Evaluation of a Design Guide for Highway Noise Barriers in the State of Texas

by

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Thesis

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Abstract

Evaluation of a Design Guide for Highway Noise Barriers in the State of Texas

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During the initial phase of study 1471, a series of phone interviews was conducted with structural engineers from five of the TxDOT districts that had experience in the design and construction of at least one noise barrier. From these phone interviews, it was concluded that the availability of a statewide design guideline would reduce the design cost and increase the cost-effectiveness of each new barrier. Thus, improvements to current materials and design concepts was researched to gather information for a design guide. Drafts of the *Design Guide* were then evaluated to make it effective and useful in the design practice. In one evaluation, a noise barrier in Houston was re-designed using the *Design Guide* and yielded results in full agreement with the original design. Other evaluations presented comments and recommendations on TxDOT policy, aesthetic issues, and the current design process in the Houston District. These recommendations were used to revise the *Design Guide*.

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Chapter 1:

Introduction

1.1 GENERAL

Every day our nation's highways are becoming more congested. Along with this increased traffic flow is an increase in noise levels. The US Environmental Protection Agency (EPA) estimated in 1979 that more than 90 million people were exposed to excessive highway noise levels (EPA 1979). The affected public has made strong demands to state highway agencies that the abatement of traffic noise become a high priority in highway programs. These agencies have responded to the public's need, primarily through the construction of noise barriers.

A noise barrier is "... typically a solid wall-like structure located between the noise source (traffic) and the impacted receiver (human activity area)" (TxDOT 1996). Its function is to interrupt the straight-line path for sound transmission between the source and receiver, thereby reducing the level of noise at the receiver. They have become the most popular method of noise abatement, due to their effectiveness and relatively low cost (TTI 1995). By the end of 1989, thirty-nine states and Puerto Rico had spent more than $635 million on the construction of over 720 miles of noise barriers (Bowlby 1992). Texas has been one of the states actively involved in highway noise abatement. By September 30, 1994, $40 million was spent for the construction of over 34 miles of noise barriers (TxDOT 1994). The Texas Department of Transportation (TxDOT) plans to continue its involvement in noise barriers, but does have some concern over the statewide approach to barrier design.

TxDOT does not endorse a standard or set of guidelines for the design of noise barriers. Each district has its own method for selecting and designing noise barriers. This approach is an inefficient use of resources, and does not consider all the various design options and design criteria. Thus, TxDOT requested the completion of a four-year study (Project 1471) that would evaluate the current design process used by each district, the types of noise barrier systems constructed in Texas, and research new materials and concepts. The final product of the study would be a *Design Guide*, including plans and specifications, to be used by TxDOT personnel statewide.

During the initial phase of this study (1471-1 1996), a series of phone interviews was conducted with structural engineers from five of the TxDOT districts that had experience in the design and construction of at least one noise barrier. In regards to standards used in design, the AASHTO *Structural Design Specifications for Noise Barriers* (AASHTO 1989) is used by engineers as a first reference. Other references used include:

- TEK Manual published by the National Concrete Masonry Association (NCMA 1984)
- *Uniform Building Code* (UBC 1991)
- AASTHO Bridge Specifications (AASTHO 1992b)
- LRFD Design Manual (AISC 1992), ACI 318 (ACI 1995), and other material codes; and

- Other applicable codes such as the Structural Welding Codes (AWS 1988)

TxDOT engineers found that these references lacked guidelines for the minimum thickness of a free-standing barrier, deflection limits (serviceability), and vehicular impact requirements. It is the goal of the *Design Guide* to answer these questions and serve as a first reference in the design of highway noise barriers in Texas. To make the *Design Guide* effective and useful, preliminary drafts of the *Guide* were evaluated by TxDOT engineers and revised based on their comments and recommendations. In this thesis, their evaluations and comments are discussed.

1.2 SCOPE AND OBJECTIVES

1.2.1 Scope and Objectives of TxDOT Project 1471

Project 1471, *Effective Noise Barrier Solutions for TxDOT,* is a four-year study, divided into three phases. Phase I consists of a literature review of existing noise barrier systems, design and evaluation methods. The results of this phase were published in February 1996 (1471-1 1996). Phase II deals with improvements to current materials and design concepts. Structural, acoustical, and aesthetic aspects are evaluated. Structural analysis of a noise barrier impacted by a dynamic load is discussed in a second publication from this project (1471-2 1996). Research is continuing on software for aesthetic evaluation of noise barriers and factors relating to acoustical design. No publication of this work is available at this time. Phase III involves the synthesis of information from Phases I and II into the *Design Guide* for TxDOT.

The *Design Guide* is organized into five binders. The first binder contains basic material dealing with noise barrier design, and the plans, specifications and detail sheets with which the *Guide* is intended to be used. The second binder contains more detailed information on acoustics. In particular, the noise barrier reduction properties of parallel noise barriers and a discussion of the software used for noise analysis are presented. The third binder presents the software developed for the aesthetic presentation of noise barriers. A discussion of the structural analysis of a noise barrier impacted by a dynamic load is presented in binder four. The last binder is in the form of a file. It presents information pamphlets for proprietary noise barriers, and plans and cost data for noise barriers in Texas.

The objectives of Project 1471, as mentioned in the first publication (1471-1 1996), are restated here:

- 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.

1.2.2 Scope and Objectives of Thesis

In this thesis, the *Design Guide* is evaluated. The *Design Guide* was developed by working with other project personnel to modify completed project reports into a *Guide* format. At the same time, communication with TxDOT personnel was needed to develop plans and specifications to be used with the *Guide*. Once a preliminary draft of the *Design Guide* was complete it was distributed to TxDOT engineers for evaluation. Their comments and concerns helped to revise the *Design Guide*.

The objectives of this thesis are:

- to present the evaluations performed by the TxDOT engineers;
- to discuss the engineers' comments and concerns;

- to identify sections of the *Design Guide* that need to be revised; and
- to recommend changes needed to make the *Design Guide* usable.

A draft of the *Design Guide* is presented in the Appendix for reference purposes.

Chapter 2:

Background

2.1 INTRODUCTION

The intent of this chapter is to provide the reader with a brief background regarding the principles behind highway noise barriers. The first part of this chapter reviews basic TxDOT policy and guidelines for noise abatement. The next three sections discuss the acoustical, aesthetic, and structural principles used in barrier design. The information presented in this chapter is taken from the draft *Design Guide* in the Appendix. It is meant to be only an introduction to the principles of highway noise barriers. More detailed information can be found in the *Design Guide*, TxDOT's *Guidelines for Analysis and Abatement of Highway Traffic Noise* (TxDOT 1996), and the two publications from Project 1471 (1471-1 1996, 1471-2 1997).

2.2 TXDOT POLICY ON NOISE BARRIERS

A traffic noise analysis is the first step taken when noise abatement is a concern. To proceed with abatement measures, the analysis must show that there is a noise impact at the site. Noise impacts are evaluated using the FHWA Noise Abatement Criteria or a relative criterion. If a noise impact is determined to exist, TxDOT must chose one of five possible noise abatement measures. The construction of noise barriers is one of those options.

2.2.1 TxDOT Classification of Highway Noise Barriers Projects

Proposed highway noise barrier projects are classified according to FHWA guidelines as Type I or Type II. A Type I project is a proposed noise-abatement project along a new highway, or along an existing highway that will be moved to a new location, or that will be physically altered either with respect to horizontal or vertical alignment, or with respect to an increase in the number of through-traffic lanes. A Type II project is a proposed noise abatement project along an existing highway. These are sometimes referred to as a “retrofit” project.

At the current time, TxDOT has only a Type I noise abatement program. Therefore, only noise barriers of Type I are considered here.

2.2.2 Feasible versus Reasonable

In order to make a flexible choice among noise abatement measures, a wide range of evaluation criteria is provided. The criteria are also intended for use with individual cases that have special circumstances. These criteria must meet two requirements: first, abatement projects must be feasible from a technical viewpoint; and second, they must be reasonable from a socio-economic viewpoint. Feasibility focuses on engineering considerations and requires that the noise abatement measures provide a “substantial reduction” (at least 5 dBA) in noise levels. Reasonableness emphasizes the cost-effectiveness of the noise-abatement measures and considers the views of the public. A proposed noise barrier must be judged both feasible and reasonable before it can be constructed by TxDOT.

2.2.3 Public Involvement

TxDOT places a high emphasis on the views of the public throughout the traffic noise analysis, especially when noise impacts are identified and noise abatement measures are considered. Public perception, notification, and approval are all part of the public's involvement with TxDOT. In regard to noise barriers, the public perceptions of the addition of a barrier to a neighborhood are evaluated. Noise barriers are meant to be a positive addition and should be well received. TxDOT also has the responsibility of informing the public when a noise barrier is under consideration. This is usually done after sufficient information is available to adequately define the proposed barrier. Lastly, no noise barrier will be constructed without the approval, by simple majority vote, of the owners of property adjacent to the proposed noise barrier.

2.3 ACOUSTIC FUNDAMENTALS

2.3.1 Definition of Sound

Acoustics relate to sound and the sense of hearing. *Sound* is a wave of energy produced by the movement of compressed air waves. It radiates spherically from a source and exerts pressure on the human eardrum. Sound energy or intensity is proportional to the square of that pressure. Put simply, sound is what we hear.

2.3.2 Sound and Noise Barriers

As stated in Chapter 1, the primary function of a noise barrier is to interrupt the straight-line path for sound transmission between the source and the impacted receiver, thereby reducing the level of noise at the receiver. The attenuation is roughly equivalent to reducing the noise level by a factor of two (halving the traffic). Additional attenuation can occur if the barrier height is increased further.

2.3.3 Transmission Loss and Insertion Loss

Sound hitting a noise barrier is subject to two types of loss. *Transmission loss* is the amount by which the sound is reduced when it is forced to travel through a barrier. Transmission loss depends on the mass of the barrier, and can be expressed as the minimum thickness, of different barrier materials, required to produce a minimum acceptable transmission loss (usually 30 dB). These minimum thicknesses are referenced in the *Design Guide* in the Appendix. If the barrier has the minimum required thickness to achieve the desired transmission loss, it can be assumed that the majority of sound is forced to travel a longer path. The decrease in noise level at the receiver as a result of this longer path is termed *insertion loss*.

2.4 AESTHETIC FUNDAMENTALS

The aesthetic design of a noise barrier involves the impact the barrier has on its physical and human surroundings. In regard to its physical surroundings, a barrier may be perceived differently in various settings. It may be imperceptible in an urban setting, and dominate a rural setting. In this thesis, impact on human surroundings is discussed from the viewpoint of the driver and of the receiver.

2.4.1 Visual Impact on the Driver

The visual impact of a noise barrier on the driver depends on four factors.

1) The speed of the vehicle: the lower the speed, the more noticeable will be the details of the barrier.

2) The height of the barrier: the greater the height, the greater tendency for a "tunnel” effect, which may cause the driver to feel uncomfortable.

3) The distance of the barrier from the roadway: if the driver is very close to the barrier, details will be practically unnoticeable; as distance increases, they will become more noticeable; and at large distances, they will again become less perceptible.

4) Surface texture: this affects the compatibility of the barrier with its physical surroundings. It is noticeable to the driver if the barrier does not complement its surroundings.

2.4.2 Visual Impact on Receiver

The receiver is affected by many of the same factors that affect the driver. For example, if the barrier is too high, receivers may feel that it towers over their homes or businesses, restricts their views, or blocks their view of businesses or signs. Another factor is the distance between the barrier and the receiver. As this distance decreases, the receiver may feel confined or restricted, and air circulation may be reduced. Color also has an influence on the visual impact of a noise barrier. If the color of the barrier is intrusive it can create negative feelings for the receiver. The most significant impact occurs when the above factors, combined with surface texture, change the patterns of light and shadow on the receiver's property.

2.5 STRUCTURAL FUNDAMENTALS

2.5.1 Design Loads for Noise Barriers

Like any structure, a noise barrier must be designed to resist the loads that it will experience during its service life. Governing design loads on a noise barrier usually include wind and gravity; under some cases, it is also necessary to consider loads such as water pressure, snow, and earthquake.

2.5.1.1 Wind Loadings on Noise Barriers

Wind loads must be considered in the design of any structure located outdoors. For a noise barrier, wind load is modeled as a pressure acting over the vertical face. This pressure is calculated using an equation from the *AASTHO Structural Design Specifications for Noise Barriers* (AASHTO 1989). The equation is based on the design wind speed of a 50-year mean recurrence interval. It also considers factors for drag, structure height, structure exposure, and location. A detailed procedure for applying design wind loads to noise barriers is available in the *AASTHO Structural Design Specifications for Noise Barriers* (AASHTO 1989).

2.5.1.2 Vehicular Impact on Noise Barriers

According to current TxDOT criteria, all objects within the clear zone must either be designed for vehicular impact or be protected by an appropriate vehicular impact barrier. The clear zone is the unobstructed, relatively flat area outside the edge of traveled way, including shoulder and sideslope, for the recovery of errant vehicles. If the noise barrier is located on the right-of-way line, general design standards would normally determine whether or not vehicular impact would have to be considered. The right-of-way is the land area (width) acquired for the provision of a highway. Any vehicular impact barrier must re-direct vehicles or slow them down without serious injury to their occupants. The design forces and energy absorption demands associated with actual vehicular impacts considerably exceed the AASHTO code-mandated design loads for vehicular impact. Noise barriers designed for vehicular impact typically must be crash-tested in accordance with NCHRP 350, Test Level 3, to gain FHWA acceptance (NCHRP 1993, FHWA 1996b).

Noise barriers designed with an integral vehicular 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 a separate vehicular impact barrier.

When considering vehicular impact, several solutions can be applied:

- place the noise barrier beyond the right of way;
- use landscaping to redirect the 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; or
- design the noise barrier for vehicular impact.

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 general strength and energy absorption requirements. For Project 1471, other analytical research has been conducted to study static and dynamic vehicular impact loadings on noise barriers. The results of the first part of that research are available in Report 1471-2 (1996). The rest of that research still in progress, should be published in the summer of 1998.

2.5.2 Movement Joints in Noise Barriers

Joints are needed in noise barriers to accommodate deformations due to structural loads, differential settlement of the underlying soil, and differential shrinkage or expansion of barrier materials. To prevent spalling, joints must allow inter-element movements. A joint may create a gap in the barrier, but must be small enough so it will not compromise the acoustical performance of the barrier. It is important that the connection to the foundation be carefully detailed to limit the deformations of the barrier under design loads, while permitting simple construction and replacement.

Chapter 3:

Evaluations of the *Design Guide*

3.1 INTRODUCTION

The objective of the *Design Guide* is to provide TxDOT with a standardized, performance-based process for designing highway noise barriers. To make the *Design Guide* effective and useful, preliminary drafts of the *Guide* were evaluated by TxDOT designers and revised based on their comments and questions. Their assistance and feedback is gratefully acknowledged.

This chapter discusses the evaluations performed by the TxDOT engineers. This chapter also appears in the appendix as part of the *Design Guide*. The first evaluation focuses on a noise barrier that had been previously designed using current TxDOT district design methods. The *Design Guide* was used to re-design the noise barrier. The last two evaluations discuss comments and recommended revisions made by TxDOT personnel from the Houston and San Antonio districts.

3.2 NOISE BARRIER EVALUATION 1 (SEPTEMBER 1997)

The information presented in this section is based on communications with Mr. Larry Blackburn and Mr. Amer Qureshi, of the Houston District.

3.2.1 TxDOT Personnel

Mr. Blackburn is a Supervising Design Engineer in the Houston District office. Mr. Qureshi works with Mr. Blackburn in the Central Design - B Division of the Houston District. Mr. Qureshi had not had any previous experience in the design of noise barriers, and was chosen for this evaluation to assess the usefulness of the *Design Guide* to a novice user.

3.2.2 The Noise Barrier

The noise barrier used in this evaluation will be located in Houston on FM 529. By August 1997, the barrier had been designed by TxDOT using the process described in the next section. The barrier was let for construction in September and was scheduled for construction in the spring of 1998.

3.2.3 Current TxDOT (Houston District) Design Process

The design of noise barriers in the Houston District is a group effort involving the Environmental, Geotechnical, Design, Bridge, and Laboratory Departments. The Environmental Department specifies the preliminary height and length of the noise barrier. The Geotechnical Department takes borings to determine the soil characteristics, and chooses a suitable footing type. The Bridge Department checks the footing design and the steel quantities. The Design Department determines the final design elements of the noise barrier, including the final proposed location, after consideration of site distances and property boundaries.

3.2.4 *Design Guide* Process and Results

Mr. Qureshi received a preliminary copy of the *Design Guide* (contained in the Appendix). After reading through the *Guide*, Mr. Qureshi used the descriptions of types of noise barriers to choose a prefabricated, integral post-and-panel-system with a panel length of 20 feet. He specified a portland cement-based material due to durability and low cost. He was given the height and length of the noise barrier by the Environmental Department. Those dimensions were 10 and 534 feet, respectively, and were chosen so that noise levels in affected residential areas would be reduced to the recommended levels.

