barrier surfaces, or from layers of water or ice on the barriers, can further impair drivers' vision.

Requirements for Vehicular Impact

Noise barriers are usually not intended to have any inherent function as vehicular impact barriers. However, if they are located close enough to the roadway to be impacted by vehicles, they must be designed so that the safety of the vehicle occupants is not compromised by the presence of the noise barrier. This normally implies either that the noise barrier be placed behind a conventional vehicular barrier, or that the lower portion of the noise barrier act as an integral vehicular barrier. Right-of-way considerations may dictate the latter solution. The performance of noise barriers with an integral vehicular impact function is discussed further in the section on structural requirements.

Requirements for Guidance and Signing

Noise barriers must not interfere with the natural placement of roadside signs, nor with the natural cues that drivers use to locate roadway entrances and exits. When signs are mounted on noise barriers, they must be clearly visible, and must not project into areas to become a hazard to vehicles.

Requirements for Orientation

If noise barriers obstruct landmarks from view, they can impair the ability of drivers to orient themselves. This can confuse drivers, reducing the capacity of the roadway and adversely affecting its safety.

Requirements for Emergency Access

Noise barriers placed between the roadway and potential receptors must not restrict emergency access between the roadway and the receptors. Emergency vehicles might need to go from the roadway to the neighborhood, or vice-versa. Fire-fighting vehicles on the roadway might need access to fire hydrants located in the neighborhood. Finally, individuals might need access from the roadway to the neighborhood in case of mechanical problems.

Requirements for Defensible Space

Noise barriers must not compromise the personal safety of vehicular occupants nor of receptors—in other words, they must not make the space around them less defensible. Noise barriers should not provide locations for concealment of individuals with criminal intent, nor should they provide access routes along which such individuals could travel, undetected, along the roadway or along the neighborhood.

Requirements for Safety from Overhead Power Lines

Noise barriers must be located a sufficient distance from overhead power lines to reduce the danger of electrical shock for those near them. This requirement is related to construction requirements involving overhead power lines and is discussed later in this document.

STRUCTURAL REQUIREMENTS FOR NOISE BARRIERS

Structural Design Requirements

These refer to the structural design of the noise barrier itself.

Determination of Primary and Secondary Design Loads. Primary design loads are those that ordinarily are critical for the barrier's structural design. These normally are wind and vehicular impact. If the barrier is located far from the right-of-way, vehicular impact may not be a design consideration.

Secondary design loads must also be considered, but are usually not critical. These normally include gravity loads, loads from water pressure, snow loads, and earthquake loads.

Design of Barrier Elements for Given Loads. Although this step might seem trivial, it is not. Structural elements in noise barriers are not easily categorized as beam, columns, or barriers. Consequently, there may be confusion about which code provisions to apply. In addition, some proprietary noise barrier systems use structural configurations or structural materials for which code design provisions are not available. In such cases, design and approval may have to be on the basis of test data or the general provisions of the building code.

Detailing of Movement and Construction Joints. The noise barrier must be provided with joints to accommodate deformations due to structural loads, differential settlement of the underlying soil, and differential shrinkage or expansion of barrier materials. The movement capabilities of the joints are determined by the most critical of the above effects. The joints must accommodate inter-element movements to prevent spalling, which can have structural as well as aesthetic consequences.

Any gaps introduced into the barriers by the joints must not be so large as to compromise the acoustical performance of the barrier. As noted earlier in this chapter (in the section dealing with drainage), this is usually not a difficult requirement to meet.

In particular, the connection to the foundation (usually a drilled shaft) must be carefully detailed to limit the deformations of the barrier under design loads, while permitting simple construction and replacement.

Requirements Imposed by Adjacent Utilities

Influence of Buried Utilities. If buried utilities exist, these impose constraints on the type of foundation that can be used for the barrier. Either the buried utilities must be re-located, or the foundation must avoid the utilities, or the barrier must be of a type not requiring a buried foundation.

Influence of Overhead Utilities. If adjacent overhead utilities exist, these impose limitations on the maximum height of the barrier, and also limitations on the way cranes are used in the construction process. It may be necessary to re-locate overhead utilities, or modify the alignment of the noise barrier.

