SPECIAL NOISE BARRIER APPLICATIONS
Phase II

WA-RD 378.1

Final Report
March 1995

Washington State Department of Transportation

Washington State Transportation Commission
Planning and Programming Service Center
in cooperation with the U.S. Department of Transportation
Federal Highway Administration

Final Report

SPECIAL NOISE BARRIER APPLICATIONS

Phase II

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Submitted to:

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Planning and Programming Service Center
Washington State Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

March 9, 1995

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DISCLAIMER

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EXECUTIVE SUMMARY

This report examines five special noise barrier applications that exist in addition to the conventional vertical reflective barrier. The acoustic, aesthetic, and economic feasibility of absorptive T-top, Y-top, slanted-top, single-wall absorptive, and absorptive parallel noise barriers are addressed as they compare to a conventional noise barrier. Based on acoustic, aesthetic, and economic impacts, conclusions and recommendations are drawn on the most promising of these special barrier applications for selected WSDOT projects. For each project selected, a standard barrier design was completed, followed by application of the five special treatments.

Because special noise barriers are acoustically superior [Cohn 1993], these barriers provide an alternative to constructing taller conventional noise barriers of similar acoustic performance. Studies have indicated that insertion loss (the net reduction in sound level after construction of a barrier) increases 1 dB for every 2 feet of barrier height as long as an adequate line-of-sight break is maintained [Cohn 1993]. Therefore, noise barrier performance can generally be improved by increasing the height. However, studies have shown that the "benefit/cost ratio generally peaks at a height of about 13 feet" [Cohn 1993, 83].

Special noise barriers offer a viable alternative to constructing taller conventional barriers which adversely affect the surrounding aesthetic environment and raise barrier costs. Because special noise barriers offer increased acoustical performance over a conventional barrier of equal height, special barrier heights could be lowered to reduce negative aesthetic and economic impacts.

Each special noise barrier's enhanced acoustical performance varies due to the different mechanisms these barriers utilize: double diffraction provided by a T-top or Y-top section, movement of the diffraction zone by slanting the upper third height of a conventional barrier, and the application of absorptive material to a T-top section or vertical wall [Cohn 1993]. The following paragraphs discuss the different mechanisms special noise barriers utilize to improve acoustic performance.

T-top and Y-top barriers increase insertion loss through double diffraction, which is similar to placing two conventional noise barriers close to one another. Thus, T-top and Y-top barriers provide acoustic performance similar to that of a knife-edge barrier when the difference in height between the two barriers is equal to the width of the top. Because a Y-top barrier does not have a continuous flat surface to provide interference with the propagating wave during double diffraction, it is less acoustically effective than a reflective T-top. Unlike T-top and Y-top barriers, slanted-top barriers provide only a slight increase in insertion loss when compared to a conventional barrier of equal height, resulting from the increase in path length caused by the movement of the diffraction zone closer to the roadway.

An increase in insertion loss can also be achieved by the application of absorptive material to T-top, single-wall and parallel barriers. Applying absorptive material to these barriers raises insertion losses by absorbing sound wave energy, particularly for higher-frequency sound levels with shorter wavelengths that can be more easily affected while diffracting across the top of the barrier. Because highway traffic noise has a dominant frequency of approximately 550 hertz, resulting in a wavelength approximately 2 feet long [FHWA 1980], a 3-foot absorptive strip was recommended for the absorptive T-top and single-wall absorptive barriers to ensure adequate absorption. Applying absorptive material to T-top and single-wall absorptive barriers would produce an additional 2 dB of attenuation, while parallel barriers treated with absorptive material would aid in reducing insertion loss degradation resulting from multiple reflections.

Four WSDOT highway projects, three in Seattle (Fourth Avenue, Magnolia Road, and Kent Commons Play Field) and one in Spokane (Spokane Community College Area), were selected to investigate the predicted field effectiveness of absorptive T-top, Y-top, slanted-top, single-wall absorptive, and absorptive parallel barriers. For each project site, a base-line standard barrier design was created to provide an insertion loss of approximately 10 dBA. Applying special noise barriers to each site required modifications in barrier heights in order to provide barriers of similar acoustic performance to the base-line standard barrier designs.

Using the acoustic "rules of thumb" established in this report and the line-of-sight breaks calculated by the Line-of-Sight program, standard barrier design heights were modified in order to apply special barrier applications. Insertion losses were calculated for each modified conventional barrier design using STAMINA 2.0/OPTIMA. The additional insertion loss provided by the application of a special barrier was then added to the insertion losses calculated using STAMINA 2.0/OPTIMA to produce each special noise barrier resultant insertion loss.

An absorptive T-top would provide an additional 4.3 dB of attenuation when compared to a conventional barrier of equal height, resulting from double diffraction and the application of absorptive material. Thus, an absorptive T-top could provide the same insertion loss as a conventional barrier 8 feet higher. Also, double diffraction results in the Y-top barrier providing an insertion loss (1.3 dB) equal to a conventional barrier 3 feet taller. Single wall barriers would provide a 2 dB increase in insertion loss, producing acoustical performance equal to a conventional barrier 4 feet taller. Unlike the absorptive T-top, Y-top, and single wall absorptive barriers, a slanted-top barrier would not produce any significant increase in attenuation, thus barrier heights should not be reduced. Also, barrier heights should not be lowered for parallel barriers in cases where insertion loss degradation is prevalent due to multiple reflections; instead absorptive material should be applied to these barriers to lessen the negative effects of insertion loss degradation.

Special noise barriers were found to be beneficial to these sites because these barriers provided attenuation similar to a taller conventional barrier. In fact, an absorptive T-top, Y-top, and single-wall absorptive barrier were recommended for project application because these barriers would lessen aesthetic and economic impacts. A slanted-top barrier was also found to be beneficial for highway projects that need to be sensitive to their surrounding aesthetic environment. Also, absorptive parallel barriers are beneficial for sites where insertion loss degradation is present due to multiple reflections.

Selection of a special noise barrier should be based on a barrier's ability to minimize acoustic, aesthetic, and economic impacts, and should be prioritized accordingly to projects on an individual basis. Analyzing the acoustic, aesthetic, and economic impacts of special barrier applications for individual projects will hopefully lead to appropriate barrier selection, and in turn the true effectiveness of these barriers will be verified. As a result of this research, it is hoped that special noise barriers will be strongly considered as an alternative solution to constructing taller conventional noise barriers.

PROBLEM STATEMENT

During the last 20 years, state highway agencies have constructed more than 500 linear miles of noise barriers in the U.S. Most of these barriers have been vertical, reflective walls made of concrete, wood, or steel with a "knife-edged" barrier top, providing a single diffraction edge with a reflective diffraction zone. Clearly, many other options are available for noise barrier shapes and treatments, including earth berms, absorptive or partially absorptive barriers, barriers with slanted sections at their tops to provide horizontal displacement of the diffraction zone, and barriers with T-tops or Y-tops to provide a double-diffraction zone. A previous study for WSDOT, *Special Noise Barrier Applications: Phase I*, found that five special applications warrant further examination: absorptive T-top barriers, single-wall absorptive barriers, slanted-top barriers, absorptive parallel barriers, and Y-top barriers.

This study examined the potential for implementing each of the five special treatments in four actual highway projects in Washington State. For each highway project, a standard barrier design was completed, and the five special treatments were applied.

OBJECTIVE

A previous study, *Special Noise Barrier Applications: Phase I*, identified five barrier applications that could improve the WSDOT noise mitigation program. The primary objective of this research was to test these five applications analytically on several actual highway projects to gain definitive information on their real potential. Four WSDOT highway noise mitigation projects were selected for use as *field laboratories* for examining the application potential of the special barrier treatments. Three of these highway projects are located in Seattle: Fourth Avenue S.E. and Magnolia Road, both located on SR-405 in King Co. and in South Snohomish Co; and Kent Commons Play Field, located on SR-167. The other project is the Spokane Community College Area, located on the Market/Greene alternative of the planned North Spokane Freeway route.

SPECIAL NOISE BARRIERS

The previous report, *WSDOT Special Noise Barrier Applications: Phase I*, recommended that five special noise barrier treatments, including shaped tops and absorptive surfaces, be considered for WSDOT highway projects. The recommended barrier treatments are listed below and are described in greater detail in the following sections of this report.

Shaped Barriers:	1. Absorptive T-top
	2. Y-top
	3. Slanted-top
Absorptive Barriers:	1. Single Wall Absorptive
	2. Absorptive Parallel

Shaped Barrier Tops

The performance of noise barriers can generally be improved by increasing their height. However, studies have shown that the "benefit/cost ratio generally peaks at a height of about 13 feet" [Cohn 1993, 83]. In addition, increasing the height of barriers diminishes the view of the surrounding environment, causing a negative aesthetic impact. Researchers have found that shaped barriers can achieve enhanced acoustical performance without increased height, thus minimizing the negative aesthetic impact. Therefore, shaped barriers provide an alternative for highway projects with conventional barrier heights of 13 feet or more, and such barriers should be considered for WSDOT projects.

Absorptive T-top Barriers

An absorptive T-top barrier is formed by placing a horizontal section treated with an absorptive application on the top of a vertical wall. Past studies have shown that the insertion loss (the net reduction in sound level after construction of a barrier) achieved by an absorptive T-top barrier is significantly greater than that achieved by a conventional barrier of the same height. The insertion loss increases because the absorptive treatment absorbs sound wave energy and the T-top section produces double diffraction, similar to that caused by placing two conventional knife-edged barriers close to one another. Thus a reflective T-top barrier provides acoustical performance similar to that of a knife-edged barrier when the difference in height between the two barriers is equal to the width of the T-top.

Applying an absorptive treatment to the T-top also increases insertion loss, particularly for higher-frequency sound levels with shorter wavelengths that can be more easily affected while diffracting across the top of the barrier. Highway traffic noise contains energy in frequency bands throughout the audible range, but the dominant frequency is approximately 550 hertz, resulting in a wavelength roughly 2 feet long. Therefore, to ensure the optimum acoustical performance of the absorptive treatment, a cap width of 3 feet should be used for absorptive T-top barriers selected for WSDOT projects. Figure 1 displays the configuration of the absorptive T-top barrier.