He chose a drilled shaft foundation with grade beams. He specified that the wind load be calculated on the barrier as recommended by AASHTO guidelines using a factor of safety of 1.3. He also specified that gravity, water pressure, snow, and earthquake loads be considered. However, many of these loads are not applicable in the Houston area. He found that the combination of wind load applied to the top of the barrier and the type of soil were the critical factors in the design of the drilled shafts. He consulted the Geotechnical and Bridge Departments for questions related to the technical details of the proposed design. His results are in full agreement with the design produced in the original barrier design.

3.2.5 Further Evaluation Comments

Mr. Qureshi did find the *Design Guide* helpful in understanding the numerous components of a noise barrier and how they work together to form the noise barrier system. It was useful in selecting the physical aspects of a noise barrier. He did not feel that there was adequate explanation of the structural aspects of noise barriers. He suggested including two or three design examples of noise barriers for different soil conditions, and also references to other reading material.

3.3 NOISE BARRIER EVALUATION 2 (APRIL 1998)

The information presented in this section is based on communication with Mr. James Darden and Ms. Debbie Taylor of the Houston District.

3.3.1 TxDOT Personnel

Mr. Darden is the head of the Project Development Department in the Houston District office. Ms. Taylor is the Environmental Supervisor in the Environmental Section of Project Development. Her previous experience in noise barrier design includes conducting preliminary noise studies, running computer programs STAMINA and OPTIMA, and reviewing final designs. Ms. Taylor was chosen to review the *Design Guide* to provide comments and revisions from a more experienced designer.

3.3.2 Current TxDOT (Houston District) Design Process

That process is described in Section 3.2.3 and will not be repeated here.

3.3.3 Comments and Revisions

Ms. Taylor's comments and suggested revisions on the *Design Guide* concentrated mainly on TxDOT policy, aesthetics, and the design process of noise barriers in the Houston district. Some corrections were made to update TxDOT policy as described in the *Design Guide*. Other additions to public involvement and approval were also noted. More explanations and examples of ways to make noise barriers more aesthetically pleasing were included. Lastly, she expanded upon the current design process for noise barriers in the Houston District. Miscellaneous editorial comments were made throughout the *Design Guide.*

3.4 NOISE BARRIER EVALUATION 3 (APRIL 1998)

The information presented in this section is based on communication with Mr. Barrlynn West from the San Antonio District.

3.4.1 TxDOT Personnel

Mr. West is the District Geologist in the Environmental Section of the Advanced Transportation and Planning Department in the San Antonio District office. Mr. West had no previous experience in the design of noise barriers, and was chosen for this evaluation to assess the *Design Guide* from the viewpoint of a novice.

3.4.2 Current TxDOT (San Antonio District) Design Process

The San Antonio District had designed one noise barrier, using two engineers: one from the Environmental Section, and the other from the Advanced Planning Section. The Seguin area office was also consulted on the design of the barrier. This process was used to design only one noise barrier, and may be modified for future designs.

3.4.3 Comments and Revisions

Mr. West had few comments on the *Design Guide*. The remarks he did have related to TxDOT policy and the acoustical function of noise barriers. He recommended revisions of some aspects of TxDOT policy and clarification regarding the acoustical function of noise barriers.

3.5 CONCLUDING REMARKS

The comments and recommendations provided by Mr. Qureshi, Ms. Taylor, and Mr. West were used to revise the *Design Guide*. This section explains how their comments were incorporated and what changes were made to the *Design Guide.*

First, a design example of a noise barrier in the Fort Worth district was incorporated in the *Design Guide* to illustrate some of the structural aspects in noise barrier design. Next, the *Design* Guide's explanations of TxDOT policy were revised to clarify when a noise barrier is mandated for consideration. Recommendations were also added to the policy, explaining how to deal with lack of public response. The chapter on noise barrier aesthetics was expanded with examples of barrier panel types and surface treatments that create a more aesthetically pleasing noise barrier. To clarify the acoustical function of noise barriers, references were cited and noted in the *Design Guide*. Lastly, the explanation of the current design process for noise barriers in the Houston District was expanded by explaining in more detail the duties of the Design Department.

Chapter 4:

Conclusions and Recommendations

4.1 SUMMARY

The objective of the *Design Guide* is to provide TxDOT with a standardized, performance-based process for designing highway noise barriers. The need for a *Design Guide* became apparent during the initial phase of study 1471. Phone interviews with TxDOT engineers found that the current design process for noise barriers in Texas is not standardized. It was concluded that the availability of a statewide design guideline would reduce the design cost and increase the cost-effectiveness of each new barrier (1471-2 1996). The *Design Guide* was evaluated by TxDOT personnel to make it effective and useful in practice. This thesis presents the evaluations and comments on the *Design Guide* made by TxDOT personnel.

4.2 CONCLUSIONS

TxDOT personnel from the Houston and San Antonio districts participated in the evaluations. From their comments and recommendations the following can be concluded:

- When used to re-design a noise barrier, the *Design Guide* is effective in yielding results in full agreement with those from the original design.

- The *Design Guide* is useful in selecting the physical aspects of a noise barrier.
- The *Design Guide* is helpful in understanding the numerous components of a noise barrier and how they work together to form the noise barrier system.
- After the addition of a design example, the *Design Guide* is a good reference for understanding the structural aspects of noise barriers.
- After minor revisions, the *Design Guide* is in agreement with current TxDOT policy.

4.3 RECOMMENDATIONS

Although three evaluations of the *Design Guide* were performed, only one involved the design of a noise barrier. The results of that evaluation, in particular, were very helpful in revising the *Guide*. Thus, it is recommended that additional evaluations involving the design (or re-design) of noise barriers be completed using the *Design Guide*.

As stated in chapter one, the final *Design Guide* will be composed of five binders. During the evaluation period, only the first binder was available. It is recommended that additional evaluations be made on the first binder and future evaluations be made on the remaining binders. This will ensure that the complete *Design Guide* is effective and useful to TxDOT engineers.

Module 1

Overview of the Design Process for Highway Noise Barriers

1.1 INTRODUCTION

Highway noise barriers (sometimes referred to as “noise walls” or “sound walls”) are intended to mitigate the effects of highway noise on activities near the highway. They do this primarily by blocking the direct path that sound must travel between the source of sound on the highway, and the receiver exposed to the sound.

In this Module 1, types of noise barriers used in Texas are introduced; the basic acoustical function of noise barriers is summarized; and the TxDOT design process for highway noise barriers is briefly reviewed, with emphasis on key decisions that must be made during that process.

1.2 BASIC TYPES OF NOISE BARRIERS

Many different noise barrier systems are 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 binder, noise barrier systems used in Texas are classified as follows:

- Noise Barrier Not Required 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
    - earth berms
- Noise Barriers Required to Resist Vehicular Impact
    - prefabricated, barrier-mounted, post-and-panel system
    - prefabricated, sloped-face wall system

As currently implemented, TxDOT policy is that all highway noise barriers that are located within the clear zone are required to resist vehicular impact. All such barriers must be crash-tested. In practical terms, the most effective way to meet these requirements is to put a crash-tested vehicle impact barrier in front of the noise barrier. The noise barrier itself would then not have to be designed for vehicular impact.

In the remainder of this Module, each system is described, and is illustrated by photographs of example walls (1471-1 1996).

1.2.1 Noise Barriers Not Required to Resist Vehicular Impact

1.2.1.1 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 1.1. The panels are usually of precast concrete, but can also be of other materials. The space between the posts can be filled either by a single panel, or occupied by several shorter panels, stacked vertically. The posts are usually of either concrete or steel. Figure 1.2 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 1.3 (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.

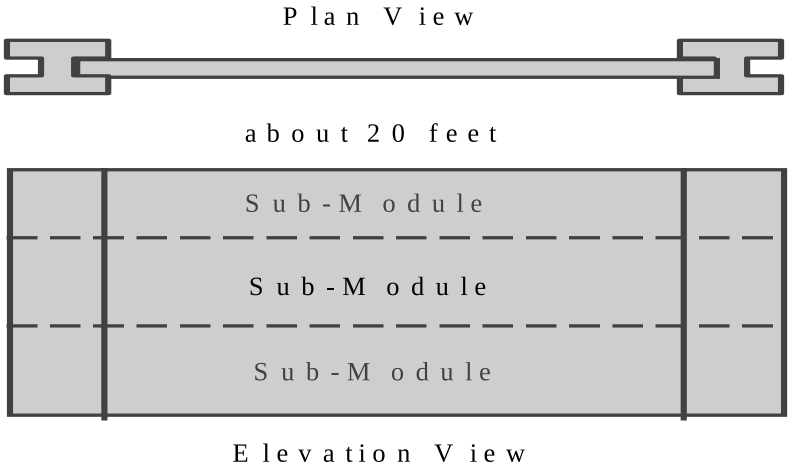


Figure A1.1 Schematic illustration of prefabricated, separate post-and-panel system for highway noise barriers

Figure A1.2 Example of prefabricated, separate post-and-panel system (Houston District)

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. The post spacing typically 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.

Figure A1.3 Close-up view of column on noise barrier of Figure 1.2

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 1.4, 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.

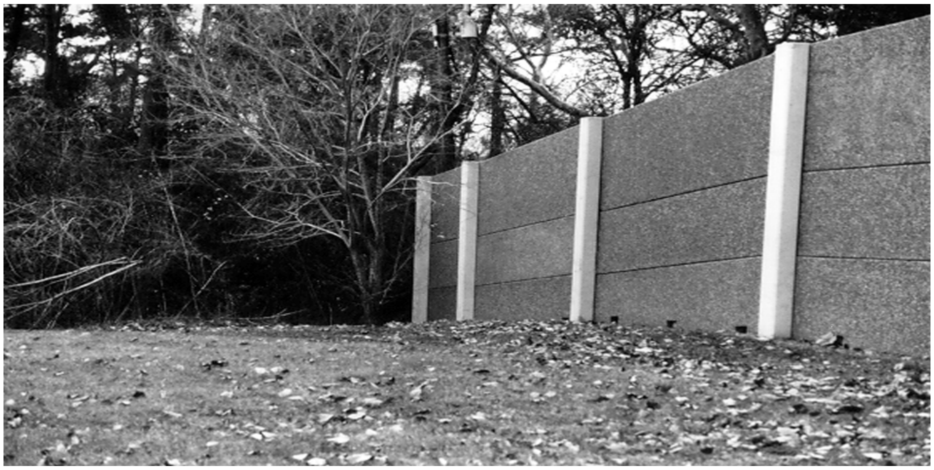


Figure A1.4 Example of prefabricated, separate noise barrier system (Houston District)

1.2.1.2 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 1.5. After the monolithic post-and-panel elements are placed, the post ends of the panels are most often bolted from the top panel to the drilled shaft foundation or post-tensioned using a cable embedded into the drilled shaft and threaded through the panel or panels as they are lowered into place.

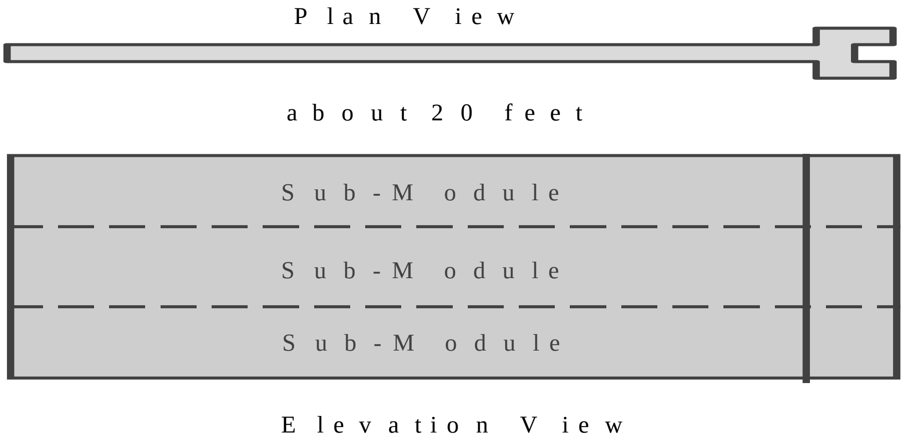


Figure A1.5 Schematic illustration of prefabricated monolithic system for highway noise barriers

1.2.1.3 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 1.6 shows an example of this system, constructed in reinforced masonry in the Austin District. The San Antonio District has a nearly identical design.

Figure A1.6 Constructed-in-place post-and-panel system (Austin District)

Although constructed-in-place reinforced concrete barriers are possible, no barriers of this type are known to exist 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.

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.

1.2.1.4 Serpentine-Wall System

A serpentine-wall system is popularly known as the fan-wall system and will be referred to as the fan-wall system throughout the rest of the *Guide*. It 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 1.7 was specifically chosen due to the presence of buried utilities.

Figure A1.7 Example of fan-wall system (Austin District)

The Houston District has constructed examples of the fan-wall system (Figure 1.8). The fan-wall system used in Houston differs in footprint from that of the one used in Austin. The Houston system is wider, requiring more ROW. Even though 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.

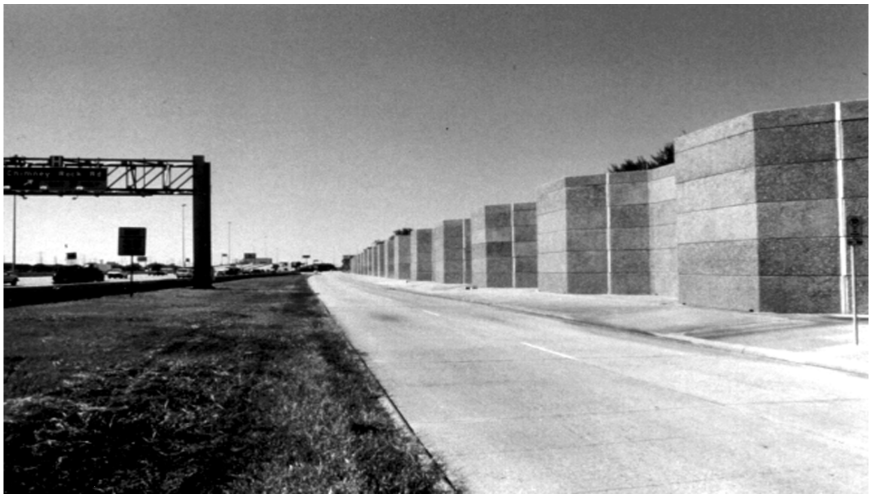


Figure A1.8 Example of fan-wall system (Houston District)

1.2.1.5 Staggered-Wall System

The staggered-wall system alternates straight 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 1.9, 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.

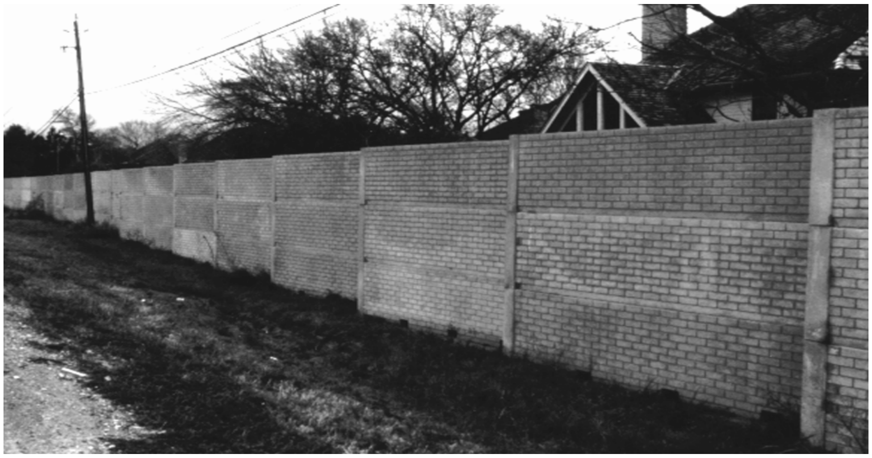


Figure A1.9 Example of staggered-wall system (Houston District)

1.2.1.6 Earth Berms

The earth berm system is simply a mound of dirt. 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. Earth berms can be topped with other types of noise barrier systems to increase the acoustical effectiveness. The main disadvantage of earth berm noise barriers is the ROW they require. Earth berms are a practical solution if space is available. The Fort Worth District has one such barrier.

1.2.2 Noise Barriers Required to Resist Vehicular Impact

1.2.2.1 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 satisfy vehicular impact and re-direction requirements for obstructions in the clear zone, 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 1.10 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 A1.10 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 stacked and 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 vehicular impact, the combination of impact barrier and mounted noise wall system has not been explicitly designed and tested for such impact. As noted later in this Binder, when a vehicle is redirected by the traffic barrier, moments in the posts holding the noise barrier can exceed the design moments from wind.

1.2.2.2 Prefabricated “Sloped-Face” Barrier Systems

The “sloped-face” noise barrier system, conceived in the Houston District, combines the potential vehicular re-direction characteristics of the mounted post-and-panel system with the aesthetic advantages of prefabricated, separate or integral systems. This system, shown in Figure 1.11, 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 threaded rod, introduced from the top and screwed into an insert that is cast in the drilled shaft.