Access for Future Maintenance. In addition, the presence of the noise barrier can restrict future maintenance access to the overhead utilities. There are no maintenance plans. This problem is handled by the utility company and is coordinated with TxDOT early in the design phase.

Soil - Foundation Requirements

Relation Between Soil Type and Foundation Type. In theory, different types of foundations would be optimum for different types of underlying soil. It might therefore be supposed that foundation design requirements would have a significant influence on the type of foundation used for any particular noise barrier. However, this is not the case.

Influence of Construction Technology of Trend toward Drilled-Shaft Foundations. The structural standardization associated with the use of a single type of foundation has significant design and cost advantages. In addition, new technology (the "auger pile" technique for excavating and placing concrete in a drilled shaft in a single operation) has significantly reduced the costs of drilled shafts in general.

Resistance to Differential Settlement and Future Collapse. Because drilled shaft foundations are highly resistant to differential settlement, and because they greatly reduce the possibility of collapse (as contrasted with foundations involving grade beams only), modern noise barrier design has tended to favor the use of drilled shaft foundations on 6 to 7 m (20 to 24-foot) centers, regardless of the underlying soil.

Requirements Related to Vehicular Impact

In assessing requirements related to vehicular impact, the first decision to be made is, "should the barrier be designed for vehicular impact at all?" If the barrier is located far from the right-of-way, design for vehicular impact would seem unnecessary. If the barrier is located on the right-of-way, general design standards would normally determine whether or not vehicular impact would have to be considered.

If it is decided that a noise barrier should be designed for vehicular impact, the performance criteria must then be clearly stated. Should the barrier be designed to re-direct vehicles, or to slow them down without serious injury to their occupants? The design forces and energy absorption demands associated with actual vehicle impacts can considerably exceed the AASHTO code-mandated design loads for vehicular impact. Noise barriers designed with an integral vehicle impact barrier in their lower portion pose additional design questions. The upper part of the barrier (the portion intended as a noise barrier only) must not collapse when a vehicle impacts the lower portion of the barrier. In such cases, it may be preferable to place the barrier so that it is not susceptible to vehicular impact, or to protect it with separate vehicular impact barrier.

In addition to these considerations, noise barriers that may be impacted by vehicles must be designed so that any debris resulting from that impact does not endanger other vehicles or the neighborhood behind the barrier. This requirement applies to the entire noise barrier, and is in addition to the general strength and energy absorption requirements of that portion of the barrier specifically designed to resist vehicular impact.

SERVICEABILITY REQUIREMENTS FOR NOISE BARRIERS

Serviceability requirements for noise barriers are related primarily to the life-cycle cost of such barriers. These include the following requirements:

Capability for Relatively Simple Replacement

Over time, noise barrier posts may lean, and need to be plumbed or replaced. As a result of vehicular impact, posts or the panels between them may be badly damaged. It must be possible to replace posts or panels without much more effort than was originally required to install them.

Resistance to Surface Degradation

Noise barriers must retain their surface appearance in spite of natural weathering, and also hazards such as graffiti. Barriers must be easy and inexpensive to clean. If necessary, they must accept clear coatings or sealers that increase their resistance to graffiti or their ability to be cleaned.

Resistance to Joint Degradation

As noted above, noise barriers must be provided with movement joints to accommodate differential movement due to various causes. If these joints are closed with elastomeric sealants, those sealants must be accessible for replacement.

CHAPTER 10. SUMMARY AND CONCLUSIONS

SUMMARY

The Center for Transportation Research (CTR) at The University of Texas at Austin was selected by the Texas Department of Transportation (TxDOT) to conduct a three-year study to develop effective highway noise barrier solutions for Texas. This research study has the following objectives:

- Evaluate existing noise barrier materials and systems in use by TxDOT with regard to their acoustic performance, visual aesthetics, structural requirements and cost-effectiveness.
- Evaluate existing noise barrier materials and systems in use by other states and the feasibility of new products and materials in comparison to existing TxDOT systems.
- Develop performance criteria for different geometric and terrain conditions that permit the quantification of acoustic performance, aesthetics, structural soundness, and life-cycle cost.
- Develop a methodology for selecting application specific designs based upon the roadway geometry, the surrounding terrain and cultural features, and the environment.
- Develop a model for evaluating parallel reflections of noise barriers and make recommendations as to when it should be used for design.
- Develop improved specific noise barrier system designs, including material specifications, acoustical and structural design methodologies, and construction details.