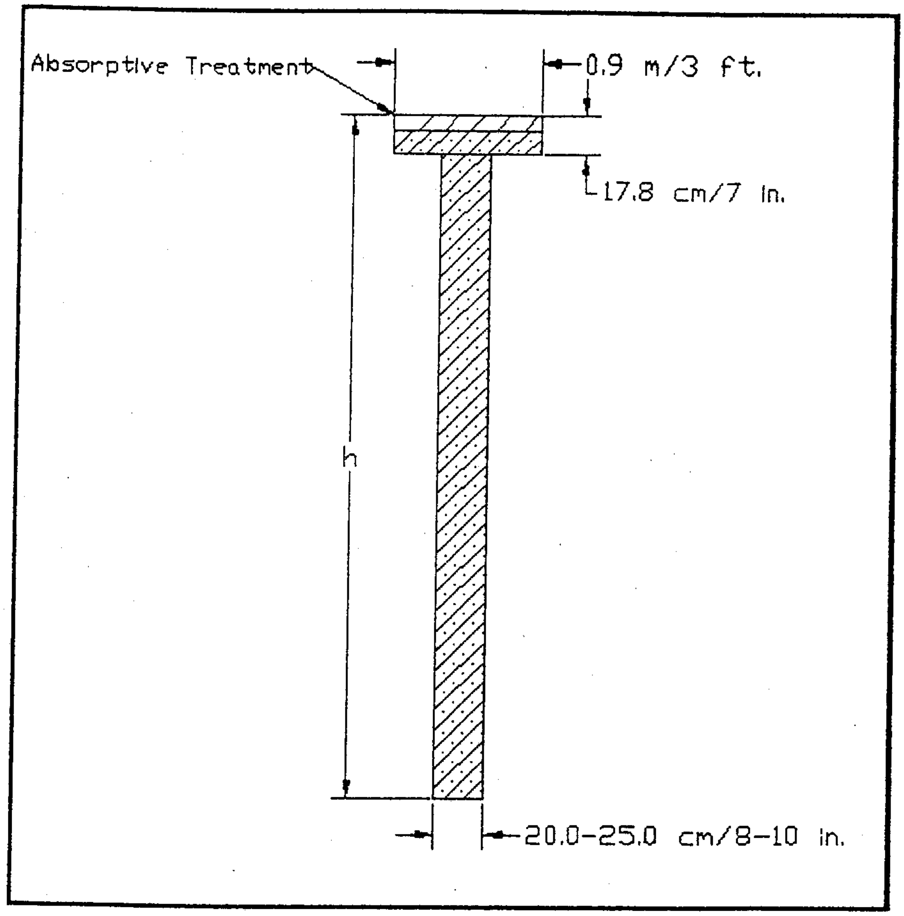

FIGURE 1 - Absorptive T-top Barrier

Y-top Barriers

Another shaped barrier under consideration for WSDOT projects is the Y-top barrier. Like the T-top barrier, the Y-top barrier also provides increased acoustical performance through double diffraction. However, unlike the T-top barrier, the ends of the horizontal section at the top of the vertical wall are not flat, but rather are slanted upward in the shape of a Y. Because the Y-top barrier does not have a continuous flat surface to provide interference with the propagating wave during double diffraction, it is acoustically less effective than a reflective T-top barrier. Nevertheless, the Y-top barrier provides better acoustical performance than a conventional barrier more than 13 feet in height. Like the absorptive T-top, because of the dominant frequency of highway traffic noise, the Y-top should have a width of 3 feet to facilitate double diffraction at both ends of the Y-top section. The Y-top barrier is depicted in Figure 2.

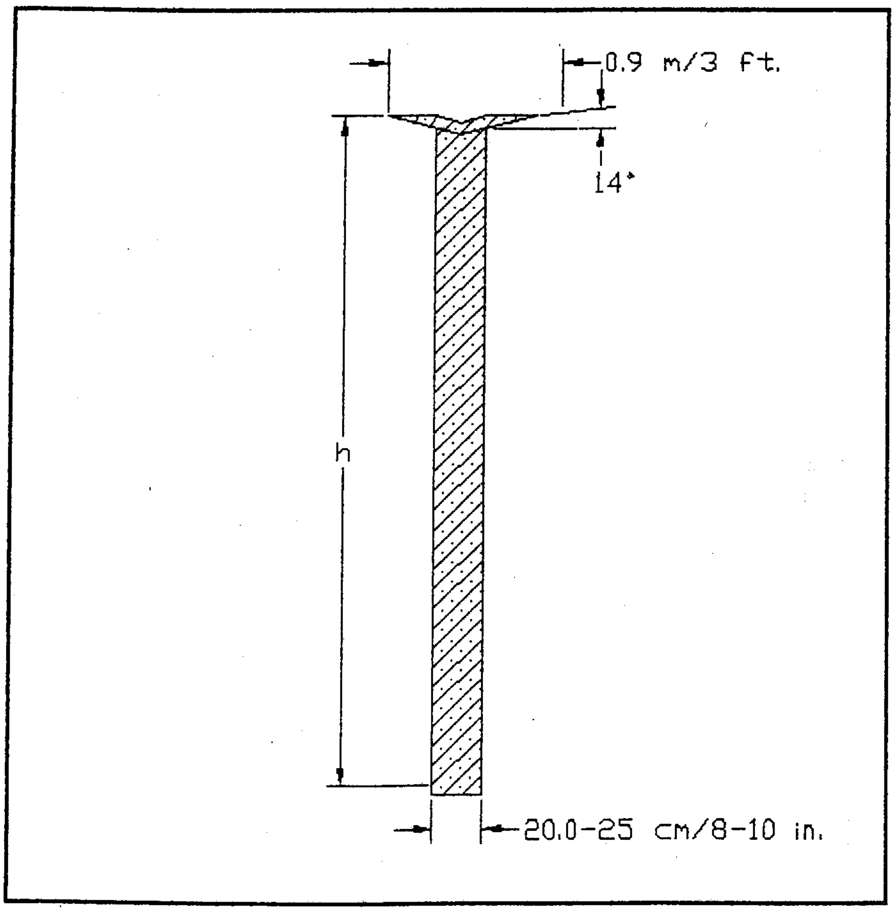

FIGURE 2 - Y-top Barrier

Slanted-top Barriers

The final shaped barrier selected for analysis is the slanted-top barrier, formed when the upper one-third of the barrier is slanted toward the traffic at an angle of 30 to 45 degrees. Slanting the top of a barrier displaces the location of the diffraction edge, resulting in an increase in path length and improved barrier performance. The slanted-top barrier is displayed in Figure 3.

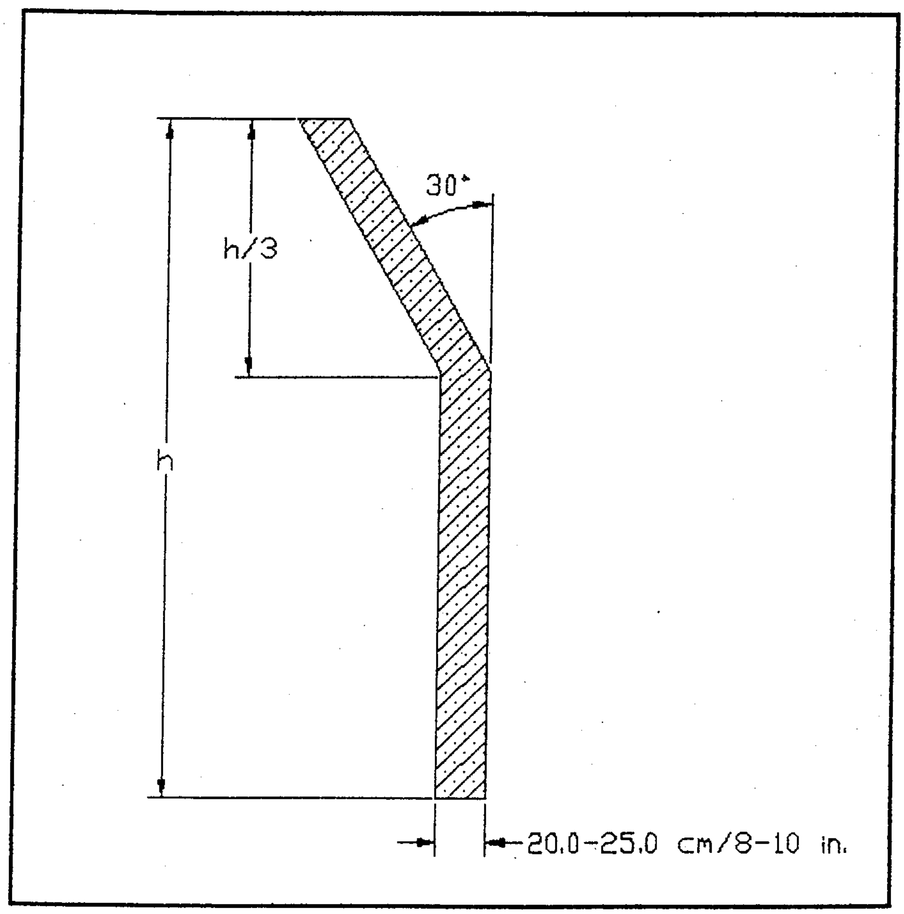

FIGURE 3 - Slanted-top Barrier

Absorptive Noise Barriers

Like shaped barriers, absorptive barriers enhance acoustical performance without increasing barrier heights. Absorptive barriers are formed by placing absorptive strips on the upper zone of a noise barrier. These strips should be 3 feet in length to ensure adequate absorption of sound waves. Depending upon the amount of acoustical performance desired, the absorptive treatment can be placed on the receiver side, the source side, or both sides of the barrier. Nicolas *et al* concluded that an absorbent covering will give the same increase in insertion loss if it is placed on either the source side or the receiver side. This study also found that covering both sides of a barrier increases the insertion loss, especially when both the receiver and the source are located near the barrier [1989].

Although absorptive noise barriers have been extensively studied for many years [Cohn 1993], the results of these studies have been inconclusive. Absorptive treatments absorb high-frequency noise better than they absorb low-frequency noise. The two absorptive noise barriers considered for WSDOT projects are single-wall absorptive barriers and absorptive parallel barriers.

Single-Wall Absorptive Barriers

Placing an absorptive treatment on a single-wall barrier increases the insertion loss of the barrier [Cohn 1993]. Thus, a shorter barrier with an absorptive treatment provides acoustic performance similar to that of a taller conventional barrier while at the same time decreasing negative aesthetic impact.

Absorptive Parallel Barriers

When reflective parallel barriers are used, multiple reflections of sound can degrade the acoustical performance of each wall, particularly when the canyon width is less than 200 feet, the barriers are at least 10 feet high, the ratio of canyon width to barrier height is less than 20:1, and the barriers are perfectly parallel and equal in height. Under these conditions, absorptive parallel barriers can be used to reduce the number of multiple reflections [Bowlby 1987], thereby decreasing the degradation in insertion loss. Therefore, the application of absorptive material is recommended for parallel barriers 10 feet or more in height. An illustration of parallel barriers with multiple reflections is presented in Figure 4.