The sloped-face system is intended to reduce the hazards of a vehicular impact. However, neither this system nor the Fort Worth barrier-mounted post-and-panel system is designed to a specific vehicular impact standard. The Houston District designs the bottom panel of this sloped-face barrier system to withstand a 10-kip concentrated static load, intended to simulate a vehicular impact. However, walls serving a dual function (as traffic barriers that define the limits of the clear zone and also act as sound walls) typically must be crash-tested in accordance with NCHRP 350, Test Level 3, to gain FHWA acceptance (NCHRP 1993, FHWA 1996b).

Figure A1.11 Example of sloped-face noise barrier system (Houston District)

1.3 PRIMER ON NOISE-BARRIER ACOUSTICS

1.3.1 Measurements of Noise

Sound is a wave. It exerts pressure on the human eardrum, and on noise-measuring instruments. Sound energy or intensity is proportional to the square of that pressure. Noise is measured in decibels (dB), a logarithmic measure of sound intensity. Small changes in dB levels mean large changes in actual sound intensity. Noise levels expressed in dBA have been weighted so that sound levels are more important if they are at frequencies to which the human ear is more sensitive. Different dBA levels are described in Table 1.1.

Table A1.1 Description of different dBA levels

Situation	**Associated Noise Level (dBA)**
recording studio	20-30
quiet room	45
typical library	50-55
typical speech range	55-70
air compressor at 50 feet	80
tractor-trailer traveling at 60 mph at 50 feet	90
jackhammer (at operator's ear)	100

Highway noise levels vary over time. To describe them in terms of a single number, the concept of "equivalent sound level" (L_{eq}) has been developed. L_{eq} is the constant sound level that contains the same average acoustic energy as the original time-varying sound level.

Current TxDOT policy mandates the consideration of Type I noise barriers for $L_{eq} \geq 66$ dBA in residential areas (see Table 1.4). Insertion loss must be at least 5 dB. This level of insertion loss is achieved by blocking the line of sight between the source and the receiver by a barrier with sufficient transmission loss. The concepts of transmission loss and insertion loss are explained below.

1.3.2 How Noise Barriers Work

Noise barriers basically reduce the sound level reaching receivers by blocking the straight-line path from the source to the receiver. While the perceived noise does not disappear, it is significantly reduced. By blocking the straight-line path even slightly, the noise barrier attenuates (reduces) the sound level at the receiver by about 5 dB (Kurze 1971). This attenuation 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 (1471-1 1996).

1.3.3 Transmission Loss

The transmission loss associated with a barrier is the amount by which the sound is reduced when it is forced to travel through the barrier. A 30-dB transmission loss means that practically all (99.9%) of the sound is being blocked. The required thickness in inches for a 30-dB transmission loss at 100 Hz is given in Table 1.2 (1471-1 1996).

Table A1.2 Required thickness in inches for 30-dB transmission loss at 100 Hz

Material	**Thickness in inches for 30-dB Transmission Loss at 100 Hz**
Steel	0.21
Concrete or Masonry	0.63
Plastic	1.81
Wood	3.66

1.3.4 Insertion Loss

Assuming that the barrier is thick enough to stop practically all of the sound going through it, the barrier blocks sound by forcing it to travel a longer path, as illustrated in Figure 1.12. This loss is termed "insertion loss." It can be estimated by hand as discussed in Module 2 of this Binder.

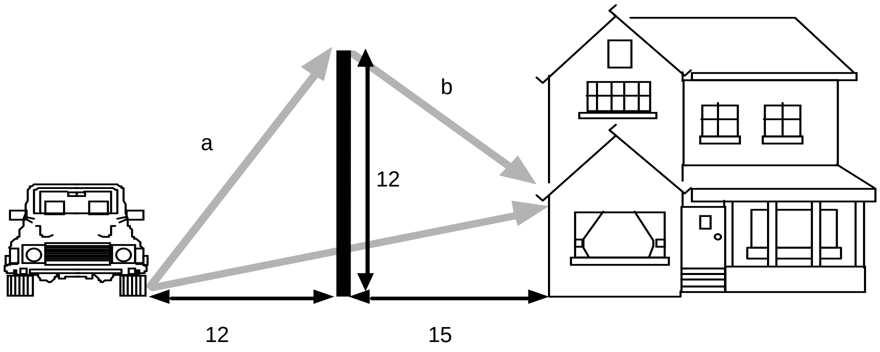


Figure A1.12 Illustration of lengthened sound path due to noise barrier

1.3.5 Effect of Different Levels of Insertion Loss

On a rule-of-thumb basis, different levels of insertion loss have the effects shown in Table 1.3 (1471-1 1996).

Table A1.3 Effects of different levels of insertion loss

Decrease in dBA Level	Corresponding Decrease in Sound Intensity	Corresponding Decrease in Perceived Loudness	Notes
10 dB	one-tenth	half	one-tenth times traffic volume
6 dB	one-fourth	--	double distance to point source
4 dB	--	--	double distance to traffic (including reflection)
3 dB	one-half	--	half traffic volume
2 dB	see note	see note	smallest perceptible difference

1.4 TXDOT POLICY ISSUES FOR NOISE BARRIERS

In this section, basic TxDOT policy regarding highway noise barriers is discussed. Fundamental definitions are reviewed; the minimum required effectiveness for noise barriers is noted; and the basic steps of the decision process for noise barriers are laid out (TxDOT 1996).

1.4.1 TxDOT Classifications of Highway Noise Barriers

In Texas, proposed highway noise barrier projects are classified according to FHWA guidelines as Type I or Type II. A Type I project is a proposed noise-abatement project along a new highway, or along an existing highway that will be moved to a new location, or that will be physically altered either with respect to horizontal or vertical alignment, or with respect to an increase in the number of through traffic lanes. A Type II project (sometimes referred to as a "retrofit" project) is a proposed noise abatement project along an existing highway.

1.4.2 TxDOT Guidelines for Analysis and Abatement of Highway Traffic Noise

1.4.2.1 Type I and Type II Noise Abatement Programs

At the current time, TxDOT has only a Type I noise abatement program. TxDOT does not have a Type II Noise Abatement Program.

A traffic noise analysis is required for all federal, federal-aid and state funded Type I highway projects. This noise analysis is the basis for decisions concerning noise abatement measures.

For a specific site to be considered for noise abatement measures, impacted receivers (see below) must experience projected noise levels in excess of the Noise Abatement Criterion given in Table 1.4. (The noise levels are to be evaluated using STAMINA). A relative criterion should be used when the predicted noise level substantially exceeds, by more than 10 dBA the existing noise level.

Type I noise abatement measures are considered for adoption by TxDOT only if they are both feasible and reasonable. A wide range of criteria is necessary to provide sufficient flexibility in abatement decision-making, and to allow consideration of special circumstances in individual cases. Feasibility generally pertains to the ability of a noise abatement measure to provide a "substantial reduction" (at least 5 dBA) in noise levels, and deals primarily with engineering considerations. Reasonableness generally pertains to the cost effectiveness of a noise abatement measure as well as the views of the public.

1.4.2.2 When is a Type I Noise Barrier Feasible from a Technical Viewpoint?

A proposed Type I noise barrier is feasible if:

1. The barrier must produce a reduction of at least 5 dBA at the impacted receivers. (Note that the noise barrier does not have to reduce noise levels at the impacted receivers to a value less than the Noise Abatement Criteria).
2. The 5-dBA noise reduction must be achievable within the constraints of access, topography, drainage, safety, and maintenance requirements. It must be achievable even considering other (non-traffic related) noise sources in the area.

Table A1.4 FHWA Noise Abatement Criteria (NAC)

Activity Category	**dBA L_{eq}**	**Description of Land Use Activity Areas**
A	57 (exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need, and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 (exterior)	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries and hospitals.
C	72 (exterior)	Developed lands, properties, or activities not included in Categories A or B above.
D	--	Undeveloped lands.
E	52 (interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals and auditoriums.

1.4.2.3 When is a Type I Noise Barrier Reasonable from a Socio-Economic Viewpoint?

A Type I noise barrier is reasonable from a socio-economic viewpoint if it meets the following criteria:

1. The proposed noise barrier must be cost-effective. A noise abatement measure (in this case, a noise barrier) is considered to be cost-effective if its total cost will not exceed $25,000 for each benefited receiver.
    - This $25,000 figure includes only the cost of construction of a noise barrier, and not the cost of any additional right of way or utility adjustments. In order for a receiver to be counted as benefited, a noise abatement measure must reduce the noise level at the receiver by at least 5 dBA, regardless of whether or not the receiver was impacted.
    - For residences, each single-family residence (owner-occupied or rental, including permanent mobile-home parks) is counted as a benefited receiver; and each first-floor unit in a duplex, apartment, or condominium complex is counted.
    - For parks, the number of benefited receivers depends on the activities practiced there. Parks with picnic areas or walking or jogging trails near the right of way may be more appropriate for noise abatement than parks that are used primarily for team sports. Major activity areas within a park, such as playgrounds or picnic tables, may be counted as separate receivers.
    - For schools, churches, hospitals, rest homes and day care centers, the number of benefited receivers is evaluated on a case-by-case basis.

- For commercial and office buildings, each first-floor property is counted as a benefited receiver.
- To determine the total number of benefited receivers, apply the minimum noise level reduction of 5 dBA to each receiver individually; do not average noise level reductions for multiple receivers. For example, if noise-level reductions for three receivers are calculated to be 4, 6 and 5 dBA, only the two receivers with noise-level reductions of 6 and 5 dBA are counted as benefited, even though the average noise-level reduction for all three receivers is 5 dBA.

2. Public Involvement: The views of the public are major considerations throughout the traffic noise analysis process, especially when noise impacts are identified and noise abatement measures are considered. Public perception, notification and approval are integral parts of the noise analysis process.
    - Public perception: Noise barriers are meant to be a positive addition to a neighborhood, and are normally well received. However, noise barriers are not always right for all people in all neighborhoods. A proposed barrier can have negative aspects if it: creates feelings of confinement; reduces air circulation; sunlight or night lighting; limits access to nearby streets; or restricts views for community members or for commercial business advertisements.

- Public Notification: Affected property owners should be notified that a noise barrier is being considered for incorporation into a highway project when sufficient information is available to adequately define, as a minimum, the overall dimensions and location of the associated noise barrier. The initial public notification of a noise barrier proposal may not occur until the public meeting or hearing for the overall environmental document. Notification might include: a clear concise description of the proposed noise barrier; a survey, questionnaire, ballot or combination thereof; a copy of the noise barrier brochure published by TxDOT/ENV; an invitation to attend a separate noise workshop; available comments and opinions from respective tenants; or proposed changes, updates or both.
- Public Approval: No noise barrier will be constructed without the approval, by simple majority vote, of the owners of property adjacent to the proposed noise barrier. Each qualifying owner is allowed one vote. If possible/practical, each qualifying owner should be provided any available comments and opinions from their respective tenants. If one or more properties located along the end of a proposed noise barrier are not in favor or do not respond after adequate effort has been made, the barrier should be terminated at these properties. Owners of property adjacent to the proposed noise barrier should also be given an opportunity to

1.5 RULES OF THUMB REGARDING ACOUSTICAL EFFECTIVENESS OF NOISE BARRIERS (1471-1 1996)

1.5.1 How Tall Must a Noise Barrier Be?

- A barrier not tall enough to block the line of sight between a source and receiver will not produce at least 5 dB of noise reduction. If a barrier is too short or has gaps between barriers, the noise can travel around the end of the barrier wall reducing the effectiveness. Note: Even with gaps, there may be enough barrier segments present such that the cumulative effect of the barrier achieves a 5 dB reduction.
- Each noise barrier must be long and high enough to effectively reduce noise levels, using the FHWA-approved computer model (OPTIMA) to determine the optimum overall barrier dimensions.

1.5.2 Noise Barriers and Neighborhood Planning

- Project design engineers should be consulted for preliminary evaluation of noise barrier locations, for input regarding sight distance requirements, right-of-way issues, utility easements, and foundation requirements.
- Noise barriers should not cause any displacements or relocations of receivers.

- It is normally not cost-effective to build a noise barrier for a single receiver.
- Large gaps for driveways and alleys entering onto a roadway greatly reduce the effectiveness of a barrier.
- Access streets should not be closed to eliminate large gaps in a noise barrier and enhance the effectiveness of a noise barrier unless requested and approved by local government officials. Associated responsibilities should be clearly spelled out in a written agreement prior to the final environmental clearance.
- Traffic noise analyses and any associated noise abatement measures are not intended to be used to reshape or reconfigure existing neighborhoods.
- Earth berms, though natural in appearance, require a large area (right of way) to reach the height required to be effective.

1.5.3 Noise Barriers on Hilly, Elevated or Depressed Sites

- Noise barriers are normally not effective for receivers on a hillside overlooking the highway, nor for receivers at heights above the top of the noise barrier.
- Depressed and elevated roadways normally result in somewhat lower noise levels (3-5 dBA), and thereby either eliminate the need for a noise barrier, or require a lower barrier than would otherwise be required.

1.5.4 Effects of Holes and Surface Texture

- Small gaps and drainage holes (less than 3 percent of the total surface area) do not significantly reduce a barrier's overall acoustical effectiveness.
- The surface roughness of a barrier matters only if it is of the same order of magnitude as the wavelength of sound that the barrier is intended to attenuate. Since the wavelength of 100-Hz sound is 10 feet, ordinary surface roughness has little effect.

1.5.5 Multiple-Reflection Issues

- Multiple reflections of traffic noise between two parallel plane surfaces, such as noise barriers or retaining walls on both sides of a highway, can theoretically reduce the effectiveness of individual barriers and contribute to overall noise levels. However, associated increases in traffic noise levels will normally not be perceptible to the human ear if the distance between the barriers is at least 10 times the average height of the barriers. For example: two parallel barriers 3 meters in height should be constructed at least 30 meters apart. During the preliminary design of noise barriers, the possible influence of parallel reflections should be checked.

1.5.6 Effects of Absorptive Materials

- Constructing barriers using sound-absorptive materials significantly reduces the noise level experienced by drivers on the roadway. It does not significantly reduce the noise level away from the highway, except when the highway has barriers on both sides. In such a “parallel-barrier” situation, absorptive materials can produce some noise reduction away from the highway by reducing sound that is reflected from the barrier on the side of the highway opposite to the receiver. This additional noise reduction is not always significant. This subject is discussed in more detail in Module 2 of this Binder.

Module 2

Acoustical Design of Noise Barriers

2.1 INTRODUCTION

This module of Binder 1 is intended to be a primer on the acoustical performance of highway noise barriers. It explains the fundamental mechanisms through which noise barriers attenuate sound, and the basis of hand calculations and the computer codes such as STAMINA that are used for the design of noise barriers.

2.2 PROPERTIES OF SOUND (1471-1 1996)

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, that is, to an increase in the energy by an order of magnitude. Figure 2.1 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 2.2, 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). Most sound sources are moving point sources. A continuous stream of such moving point sources can be idealized as a line source. Sound energy from a line source is attenuated over a cylindrical wave front, and is attenuated inversely with distance. Thus, noise from real traffic sources will be attenuated by a factor between 1/d and $1/d^2$, where d is the distance from the source. Hence, for road noise sources, it is reasonable to assume that a doubling of the distance from source to receiver will result in a drop of at most 6 dB, 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.

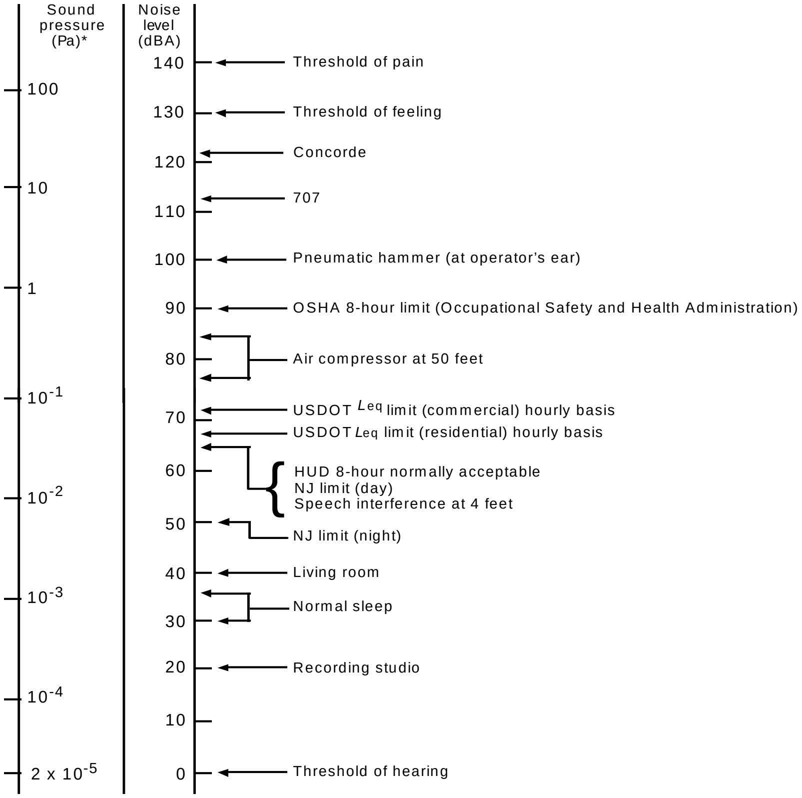


Figure A2.1 Typical sound pressure levels in dBA

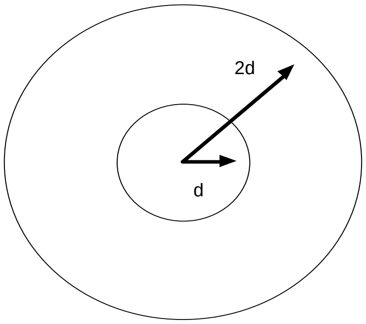


Figure A2.2 Geometrical spreading of sound from a point source

2.3 HAND CALCULATIONS OF INSERTION LOSS

Insertion loss can be estimated by using the model proposed by Kurze and Anderson **(**Kurze 1971). It is the result of compiling data of many researchers onto a single plot and developing a curve fit for a point source. The equation is below and the plot is shown in Figure 2.4.

$$\text{IL} = 5\text{dB} + 20\log\left(\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}\right)\text{dB} \qquad \text{up to } N = 12.5$$

$$\text{IL} = 20\text{ dB} \qquad \text{for } N > 12.5$$

N is defined as the Fresnel number which is a nondimensional measure of how much farther the sound must travel as a result of the barrier. It is calculated with the following equation:

$$N = \frac{(a + b - \ell)f}{c_o}$$

a, b, and ℓ are distances determined from geometry
f is the sound frequency in Hz
c_o is the speed of sound propagation in air
(approximately 1100 ft / sec)

The illustration below is used in an example calculation. The noise wall is 12 ft away from the nearest tire, and is 12 ft tall. A house is 15 ft beyond the barrier and has a window at a height of 4 ft.