The CTR proposal divides the study into three work phases; the first of which is completed with this report. The first phase consisted of a review of existing worldwide literature and a documentation of the current practice in Texas. Phase II will review existing practices in noise barriers in other states and Phase III will produce a recommended guideline for TxDOT district offices to use to analyze, design and construct effective noise barriers.

This final chapter summarizes the findings of Phase I and the conclusions derived by the researchers. Chapter 9 of this report, Preliminary Performance Criteria, has been developed as a draft stand-alone document. After feedback has been received from TxDOT, the final document will be made available to TxDOT personnel for use as a guide in determining if noise barriers have been effectively analyzed, designed and constructed.

Literature Review

Chapter 2 of this report summarizes the literature review. It documents the importance of mitigating highway traffic noise, and reviews the methods traditionally used for acoustical measurement of noise barrier performance. The NCHRP *181 Synthesis 181*, prepared by Bowlby in 1992 [2], and the report published by the Danish Ministry of Transport, *Noise Barriers - A Catalogue of Ideas* [10], were found to be excellent reviews of the current design practices and noise barrier technology. These documents and many others are maintained in CTR's library of noise barrier reference material.

Our literature review includes several acoustical reports, including field tests of parallel noise barriers. The literature review did not gather much data on life-cycle costs of noise barriers. The review indicates that noise barriers are generally regarded as cost-effective if they cost less than $25,000 ($30,000 in California) per first-row residence. We shall continue to search for additional information in this area.

Communication with TxDOT Districts

This project began with a meeting of the study's research committee to set the specific objectives of the research team. As a result of this meeting, the team was directed to visit five district offices, and to invite representatives from all districts to attend one of the five meetings. Meetings with District personnel were held in Austin, San Antonio, Fort Worth, Dallas and Houston. The purposes of the meetings were to inform the districts of the scope of this research project, to provide background on the basic acoustical theory behind noise barriers, and to hear and discuss the experiences of districts that have constructed noise barriers. The five meetings were very successful, and were attended by 67 TxDOT personnel from nine different districts.

In developing the agenda for the district meetings, it became apparent that very few personnel in the district offices had received any formal training on the basic acoustical theory of noise barriers. We were then invited to include in our presentation to the district offices, basic material on "How Noise Barriers Work." That part of our presentation was very well received by the district offices, and is summarized in Chapter 3. Key concepts from that chapter are summarized in the following section.

How Noise Barriers Work

To design and construct effective noise barriers, it is first necessary to understand how noise barriers work, and to recognize the limitations of noise barrier performance. Problems can arise when a computer program for predicting the acoustical performance of noise barriers are trusted explicitly, without understanding its working principles and limitations.

Noise barriers basically reduce the sound level reaching receptors by blocking the straight-line path from the source to the receptor. The perceived noise, while not disappearing, is significantly reduced. By blocking the straight-line path even slightly, the noise barrier attenuates (reduces) the sound level at the receptor by about 5 dB. This attenuation, based on a logarithmic measure of sound energy, is roughly equivalent to reducing the source noise by a factor of two (halving the traffic). Making the barrier even higher, so that the sound is forced to travel along a longer path, usually produces an additional attenuation of at least 3 dB. The combined effect (a noise attenuation of 8 dB) is roughly equivalent to reducing the traffic by a factor of 4.

For this attenuation to occur, the barrier must simply have enough mass to block most of the sound energy that strikes it. This mass is achieved by making the barrier thick enough—about 6 mm (0.25 inches) thick if it is made of steel, about 18 mm (0.75 inches) thick if it is made of concrete, masonry, or glass, and about 100 mm (4 inches) thick if it is made of wood. From an acoustical point of view, the wall's texture is unimportant. Gaps and openings in the wall are acoustically unimportant, provided that they do not exceed three percent of the wall's surface area. Finally, from the point of view of a receptor located on the far side of a single barrier, sound absorption is irrelevant—it makes no difference whether the barrier absorbs sound, or simply reflects it back toward the source. Thus, while sound-absorbing materials may have some benefits for reducing noise on the highway itself, or for reducing noise in situations involving parallel barriers, they are irrelevant for most noise barrier applications.