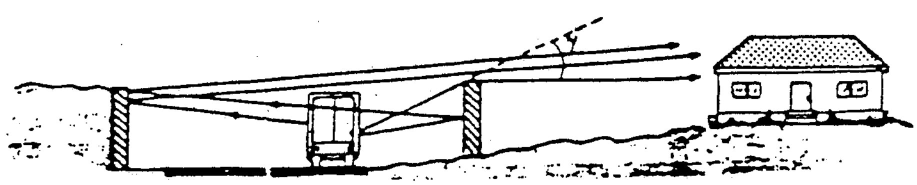

FIGURE 4 - Parallel Barriers

SPECIAL NOISE BARRIER FEASIBILITY AND IMPACTS

This study reviewed the unique feasibility and impact (acoustic, aesthetic, and economic) of each of the five recommended special barrier applications to determine whether they are appropriate for use in WSDOT projects. In some instances, the special noise barriers may be superior in every way to conventional barriers.

Acoustic Feasibility

Under certain circumstances, special noise barriers perform better acoustically than conventional barriers. These circumstances were examined to aid in selecting the appropriate barrier for an individual site.

One limitation in the application of special noise barriers is line-of-sight breaks. A line-of-sight break is the difference between the height of the barrier and the distance at which the line of sight intersects with the barrier. Figure 5 gives a visual explanation of a line-of-sight break. To maintain an adequate line-of-sight break, a special noise barrier must be at least 2 feet through the line of sight [Cohn 1993]. As long as a 2-foot line-of-sight break is maintained, the height of a conventional barrier could be reduced by the use of a shorter special noise barrier.

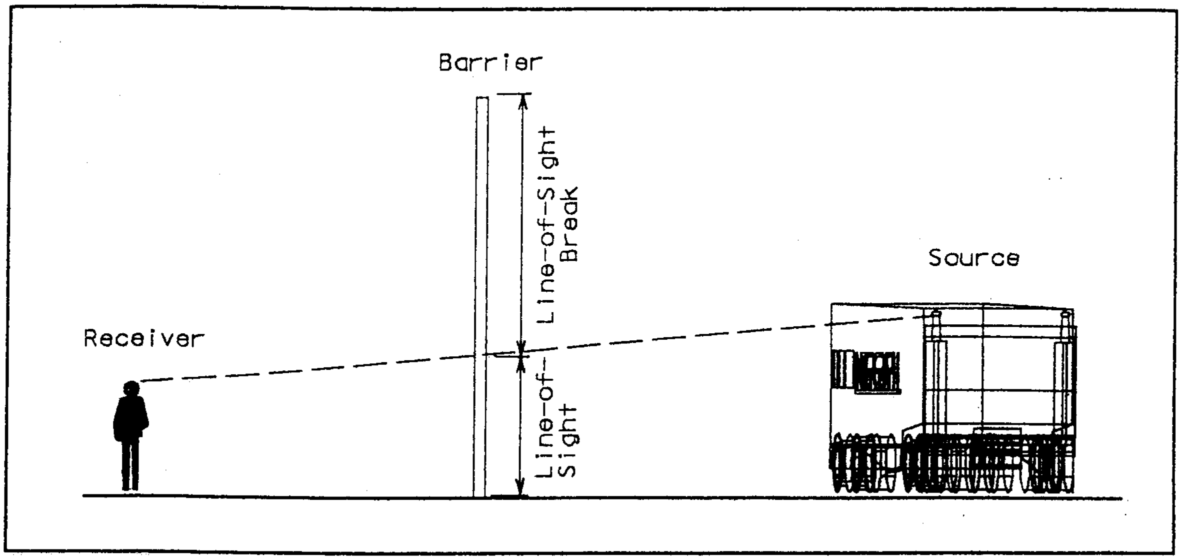

FIGURE 5 - Line-of-Sight Break

Special noise barriers are not recommended for some conventional barrier heights. Shaped-barrier tops are applicable when barrier heights exceed 13 feet because the benefit/cost ratio generally peaks at this height. However, if line-of-sight breaks are maintained, increased acoustical performance can be achieved regardless of barrier height, and single-wall absorptive barriers are recommended. Absorptive materials could be applied to almost any WSDOT project with single-wall barriers. Unlike single-wall absorptive barriers, absorptive parallel barriers are limited to barriers taller than 10 feet, because only at this height will multiple reflections cause significant insertion loss degradation, warranting the application of absorbent materials.

In addition, the amount of attenuation needed for a particular barrier height should be considered. The five special noise barriers under consideration offer differing amounts of insertion loss over a conventional barrier of the same height. Therefore, special noise barriers should also be selected on the basis of the amount of acoustical performance needed for a particular site. The acoustical performance of each special noise barrier is presented in this report.

Acoustic Impacts

The acoustical performance of each special noise barrier is different because each provides increased insertion loss through a different mechanism: double diffraction (T-top and Y-top barriers), displacement of the diffraction edge (slanted-top barriers), and absorptive treatments (T-top sections, single-wall barriers, and parallel barriers). To determine the acoustical performance of each special noise barrier, the information presented in the previous report, *WSDOT Special Noise Barrier Applications: Phase I*, was expanded to establish acoustic "rules of thumb," which were used to calculate the insertion losses provided by each application.

Absorptive T-top Barrier

For the reasons discussed earlier in this report, T-top barriers with 3-foot caps were selected for WSDOT projects. To calculate an insertion loss for these caps, a linear relationship between insertion loss and cap width was assumed. This assumption provided a reasonable approximation of insertion loss for caps of varying widths. Because the cap widths differ by only a few feet, this assumption should be valid. The acoustical performance of the absorptive T-top barrier was determined by applying the following "rules of thumb" from the Phase I report:

> May and Osman determined that an absorptive T-top with a cap width of 2 feet results in an additional 1.9 dB of attenuation when compared to a reflective T-top with the same cap width [1980-1]. The amount of additional attenuation an absorptive T-top barrier could provide in comparison to a reflective T-top barrier was calculated as follows on a per-foot cap width basis:
>
> 1.9 dB/2 foot cap width = 0.95 dB/foot of cap width
>
> For a 3-foot cap width, the additional attenuation the absorptive T-top provides when compared with the reflective T-top results in the following:
>
> 0.95 dB/foot of cap width * 3 feet = 2.8 dB
>
> In addition to the two previous calculations, a comparison between the acoustical performance of a reflective T-top barrier and that of a conventional barrier was determined to develop an acoustical performance relationship between an absorptive T-top and a conventional barrier. The acoustical performance between a reflective T-top and a conventional barrier is based upon the "rule of thumb" that the increased performance resulting from the reflective T-top is <u>at least</u> equivalent to that which would result if the T-top

section were stood on its end and added to the height of the vertical section of the barrier. Therefore, insertion loss increases 1 dB for every 2 feet of height beyond the line-of-sight break as long as an adequate line-of-sight break is maintained. A reflective T-top noise barrier with a 3-foot cap width may provide the following additional attenuation in comparison to a conventional barrier of equal height:

1 dB/2 foot * 3 foot cap width = 1.5 dB

Adding the two previous calculations resulted in the following additional attenuation for an absorptive T-top with a 3-foot cap width when compared with a conventional barrier of equal height:

2.8 dB + 1.5 dB = <u>4.3 dB</u>

Therefore, an absorptive T-top barrier could achieve the same insertion loss as a conventional barrier 8 feet higher as long as the line-of-sight break was maintained. Reducing the height of a conventional barrier by 8 feet would significantly minimize negative aesthetic impacts. Therefore, in some instances tall conventional barriers could be lowered and capped with absorptive T-tops.

Y-top Barriers

The amount of additional attenuation provided by a Y-top barrier was calculated by applying the "rule of thumb" found in the Phase I report. Like that of the absorptive T-top barrier, the insertion loss of the Y-top barrier was determined by assuming a linear relationship between insertion loss and span width. The insertion loss for a 3-foot wide Y-top was calculated as follows:

May and Osman found that a Y-top barrier with an 8-foot span provides 3.5 dB of additional attenuation when compared with a conventional barrier [1980-1]. A Y-top barrier with a 3-foot span, then, would produce the following additional attenuation in relation to a conventional barrier of equal height:

3.5 dB/8 foot span = 0.438 dB/ foot of span

0.438 dB/foot of span * 3 feet = 1.3 dB

The calculated insertion loss of 1.3 dB means that the same insertion loss provided by a conventional barrier could be achieved by a Y-top barrier approximately 3 feet shorter. Thus, Y-top barriers should be considered when tall conventional barriers need to be shortened.

Slanted-top Barriers

Since a slanted-top barrier enhances acoustical performance through displacement of the diffraction edge, the acoustical performance of this type of barrier was determined by STAMINA/OPTIMA. Because of limitations in the STAMINA/OPTIMA program, a direct model of slanted-top barriers could not be created. Therefore, the barrier location was moved closer to the roadway to simulate the displacement of the diffraction edge produced by a slanted-top barrier.

Two data files were created for STAMINA/OPTIMA to model slanted-top barriers. The first data file included two 2000-foot, parallel roadways spaced 50 feet apart, a 2000-foot, 12-foot high barrier spaced parallel and 50 feet from the roadways, and receivers placed in a line 50, 100, 150 feet away from and perpendicular to the middle of the barrier. Other input parameters were a 60 mph vehicle speed, a volume of 4000 vph with heavy and medium truck percentages of 5 and 3 percent, respectively, $\alpha=0.5$, and a shielding factor of zero. Except for the placement of the barrier 5 feet closer to the roadways, the second data file was exactly like the first. The results of the STAMINA/OPTIMA modeling indicated the acoustical performance of a slanted-top barrier is approximately equal to a conventional barrier. The OPTIMA output is presented in Table I on page B-1.

Single-Wall Absorptive Barriers

The Ph.D. dissertation Performance of Absorptive Treatments for Single Highway Noise Barriers [Kim 1992] discussed the additional attenuation provided by applying absorptive treatments to noise barriers. Dr. Kim stated that placing an absorptive treatment one wave length from the top of the barrier resulted in up to an additional 4 dBA of attenuation in the shadow zone. The additional attenuation provided by the absorptive treatments decreases as the distance between the barrier and the receiver increases. Therefore, 2 dBA of attenuation was considered as the acoustic "rule of thumb" for this report.

Absorptive Parallel Barriers

Multiple reflections degrade the insertion loss of parallel barriers. In fact, the insertion loss of parallel barriers is decreased by approximately 2 to 4 decibels if the width of the canyon is less than 200 feet, the height of the barrier is at least 10 feet, the ratio of canyon width to barrier height is less than 20:1, and the barriers are perfectly parallel and of equal height [Cohn 1993]. Under such circumstances, benefit can be gained by applying absorbent material to these barriers, thus reducing the negative effects of multiple images [Bowlby 1987] and reducing insertion loss degradation.