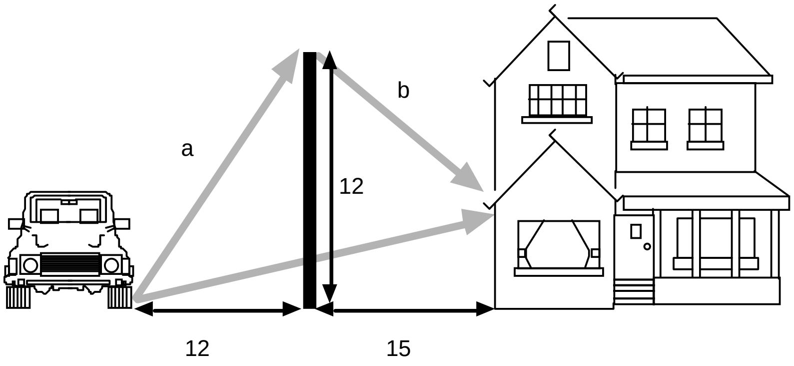


Figure A2.3 Illustration of lengthened sound path due to noise barrier

The path lengths are:

$$a = 12^2 + 12^2 = 17 \text{ feet}$$

$$b = 15^2 + 8^2 = 17 \text{ feet}$$

The direct path length is:

$$\ell = 27^2 + 4^2 = 27.3 \text{feet}$$

Hence:

$$a + b - \ell = 34 - 27.3 = 6.7 \text{feet}$$

at f = 100 Hz the Fresnel Number is

$$N = \frac{6.7 * 100}{1100} = 0.61$$

and the insertion loss calculated from the equation is

$$\text{IL} \;=\; 5 + 20 \log \frac{\sqrt{2\pi * 0.61}}{\tanh \sqrt{2\pi * 0.61}} \approx 10 \text{ dB}$$

The calculated insertion loss can be compared with the predicted value in the graph below (referred to as eqn 19). It is found that the insertion loss is close to the predicted value from experimental data.

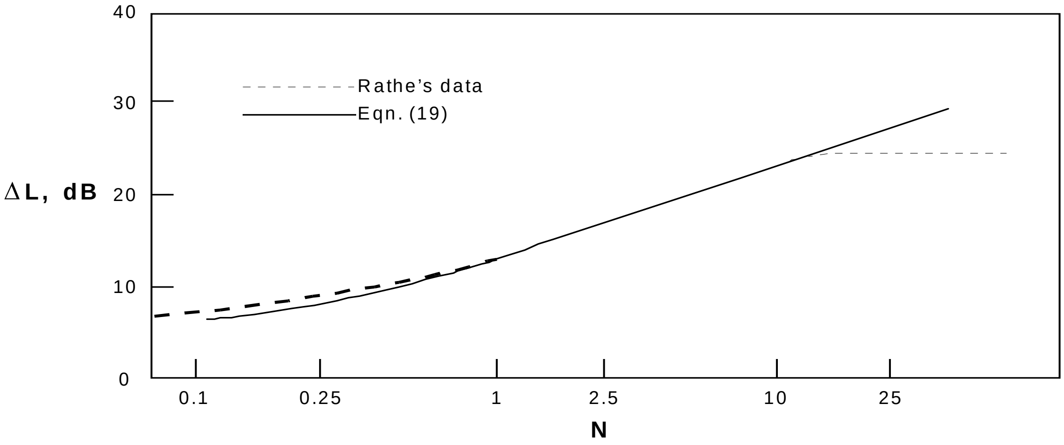


Figure A2.4 Insertion loss vs. Fresnel number for experimental and empirical data

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.

2.4 CALCULATIONS OF INSERTION LOSS USING COMPUTER PROGRAMS

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 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.

2.4.1 STAMINA 2.0 and OPTIMA

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 section 2.2, 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 (Kurze 1971), and a single wall design curve for point sources from Maekawa's (1968) 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.

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

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 (Hendricks 1987).

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.

2.5 CALCULATIONS OF INSERTION LOSS USING PROGRAMS COMPATIBLE WITH TNM

2.5.1 Overview of FHWA’s Traffic Noise Model (TNM)

The FHWA’s Traffic Noise Model is a computer program, now under development, that is intended for use in computing highway traffic noise at nearby receivers, and to aid in the design of roadway noise barriers. This entirely new, Windows-based computer program will use state-of-the-art emission levels and acoustical algorithms to compute noise levels along highways. This overview, adapted from an article in the *Wall Journal* (FHWA 1996a), is intended to summarize the basic features of the program as they have been presented to the technical community.

The program's release was originally scheduled for Spring 1996. The release is now scheduled for Fall 1997. Because of this delay, Research Study 1471 will probably not be able to use the program. Instead, the Study will use the program RAYVERB, which is computationally consistent with the model of TNM now under development. The following explanation is relevant to RAYVERB as well as TNM.

2.5.2 Input to TNM

Within Windows, TNM will allow digitized input using a generic Windows digitizer driver, plus the import of DXF files from CAD programs and input files from Stamina 2.0. To aid during input, TNM will show and plot the following graphical views:

- plans;
- skew sections;
- perspectives; and
- roadway profiles, which help during input of roadway Z coordinates.

These input graphics will be dynamically linked to input spreadsheets, where non-coordinate input will be entered and digitized input may be modified.

2.5.3 Vehicle Noise Emissions Considered by TNM

TNM will include noise sources based on 1994-1995 data for the following cruise-throttle vehicle types:

- automobiles;
- medium trucks;
- heavy trucks;
- buses; and
- motorcycles.

Noise emissions will be characterized in terms of A-weighted sound levels, one-third-octave-band spectra, and subsource-height strengths for three pavement types:

- dense-graded asphaltic concrete (DGAC);
- Portland cement concrete (PCC); and
- open-graded asphaltic concrete (OGAC).

However, the FHWA required analysis is only permitted to use the composite pavement which is the default setting of the average of the three different pavement types.

In addition, TNM will address noise emissions for vehicles on upgrades and vehicles accelerating away from traffic-control devices:

- stop signs;
- toll booths;
- traffic signals; and

- on-ramp startpoints.

TNM will combine these noise emissions with its internal speed computations to account for the full effect (noise emissions plus speed) of roadway grades and traffic-control devices.

TNM will also allow user-defined vehicles. For each, the user will enter three measured parameters for A-level emissions as a function of speed (cruise throttle, average pavement).

To document input, TNM will plot its input graphics and the following input tables:

- roadways;
- traffic for TNM vehicles;
- traffic for user-defined vehicles;
- receivers;
- barriers;
- building rows;
- terrain lines;
- ground zones;
- tree zones;
- noise contour zones;
- receiver adjustment factors;
- structure barriers; and
- barriers with important reflections.

2.5.4 Calculation and Sound Propagation in TNM

TNM will calculate the propagation of sound energy, in one-third-octave bands, between roadways and receivers. Calculation of sound propagation will take the following factors into account:

- divergence;
- atmospheric absorption;
- intervening ground (acoustical characteristics and topography);
- intervening barriers (walls, berms, and combinations or sequences thereof)
- intervening rows of buildings; and
- intervening areas of dense trees and undergrowth.

TNM will compute the effect of intervening ground (defined by its type, or optionally by its flow resistivity) with theory-based acoustics that have been calibrated against field measurements. In addition, TNM will allow sound to propagate underneath selected intervening roadways and barriers, rather than being shielded by them. TNM will also compute single reflections from vertical wall barriers, with user-selected Noise Reduction Coefficients.

2.5.5 Noise Barrier Design Using TNM

During calculation, TNM will vary the height of proposed barriers above and below the input height, in order to calculate the effect of perturbations in barrier height. During the barrier-design phase, using selected receivers, TNM will dynamically display sound-level results for any combination of height perturbations selected by the designer. TNM will also contain an input-height check, to determine if noise barriers break the lines of sight between sources and receivers.

2.5.6 Output from TNM

TNM will produce the following result tables:

- sound levels;
- diagnosis by barrier segment;
- diagnosis by vehicle type;
- barrier descriptions (including cost/benefit information); and
- barrier segment descriptions.

Each of these tables will be dynamically linked to TNM's barrier-design perspective, so that tabulated results will change dynamically as the user modifies the heights of barrier segments.

TNM will compute three measures of highway traffic noise:

- L_{aeq1h} (hourly A-weighted equivalent sound level;
- L_{dn} (day-night average sound level); and
- L_{den} (Community Noise Exposure Level, where "den" means "day/evening/night").

TNM will compute these three noise measures at user-defined receiver locations. In addition, it will compute three types of contours:

- sound-level contours;
- insertion-loss contours for noise barriers;
- level-difference contours between any two noise-barrier designs.

2.5.7 How TNM Will Consider Effects of Insertion-Loss Degradation due to Parallel Barriers

For selected cross sections, TNM will also compute the effects of multiple reflections between parallel barriers or retaining walls flanking a roadway. The resulting parallel-barrier degradations will be entered as adjustment factors for individual receivers in TNM's full set of calculations.

To document parallel-barrier input and results, TNM will produce the following parallel-barrier tables:

- roadways for TNM vehicles;
- roadways for user-defined vehicles;
- cross section; and
- analysis locations (including results).

2.6 ABSORPTIVE MATERIALS AND HIGHWAY NOISE BARRIERS

2.6.1 Potential Advantages of Absorptive Materials

The purported advantages of using sound absorptive material on noise barrier surfaces are (Wall Journal 1996):

1. Elimination or reduction of noise reflections. In single noise barrier configurations, this means that the unprotected residences (or other locations of interest on the opposite side of the highway) experience less of an increase in noise levels. In situations involving parallel noise

barriers (one on each side of the highway) each of the noise barrier's performance is degraded less by the presence of the other.

2. The performance of a single noise barrier increases. Receivers behind a noise barrier lined with absorptive material on the highway side or on both sides are benefited by a further reduction in noise.

2.6.2 Potential Disadvantages of Absorptive Materials

The primary disadvantage of absorptive materials is their additional cost compared to conventional materials. For highway noise barriers the improved insertion loss is minimal, and does not warrant the additional expense of absorptive materials. Sound-absorptive materials should only be considered when it can be shown through accepted modeling techniques, calibrated by reliable noise measurements, that noise reflections are a legitimate problem (Wall Journal 1996).

2.6.3 Further Comments Regarding Absorptive Materials

Ideally, an absorptive barrier would absorb all of the sound incident on it. If this were the case, the receiver would only hear the smaller amount of incident sound diffracted over the top of the barrier; the far barrier that used to reflect the sound and cause it to diffract over the top of the near barrier would theoretically absorb all the sound incident on it, and the effectiveness of the two parallel barriers would be the same as a single barrier. Unfortunately, ideal absorptive barriers do not exist, and some residual noise will reflect off the far barrier and diffract over the top of the near barrier, entering the residential area. Nevertheless, the overall resultant noise level should be less for absorptive barriers than reflective ones (Watts 1996). Full-scale tests by Watts confirm these ideas. He found that for a point source, the absorptive barrier “effectively eliminated the degradation since the measured increase in mean level was only 0.3 dB. The expected increase for a line source was calculated to be slightly higher at 0.5 dB" (Watts 1996).

Given these results, however, one would think that making the barriers absorptive would be a simple solution to the multiple-reflection problem. However, it has complications, both in performance and in cost. Since many sound-absorbing materials function by “forcing air molecules to move in and around many tiny fibers or passages”, many of them are porous (Menge 1980). In the experiments by Lane (1989), porous concrete, an effective sound absorber at the typical frequency range of highway traffic noise, was tested for freeze-thaw resistance. Repeated freeze-thaw cycles resulted in a substantial loss of mass and deterioration of the surface, making porous concrete unsuitable for use in absorptive barriers in environments where they would have to endure freeze-thaw cycles (Lane 1989). In addition, absorptive barriers can be very expensive to manufacture (Menge 1978).

2.7 CHARACTERISTICS OF COMMON BARRIER MATERIALS

Highway noise barriers are made of many different materials. In this section, those materials are reviewed, with particular emphasis on the specifications commonly used to identify them and prescribe their quality. Previous work by the University of Louisville (HITEC 1996) proposes the evaluation criteria summarized here. Those criteria are not intended to be all-inclusive. The information given below is proposed as a basis for TxDOT and its own materials evaluation personnel use in developing appropriate criteria.

In addition to meeting materials standards, noise barriers of each material must meet the requirements of the appropriate structural design code. Those requirements are discussed in Module 4 of this Binder.

2.7.1 Aluminum

Aluminum is useful for highway noise barriers because of its generally low maintenance requirements. It is also light in weight. However, note that Section 1.3.3 prescribes minimum thicknesses for acceptable acoustical performance. Aluminum's value in the recycling market has given TxDOT problems with thefts of aluminum components such as guardrails. This possibility should also be considered for aluminum noise barrier components.

In specifying aluminum highway barriers, the University of Louisville recommends that panels made of aluminum should have a minimum nominal thickness of 0.063 inch, and should conform to the thickness tolerances of the

Aluminum Association. Also, any shearing, cutting, or punching of the panels should preferably be done before any coatings are applied to the panels.

2.7.2 Concrete and Portland Cement-Based Materials

Concrete and portland cement-based materials are widely used for highway noise barriers, both as precast and as cast-in-place elements. Minimum practical thicknesses for fabrication are usually sufficient to ensure acoustical effectiveness. Maintenance costs are usually low. Long-term durability of concrete and other portland cement-based materials in highway noise barrier applications is most critically affected by resistance to freeze-thaw cycling when saturated.

Several specifications are available for evaluating resistance to freeze-thaw deterioration. The one most often used has been ASTM C666 ("Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing"). However, the University of Louisville recommends that precast concrete panels and other Portland cement-based materials be tested for resistance to salt scaling and freeze-thaw conditions in accordance with Section 6.3.2.1 of Canadian Standards for Noise Barrier on Roadways, which is a modified version of ASTM C672 ("Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals").

In that modified standard, a specimen's loss of mass is determined after exposure to a prescribed number of freeze-thaw cycles involving distilled water, ordinary water, or even deicing solution. The acceptance criterion is based on the effects of freeze-thaw deterioration or salt scaling, or both, on the concrete's acoustical and structural performance, and on the severity of exposure anticipated in service. In general, test specimens should not exhibit any cracking, spalling, or aggregate disintegration after exposure to the required number of cycles. When severe exposure is anticipated, acceptance criteria could also include a maximum permissible loss of mass after cycling.

To date, no single definitive, cost-effective and widely accepted method is available for evaluating noise barriers for resistance to salt scaling. The University of Louisville recommends the modified ASTM C672 as a good starting point, but notes the possible need for future modifications. For example, the number of freeze-thaw cycles between tests might be increased in the later stages of the evaluation, to reduce testing costs without increasing the risk of unacceptable materials.

2.7.3 Masonry

Masonry is widely used for highway noise barriers because of its durability and aesthetic appeal. Masonry units can be laid in place, or used in prefabricated panels that are later placed between post or column elements.

Masonry comprises units, mortar, grout, and accessory materials. Units must be of concrete or fired clay masonry. Concrete masonry units should be hollow load-bearing units conforming to ASTM C90. Fired clay units (solid or hollow) should conform to ASTM C62, C216, or C652. Masonry mortar should conform to ASTM C270, and masonry grout, to ASTM C476. Reinforcement can be either deformed bars or wire joint reinforcement. It and other accessories should conform to the specifications of the Masonry Standards Joint Committee (MSJC 1995a, 1995b). A panel cap or flashing should be used to protect the top course and posts of masonry walls.