Noise Analysis Software

As discussed in Chapter 4 of this report, STAMINA and OPTIMA are FHWA-developed computer programs used by TxDOT districts to determine if a noise barrier is needed, and to optimize the barrier location and height. These programs have the following deficiencies:

- They do not accept CAD files as input
- They have no graphical output
- They conduct the acoustical analysis using a single frequency
- They do not permit sound sources to be adjusted to take into account the effects of
    - traffic flow (other than volume and speed)
    - pavement surface type

- They tend to over-predict noise levels, both with and without a barrier
- They tend to underestimate the negative effect of street and driveway gaps on noise barrier performance
- They do not permit analysis of the acoustical performance of parallel barriers
- They do not permit consideration of absorptive barrier surfaces

The need for better noise analysis software has been filled by commercial programs such as TrafficNoiseCAD and SoundPLAN. It is expected that the FHWA's new computational program (Traffic Noise Model, or TNM), to be released later this year, will correct the identified deficiencies of STAMINA and OPTIMA and permit more accurate and detailed analysis. However, the new TNM will require more powerful computer hardware than the currently used programs.

TxDOT Noise Barriers

TxDOT has constructed or planned noise barriers in Austin, Dallas, Fort Worth, Houston, Denton, El Paso, San Antonio and College Station. Chapter 5 includes provided photographs of typical noise barriers in several categories.

- Noise Barriers Not Intended to Resist Vehicular Impact
  - prefabricated separate post and panel system
  - prefabricated integral post and panel system
  - constructed-in-place post and panel system
  - fan-wall system
  - reinforced earth berms
- Noise Barriers Intended to Resist Vehicular Impact
  - prefabricated, barrier-mounted post and panel system
  - prefabricated safety-shape wall system

Each of the different noise barrier systems has its own advantages and disadvantages. The prefabricated separate post and panel system (using elements of precast concrete) is the most prevalent in Texas. However, walls representing other systems are used as well:

- Reinforced masonry constructed in place in Austin and San Antonio

- Precast concrete panels mounted on T501 barrier in Fort Worth
- Precast concrete safety-shape walls system in Houston
- Fan-walls in Austin and Houston
- Constructed-in-place concrete walls in Dallas.
- Earth berms in Fort Worth

TxDOT Experience with Noise Barriers

The researchers conducted both face-to-face and telephone interviews with TxDOT noise barrier designers. The results of those interviews are presented in Chapter 6. According to TxDOT designers, structural design of noise barriers is usually governed by the design wind load or by the AASHTO-mandated 45-kN (10-kip) horizontal load simulating the effects of vehicular impact. Design wind pressures varied by district from a high of 146 kg/m^2 (30 psf) to a low of 98 kg/m^2 (20 psf).

Noise barrier design was also reported to be significantly affected by the presence of overhead or underground utilities, and by the type of foundation needed. The most common foundation type was pier and beam.

Acoustical Research

As described in Chapter 7, the researchers have conducted a laboratory experiment which indicates that a noise barrier with a jagged top could have a 5-8 dB improvement in insertion loss as compared to barrier with a straight top (and a height equal to the average height of the jagged-topped barrier). This means that jagged-topped noise barriers may achieve a desired sound attenuation more economically than straight-topped barriers. More information on this concept will be provided in a separate report to be issued for this project.

Structural Research

Computer analysis is being conducted to determine the effects of vehicular impact and wind loading on typical noise barrier designs. This research will continue and will be used to develop structural performance criteria for noise barriers. These criteria will be incorporated into the design guide. More information on these subjects will be supplied in future project reports.

TASKS TO BE PERFORMED IN PHASE II

As stated earlier, the researchers are transitioning into Phase II of this three-phase study. The tasks required in Phase II are as follows:

- Compare the noise barrier systems in use in other states with those used by TxDOT.
- Evaluate potential benefits of new sound-absorbing materials.
- Evaluate acoustical design procedures, parallel reflections, and noise analysis software.
- Evaluate software for aesthetic evaluation of noise barriers before construction.
- Prepare a report on the current state-of-the-art in noise barrier technology.