REBAR, a program included in the *Noise Software Library* of the University of Louisville, was developed to calculate the amount of insertion loss degradation caused by the numerous image sources created by multiple reflections. This software program allows the designer to examine the effects of parallel barriers without performing burdensome calculations. In this study, REBAR was used to determine the decrease in insertion loss associated with the multiple reflections of parallel barriers. Table II on page B-2 shows the decrease in insertion loss calculated by REBAR for the Spokane Community College Area's reflective and absorptive parallel barrier designs.

Aesthetic Feasibility

Because public acceptance of barrier designs is crucial to the success of most projects, the aesthetic impact of the barriers is a very important consideration in the design process. To gain positive public perception, most state highway agencies are forced to design beyond their specified design noise level criteria and to develop designs that "match and harmonize with established architectural features" [Hurd 1987].

Five concepts should be investigated to determine whether the barrier design will achieve harmony with the surrounding community:

1. Barrier Size and Mass
2. Material Selection
3. Landscaping
4. Color
5. Citizen Involvement [Cohn 1981]

Increasing the size and mass of a barrier improves its performance. However, the "benefit/cost ratio generally peaks at around 13 feet" [Cohn 1993]. Because special noise barriers are shorter than conventional barriers, they can have a very positive aesthetic impact.

An important aesthetic consideration is selecting the proper materials for the final design of the barrier system. Some states have performed social surveys to gauge the perceived effectiveness of different types of barriers [Cohn 1981]. The results, presented from most favorable to least favorable, are shown below.

1. Earth Berm
2. Wall-Berm Combination
3. Wood or Concrete (tie)
5. Metal

Berms are very acceptable because they blend in and are perceived to be part of the natural highway environment. However, "large areas of right-of-way are required for mounds of significant height" [Simpson 1976], and it may not be possible to obtain enough land to construct a berm in an urban or suburban area. On the other hand, a wall-berm combination requires less land and results in a shorter wall that is perceived as less offensive by neighboring communities.

The results of the social survey cited above indicated a tie in the acceptability level of wood and concrete. In naturally wooded regions with abundant vegetation, a wooded barrier harmonizes with the natural setting, and such a barrier can also match the privacy fences located in many suburban areas. Concrete can be molded to resemble wood panels or shaped into other configurations that harmonize with established architectural features [Hurd 1987]. Surface coloring also helps concrete barriers blend with their surroundings. Pigments may be added to concrete mixes to obtain a color suitable for the project. The use of earth-toned colors (light browns, etc.) is encouraged because these colors look more attractive than regular Portland cement concrete and do not attract unwanted attention to the barrier [Hurd 1987].

Landscaping also enhances the ability of the barrier to blend into its environment. For instance, the use of separate posts and panels in a vegetative environment lends the appearance of wood. One study found that effective landscaping can raise the perceived effectiveness of the barrier by a psychological attenuation of 7 dBA [Cohn 1984].

The people surveyed found metal an unpopular choice of material for barrier construction, in part because of its maintenance disadvantages. Metal requires more frequent painting and treatment with chemicals to inhibit rusting. These maintenance costs can be considerably larger than those associated with a tinted concrete barrier [Hurd 1987].

Public involvement in barrier development is crucial to a highway noise barrier project. The following are some of the issues raised by the public about the placement of noise barriers along highways:

1. Why spend so much on so few?
2. Why should I pay for someone else's comfort?
3. They make the highway ride noisier.
4. They make driving monotonous.
5. They block scenery.
6. Barriers are eyesores [Cohn 1981].

Complaints such as these illustrate the necessity of public involvement in the barrier design process. "If the public believes it played a legitimate role in barrier development, it will receive the final design in a more favorable light" [Cohn 1984].

After a particular barrier design has been found to be compatible with a certain project, the acceptability of the design must be determined. Acceptability will be affected by several issues, each of which has pros and cons.

Pros:
1. Greater sense of privacy.
2. Perception of increased security from the drivers of vehicles that have broken down or from other intruders.

Cons:
1. Blocking view of road or from road.
2. Blocking breezes.
3. Blocking sunlight from gardens [Bowlby 1992].

Special noise barriers can enhance the aesthetic quality of the barrier design, while at the same time diminishing or eliminating negative impacts. Because special noise barriers are designed to be acoustically more effective than conventional barriers, barrier height can be reduced, thus decreasing costs and barrier mass for a given project.

Aesthetic Impacts

Special barrier applications not only reduce noise levels but also reduce the height of the barriers, making the barriers more aesthetically pleasing and acceptable to adjacent communities because the appearance of encroachment on adjacent properties is lessened. Shorter barriers provide some privacy and a sense of security for residences near the roadway, but they do not block as much sun or affect natural air ventilation as much as conventional barriers. This report discusses five special barrier applications that could improve the aesthetics of the barrier design.

Absorptive T-top, Y-top, single-wall absorptive, and absorptive parallel barriers are more aesthetically pleasing because they can provide increased attenuation with less height than conventional barriers. Slanted-top barriers also offer some aesthetic enhancements; slanting the upper third of the barrier away from the receiver allows more sunlight to reach nearby residences and makes the barrier seem to encroach less upon the affected receivers. However, this type of barrier may present an unwanted obstacle on the roadway by causing the appearance of constricted lateral clearance, resulting in reduced flow rates and capacity [McShane 1990].

Economic Feasibility

To develop a complete evaluation of these special noise barriers, this study addressed the economic impacts associated with each type of special barrier. The ultimate goal of any barrier design is to maximize noise reduction while minimizing cost [FHWA 1982]. It is assumed that reducing barrier heights will ultimately reduce barrier costs, thereby optimizing the placement of barriers adhering to WSDOT feasibility criteria.

Most of the costs associated with any barrier design are the result of initial construction and continued maintenance, and different structural and maintenance requirements are associated with each type of special noise barrier. These requirements include the cost of materials and construction, resistance to environmental conditions, durability, and ease of repair and maintenance [Hayek 1990]. Other costs that could influence the price of a barrier include labor, the cost of transporting materials, foundation requirements depending on soil types, and prevailing economic conditions [Bowlby 1992].

Although special barriers offer increased attenuation over conventional barriers, the maintenance and structural considerations associated with each type of barrier will affect its economic feasibility for each of the WSDOT projects. The following sections of this report examine important economic elements that could affect the selection of a special noise barrier.

Structural Considerations

Because noise barriers are subjected to wind loads, they must be designed to effectively resist these loads. Wind load dictates the strength requirements of the posts used in most barrier designs, and these posts are a significant component of barrier costs [Cohn 1993]. Steel reinforcements are needed in these posts to take up the stress as the panels rock back and forth [Bowlby 1992]. In addition, the design criteria for barrier foundations are based on the expected wind loads of a particular geographic area. For example, barriers that might experience hurricane force winds will need a stronger foundation to resist these excessive loads. Such foundation requirements could become quite expensive.

Many different design criteria for noise barrier construction have been used across the U.S. to ensure structural stability. Some of the design specifications used are the *AASHTO Standard Specifications for Structural Support for Highway Signs, Luminaries, and Traffic Signals*, local building codes, and the *1989 Guide Specifications for Structural Design of Sound Barriers.* The *Guide Specifications for Structural Design of Sound Barriers* provided consistent criteria for the construction of noise barriers while allowing the designers some flexibility in the choice of the final design [Bowlby 1992]. Some agencies use a combination of these design specifications.

State DOTs have developed their own noise barrier programs to deal with the unique problems and goals of their individual states. For instance, the particular geology of a state may call for better footings to control settlement, etc. *The Guide on*

Evaluation and Attenuation of Traffic Noise discussed examples of barrier designs from three states. One state used the AASHTO guidelines; another state used local building codes; and the third state used a combination of the two design techniques. The study concluded that the design criteria had been too conservative and that the "least conservative design has had excellent results without compromising the structural design of the noise walls" [AASHTO 1984].

Most areas of the country have building codes for bridges and regulations to ensure compliance with these codes. Bridges offer different challenges for designing noise barriers, including wind loading, methods of attachment, and weight and safety. Wind loading is always a concern in the stability of a structure. Because wind loads cause the deck of a bridge to bend, the connections used to attach the noise barriers to the bridge are crucial and must be strong enough to resist this bending movement. Additionally, the weight and safety of a barrier must be considered early in the design process, especially if the barrier is to be constructed on an existing bridge. The bridge may not have been originally designed to accommodate the additional weight and new wind loads associated with the noise barrier; thus the safety of the bridge comes into question.

Barriers on bridges must be designed to be safe for traffic using the bridge. If possible, the barrier should be light and elastic and should be slanted away from the road to decrease the possibility of contact between vehicles and barriers. Such contact could damage the barrier or cause injuries to motorists.

Hajek and Blaney stated that foundation requirements usually do not favor increases in barrier heights [1984]. Therefore, special noise barrier applications offer some structural advantages over conventional barriers of equal performance, primarily in the area of height reduction. Reducing the height of the barrier decreases wind loading, thus lowering foundation requirements. However, T-tops could create a pocket that may cause more wind problems.

Absorptive T-top Barriers need some additional supports and ties to ensure a solid connection between the cap and the barrier. These added costs could be offset by the reduction in barrier height and by decreased foundation requirements.

Y-top Barriers require some added support at the top of the barrier. The foundation requirements for a Y-top barrier are lower, but the Y-top may create other problems. For example, the accumulation of debris in the Y-top could block drainage and cause water to pond on the surface of the Y-top, adding weight to the barrier. Correcting this problem would require drilling large drainage holes in the barrier or manually removing debris from the Y-top, both of which would increase maintenance costs.

Slanted-top Barriers require extra support and stronger foundations to help hold the slanted, upper third of the barrier. Because the slanted-top barrier offers little additional attenuation over a conventional barrier, the added costs of its structural requirements are only justified when aesthetics are crucial to a community's acceptance of a noise barrier design.

Absorptive Barriers are conventional barriers with an absorptive strip placed along their top edge. Depending on the type of absorptive material chosen, the complexity of the support and attachment required may vary. For example, the absorptive strip may be glued or nailed to a barrier, or absorptive material could be incorporated into the barrier itself (i.e., absorptive aggregate). Absorptive barriers improve acoustical performance and encourage reduction in the height of barriers, thus reducing foundation requirements.

Maintenance Considerations

Maintenance factors influence the construction costs of special noise barriers and should be considered when analyzing the overall economic impact associated with a special barrier application. Currently, state highway agencies provide only limited data about the maintenance costs of highway barriers [Bowlby 1992]. Therefore, this report discusses the elements that could increase the costs of each special noise barrier under consideration, such as the durability of the materials used, the cost of removing accumulated debris, and the periodic maintenance required. Because many variables affect the maintenance costs of a barrier, it is difficult to determine the exact costs for individual sites. The following sections of this report examine significant maintenance elements that could affect the selection of a special noise barrier.