2.7.4 Plastics

Plastics are sometimes used for highway noise barriers. Their attractive features include light weight. As noted earlier, a minimum weight is necessary for acoustical effectiveness. Its principal potential drawbacks are deterioration under exposure to ultraviolet radiation and ozone.

Panels made of plastic or fiberglass should be tested for resistance to ultraviolet-light exposure in accordance with ASTM G53. The specimen is alternately exposed to ultraviolet light alone from a series of fluorescent lamps and to condensation alone in a repetitive cycle. There must be no delamination, fading, chalking, or embrittlement after 1500 hours of exposure. All glazing material must comply with the requirements of ANSI Standard Z 26.1.

2.7.5 Steel

Steel is attractive for use in highway noise barriers because of its low cost. Its chief potential drawback is its vulnerability to corrosion. This vulnerability is most often counteracted by galvanizing and coating the steel.

According to the University of Louisville, all steel panels should be at least 20-gauge galvanized steel, and should also be protected with a coating with satisfactory tested resistance to weathering, fog-spray exposure, and flame spread. Whenever possible, the coating should only be applied after the steel is sheared, punched or cut. Panels should be connected using aluminum pop rivets with an aluminum or stainless steel mandrel.

2.7.6 Wood

Wood is used for noise barriers in areas with abundant supplies of this material. Its principal potential drawbacks include its relatively low mass, in that a significant thickness is needed to achieve a satisfactory transmission loss. Drawbacks also include the need to avoid gaps between pieces of wood, and possibly higher maintenance costs to control decay.

Resistance to rot and decay is the most important maintenance consideration. According to the University of Louisville, any wood products used in noise barriers should either be naturally resistant to decay for a minimum period of 20 years, or be pressure-treated. All pressure-treated wood should have a Certificate of Preservative Treatment from an appropriate facility. Minimum retention should be 0.6 pound per cubic foot. The moisture content of all sheathing should be reduced to a maximum of 15% before and after pressure treating. Timber columns should be reduced to an exterior moisture of 15% to the depth of the penetration of the preservative and an interior moisture content of

30% maximum. All wood products should be treated to resist insect infestation, and be coated with a wood sealer or stain.

Laminated wood panels must resist warping, splitting, or loosening of particles, knots, and imperfections. Any sheathing must be double-depth, tongue and groove.

Glue-laminated wood containing a wet-use adhesive should conform to ANSI/AITC A190.1. Any preservative treatment should be in accordance with AWPA C-28. Any wood to be glue-laminated should be preservative-treated under pressure, to a retention of 0.4 pound per cubic foot, prior to gluing. All glues should be water-resistant in accordance with CSA Standard 0112-M. Non-laminated wood should be No. 2 grade or better. Any plywood used should be an exterior type conforming to the requirements of U.S. Product Standards PS-1. Comparable ASTM standards are acceptable substitutes for the Canadian standards mentioned above.

2.8 EVALUATION OF PROPRIETARY BARRIER MATERIALS

In general, barrier materials should be evaluated on the basis of acoustical effectiveness (mass), structural integrity, durability, and initial and life-cycle cost.

- All cementitious materials should be evaluated for durability as noted above.
- All exposed metal components, including connectors, should be fabricated of nonferrous materials or of stainless steel, or be hot-dip galvanized after fabrication according to the requirements of ASTM A 123, A 153, A 307,

or A 325. All exposed steel (except weathering steel) must be primed and painted in accordance with the TxDOT's normal requirements for coatings.

- Any welds should conform to the ANSI/AWS D1.4, Structural Welding Code for Reinforcing Steel. Where permitted, field welds should conform to CSA Standards W 186-M1990, W 47.1, and W 59. All field welds should be cleaned and painted with an organic zinc-rich paint conforming to the requirements of CAN/CGSB 1.181-92 and matching the color of the surrounding surfaces. Comparable U.S. standards are acceptable substitutes for the Canadian standards mentioned above.
- All barrier materials should be tested in accordance with ASTM E84 to determine their flame-spread and smoke-development classifications.
- All barrier materials should demonstrate satisfactory performance under prolonged periods of exposure to moisture. Edges of absorptive materials should be sealed to preclude moisture from entering the interior. Water absorption testing should be performed in accordance with the ASTM standard appropriate for the material being tested.
- All barrier materials should demonstrate resistance to fungus in accordance with ASTM G 21 or a comparable standard.
- The cost of the installed noise barrier must compare well to the moving average cost of noise barriers. All costs involved in the purchase and installation of the noise barrier system should be clearly identified. The projected or estimated life-cycle cost should be provided, along with the

calculations and input parameters used in determining that cost. Any material used in sound barriers should have a minimum predicted maintenance-free life span acceptable to TxDOT under the expected service conditions.

Module 3

Aesthetic Design of Noise Barriers

3.1 GENERAL GUIDELINES FOR AESTHETIC DESIGN OF NOISE BARRIERS

3.1.1 Selected Publications on Aesthetics

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 have recently concluded a two-year study (TTI 1995), prepared for the Dallas District, in which all 50 states were sent a comprehensive written survey on noise barriers and aesthetic treatments.

Aesthetic standards for noise wall design are more codified in Europe than in the U.S. In 1991, the Danish Ministry of Transport published Report 81, *Noise Barriers - A Catalogue of Ideas* (Denmark 1991). This report contains a comprehensive photographic database of the different types of noise barriers 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 (Blum 1976). The manual is a guide to the basic principles that affect visual perception, and to 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 to supplement technical information concerning noise abatement, in an effort to produce highway noise barriers which are functional, attractive and visually related to the surrounding environment.

3.1.2 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. The impact on drainage and flood control are discussed in 1471-1 (1996).

3.1.3 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 the 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. The surface texture of a noise barrier differs with the type of material used to construct the barrier. For example, wood textured concrete can have horizontal or vertical planks. The aesthetic advantage of using horizontal planks is that the seams in stacked panels are less noticeable. However, solid panels may be aesthetically preferred for wall heights under 14 feet.

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; or they can be decorated or patterned with symbols that are historically meaningful for the area (1471-1 1996).

A new concept established by the New Jersey Department of Transportation creates community themes through the use of "gateways." A gateway is an architectural accent that looks like a designer panel. It is located in areas that are particularly likely to attract the attention of highway users. Along a highway, a sequence of similar gateways would be constructed; each gateway would have a slight variation, to give the community a unique quality with which to identify (Billera 1996).

Figure A3.1 Example of the gateway concept (Billera 1996)

3.2 ROLE OF OPACITY (1471-1 1996)

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 may be 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.

3.3 SPECIFIC VISUAL AIDS DEVELOPED IN STUDY 1471 FOR THE AESTHETIC DESIGN OF NOISE BARRIERS

Through the use of Microstation V5.0 or later, the user can combine digital photos of noise barriers with stored textures and perspectives to create a presentation of proposed noise barriers. A rendered image of a completed noise barrier is made and can be shown to prospective community users. These aids are discussed further in Binder 3.

Module 4

Basic Structural Design of Noise Barriers

4.1 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 (1471-1 1996).

4.2 CURRENT AASHTO GUIDELINES FOR STRUCTURAL DESIGN OF NOISE BARRIERS

In 1989, AASHTO published a set of recommended guidelines, *AASHTO Structural Design Specifications for Noise Barriers* (AASTHO 1989) 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. Noise barriers that are required to be designed for vehicular impact must be crash-tested in accordance with NCHRP 350, Test Level 3, to gain FHWA acceptance (NCHRP

1993, FHWA 1996b). All other noise barriers should prudently be designed to resist some level of vehicular impact.

4.3 DESIGN LOADS FOR NOISE BARRIERS

4.3.1 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 the equation below of the *AASHTO Structural Design Specifications for Noise Barriers* (AASTHO 1989).

$$P = 0.00256(1.3V)^2 C_d C_c$$

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 Sound Barriers* (AASHTO 1992a).

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). Calculations of wind-load deflections should include effects of elastic and inelastic-deformations of the soil-foundation system.

4.4 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 (1471-1 1996).

4.5 STRUCTURAL DESIGN PROCESS FOR NOISE BARRIERS

These refer to the structural design of the noise barrier itself. Loads, structural members, and joints are discussed and recommendations to be followed are given in choosing these design parameters.

4.5.1 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.

4.5.2 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.

4.5.3 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 in 1471-1 (1996), 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. This is discussed further in Binder #4.

4.6 STRUCTURAL DESIGN REQUIREMENTS IMPOSED BY ADJACENT UTILITIES

4.6.1 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.

4.6.2 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.

4.6.3 Access for Future Maintenance

In addition, the presence of the noise barrier can restrict future maintenance access to the overhead utilities. This problem is handled by the utility company and should be coordinated with TxDOT early in the design phase.

4.7 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 within the clear zone, it must be designed for vehicular impact. If the barrier is located on the right-of-way line, 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 slow them down without serious injury to their occupants? The design forces and energy absorption demands associated with actual vehicle impacts 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. Noise barriers designed for vehicular impact typically must be crash-tested in accordance with NCHRP 350, Test Level 3, to gain FHWA acceptance (NCHRP 1993, FHWA 1996b).

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

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.

4.8 BASIC STRUCTURAL CHOICES FOR NOISE BARRIERS

Basic structural choices for noise barriers are discussed in general in Module 1.2 of this binder. As noted there, the following basic structural choices are available:

- Noise Barrier Not Required 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
    - earth berms
- Noise Barriers Required to Resist Vehicular Impact
    - prefabricated, barrier-mounted, post-and-panel system
    - prefabricated, sloped-face wall system

In the remainder of this section, the factors favoring various choices are briefly discussed.

4.8.1 Preferred Structural Choices for Noise Barriers on Grade

For barriers on grade, barrier weight is not usually an issue. Earth berms, while often appealing aesthetically, require significant right-of-way. Fan-wall systems also require significant right-of-way, can be associated with higher mowing costs, and can provide undesirable places for concealment. Unless those potential drawbacks are not an issue, the best structural choice usually involves a post-and-panel system. Structural costs and utility disruption can be reduced by making the barrier self-supporting between posts, thereby eliminating the need for a continuous grade beam.

From a structural viewpoint, any material discussed in this binder can function satisfactorily. The choice of material depends on aesthetics and life-cycle cost. The choice between constructed-in-place versus prefabricated barriers is primarily one of economics. It is also influenced by the effects of any lane closures required while the barrier is being constructed.

Any barrier must be able to accommodate differential movement caused by long-term expansion (for example, clay masonry), long-term shrinkage (for example, cementitious materials), and thermal expansion or contraction (all materials).

4.8.2 Preferred Structural Choices for Noise Barriers on Bridges

Structural choices for noise barriers on bridges are affected by four factors not present for barriers on grade:

1. barrier weight is more important;
2. barrier aesthetics must consider both sides of the barrier;
3. structural details must accommodate differential movement due to the deflections of the bridge; and
4. construction constraints are different.

The first of these is self-evident. The bridge must be able to support the weight of the barrier or barriers. Since one aspect of a barrier's acoustical effectiveness (transmission loss) depends on its mass, there is no magic material. All acoustically effective barriers must weigh at least a minimum amount.

Noise barriers in general must be aesthetically appealing from the vantage point of the receptor as well as the motorist. This requirement is particularly important for noise barriers on bridges; the barrier is visible to motorists using the bridge, and also to motorists passing under the bridge. Details that are visually pleasing to those crossing the bridge may not be pleasing to those approaching the bridge from a distance, and passing under it.

As noted above, any barrier must be able to accommodate the differential movement required of it. In addition to the movements noted above, barriers on bridges must accommodate the deformations of the bridge itself, caused by inherent expansion or shrinkage of the bridge materials, by thermal deformations, and by load-induced deformations. A barrier on a bridge must be able to accommodate more differential movement than the same barrier located on grade nearby. Its movement joints must be wider or more closely spaced. The increased demands on such joints tend to favor prefabricated post-and-panel systems for barriers on bridges.

Construction constraints are more restrictive for barriers on bridges. The same economic and lane-closure issues exist as for barriers on grade; these are accompanied by possible additional constraints imposed by maximum weight of construction equipment, or by clearance to overhead utilities or signs.

4.8.3 Overall Structural Evaluation Criteria for Proprietary or Innovative Systems for Noise Barriers

Proprietary or innovative systems for noise barriers must meet the same criteria as any other barrier -- acoustical, aesthetic, economic, and structural. From a structural viewpoint, such systems must embody satisfactory responses to the following questions:

1. Does the system have a clearly defined load path for transmitting its forces to the ground?
2. Is that load path sufficiently independent of construction tolerances? For example, some precast systems resist load by means of a relatively short

interior lever arm between the centroid of a vertical post-tensioning bar, and the compressive reaction of a precast column element on the foundation. Small changes in the position of the post-tensioning element can significantly decrease the overturning moment capacity of the barrier.

3. Is that load path sufficiently reliable? For example, will vehicular impact against one column of the system imperil its overall structural integrity?
4. Are the barrier’s service-level deflections sufficiently small? For example, some precast systems use neoprene pads or other shims under precast column elements, to make the construction process easier. If the spaces under those column elements are not subsequently filled with grout, the column may bear against the pads, making prestressing difficult, and also resulting in much larger deflections than would normally be anticipated. Also, bond deterioration around embedded elements may increase their axial flexibility.
5. Is the barrier resistant to deterioration in service? For example, are metallic connecting parts in the barrier adequately protected against corrosion caused by environmental exposure, or by galvanic action between dissimilar metals within the barrier?

Module 5

Sample Plans, Specifications, and Design Example

5.1 INTRODUCTION

To be included in a TxDOT project, a highway sound wall system must be able to be described in TxDOT contract documents (specifications and drawings).

This module comprises a sample set of specifications, drawings, and a design example. The specifications and drawings are based on work supplied to this study by John Vogel of the Houston District. His assistance is gratefully acknowledged. The design example is extracted from a thesis by Ronald Peron of the University of Texas at Austin.

The sample specifications are applicable to most commonly used sound wall materials and systems, and can address many if not all proprietary systems. The sample drawings are also applicable to a variety of systems and materials. The sample specifications and drawings should be adapted to the particular needs of each project.

5.2 SAMPLE SPECIFICATIONS

SPECIAL SPECIFICATION

ITEM 5246

SOUND WALLS

1. DESCRIPTION. THIS ITEM SHALL GOVERN FOR FURNISHING THE MATERIALS AND CONSTRUCTING A SOUND WALL AS SHOWN ON THE PLANS AND REQUIRED BY THIS ITEM.

2. MATERIALS. ALL MATERIALS SHALL CONFORM TO THE PERTINENT REQUIREMENTS OF THE FOLLOWING STANDARD SPECIFICATION ITEMS:

   - ITEM 420, “CONCRETE STRUCTURES”
   - ITEM 421, “PORTLAND CEMENT CONCRETE”
   - ITEM 425, “PRESTRESSED CONCRETE STRUCTURAL MEMBERS”
   - ITEM 426, “PRESTRESSING”
   - ITEM 427, “SURFACE FINISHES FOR CONCRETE”
   - ITEM 437, “CONCRETE ADMIXTURES”
   - ITEM 440, “REINFORCING STEEL”
   - ITEM 441, “STEEL STRUCTURES”
   - ITEM 442, “METAL FOR STRUCTURES”
   - ITEM 445, “GALVANIZING”
   - ITEM 446, “CLEANING, PAINT AND PAINTING”
   - ITEM 449, “ANCHOR BOLTS”

- ITEM 575, “EPOXY”

UNLESS OTHERWISE SHOWN IN THE PLANS, SOUND WALL PANELS SHALL BE CONCRETE. SOUND WALL POSTS SHALL BE CONCRETE OR STEEL. CONCRETE FOR PRECAST AND CAST-IN-PLACE COMPONENTS SHALL BE CLASS “F” WITH f ’c = 4000 PSI MINIMUM. CONCRETE FOR PRESTRESSED COMPONENTS SHALL BE CLASS "H" WITH f ‘c = 5000 PSI MINIMUM.

ANCHOR BOLTS, NUTS AND WASHERS SHALL BE GALVANIZED FOR CORROSION PROTECTION. ALL EXPOSED STEEL COMPONENTS SHALL BE GALVANIZED OR PAINTED WITH THE PROTECTION SYSTEM SHOWN ON THE PLANS.

JOINT FILLERS, GROUT, AND OTHER INCIDENTAL MATERIALS SHALL BE AS SHOWN ON THE PLANS OR APPROVED BY THE ENGINEER.

3. GENERAL

- OPTIONS. THE CONTRACTOR MAY FURNISH ANY PROPRIETARY SOUND WALL SYSTEM WHICH MEETS THE REQUIREMENTS OF THIS SPECIFICATION AND COMPLIES WITH THE DESIGN CRITERIA SHOWN ON THE PLANS. ALL SOUND WALL SYSTEMS SHALL UTILIZE DRILLED SHAFTS WITH THE SAME SPACING, DIAMETER, LENGTH AND REINFORCING STEEL AS SHOWN ON THE

PLANS. THE CONTRACTOR SHALL PROVIDE FOR USE OF THESE SYSTEMS IN ACCORDANCE WITH ITEM 7.3.