The performance criteria reported in Chapter 9 are intended to be preliminary. They are proposed as design goals, and constitute a necessary step in the development of the noise barrier design guide. They are submitted for consideration and review by TxDOT. The performance criteria document is envisioned as an important aspect of TxDOT policy on how noise barriers should be analyzed, designed and constructed. Once these performance criteria are validated and quantified, standardized noise wall designs can be developed that meet them. Therefore, it is important that CTR work with TxDOT to validate the noise barrier performance criteria.

In Phase II it will be necessary to contact noise barrier designers in other states. The researchers have established communication with members of the TRB Highway Noise Subcommittee; these contacts will be more fully exploited in Phase II.

The issue of noise barrier absorption will be further explored in Phase II. Manufacturers' claims will be analyzed and checked by test if necessary. The performance criteria will be revised to address the possible application of absorptive materials.

The issues of acoustical design procedures, parallel reflection, and noise analysis software will also be fully addressed. As reported earlier, there are serious deficiencies with the existing software used for barrier analysis. The new FHWA TNM/TNS is expected to be released soon. There are many issues to review for using this new software.

The new software will be capable of a more detailed analysis. However, the districts will need training not only on the software, but on how to interpret the results. The new software will add many new features including a parallel noise barrier analysis. The researchers will explore the limits of this software and make recommendations on how it should be used for effective noise barriers.

Some of the research team are also working on a complimentary project to evaluate the effectiveness of the noise barrier constructed on FM3009 in the San Antonio District. This field analysis will provide additional data for evaluating TxDOT noise analysis procedures.

A separate task is planned to evaluate software that could be used by district offices to evaluate the aesthetic aspects of noise barriers and present renderings to the public. This has proven useful in other states and will be evaluated. The research project conducted by Texas A&M University which surveyed aesthetic treatment of noise barriers by the states will be reviewed.

Research into the potential acoustical advantage of a jagged-edge barrier will continue with further analysis. Extrapolation of laboratory scale experiments to potential field results will be attempted. A separate technical report will be provided during Phase II. Research into structural analysis of noise barriers started in Phase I will continue into Phase II.

Concluding Remarks

- TxDOT needs performance-based design standards and materials specifications for noise barriers.
- Potential advantages in sound attenuation may be obtained by altering the fundamental shape of the noise wall (for instance, by using a jagged top edge or sloping the traffic face of the barrier).
- Structural design criteria must be extended to address drift limits and the effects of vehicular impact.
- The capabilities of noise modeling programs should be systematically documented in order to provide TxDOT personnel with the best available for estimating current and future noise levels.

It is the intent of this research study to address these needs.

REFERENCES

1. "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," US EPA, March 1974.
2. Bowlby, W., *NCHRP Synthesis of Highway Practice 181: In-Service Experience with Traffic Noise Barriers*, Transportation Research Board, National Research Council, Washington DC (1992).
3. Wirt, L. S., "The Control of Diffracted Sound by Means of Thnadners (Shaped Noise Barriers)," *Acustica* 42 (1979), pp. 73-88.
4. Kurze, U. J. and Anderson, G. A., "Sound Attenuation by Barriers," *Appl. Acoust.* 4, pp. 35-53, 1971.
5. Maekawa, Z., "Noise Reduction by Screens," *Appl. Acoustic.* 1, pp. 157-173, 1968.
6. *Report on Reevaluation of the Connecticut Department of Transportation Retrofit Noise Abatement Program*, The Office of Environmental Policy, Connecticut Department of Transportation.
7. Hatano, M., and Hendriks, R.W., "Traffic Noise Attenuation as a Function of Ground and Vegetation," Interim Report, California Department of Transportation, Office of Transportation Materials and Research, Sacramento, September 1989.
8. *Noise Guideline 1992*, Texas Department of Transportation, Division of Highway Design, Austin, Texas.
9. Herman, L., Bowlby, W., and Brisson, R., "Determination of Traffic Noise Barrier Effectiveness: An Evaluation of Noise Abatement Measures Used on I-440," Tennessee Department of Transportation, Nashville, TN, 1990.
10. "Noise Barrier—A Catalogue of Ideas," Road Data Laboratory, Road Directorate, Ministry of Transport, Report 81, Denmark, 1991.
11. Blum, Randolph F., A Guide to Visual Quality in Noise Barrier Design, Implementation Package 77-12, U.S. Department of Trasportation, Federal Highway Administration, December 1976.
12. Hendriks, R.W., "Field Evaluation of Acoustical Performance of Parallel Noise Barriers Along Route 99 in Sacramento, California," Report FHWA/CA/TL-91-01.
13. *Effectiveness of Parallel Noise Barriers—An Iowa* Study, Final Report, Federal Highway Administration Work Order DTFH71-83-3610-1A-12, Iowa Department of Transportation, Planning and Research Division, August 1987.