The most important maintenance factor that can inflate the cost of a special noise barrier is the durability of the materials used, because this factor has a significant impact on the service life of the barrier. Therefore, the types of materials used should be considered carefully to prevent the need for replacement. For example, many states have experienced problems with the durability of wooden barriers, including rotting, warping, racking, and shrinking. Nevertheless, the wooden materials used in barriers react differently in different environments, and the use of wooden barriers could be appropriate in certain areas of the country [Bowlby 1992]. Stockpiling spare parts should be considered to facilitate the replacement of damaged barrier sections.

In the case of barriers treated with absorptive material, special attention should be given to the selection of a particular treatment. The durability of absorptive treatment when exposed to seasonal weather conditions, such as severe freeze-thaw cycles, has not been proven. Absorptive barriers should also be resistant to acts of vandalism, impacts from vehicles, and the presence of chlorides from snow plowing operations and spray. The previous report (Phase I) found that one absorptive treatment, Durisol, provides adequate durability. Durisol is a concrete-based material that uses wood chips (as an absorbing agent) pressed into the mix. A Durisol product literature states that the Durisol material achieves a noise reduction coefficient of between 0.75 and 0.85.

In addition to the durability of materials used, another factor affecting the costs of barrier maintenance is debris accumulation. Removing debris is essential to preserving the structural integrity of a barrier. For shaped barrier tops, periodic removal of debris should be included in maintenance costs. For instance, the flat top of an absorptive T-top barrier may collect debris, including snow. Varying the thickness of the flat T-top to produce a sloped surface can reduce the frequency with which debris removal is required. Y-top barriers also require debris removal, because the Y-top shape produces a channel on top of the barrier in which debris is apt to collect. If periodic removal of debris is not performed, drainage holes will be plugged, and standing water will result. Additionally, it may be necessary to remove snow from the trough of the Y-top.

Other periodic maintenance requirements will be associated with any type of noise barrier, including removal of graffiti, repair of damage caused by vehicle accidents and snow removal equipment, and repair of the normal deterioration of a noise barrier (such as fading of color) caused by exposure to the surrounding environment. Removing graffiti from barrier walls requires sandblasting or painting and increases maintenance costs. Two methods developed by various states to combat graffiti on barrier walls are roughing textured surfaces and planting vegetation [Bowlby 1992].

Maintenance to areas between the right-of-way line and the barrier should also be considered. These areas may require periodic landscaping and trash removal. To reduce landscaping maintenance, some states have planted low-maintenance vegetation in these areas. A few states have granted title to property owners behind the barrier wall to shift the landscaping responsibilities from the state to the homeowner [Bowlby 1992].

Economic Impacts

To assess the costs involved in the construction of special noise barriers, the authors of this report contacted several contractors to obtain a comparison of the costs of conventional barriers and special barriers of equal acoustical performance.

One of the contractors interviewed was Highway Structures, Inc., which was responsible for constructing many highway noise barriers along I-264 in Louisville, Kentucky. This company provided cost estimates for various types of barriers constructed from prestressed, prefabricated concrete panels, with posts spaced approximately 40 feet apart. The following is a list of approximate increases in costs of special barriers as compared to the costs of a comparable conventional barrier of the same height (represented by a factor of 1.00).

HIGHWAY STRUCTURES INC. (PRE-STRESS)

Barrier Type	Cost Factors
Conventional	1.00
Slanted Top	1.273
Y-top	1.363
Absorptive T-top	1.182 + cost of absorptive material
Single-wall Absorptive	1.00 + cost of absorptive material

Bornstein Building Co., Inc., also provided estimates for the special barriers. These estimates were given as unit costs based on 100-linear-foot, cast-in-place, reinforced concrete with conventional formwork.

BORNSTEIN BUILDING CO. (CAST-IN-PLACE)

Barrier Type	Cost Factors
Conventional	1.00
Slanted Top	1.41
Y-top	1.53
Absorptive T-top	1.41 + cost of absorptive material
Single-wall Absorptive	1.00 + cost of absorptive material

It is easy to see that special barriers of prestressed concrete panels are proportionally less expensive to construct than special barriers built with conventional formwork. The conventional formwork appears to be more labor intensive, and there is less quality control on the materials used in conventionally formed concrete. A future project may include a more detailed comparison of the differential costs between prestressed and formed-in-place concrete.

The firm de AM-RON Building Systems, Inc., of Owensboro, Kentucky, a manufacturer of precast, prestressed concrete, provided an approximate price list of the individual panels based on square-foot units. The price list is as follows:

1. Flat Soundwall Panels	$ 5.50
2. Slanted-top Panels	$ 8.25
3. T-top Panels	$ 9.63
4. Y-top Panels	$ 11.00

It should be noted that these costs are for only one square foot of material and do not include transportation and construction costs. Also, the de AM-RON representative stated that the Y-top design is impractical from a manufacturing standpoint and would have to be formed in place.

Absorptive barrier costs were based on the use of the absorptive treatment Durisol, manufactured and marketed by the Fanwall Corporation. Discussions with a Fanwall representative suggested that the cost of this absorptive treatment would be an additional $7 per square foot.

STANDARD BARRIER DESIGN

After the acoustic, aesthetic, and economic impacts of each special noise barrier had been analyzed, the next task was to create a baseline, standard barrier design for the four individual projects selected for analysis. The acoustic, aesthetic, and economic performance of each special barrier design was measured against that of standard barrier designs. Such a comparison will allow the appropriate selection of a special noise barrier for the four WSDOT projects under consideration:

Seattle:
1. Fourth Avenue S.E.
2. Magnolia Road
3. Kent Commons Play Field

Spokane:
1. Spokane Community College Area

Because no current methodology can predict the effects of shaped barriers on highway noise, the adjustments or "rules of thumb" discussed earlier were applied to vertical, reflective, knife-edged barriers. The acoustical performance of a shaped barrier was determined by adjusting vertical, reflective barriers and L_{eq} values predicted by STAMINA 2.0/OPTIMA.

STAMINA 2.0 and OPTIMA Modeling

Noise Software Library

The standard, conventional barrier design was accomplished by using the *Noise Software Library* at the University of Louisville. Software programs included STAMINA 2.0, OPTIMA, AUTOBAR, LOS (Line-of-Sight), and REBAR. STAMINA 2.0 is the 1982 version of the FHWA noise prediction model, modified to include the new WSDOT vehicle emission levels. STAMINA creates an output file that becomes an input file for OPTIMA and AUTOBAR. AUTOBAR is an automated barrier design algorithm that interacts with OPTIMA to reach design criteria that were established by the user. LOS determines the line-of-sight elevations at the location of the proposed barrier between a receiver and a specified source height. REBAR calculates the amount of insertion loss degradation associated with parallel barriers.

Modeling Procedures

The first task consisted of drawing and labeling roadways, receivers, and barriers on the plan sheets. After all points were labeled, a MICRO-STATION INTERFACE was used to electronically generate X-Y coordinates for each of the roadway, barrier, and receiver points. This interface then saved the digitized data in a format required by STAMINA 2.0.

The elevations (Z-coordinates) were entered into the data files via STINPUT, a program that allows the manual entry of data into individual data files. The elevations were obtained from either contour maps, cross section sheets, or profile sheets. STINPUT was used to enter other information into the data files. Roadway segments with positive grades were marked in the files because heavy trucks generate more noise when they are traveling along uphill grades. Vehicle traffic and speed data were recorded. Delta-Z values of 2.0, with perturbation values of 3, were placed into the files to provide AUTOBAR with design parameters that limit the number of iterations performed while attempting to satisfy design criteria.

Besides the data mentioned previously, assumptions were made concerning the remaining data file parameters. Noise attenuation caused by hard-site and soft-site conditions was accounted for by entering the appropriate alpha factors.

After all four data files had been completed, STAMINA 2.0 was executed for each of the selected sites to predict no-barrier and barrier L_{eq} values and barrier insertion loss. AUTOBAR was then used to recommend baseline barrier heights. These barrier heights were then compared with the WSDOT barrier height recommendations listed in the reports. The final OPTIMA runs were used to compute receiver L_{eq} values, barrier heights, and square footage for each barrier design.

Finally, LOS was used on each of the final barrier designs. A fundamental rule in noise mitigation states that the line-of-sight between a receiver and a source must be broken to achieve significant noise reduction. The LOS files presented the line-of-sight elevations that were used to determine which special barrier applications were practical for each site.

REBAR was used to calculate insertion loss degradation associated with parallel barriers. Insertion loss degradation was calculated for both reflective and absorptive parallel barriers.

For each of the sites modeled, the resulting data, OPTIMA, and LOS files were bound separately from this report so WSDOT personnel could view the information Louisville used to create each standard barrier design. A document entitled *Barrier Design Files-Supplement to Special Noise Barrier Applications: Phase II* presents the data, OPTIMA, and LOS files.

Previous studies have indicated that modeling accuracy is related to the selection of appropriate reference mean emission levels. In fact, a published study by Harris entitled "Determination of Effectiveness of Noise Barrier Along I-285, Atlanta" found that STAMINA tends to over predict highway noise levels [1982]. Another article published by Harris, "Determination of Reference Mean Emission Levels in Georgia," investigated the possibility that this tendency to over predict is attributable to the selection of the reference mean emission levels. The FHWA version of STAMINA 2.0 uses reference mean emission levels developed in 1975 after a Four-State Noise Inventory conducted by the FHWA. Since this inventory was conducted in such a limited geographic region, Harris suggested that the FHWA reference mean emission levels may not be applicable to every state [1984]. Therefore, to accurately model the four sites selected for WSDOT projects in this report, both the emission levels published by the FHWA in 1975 and the 1993 Washington State reference mean emission levels were used. A comparison between the two noise predictions for each project is displayed in Tables III-VI on pages B-4-B-7.

For the Spokane Community College Area and Kent Commons, no-barrier and barrier L_{eq} values obtained by using the 1975 FHWA reference mean emission levels were 0.6 to 1.5 dBA greater than the results obtained by using 1993 Washington State emission levels. In contrast, for the other two projects, Magnolia Road and Fourth Avenue SE, the no-barrier and barrier L_{eq} values obtained by using the 1975 FHWA levels were not significantly different (less than ± 0.5 dBA) than those obtained by using the 1993 Washington State emission levels.

Seattle Projects

For each WSDOT project, the first task was assembling the necessary data for STAMINA 2.0 and OPTIMA modeling. Data for the Seattle projects included roadway design plans, topographic maps, cross sections, noise reports, traffic data, and photographs of the areas to be investigated. This information, along with aerial photographs, was used to create input files for use in computer-aided design and analysis. A brief description of each site is presented below.