- <u>WORKING DRAWINGS.</u> PRIOR TO FABRICATION, THE CONTRACTOR SHALL PREPARE AND SUBMIT WORKING DRAWINGS AND DESIGN CALCULATIONS FOR THE PROPOSED SOUND WALL SYSTEM TO THE ENGINEER FOR APPROVAL. ALL DRAWINGS SHALL BE SUBMITTED ON 11" X 17" SIZE SHEETS. THE CONTRACTOR SHALL SUBMIT TO THE ENGINEER SEVEN (7) SETS OF CASTING DRAWINGS FOR PRECAST SEGMENTS AND SHOP DRAWINGS FOR EACH DETAIL OF THE PLANS REQUIRING THE USE OF STRUCTURAL STEEL, SEVEN (7) SETS OF CONSTRUCTION DRAWINGS AND TWO (2) SETS OF DESIGN CALCULATIONS. UPON COMPLETION OF CONSTRUCTION, ONE (1) SET OF REPRODUCIBLE AS-BUILT DRAWINGS SHALL BE SUBMITTED TO THE ENGINEER.

  CASTING DRAWINGS SHALL INCLUDE ALL INFORMATION NECESSARY FOR PRECASTING WALL ELEMENTS. CASTING DRAWINGS SHALL REFLECT THE SHAPE AND DIMENSION OF PRECAST COMPONENTS, THE SIZE, QUANTITY AND DETAILS OF THE REINFORCING STEEL, THE QUANTITY TYPE, SIZE AND

DETAILS OF CONNECTION AND LIFTING HARDWARE, THE SIZE AND LOCATION OF DRAIN OPENINGS, AND ANY ADDITIONAL DETAILS NECESSARY.

CONSTRUCTION DRAWINGS SHALL INCLUDE A NUMBERED WALL COMPONENT LAYOUT, AND SHALL REFLECT FIELD VERIFIED HORIZONTAL AND VERTICAL ALIGNMENT OF THE WALL. THE DRAWINGS SHALL ALSO INCLUDE ALL INFORMATION NEEDED TO ERECT THE WALL INCLUDING THE PROPOSED DRILLED SHAFT ELEVATIONS AND LENGTH, LIMITS OF RIPRAP, THE TYPE, DETAILS, AND CONSTRUCTION PROCEDURE FOR CONNECTING THE WALL TO THE DRILLED SHAFTS, DETAILS NECESSARY TO ACCOUNT FOR CHANGE OF GRADE, ALL EXISTING AND PROPOSED UTILITIES, AND ANY ADDITIONAL DETAILS NECESSARY TO COMPLETE THE WORK.

DESIGN CALCULATIONS SHALL INCLUDE A SUMMARY OF ALL DESIGN PARAMETERS USED, INCLUDING MATERIAL TYPES, STRENGTH VALUES AND ALLOWABLE STRESSES, AND ASSUMED LOADS AND LOAD COMBINATIONS. CALCULATIONS SHALL BE SUBMITTED COVERING THE RANGE OF HEIGHTS AND LOADING CONDITIONS ON THE PROJECT.

DRAWINGS AND DESIGN CALCULATIONS SHALL BEAR THE SEAL OF A REGISTERED PROFESSIONAL ENGINEER THAT IS REGISTERED IN THE STATE OF TEXAS.

4. CONSTRUCTION METHODS. CONSTRUCTION OF SOUND WALLS SHALL CONFORM TO THE DESIGN AND DETAILS SHOWN ON THE PLANS AND TO THE PERTINENT REQUIREMENTS OF THE FOLLOWING ITEMS:

   - ITEM 424, "PRECAST CONCRETE STRUCTURES (FABRICATION)"
   - ITEM 429, "CONCRETE STRUCTURE REPAIR"
   - ITEM 447, "STRUCTURAL BOLTING"
   - ITEM 448, "STRUCTURAL FIELD WELDING"
   - ITEM 449, "ANCHOR BOLTS"
   - ITEM 575, "EPOXY"

   ALL POSTS SHALL BE SET PLUMB AND FIRM TO THE LINE AND GRADE SHOWN ON THE PLANS. HORIZONTAL ALIGNMENT TOLERANCE SHALL NOT EXCEED 3/4 INCH FROM POST TO POST. THE OVERALL VERTICAL TOLERANCE OF THE WALL (PLUMBNESS FROM TOP TO BOTTOM) SHALL NOT EXCEED 1/2 INCH PER 10 FEET OF WALL HEIGHT.

5. MEASUREMENT. SOUND WALLS WILL BE MEASURED BY THE LINEAR FOOT ALONG THE ALIGNMENT OF THE WALL.

LENGTH WILL BE MEASURED FROM CENTER TO CENTER OF POSTS.

6. PAYMENT. THE WORK PERFORMED AND MATERIAL FURNISHED IN ACCORDANCE WITH THIS ITEM AND MEASURED AS PROVIDED FOR UNDER "MEASUREMENT" WILL BE PAID FOR AT THE UNIT PRICE BID FOR "SOUND WALL", OF THE HEIGHT SPECIFIED. THIS PRICE SHALL BE FULL COMPENSATION FOR FUNISHING AND INSTALLING ALL WALL MATERIALS INCLUDING ANCHORAGE INTO THE DRILLED SHAFT; FOR ALL SOUND WALL PREPARATION, HAULING AND ERECTION; AND FOR ALL LABOR, TOOLS, EQUIPMENT AND INCIDENTALS NECESSARY TO COMPLETE THE SOUNDWALL.

5.3 SAMPLE DRAWINGS

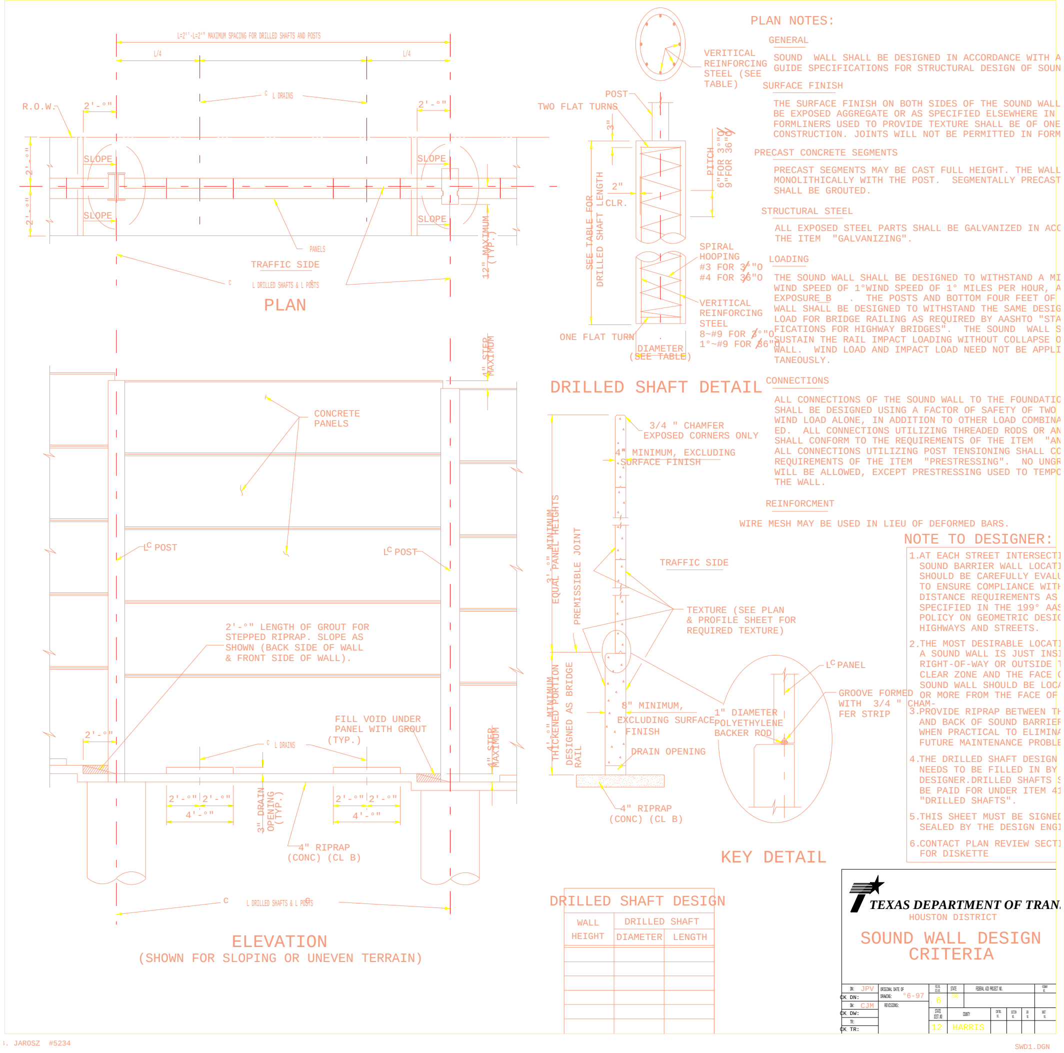


Figure A5.1 Sound Wall Design Criteria

5.4 SAMPLE STRUCTURAL DESIGN EXAMPLE OF A SOUND WALL (1471-2 1996)

For purposes of this report, a design is performed to illustrate the critical design loads and parameters. As an example, the actual sound wall dimensions and geometry of a Fort Worth mounted sound wall are used. The drawings of this wall are shown in section 5.5.

Specifications used:

- 1992 AASHTO Guide Specifications for Structural Design of Sound Barriers (AASHTO 1992)

Sound Wall Dimensions:

- Panel dimensions: 1.47-m wide by 0.61-m tall by 0.13-m thick (4.83-ft wide by 2-ft tall by 0.416-ft thick)
- Post dimensions: W6x15
- Post height: 2.43 m (8 ft)
- Post spacing: 1.52 m (5 ft)
- Total wall height: 3.25 m (10.7 ft)

Minimum Specified Properties (Specified on TXDOT Construction Plans):

- Reinforcement Yield Strength : 276 MPa (40 ksi)
- Concrete Specified Compressive Strength (f'_c): 28 MPa (4 ksi)
- Post Steel Yield Strength: 247 kMPa (36 ksi)

Parameters Used:

- Design wind speed: 128 kph (80 mph)
- Exposure category: Exposure B2
- Design Wind Pressure: P = 958 Pa (20 psf) (AASHTO Table 1-2.1.2C)

Load Cases Considered: Wind, Gravity

Load Combination: (1.3 or 1.0) D + 1.3W

Wind Load Analysis:

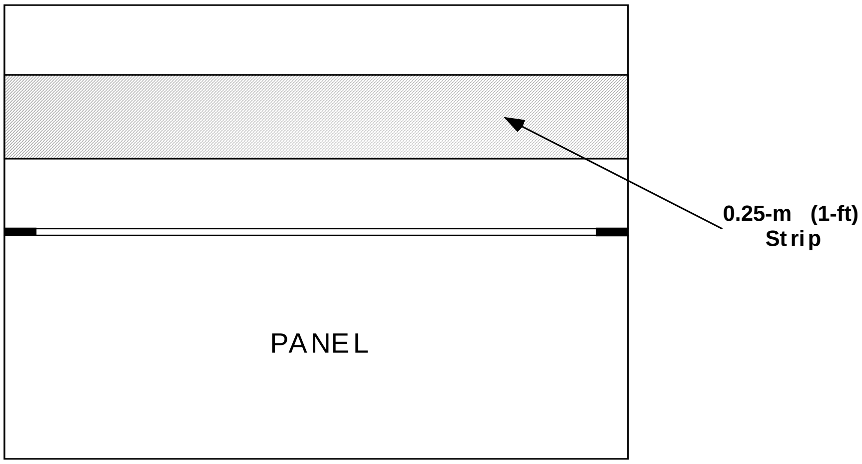


Figure A5.2 Horizontal Strip for Panel Design (Wind Load)

Panel Design:

- Lateral flexural check: Consider 0.3 m (1-ft) horizontal strip as shown. Assume simply supported panels.

  $$M = \frac{wL^2}{8} = \frac{(958\,Pa \cdot 0.3m)(1.5m)^2}{8} = 0.081 \text{ kN-m (0.75 kip-in)}$$

  ϕM_n = 0.9 A_s f_y (0.9d) = 1 kN-m (8.91 kip-in)

  M_u = 1.3 M = 0.105 kN-m < ϕM_n = 1 kN-m OK

- Lateral shear check: Consider 0.3 m (1-ft) horizontal strip as shown. Assume simply supported panels.

  $$V = \frac{wL}{2} = \frac{(958\,Pa \cdot 0.3m)(1.5m)}{2} = 0.22 \text{ kN (50 lbs)}$$

  ϕV_n = 0.85 x 2 ($\sqrt{f'_c}$) bd = 28.7 kN (6.45 kips)

  V_u = 1.3 V = 0.29 kN < ϕV_n = 28.7 kN OK

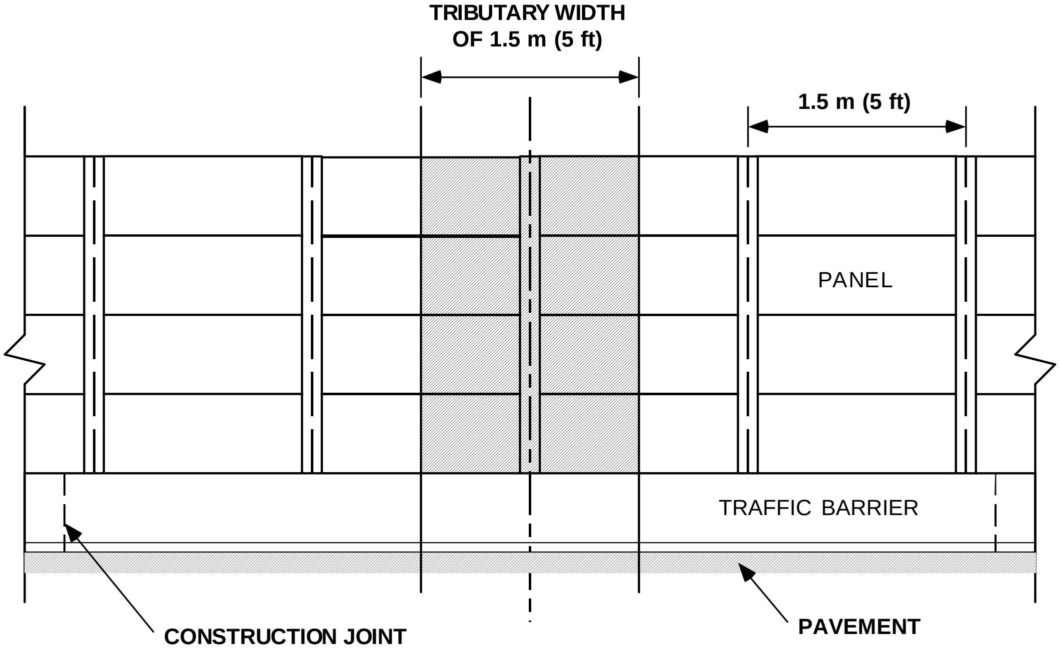


Figure A5.3 Tributary Width for Post Design (Wind Load)

Post Design:

- Flexural check: Consider a 1.5-m (5-ft) tributary width as shown.

$$M = \frac{wH^2}{2} = \frac{(958\,Pa \cdot 1.5m)(2.4m)^2}{2} = 4.34 \text{ kN-m (3.2 kip-ft)}$$

$\phi M_n = 0.9\, S_x\, f_y = 49$ kN-m (38.2 kip-ft)

$M_u = 1.3\, M = 5.64$ kN-m $< \phi M_n = 49$ kN-m OK

- Shear check: Consider a 1.5-m (5 ft) tributary width as shown.

V = wH = (958 Pa x 1.5 m)(2.4 m) = 2.22 kN (0.5 kips)

$\phi V_n = 0.85 \times A\, F_y = 1239$ kN (278.5 kips)

$V_u = 1.3\ V = 2.89\ \text{kN} < \phi V_n = 278.5$ kips OK

- Anchor bolt check: Based on LRFD design [LRFD 1986]
  - ♦ Bolt type: A325 Headed Bolt
  - ♦ Bolt size: 19 mm (3/4") ϕ
  - ♦ Bolt area: 284 mm^2 (0.44 in^2)
  - ♦ Embedment length: 0.46 m (18 in.)
  - ♦ Yield strength: F_y = 724 MPa (105 ksi)
  - ♦ Ultimate Strength: F_u = 827 MPa (120 ksi)
- Tension Capacity:

$T_u = \phi\ F_u\ A_g$

$= 0.75 \times 827\ \text{MPa} \times 284\ \text{mm}^2$

$= 177$ kN (39.76 kips)

Using LRFD (1986) Table 8-26, the minimum embedment length is 17d or 324 mm (12.75 in), which is provided. However, the minimum edge distance required is 7d or 133 mm (5.25 in), which is not satisfied in this design. To prevent a side blow-out failure, reinforcing bars form a closed loop around the anchor bolts. Since the anchor bolts intersect the vertical reinforcement in the traffic barrier, the anchor bolt capacity was assumed to be that of a lap splice connection with the reinforcing bar. This capacity was calculated using the ACI Code (1995) provision for splice length.