14. Flemming, G. and E.J. Rickley, "Parallel Barrier Effectiveness—Dulles Noise Barrier Project," Final Report, USDOT, Cambridge, Massachusetts, May 1990.
15. Pejaver, D.R. and J.R. Shadley, "A Study of Multiple Reflections in Walled Highways and Tunnels," Report No. DOT-FH-11-8287, prepared for Federal Highwa Administration, Washington, D.C., 1976.
16. Rickley, E.J., U. Ingard, Y.C. Cho and R.W. Quinn, "Roadside Barrier Effectiveness: Noise Measurement Program," Report No. DOT-TSC-NHTSA-78-24, National Highway Traffic Safety Administration, Washington, D.C., 1978.
17. Menge, C.W., "Highway Noise: Sloped Barriers as an Alternative to Absorptive Barriers," Noise Control Engineering, Vol. 14, No. 2, March-April 1980, pp. 74-78.
18. Legillon, H., "Les ecrans absorbants en bordure de routes: Utilite et caracterisation," Bulletin de Liaison de la Laboratoire des Ponts et Chausees, Vol. 96, July-August 1978, pp. 33-39.
19. May, D. and M. Osman, "Highway Noise Barriers: New Shapes," Journal of Sound and Vibration, Vol. 71, No. 1, 1980, pp. 73-101.
20. U.S. Department of Transportation, Federal Highway Administration, "Highway Traffic Noise Analysis and Abatement—Policy and Guidance," Office of Environment and Planning, Noise and Air Quality Branch, Washington, D.C., June 1995.
21. *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, 23 C.F. R. Part 772, Federal Highway Administration, Washington, D.C., 1982.
22. Highway Traffic Noise Barrier Construction Trends, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., August 1994.
23. Godfrey, S.H., Storey, B.B., Highway Noise Barriers:1994 Survey of Practice, Texas Department of Transportation, Texas Transportation Institute, November 1994.
24. Hendriks, R. W. and Hatano, M. M., "Evaluation of Noise Barriers," *Final Report FHWA/CA/TL-97/03*, California Department of Transportation, Sacramento, January 1987.
25. Bowlby, W., L.F. Cohn, and R.A. Harris, "Design Method for Parallel Traffic Noise Barriers, "Journal of Transportation Engineering, Vol. 113, No. 6, pp. 672-685, American Society of Civil Engineers, New York, November 1987.
26. Lee, V.M., R.A. Michalove, and S. Slutsky, "Tilted Parallel Barrier Program: Application and Verification in Transportation Research Record 1176," Transportation Research Board, National Research Council, Washington, D.C., 1988.
27. Advertisements, *The Wall Journal*, Issue No. 16, March/April 1995.