Fourth Avenue SE and Magnolia Road

The data necessary for creating a standard barrier design for the Fourth Avenue SE and Magnolia Road locations was obtained from *Traffic Noise Analysis: State Route 405 (OL-1284)* as prepared by WSDOT Environmental and Special Services Northwest Region. This report presented traffic volumes and percentages of truck and auto traffic, as well as a brief description of the Fourth Avenue SE and Magnolia Road projects. Both sites are located on SR-405 in King Co. and in South Snohomish Co. Because high-occupancy vehicle (HOV) lanes are being added to SR-405, WSDOT selected these two sites for possible special noise barrier applications.

Fourth Avenue SE is located in Segment B of the SR-405 project, which extends from SR-527 to Danvers Road. This segment is primarily designated as residential, with some commercial activity at interchanges. Sixteen first-row single-family receivers on Fourth Avenue SE border the SR-405 right-of-way, and 11 second-row residences are located across Fourth Avenue.

The Magnolia Road site is located in Segment C of the SR-405 project, which lies between Danvers Road and I-5. The Magnolia Road site is on the west side of SR-405 between 196th Street SW and I-5. This is primarily a residential area, consisting of single-family homes.

For the receivers at the Fourth Avenue SE site, existing L_{eq} levels range from 65 to 67 dBA for first-row receivers and from 59 to 63 dBA for second-row receivers. Current L_{eq} values at the Magnolia Road site are 64 to 70 dBA. The addition of HOV lanes to SR-405 will cause an increase in traffic volume. The vehicle mix of the traffic for both sites (96% autos, 2% medium trucks, and 2% heavy trucks) and traffic speed (55 miles per hour) were obtained from *OL-1284.* Alpha and shielding factors for the Fourth Avenue and Magnolia Road sites were 0.5 and 0.0, respectively. Site maps depicting roadway, barrier, and receiver locations for Fourth Avenue and Magnolia Road are located on page A-1 and A-2.

Fourth Avenue barrier heights were established by using the LOS program. WSDOT recommended a 12-foot tall barrier for Fourth Avenue SE along the shoulder of SR-405. However, because the line-of-sights ranged from 12 to 14 feet and an insertion loss of at least 10 dBA was desired, Louisville recommended 18-foot tall barrier segments where the line-of-sight fell below 12 feet. For the remaining barrier segments, a 20-foot tall barrier was recommended. The line-of-site breaks are displayed in Table VII on page B-9.

Because Louisville's standard barrier design deviates from WSDOT's design as a result of line-of-sight restrictions, the two designs differ in both acoustical performance and cost. Report *OL-1284* predicted that the WSDOT barrier design will provide insertion losses of 7 to 11 dBA at a cost of approximately $360,000. The modified Louisville design predicted insertion losses of 10 to 12 dBA for the front-line receivers at a cost of $538,700 for 35,911 square feet of concrete barrier. Table VIII on page B-10 presents a comparison of the barriers proposed by Louisville and WSDOT.

Magnolia Road barrier heights were established by calculating line-of-sights, which ranged from 0 to 10 feet. Line-of-site breaks for Magnolia are shown in Table IX on page B-11. WSDOT recommended a 14-foot tall barrier for Magnolia Road. Unlike WSDOT's 14-foot barrier design, Louisville designed a barrier that was 20 feet tall to achieve an approximate insertion loss of 10 dBA.

The two standard barrier designs developed by WSDOT and Louisville were compared. The WSDOT barrier design produced insertion losses of 6 to 10 dBA. An increased insertion loss of 8 to 11 dBA for front-line receivers was achieved by Louisville's 20-foot barrier design at a cost of $361,700 for 24,114 square feet of concrete barrier.

Kent Commons Play Field

The Kent Commons Play Field project involves widening SR-167 and adding HOV lanes along residential, commercial, and undeveloped property. This project is bordered on the north and west by SR-167. Future noise levels for the nearest receivers at Kent Commons are expected to range from 69 to 71 dBA.

The data needed to create a standard barrier design for Kent Commons were obtained from WSDOT *Noise Report XLO647*, which contained truck and auto percentages and speeds. To determine traffic volumes, WSDOT used a 2+HOV definition ("acceptable level of service", page 3) in its noise report, whereas Louisville used 1400 pcphpl (passenger cars per hour per lane) and 1000 pcphpHOVl (passenger cars per hour per High Occupancy Vehicle lane). This judgment was made assuming "acceptable level of service" (Level of Service=C). The volumes were obtained from page 7-33 of the Highway Capacity Manual. Besides traffic volumes, alpha and shielding factors of 0.5 and 0.0, respectively, were used to model the Kent Commons site. Kent Commons Play Field's site map is presented on page A-3.

As in the two previous projects, line-of-sights were calculated to establish barrier heights. Most of the line-of-sights for Kent Commons ranged from 0 to 4 feet. *Noise Report XL0647* advised using a 10-foot barrier along the shoulder of SR-167 at

Kent Commons Play Field. Louisville's barrier design used a 19-foot barrier that would provide adequate line-of-sight breaks for special barrier applications, while producing at least a 9 dBA insertion loss. The line-of-sight breaks for Kent Commons are located in Table XI on page B-13.

The 19-foot tall barrier designed by Louisville provided an insertion loss of approximately 8 to 11 dBA, whereas the 10-foot barrier designed by WSDOT produced an insertion loss of 7 to 9 dBA. A comparison of the noise analysis results of the two designs is presented in Table XII on page B-14. The size of the Kent Commons Play Field noise barrier design was 50,838 square feet, and it would cost $711,700 as modeled.

Spokane Project

WSDOT supplied Louisville with aerial photographs, peak-hour traffic data, and preliminary cross-sections for the planned North Spokane Freeway (NSF) route. A draft noise report, a City of Spokane Map, an EIS map, and a preliminary NSF map of all options were also provided. These reports contained information on the Spokane Community College Area, which was used by Louisville for analytical and modeling considerations.

The NSF project is located in the eastern quadrant of the city of Spokane. The project consists of a collector/distributor system adjacent to I-90 and a new freeway from I-90 northward to U.S. 395 in Spokane County. The NSF project includes two alternative routes: the Market/Greene Alternative and the Havana Alternative. If the

Market/Greene alternative is selected, noise levels in the Spokane Community College area will increase significantly. Therefore, the Spokane Community College Area was selected as a possible site for implementation of special noise barrier applications.

Spokane Community College Area

The Spokane Community College Area consists of the actual college campus and a residential neighborhood across the NSF. The proposed Market/Greene Alternative would be adjacent to the college and the neighborhood. Portions of this alternative would be elevated above an existing parking facility at the Spokane Community College Campus. The WSDOT *Summary of Noise Analysis Results* predicts noise levels exceeding the 67 dBA noise abatement criteria for schools and residences (exterior) as stated in 23CFR772, August 1993.

Traffic volumes were determined by using the transportation modeling results from TMODEL2 (TM2), which consisted of traffic modeling plots for the Market/Green alternative. These plots presented projected traffic volumes for the year 2020 at pm peak hour, for both north and southbound directions. In addition, a telephone conversation with WSDOT personnel provided data on the vehicle mix of traffic (87% autos, 8% medium trucks, and 5% heavy trucks) and the vehicle speed (60 mph) to be assumed for modeling purposes. Alpha and shielding factors were 0.0 and 0.0, respectively. A site map depicting the location of roadway, barrier, and receiver elements is located on page A-4.

In addition to the input parameters, 14 receivers were modeled on the south side of Market/Greene to represent the neighborhood across from the Spokane Community College. These receivers were located near first-row and second-row houses of the residential area. Line-of-sights for the 14 residential receivers were approximately 4 to 6 feet.

To represent the Spokane Community College Campus, receivers were located near first-row and second-row buildings. Because several of these buildings have second and third stories, six receivers were modeled 25 feet above the ground to represent these buildings. Line-of-sights located at ground level were approximately 4 to 9 feet, whereas line-of-sights for the elevated, second-story receivers were approximately 9 to 14 feet. The line-of-sight breaks are shown in Table XIII on page B-15.

A 10-foot barrier design was recommended by WSDOT. In contrast, Louisville used a 20-foot barrier design for both the north and south corridors of the project to achieve a significantly higher insertion loss (10 dBA) than that provided by the WSDOT barrier design. The 10-foot barrier designed by WSDOT resulted in 67 dBA L_{eq} contours approximately 800 feet from the centerline. Louisville's modeling could not produce a 67 dBA L_{eq} contour because the 20-foot barrier design lowered L_{eq} values below 67 dBA. For the receivers modeled, no-barrier L_{eq} values were approximately 69 dBA, and 20-foot barrier L_{eq} values were 59 dBA. Thus, an insertion loss of approximately 10 dBA was achieved by the 20-foot barrier design. Table XIV on page B-16 displays L_{eq} values for the 40 receivers modeled. The 20-

foot barrier design contained 144,506 square feet at a cost of $2.2 million assuming a cost of $15/square foot for construction and materials.

After the standard barrier design was created and the acoustical results were compared, REBAR was used to determine the amount of insertion loss degradation associated with Spokane's parallel barrier design. REBAR calculations determined insertion loss degradation associated with reflective and absorptive barriers.

First, REBAR was used to calculate insertion loss degradation associated with 24-foot reflective barriers (NRC = 0.0) in comparison to a single barrier 24 feet tall. For the neighborhood located across from Spokane Community College, the insertion loss degradation resulting from reflective parallel barriers ranged from 1.3 to 2.7 dBA, resulting in an insertion loss of approximately 8 dBA. The insertion loss for the Spokane Community College side of the project was decreased by 2.3 to 5.6 dBA, producing an insertion loss of approximately 8 dBA.

Applying absorptive material to parallel barriers can significantly decrease the amount of insertion loss degradation. Since Durisol is the recommended absorptive treatment, the REBAR analysis incorporated a noise reduction coefficient of 0.75 for the entire height of both barriers. In order to achieve an insertion loss (8 dBA) similar to a 24-foot tall reflective parallel barrier design, absorptive material was applied to parallel barriers 18-feet in height, resulting in a slight (1 dBA) increase in insertion loss. Table II on page B-2 displays the modeled receivers' insertion loss for both reflective and absorptive parallel barriers.

MODIFICATIONS TO STANDARD BARRIER DESIGN

Methodology for determining the selection of a special noise barrier application for each project site consisted of assessing the characteristics of each site and considering the acoustic, aesthetic, and economic impacts associated with special noise barriers. Therefore, special noise barriers which demonstrate the greatest potential for minimizing acoustic, aesthetic, and economic impacts for a particular site are given the most consideration. Each project site has characteristics which may warrant the use of a particular special noise barrier. Some characteristics which influence the special noise barrier selection include impacted receivers, the existing noise levels, line-of-sight breaks, and the height and attenuation provided by the base-line barrier design.