- Lap splice capacity,

Required development length of #5 bar = $\dfrac{0.04 A_b f_y}{\sqrt{f_c^{'}}}$ = 197 mm (7.75 in)

The minimum lap splice is 305 mm (12 in), which is greater than 1.3 ℓ_d. Therefore, use the minimum splice length.

Required length of splice = 381 mm (15 in) > 305 mm (12 in).

Therefore, the #5 reinforcing bar can develop its full capacity and will control the splice capacity.

$T_u = \phi F_y A_g = 0.75 (276 \text{ MPa}) 0.198 \text{ m}^2 = 41 \text{ kN} (9.2 \text{ kips})$

Use this capacity for the capacity of the anchor bolts.

- Axial force in anchor bolt due to post flexure: (4 bolts per post)

  Assume 0.127m (5 in) between concrete compression block and anchor bolt in tension.

  2T = M / (lever arm)

  = 4.34 kN-m / (0.127 m)

  = 34.2 kN

  T = 17.1 kN per bolt (7.68 kips per bolt)

  $1.3\ T = 22.2 \text{ kN} < T_u = 41.0 \text{ kN}$ OK

In a typical design, the foundations and base plates would need to be designed. Additional load cases such as seismic and flood may also be checked when applicable in the design or analysis.

- Estimate stiffness of traffic barrier:

  Due to the rigidity of the traffic barrier, the stiffness was assumed to be dependent only on the axial stiffness of the foundation bars. For these estimates, assume that all the force is in the outer bars and that only 10 bars are effective for stiffness. The load is applied at a height of 0.53 m (21 in) from the pavement surface and the distance from the back edge of the traffic barrier to the outer foundation bars is 0.23 m (9 in).

$\sum$ Moments about the back edge of barrier, P = 4.448 kN (1.0 kip)

P x Height of Loaded Point = (9.0 F_{bar}) (number of bars effective)

= 9.0 F_{bar} (10 bars)

F_{bar} = 1.02 kN (0.23 kips)

Find deflection of outer bar:

δ_{bar} = PL/AE = 1.02 kips x 216mm / 1.98 mm^2 x 200 MPa

= 5.6 x 10^{-3} mm (2.2 x 10^{-4} in)

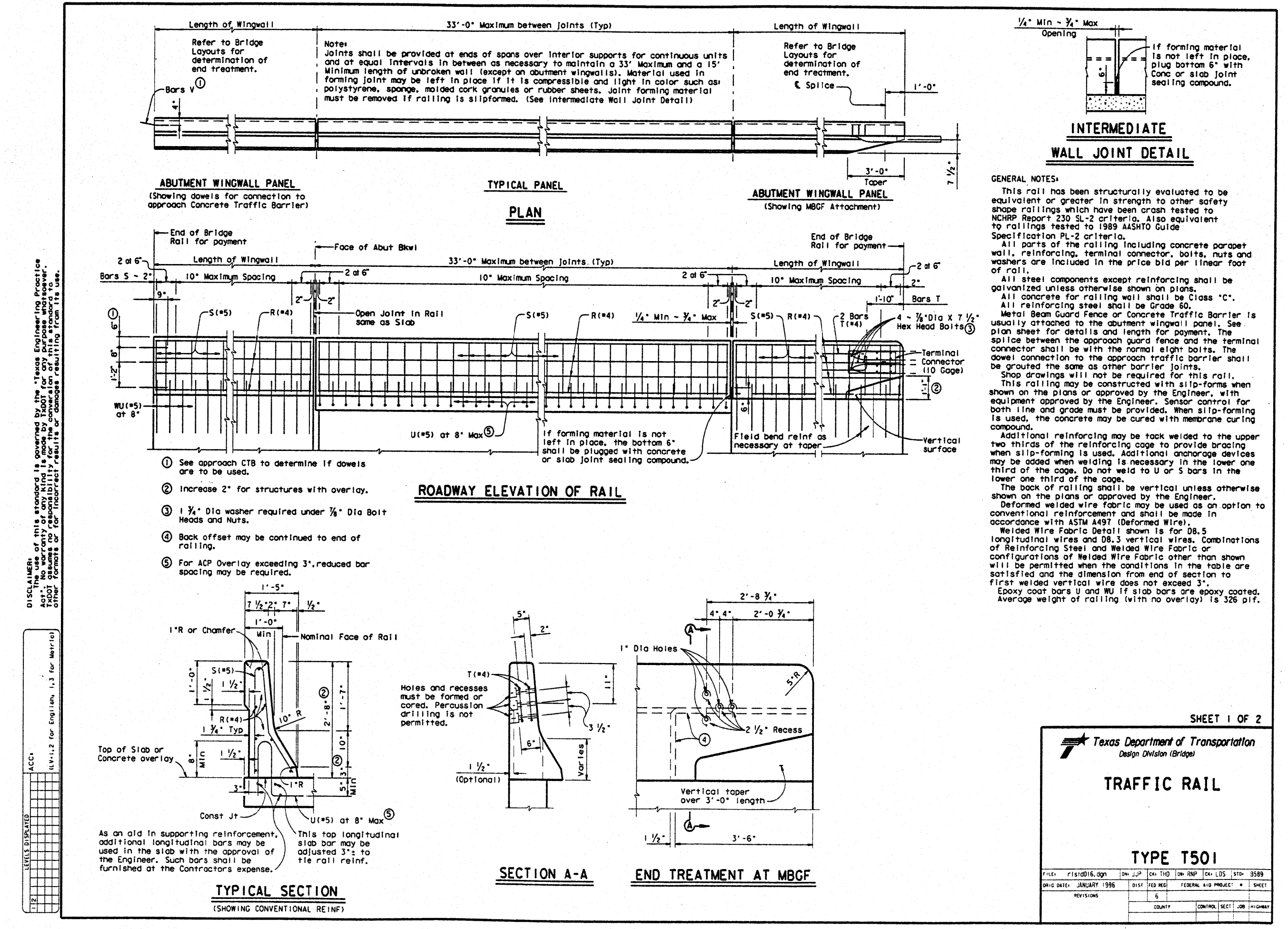
Find the corresponding deflection at the load point:

$\delta_{load} = \delta_{bar}$ (0.53m / 0.23m) = 0.13 mm (5.1 x 10^{-3} in)

Therefore, K_{wall} for overturning = 4.448 kN / 0.13 mm = 34 kN/mm (1960 k/in)

5.5 FORT WORTH MOUNTED SOUND WALL DRAWINGS

(TxDOT 1990, TxDOT 1994)



Note:

Joints shall be provided at ends of spans over interior supports for continuous units and at equal intervals in between as necessary to maintain a 33' Maximum and a 15' Minimum length of unbroken wall (except on abutment wingwalls). Material used in forming joint may be left in place if it is compressible and light in color such as: polystyrene, sponge, molded cork granules or rubber sheets. Joint forming material must be removed if railing is slipformed. (See Intermediate Wall Joint Detail)

① See approach CTB to determine if dowels are to be used.

② Increase 2" for structures with overlay.

③ 1 ¾" Dia washer required under ⅞" Dia Bolt Heads and Nuts.

④ Back offset may be continued to end of railing.

⑤ For ACP Overlay exceeding 3", reduced bar spacing may be required.

GENERAL NOTES:

This rail has been structurally evaluated to be equivalent or greater in strength to other safety shape railings which have been crash tested to NCHRP Report 230 SL-2 criteria. Also equivalent to railings tested to 1989 AASHTO Guide Specification PL-2 criteria.

All parts of the railing including concrete parapet wall, reinforcing, terminal connector, bolts, nuts and washers are included in the price bid per linear foot of rail.

All steel components except reinforcing shall be galvanized unless otherwise shown on plans.

All concrete for railing wall shall be Class "C".

All reinforcing steel shall be Grade 60.

Metal Beam Guard Fence or Concrete Traffic Barrier is usually attached to the abutment wingwall panel. See plan sheet for details and length for payment. The splice between the approach guard fence and the terminal connector shall be with the normal eight bolts. The dowel connection to the approach traffic barrier shall be grouted the same as other barrier joints.

Shop drawings will not be required for this rail.

This railing may be constructed with slip-forms when shown on the plans or approved by the Engineer, with equipment approved by the Engineer. Sensor control for both line and grade must be provided. When slip-forming is used, the concrete may be cured with membrane curing compound.

Additional reinforcing may be tack welded to the upper two thirds of the reinforcing cage to provide bracing when slip-forming is used. Additional anchorage devices may be added when welding is necessary in the lower one third of the cage. Do not weld to U or S bars in the lower one third of the cage.

The back of railing shall be vertical unless otherwise shown on the plans or approved by the Engineer.

Deformed welded wire fabric may be used as an option to conventional reinforcement and shall be made in accordance with ASTM A497 (Deformed Wire).

Welded Wire Fabric Detail shown is for D8.5 longitudinal wires and D8.3 vertical wires. Combinations of Reinforcing Steel and Welded Wire Fabric or configurations of Welded Wire Fabric other than shown will be permitted when the conditions in the table are satisfied and the dimension from end of section to first welded vertical wire does not exceed 3".

Epoxy coat bars U and WU if slab bars are epoxy coated.

Average weight of railing (with no overlay) is 326 plf.

SHEET 1 OF 2

Texas Department of Transportation
Design Division (Bridge)

TRAFFIC RAIL

TYPE T501

FILE: rlstd016.dgn	DN: JJP	CK: THD	DW: RNP	CK: LDS	STD: 3589
ORIG DATE: JANUARY 1996	DIST	FED REG	FEDERAL AID PROJECT ●		SHEET
REVISIONS		6			
	COUNTY		CONTROL	SECT / JOB	HIGHWAY

Figure A5.4 TxDOT T501 Traffic Rail Construction Drawings (Sheet 1 of 2)

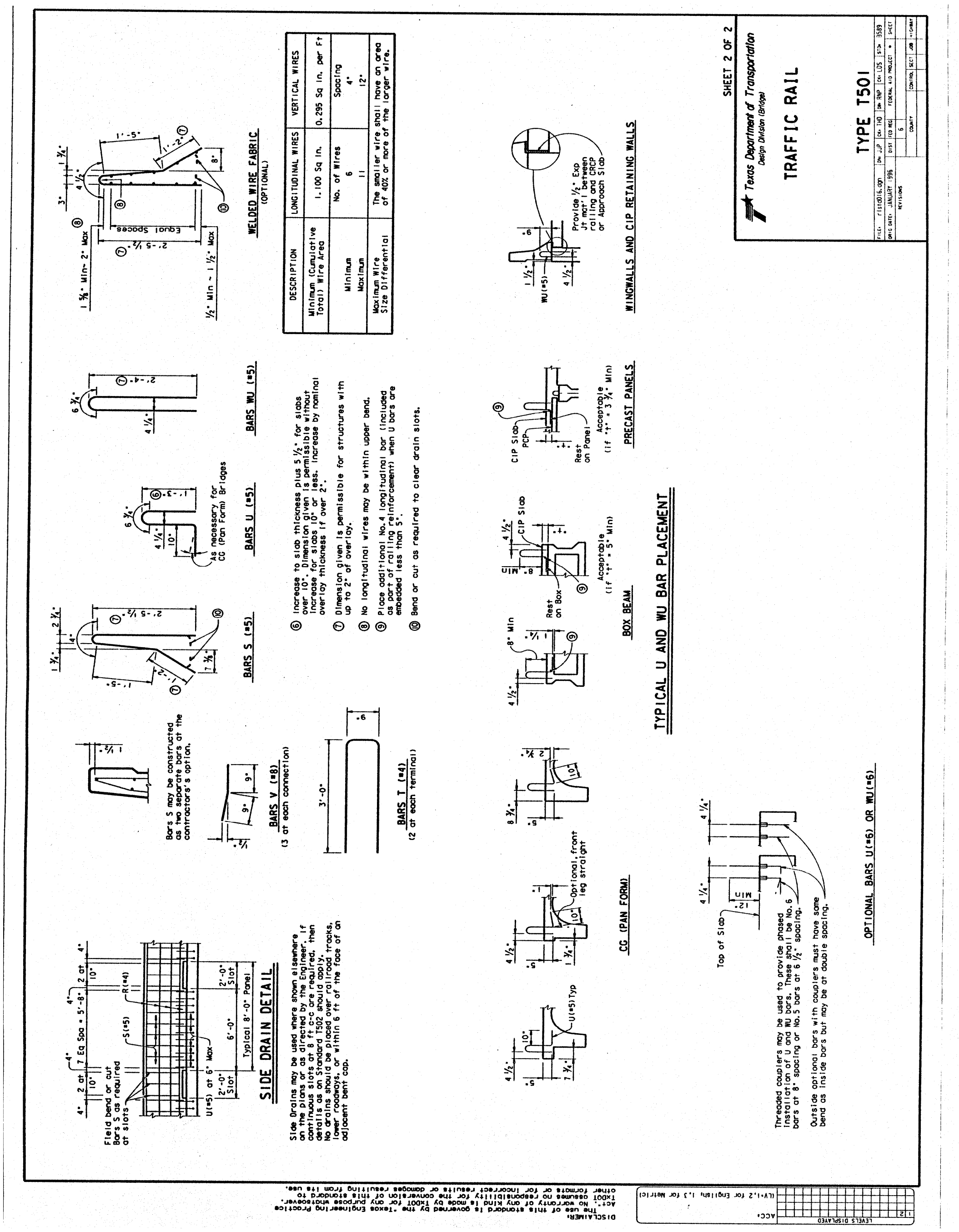
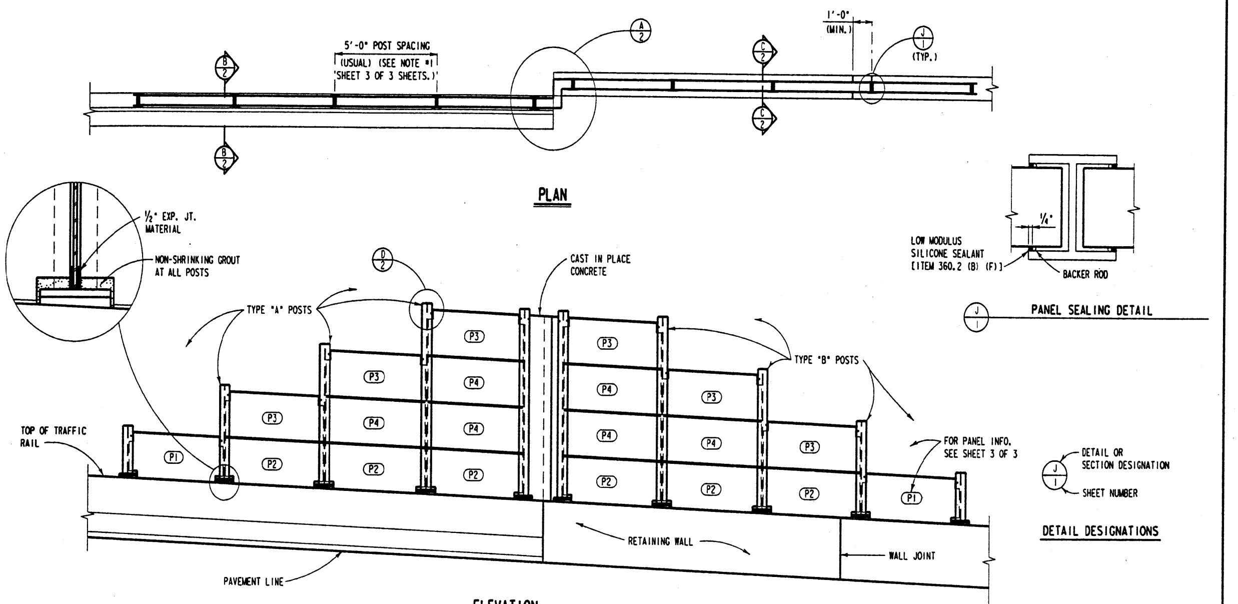


Figure A5.5 TxDOT T501 Traffic Rail Construction Drawings (Sheet 2 of 2)



GENERAL NOTES:

DESIGN FOR SOUND ATTENUATING WALL IS BASED ON WIND VELOCITY OF 80 M.P.H. IN ACCORDANCE WITH A.A.S.H.T.O., "GUIDE SPECIFICATIONS FOR STRUCTURAL DESIGN OF SOUND BARRIERS."

MAXIMUM HEIGHT ABOVE TOP OF RAIL OR RETAINING WALL IS 10' WITH TYPE "A" POST AND 12' WITH TYPE "B" POST.

ALL CONCRETE SHALL BE CLASS "C".

ANCHOR BOLTS SHALL CONFORM TO ASTM A193 GRADE B7, A325 OR A449. NUTS SHALL CONFORM TO ASTM A194 GRADE 2. THREADS SHALL BE 3/4 -10 UNRF-2A OR 2B.