28. "SoundPLAN," Pelton March Kinsella Consultants in Acoustics, Theatre, Television and Audio/Visual Design, 7950 Elmbrook Drive, Suite 100, Dallas, TX 75247-4951.
29. Horak, E., B.M.J.A. Verhaeghe, F.C. Rust and C. Van Herden, "The Use of Porous Asphalt on Major Roads in Johannesburg," *Proceedings,* 6th Conference on Asphalt Pavements for Southern Africa.
30. Ogle, T. W. and R. L. Wayson, "The Effect of Vehicle Speed on Sound Frequency Spectra," *Proceedings,* Noise Conference 94: Progress in Noise Control for Industry, Fort Lauderdale, FL, May 1994.
31. *Structural Design Specifications for Noise Barriers,* American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 1989.
32. *Concrete Masonry Highway Noise Barriers,* National Concrete Masonry Association.(NCMA-TEK 106A), Herndon, Virginia.
33. *Uniform Building Code*, International Conference of Building Officials, Whittier, CA, 1991.
34. *Standard Specifications for Highway Bridges 15th Edition*, American Association of State Highway and Transportation Officials, Washington, D.C., 1992.
35. *Manual of Steel Construction, Load And Resistance Factor Design*, American Institute of Steel Construction Inc.(AISC), Chicago, IL, 1986.
36. *Building Code Requirements for Reinforced Concrete, ACI 318.* American Concrete Institute, Detroit, MI, 1989.
37. *Structural Welding Code - Steel, 11th ed.*, American Welding Society, Miami, FL,1988.
38. Michie, Jarvis D., *NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program, National Academy Press, Washington D.C., 1981.
39. Beason, W. Lynn, and Bullard, D. Lance, "Development of A Limited-Slip Portable Concrete Barrier Connection," Research Report 1959-1, Texas Transportation Institute, College Station, Texas, 1993.

APPENDIX

TELEPHONE SURVEY QUESTIONNAIRE

Notes:

Some questions were not answered or omitted due to lack of personal experience, or were covered in an explanation of another question.

The following are a list of questions that were covered in the phone interview. In order to receive more details, a brief follow-up mail survey was sent to each participant.

Design:

1) What design specifications do you use? AASHTO Specifications?
2) How do you decide what systems/materials to put in plans, specs., and estimates?
3) Who is responsible for deciding which performance and design criteria to apply?
4) Who is responsible for quantifying this criteria?
5) Have you ever changed any design specifications based upon experience?
6) Do you allow contractors to bid unspecified alternates or provide alternates to be bid?
7) What is your process for reviewing/approving proposed materials/systems?
8) Describe special details for the following:
    - Fire Hose and Maintenance access
    - provisions for vehicular impact
    - drainage, flood control
    - foundations
9) Have you experienced any structural or material failures with noise walls?
10) If there any additional information that you would like to add describing what your district has learned regarding noise wall design?

Thank you very much for your time and cooperation. In order to assist our efforts, would you be able to complete a mailed survey pertaining to individual noise walls. This information will be used to create a database that will later be included in a product review section of our final design guideline.

To whom should I send it?

List of TxDOT personnel interviewed

Fort Worth District
John Chase
P.O. Box 6868
Fort Worth, Texas 76115
Phone: 817-370-6580

Austin District
Joe Tejidor
P.O. Drawer 15426
Austin, Texas 78761-5426
Phone: 512-832-7136

Dallas District
Van McElroy
P.O. Box 3067
Dallas, Texas 75221-3067
Phone: 214-320-6171

Houston District
John Vogel (engineering)
P.O. Box 1386
Houston, Texas 77251-1386
Phone: 713-802-5235

Mark Anthony (Research & plan preparation)
P.O Box 1386
Houston, Texas 77251-1386
Phone: 713-802-5235

San Antonio District
Jon Kilgore
4615 NW Loop 410
P.O. Box 29928
San Antonio, TX 78284-3601
Phone: 210 615-5882

Example Noise Wall Information Sheet

Wall No. ______

DISTRICT: ______________________________

STATE: ______________ CITY: ______________ ROUTE ______________

DESIGNER: ______________________________

Information:
Material(s ______________________________
Structural Type: (panel, fan, earth berm) ______________________________
Height and Length: ______________________________
Foundation Type ______________________________
Location with respect to ROW ______________________________
Drainage system ______________________________
Utilities: (overhead, buried) ______________________________
Finishes: (color, texture) ______________________________
Openings for access to ROW ______________________________
Vehicular Impact Considered? (Yes, No) ______________________________
Traffic: (current, design)
ADT ______________________________
%Trucks ______________________________
Cost: ______________________________
Year Constructed: ______________ Type I or II ______________
Maximum Design Wind Load ______________________________
Proprietary: (Yes, No) ______________________________
Included in File:
Structural Plans ______________________________
Pictures ______________________________
Foundation Plans ______________________________
Specifications ______________________________
Architectural Plans ______________________________
Acoustic Test Results ______________________________
Other ______________________________
Additional Information:

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