Because impacted receivers influence special noise barrier selection, providing optimal attenuation for an increased number of sensitive receivers is important. Also, existing site noise levels influence selection because receivers that are exposed to a larger increase in noise levels require more attenuation. The line-of-sight breaks will provide restrictions for the application of special barriers. Because special barriers require that a 2-foot line-of-sight break be maintained, the increased acoustical performance provided by some special barriers allows for a reduction of barrier heights. The reduction of barrier heights could reduce adverse aesthetic and economic impacts associated with noise barrier construction.

Because consistent criteria is needed for applying special noise barriers, the following step-by-step procedure was used for the sites investigated in this report and could standardize the special barrier design process.

Step 1: Establish a conventional barrier design for a project.

Step 2: Calculate line-of-sight breaks on the conventional barrier design.

Step 3: Lower conventional barrier heights based on the 2-foot line-of-sight restriction and calculate resulting insertion losses.

Step 4: Apply added insertion losses of the special barriers presented as acoustical "rules of thumb" from this report.

Step 5: Calculate costs of all barriers.

Step 6: Identify additional maintenance costs and determine aesthetic impacts.

Step 7: Select final barrier design.

An illustration of how these steps were applied to the projects of this report is as follows.

Step 1.

The standard conventional barrier designs for the four sites are presented in the previous section of this report.

Step 2.

Because the LOS program calculates when the line-of-sight is above the top of the barrier, all barrier heights in the data files were lowered to zero to determine the location where the line-of-sight hits on the barrier. For these projects, the LOS breaks were calculated by subtracting the line-of-sight from the established conventional barrier height and are presented in Tables VII, IX, XI, and XIII.

Step 3. & Step 4.

Based on the 2-foot line-of-sight restriction, conventional barrier designs were lowered and OPTIMA was executed to determine new values for insertion loss. The acoustic "rules of thumb" were applied to the resulting design's insertion loss. Barrier heights and insertion losses are presented in Tables XV-XVIII on pages B-18-B-21.

Step 5.

Costs of conventional barriers were provided by WSDOT, and were $15 per square foot for the Fourth, Magnolia, and Spokane sites and $14 per square foot for the Kent site. Special noise barrier costs were determined using the cost estimates provided by Highway Structures, Inc. and Bornstein Building Company. The cost factors presented earlier in this report were directly applied to each barrier design. Final costs are given in Tables XV-XVIII on pages B-18-B-21. An example detailing the cost calculations for a conventional and absorptive T-top barrier is presented on the next page.

Example Cost Calculations (Fourth Avenue)

Conventional Barrier (18' & 20' Barrier Sections)

Square Feet of Barrier Material * Unit Cost

35911 sqft. * $15/sqft. = $538,700

Absorptive T-top Barrier (13' & 15' Barrier Sections)

(Square Feet of Barrier Material * Conventional Barrier Unit Cost * Cost Factor) + (Unit Cost of Absorptive Material * 3 Foot Absorptive Strip * Linear Feet of Barrier)

Highway Structures Inc.

(26487 sqft. * $15/sqft. * 1.182) + ($7/sqft. * 3 ft. * 1882 L.F.)
= $509,100

Bornstein Building Co.

(26487 sqft. * $15/sqft. * 1.41) + ($7/sqft. * 3 ft. * 1882 L.F.)
= $599,700

Final Cost (Average of 2 Estimates)

($509,100 + $599,700) / 2 =$554,400

Because barrier material and labor costs can be different in various areas of the state, WSDOT barrier designers should inquire about price ranges from local contractors and material suppliers to obtain a more accurate cost analysis of the special barriers. Although concrete was the material of choice in this report, designers could investigate using materials less expensive than concrete in their highway noise barrier programs.

Step 6.

After the initial cost of each barrier is determined, any additional maintenance costs resulting in those barriers should be identified. The economics section of this report includes possible maintenance increases associated with special noise barrier applications. In addition to maintenance considerations, attention should be given to whether aesthetics are improved by the application of one of these special barriers. Tables XV-XVIII on pages B-18-B-21 give a checklist to illustrate maintenance and aesthetic considerations.

Step 7.

The selection of the final barrier should incorporate the ideas presented in the previous six steps. However, goals of this report include the hope that a few of these designs will be applied to actual highway projects in Washington State as field laboratories. Therefore, Louisville's selection recommendations are presented below.

Fourth Avenue

The Fourth Avenue site consisted of 16 front-line receivers and 11 second-line receivers with existing L_{eq} levels of 65-67 dBA and 59-63 dBA for first and second row receivers, respectively. Eleven and 13-foot line-of-sight resulted in a standard barrier design of 18-foot (BFA-BFI) and 20-foot (BFJ-BFS) barrier sections to achieve an insertion loss of at least 10 dBA for front-line receivers.

A 3 foot shorter single-wall absorptive barrier would be the least expensive special barrier to construct ($493,400), while still providing a 10 dBA insertion loss. The cost of an equally performing conventional barrier would be $45,000 greater than the shorter single-wall absorptive barrier. Also, reducing barrier height by 3 feet would lessen aesthetic impacts.

Magnolia Road

The Magnolia Road Project Area is located along SR-405. This is a residential area with L_{eq} values ranging from 64 to 70 dBA. Improvements to SR-405 are expected to increase traffic volumes, creating future noise levels ranging from 66 to 75 dBA. Therefore, investigation into possible noise mitigation procedures were performed.

The Magnolia Road site offers an opportunity to study absorptive T-tops. After reducing the 20-foot barrier sections to 13 feet, an absorptive T-top barrier would provide the same acoustic performance (10 dBA insertion loss) as a conventional barrier 7 feet taller, while costing $30,000 less. The 7 foot reduction in height would significantly improve aesthetics and would create greater acceptability among property owners.

Kent Commons Play Field

A 19-foot standard barrier design would offer at least a 9 dBA insertion loss to Kent Commons Play Field receivers. An increased insertion loss of 10 dBA would be achieved by a shorter, 16-foot Y-top barrier. Reducing barrier heights by 3 feet would improve the aesthetic quality of the surrounding environment. A 16-foot Y-top barrier would cost approximately $130,000 more than a conventional barrier 19 feet high; however, the Y-top barrier would reduce aesthetic impacts by the 3 foot reduction in height.

Spokane Community College Area

The Spokane Community College Area is an elevated section of the Market/Greene alternative of the North Spokane Freeway with impacted receivers located on the east (neighborhood) and west (Spokane Community College) sides of the freeway. Line-of-sight breaks for the neighborhood and Spokane Community College were approximately 11 to 16 feet. A 20-foot barrier design was recommended to obtain an insertion loss of at least 10 dBA.

Three barrier designs were analyzed, one involved the investigation of a barrier design for the neighborhood, another investigated a barrier design for the Spokane Community College, and the third design consisted of parallel barriers for both sides of the Market/Greene alternative.

The 20-foot standard barrier design for the neighborhood was lowered to 16 feet to apply an equally performing (10 dBA insertion loss) single wall absorptive barrier. Since the Market/Greene alternative is an elevated section of freeway, the 4-foot reduction in height would offer the neighborhood a less obstructive view. In addition, the cost of the single-wall absorptive barrier ($864,900) is less than the absorptive T-top, Y-top and slanted-top barriers of equal acoustical performance ($907,000, $1,294,400, and $1,333,500). The single-wall absorptive barrier would cost $130,000 less than a 20-foot tall conventional barrier.

Spokane Community College's 20-foot standard barrier design was also lowered to apply special noise barriers of the same acoustic performance (10 dBA insertion loss). Because of barrier height reduction, all four special barrier types would enhance the surrounding environment; however, an absorptive T-top would provide the best aesthetic improvement because this barrier allows for the greatest reduction in height (7 feet). An absorptive T-top barrier would also cost less than a Y-top or slanted top barrier of equal acoustic performance ($457,200 and $503,300 less), and would be less expensive ($102,800) than constructing a 20-foot high conventional barrier.

Because the Spokane Community College Area has receivers located on both sides of the Market/Greene alternative, a parallel barrier design would need to be constructed to accommodate for both sets of receivers. Past research has determined that the application of absorptive material to parallel barriers is beneficial in reducing insertion loss degradation due to multiple reflections. REBAR was used to investigate the degradation in insertion loss for a 24-foot reflective (NRC=0.0) and an 18-foot absorptive (NRC=0.75) parallel barrier design. A 24-foot reflective parallel barrier would produce an 8 dBA insertion loss, while the application of absorptive material to 18-foot high barrier sections would improve the insertion loss to approximately 9 dBA for some of the receivers modeled. In addition to the slight improvement in insertion loss, reducing barrier sections by 6 feet would significantly improve the aesthetic quality of the surrounding environment. Table II on page B-2 displays insertion losses for the reflective and absorptive parallel barrier designs. Although the 18-foot absorptive parallel barrier design would increase costs by $260,300, receivers on both sides of the freeway would benefit by providing an insertion loss similar to a 24-foot tall reflective design.

CONCLUSIONS AND RECOMMENDATIONS

Each modeled WSDOT highway project could benefit from the construction of a special noise barrier. The five special noise barriers under consideration show excellent promise as viable alternatives to constructing taller conventional barriers. As discussed earlier, special noise barriers provide increased acoustical performance over conventional barriers of the same height. Thus special noise barriers could improve the aesthetics of the highway environment; and costs could be lowered because less material is needed for construction, and foundation requirements are reduced. Because the acoustic, aesthetic, and economic impacts vary with each application, an analysis of each of these impacts on a particular site should be part of the process of selecting a particular type of barrier. Recommendations for the sites investigated are presented below.

Fourth Avenue S. E.:	Single-wall absorptive
Magnolia Road:	Absorptive T-top
Kent Commons Play Field:	Y-top
Spokane Community College Area:	Single-wall absorptive (Neighborhood) Absorptive T-top (SCC) Absorptive parallel (Both sides)

Proposed Phase III research includes the construction of scale models representing the four projects presented in this report. Scale modeling would verify the use of the acoustic "rules of thumb" in this study and the mathematical formulation presented in the previous Phase I report before the implementation of special noise barriers in Washington State.

It is hoped that one or more of the recommendations provided will be used in actual field studies in Washington State. This would provide data that could encourage the expanded use of special barrier applications across the state. With the proper site selection, the true effectiveness of these special noise barrier applications could be verified.