ALL STEEL COMPONENTS EXCEPT REINFORCING STEEL AND LOCKNUTS SHALL BE GALVANIZED UNLESS OTHERWISE SHOWN IN PLANS. LOCKNUTS SHALL BE CAD PLATED AND WAXED, ALL STEEL STOVER LOCKNUTS OR APPROVED EQUAL.

ANCHOR BOLTS AND POSTS SHALL BE SET VERTICAL.

PANELS ARE TO FOLLOW THE PROFILE OF THE TOP OF RAIL OR RETAINING WALL. IT IS ANTICIPATED THAT GRADES OF UP TO ABOUT 2% MAY BE ACCOMMODATED WITH ENDS OF PANELS SQUARE WITH TOP AND BOTTOM. OTHERWISE ENDS SHALL BE CAST AT AN ANGLE AS REQUIRED.

BOTH SIDES OF PANELS SHALL RECEIVE AN EXPOSED AGGREGATE (RIVER ROCK) FINISH.⊕ OVERALL THICKNESS OF PANEL TO BE 5" INCLUDING EXPOSED AGGREGATE.

EXPOSED AGGREGATE SHALL BE GRADE 5 AS DESCRIBED IN THE ITEM "CONCRETE FOR STRUCTURES". COARSE AGGREGATE SHALL BE PREDOMINATELY UNCRUSHED GRAVEL AND SHALL BE COLORED PREDOMINATELY IN SHADES OF RED, BROWN, BLACK OR COMBINATIONS THEREOF. THE CONTRACTOR WILL BE REQUIRED TO SUBMIT REPRESENTATIVE SAMPLES TO THE ENGINEER FOR COLOR APPROVAL PRIOR TO USE.

RETAINING WALL BARS U AND RAILING BARS S IN EXCESS OF NORMAL SHALL BE INCLUDED IN UNIT PRICE FOR SOUND ATTENUATING WALL.

OPTIONAL REINFORCING SHOWN FOR TRAFFIC RAIL (TYPE T501) WILL NOT BE ALLOWED.

CAST-IN-PLACE CONCRETE SHALL RECEIVE A CLASS B, TYPE 1 FINISH.⊕

⊕ TYPE 1 FINISH AND SEALER FOR EXPOSED AGGREGATE FINISH SHALL BE AS SPECIFIED IN THE SPECIAL PROVISION TO THE ITEM "SURFACE FINISHES FOR CONCRETE."

TEXAS DEPARTMENT OF TRANSPORTATION

SOUND ATTENUATING WALL

(FW)RWSAW

SHEET 1 OF 3 SHEETS

FWSAW.DGN
ORIGINAL DRAWING DATE: OCT 1990
DN: WCC
CK: JEC
DW: SP
CK: WCC
REVISIONS:

FED. RD. DIV. NO.	FEDERAL AID PROJECT NO.		SHEET NO.
6			
STATE	STATE DIST. NO.	COUNTY	
TEXAS	02	TARRANT	
CONT.	SECT.	JOB	HIGHWAY NO.

OSA7:[302136]SWALLDET.DGN

Figure A5.6 TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 1 of 3)

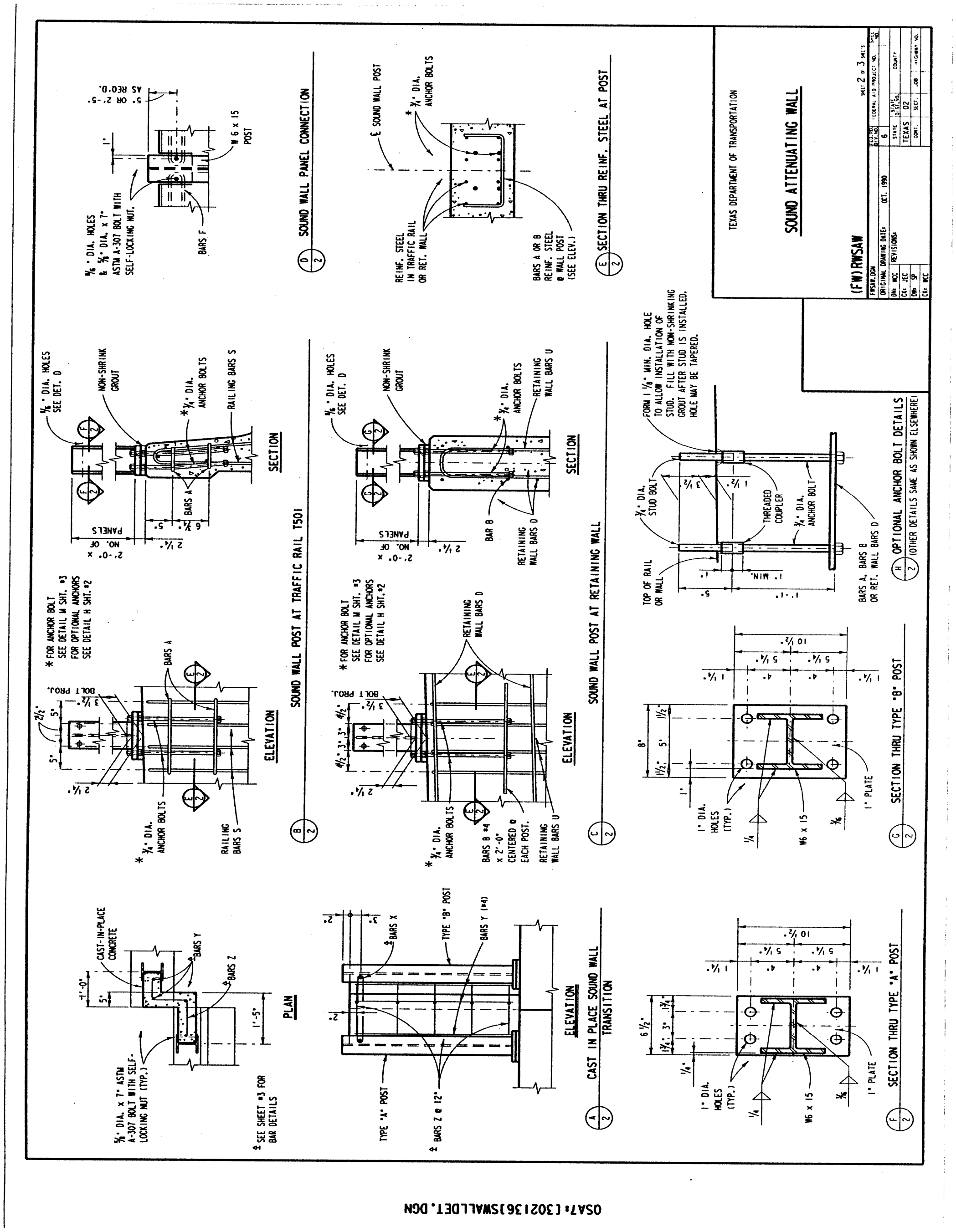


Figure A5.7 TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 2 of 3)

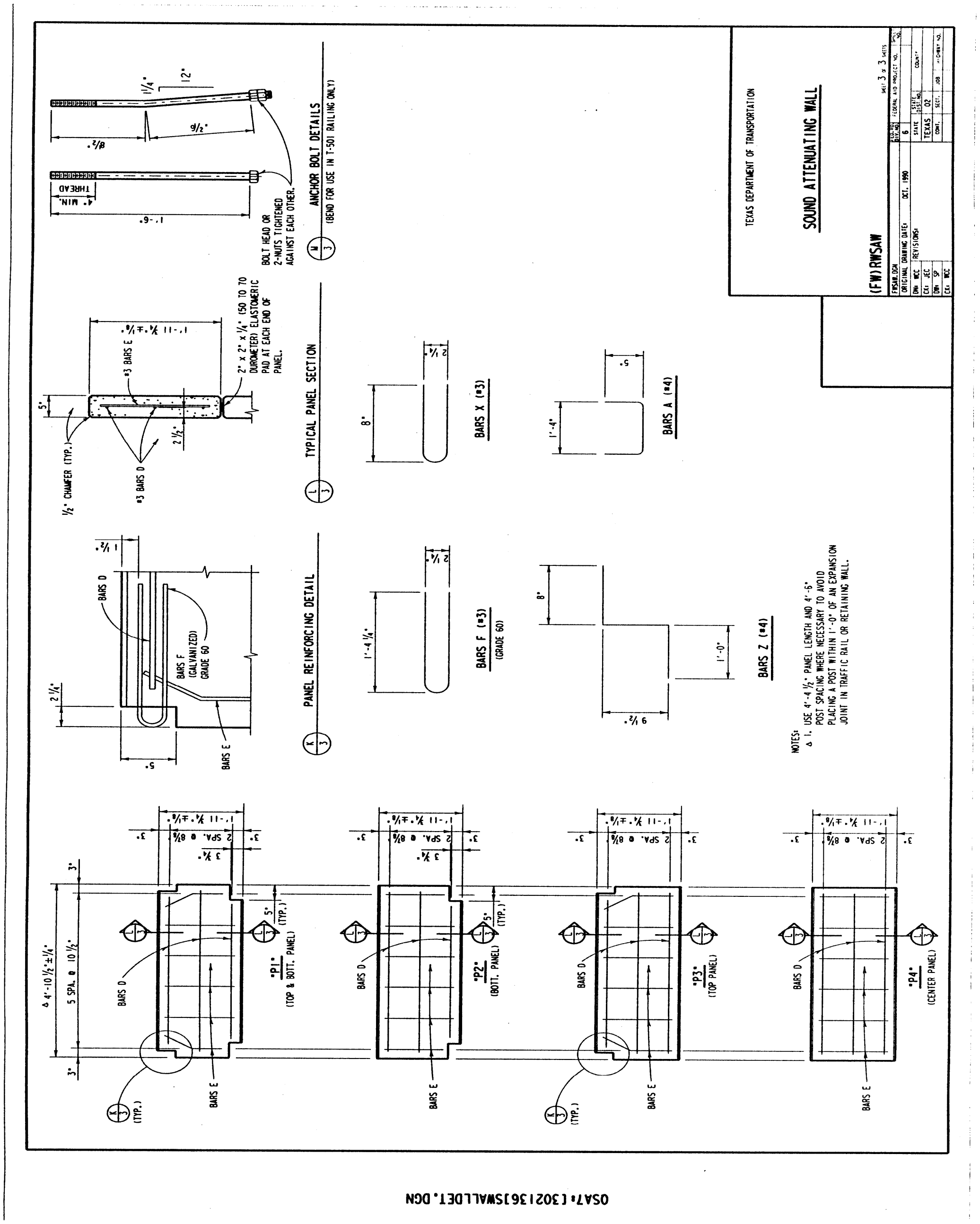


Figure A5.8 TxDOT Mounted Sound Wall Construction Drawings - Fort Worth District (Sheet 3 of 3)

Module 6

Evaluations of the *Design Guide*

6.1 INTRODUCTION

The objective of the *Design Guide* is to provide TxDOT with a standardized, performance-based process for designing highway noise barriers. To make the *Guide* effective and useful, preliminary drafts of the *Guide* were evaluated by TxDOT designers and revised based on their comments and questions. Their assistance and feedback is gratefully acknowledged.

This chapter discusses the evaluations performed by the TxDOT engineers. The first evaluation focuses on a noise barrier that had been previously designed using current TxDOT district design methods. The *Design Guide* was used to re-design the noise barrier. The last two evaluations discuss comments and recommended revisions made by TxDOT personnel from the Houston and San Antonio districts.

6.2 NOISE BARRIER EVALUATION 1 (SEPTEMBER 1997)

The information presented in this section is based on communications with Mr. Larry Blackburn and Mr. Amer Qureshi, of the Houston District.

6.2.1 TxDOT Personnel

Mr. Blackburn is a Supervising Design Engineer in the Houston District office. Mr. Qureshi works with Mr. Blackburn in the Central Design - B Division of the Houston District. Mr. Qureshi had not had any previous experience in the design of noise barriers, and was chosen for this evaluation to assess the usefulness of the *Design Guide* to a novice user.

6.2.2 The Noise Barrier

The noise barrier used in this evaluation will be located in Houston on FM 529. By August 1997, the barrier had been designed by TxDOT using the process described in the next section. The barrier was let for construction in September and was scheduled for construction in the spring of 1998.

6.2.3 Current TxDOT (Houston District) Design Process

The design of noise barriers in the Houston District is a group effort involving the Environmental, Geotechnical, Design, Bridge, and Laboratory Departments. The Environmental Department specifies the preliminary height and length of the noise barrier. The Geotechnical Department takes borings to determine the soil characteristics, and chooses a suitable footing type. The Bridge Department checks the footing design and the steel quantities. The Design Department determines the final design elements of the noise barrier, including the final proposed location, after consideration of site distances and property boundaries.

6.2.4 *Design Guide* Process and Results

Mr. Qureshi received a preliminary copy of the *Design Guide*. After reading through the *Guide*, Mr. Qureshi used the descriptions of types of noise barriers to choose a prefabricated, integral post-and-panel-system with a panel length of 20 feet. He specified a portland cement-based material due to durability and low cost. He was given the height and length of the noise barrier by the Environmental Department. Those dimensions were 10 and 534 feet, respectively, and were chosen so that noise levels in affected residential areas would be reduced to the recommended levels.

He chose a drilled shaft foundation with grade beams. He specified that the wind load be calculated on the barrier as recommended by AASHTO guidelines using a factor of safety of 1.3. He also specified that gravity, water pressure, snow, and earthquake loads be considered. However, many of these loads are not applicable in the Houston area. He found that the combination of wind load applied to the top of the barrier and the type of soil were the critical factors in the design of the drilled shafts. He consulted the Geotechnical and Bridge Departments for questions related to the technical details of the proposed design. His results are in full agreement with the design produced in the original barrier design.

6.2.5 Further Evaluation Comments

Mr. Qureshi did find the *Design Guide* helpful in understanding the numerous components of a noise barrier and how they work together to form the noise barrier system. It was useful in selecting the physical aspects of a noise barrier. He did not feel that there was adequate explanation of the structural aspects of noise barriers. He suggested including two or three design examples of noise barriers for different soil conditions, and also references to other reading material.

6.3 NOISE BARRIER EVALUATION 2 (APRIL 1998)

The information presented in this section is based on communication with Mr. James Darden and Ms. Debbie Taylor of the Houston District.

6.3.1 TxDOT Personnel

Mr. Darden is the head of the Project Development Department in the Houston District office. Ms. Taylor is the Environmental Supervisor in the Environmental Section of Project Development. Her previous experience in noise barrier design includes conducting preliminary noise studies, running computer programs STAMINA and OPTIMA, and reviewing final designs. Ms. Taylor was chosen to review the *Design Guide* to provide comments and revisions from a more experienced designer.

6.3.2 Current TxDOT (Houston District) Design Process

That process is described in Section 3.2.3 and will not be repeated here.

6.3.3 Comments and Revisions

Ms. Taylor's comments and suggested revisions on the *Design Guide* concentrated mainly on TxDOT policy, aesthetics, and the design process of noise barriers in the Houston district. Some corrections were made to update TxDOT policy as described in the *Design Guide*. Other additions to public involvement and approval were also noted. More explanations and examples of ways to make noise barriers more aesthetically pleasing were included. Lastly, she expanded upon the current design process for noise barriers in the Houston District. Miscellaneous editorial comments were made throughout the *Design Guide.*

6.4 NOISE BARRIER EVALUATION 3 (APRIL 1998)

The information presented in this section is based on communication with Mr. Barrlynn West from the San Antonio District.

6.4.1 TxDOT Personnel

Mr. West is the District Geologist in the Environmental Section of the Advanced Transportation and Planning Department in the San Antonio District office. Mr. West had no previous experience in the design of noise barriers, and was chosen for this evaluation to assess the *Design Guide* from the viewpoint of a novice.

6.4.2 Current TxDOT (San Antonio District) Design Process

The San Antonio District had designed one noise barrier, using two engineers: one from the Environmental Section, and the other from the Advanced Planning Section. The Seguin area office was also consulted on the design of the barrier. This process was used to design only one noise barrier, and may be modified for future designs.

6.4.3 Comments and Revisions

Mr. West had few comments on the *Design Guide*. The remarks he did have related to TxDOT policy and the acoustical function of noise barriers. He recommended revisions of some aspects of TxDOT policy and clarification regarding the acoustical function of noise barriers.

6.5 CONCLUDING REMARKS

The comments and recommendations provided by Mr. Qureshi, Ms. Taylor, and Mr. West were used to revise the *Design Guide*. This section explains how their comments were incorporated and what changes were made to the *Design Guide.*

First, a design example of a noise barrier in the Fort Worth district was incorporated in the *Design Guide* to illustrate some of the structural aspects in noise barrier design. Next, the *Design Guide's* explanations of TxDOT policy were revised to clarify when a noise barrier is mandated for consideration. Recommendations were also added to the policy, explaining how to deal with lack of public response. The chapter on noise barrier aesthetics was expanded with examples of barrier panel types and surface treatments that create a more aesthetically pleasing noise barrier. To clarify the acoustical function of noise barriers, references were cited and noted in the *Design Guide*. Lastly, the explanation of the current design process for noise barriers in the Houston District was expanded by explaining in more detail the duties of the Design Department.

Module 7

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