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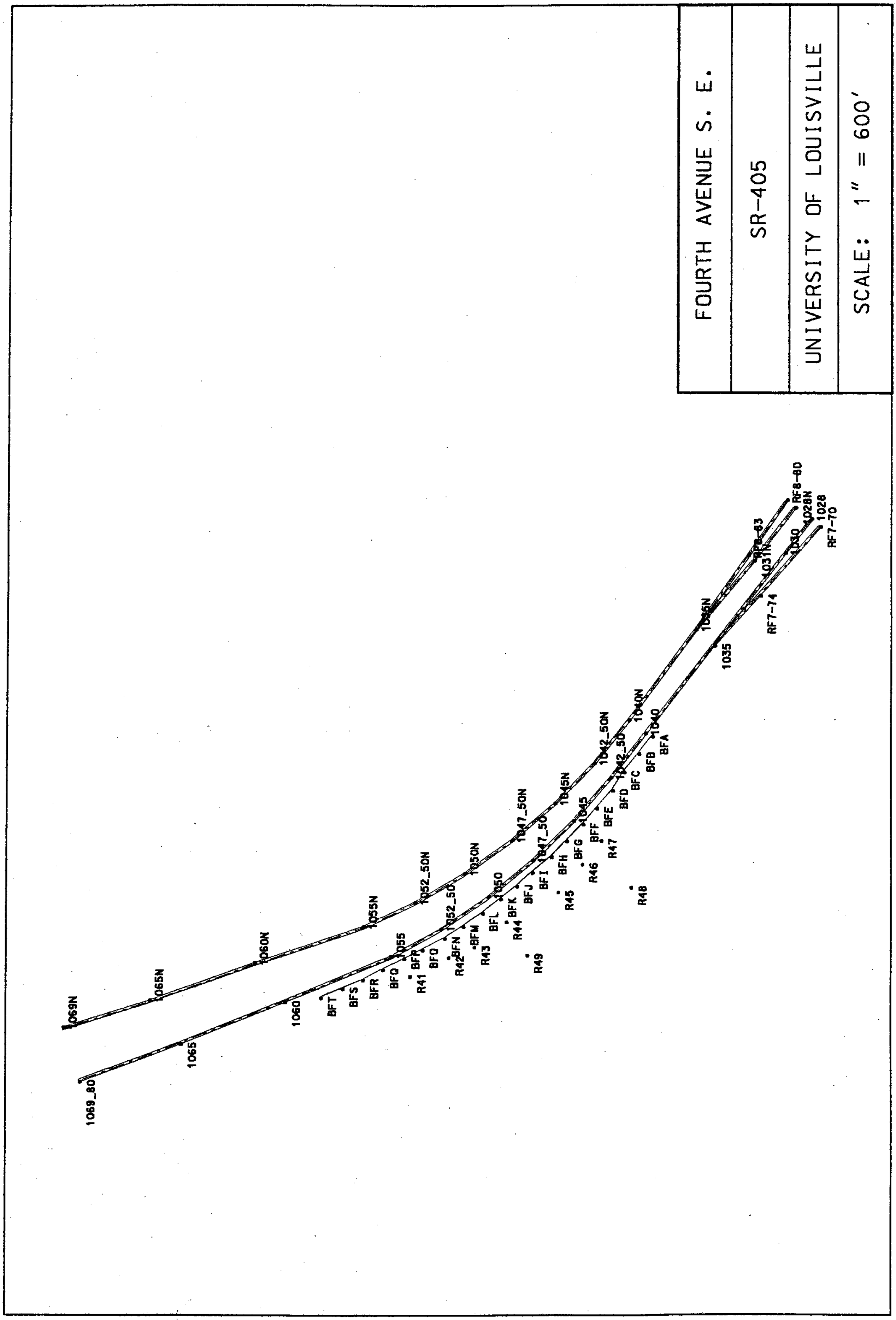
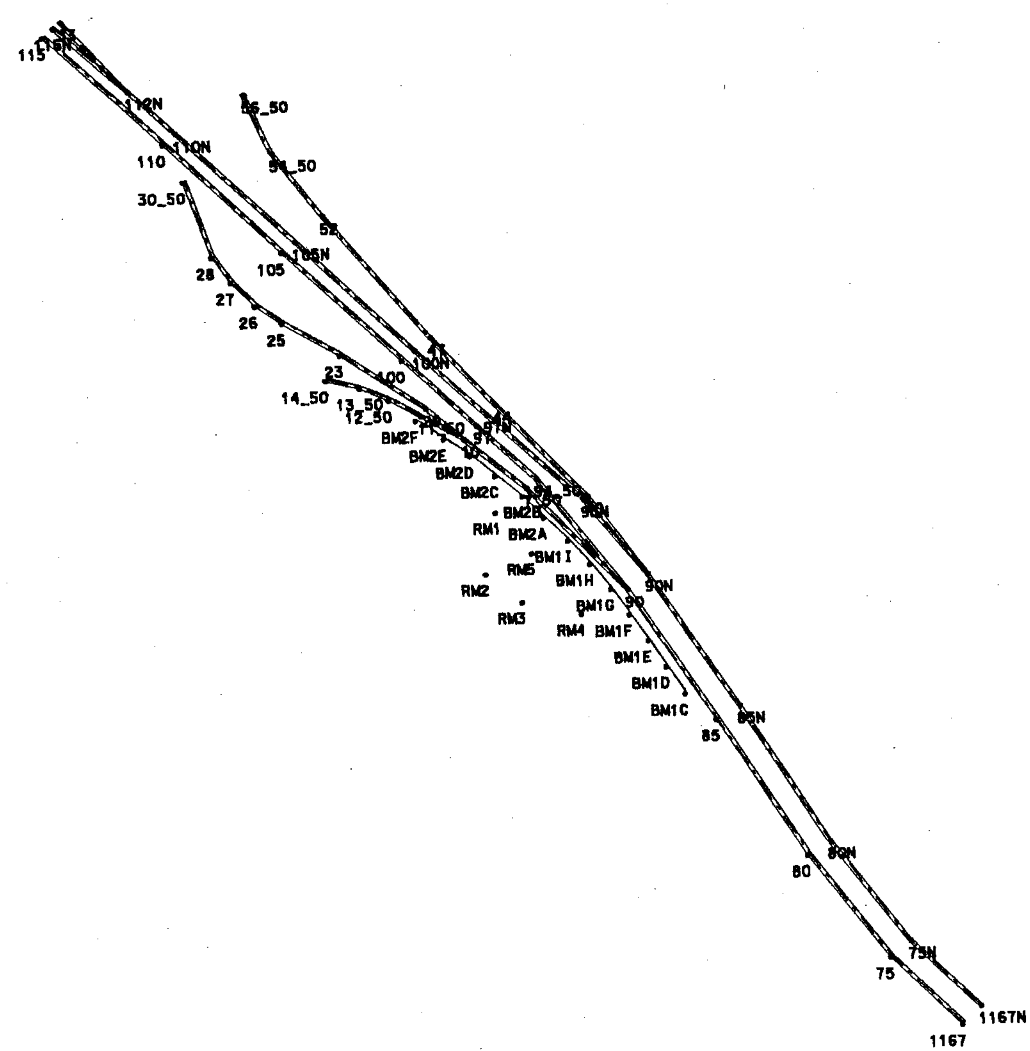
APPENDIX A
SITE MAPS


FOURTH AVENUE S. E.
SR-405
UNIVERSITY OF LOUISVILLE
SCALE: 1" = 600'

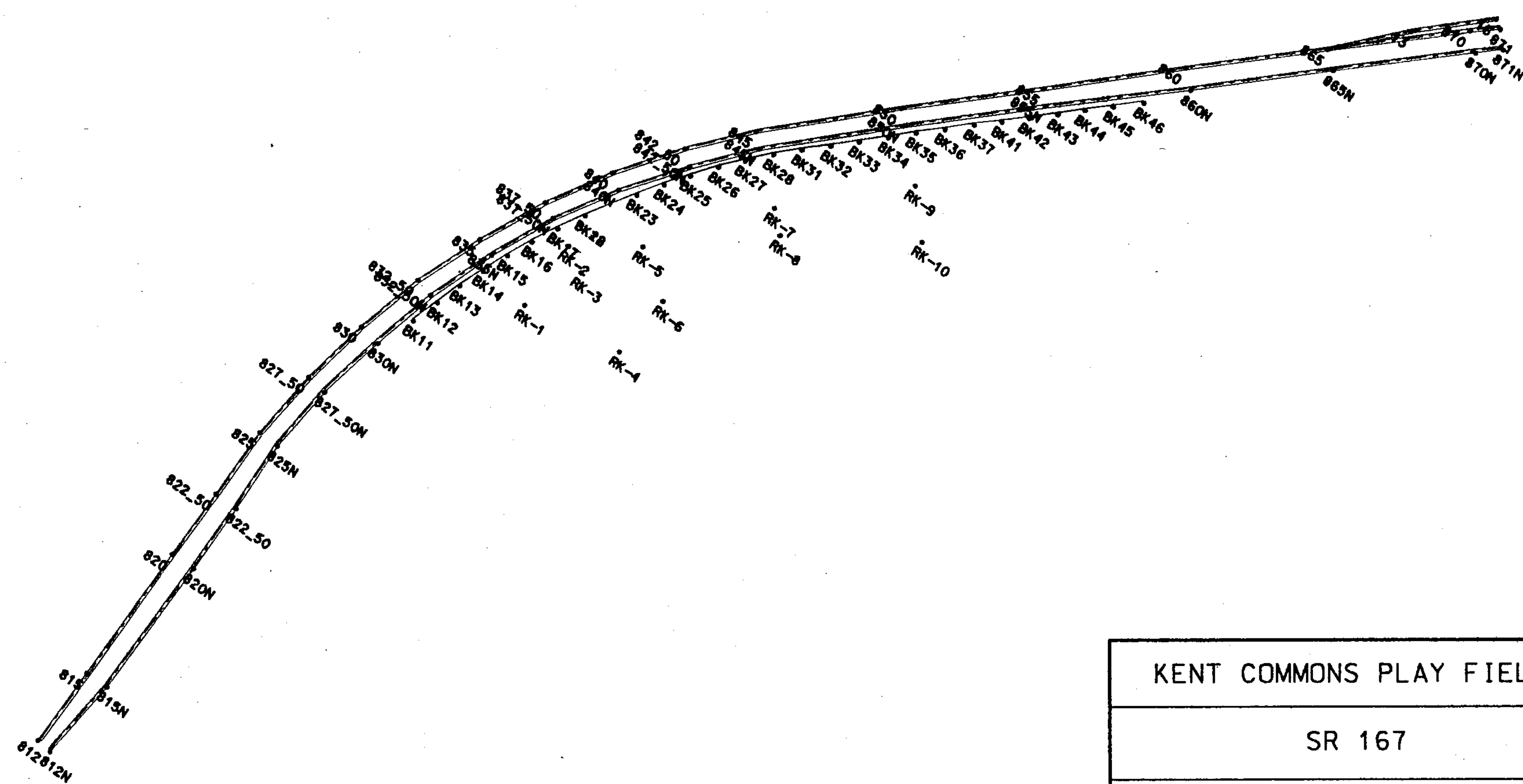


MAGNOLIA ROAD

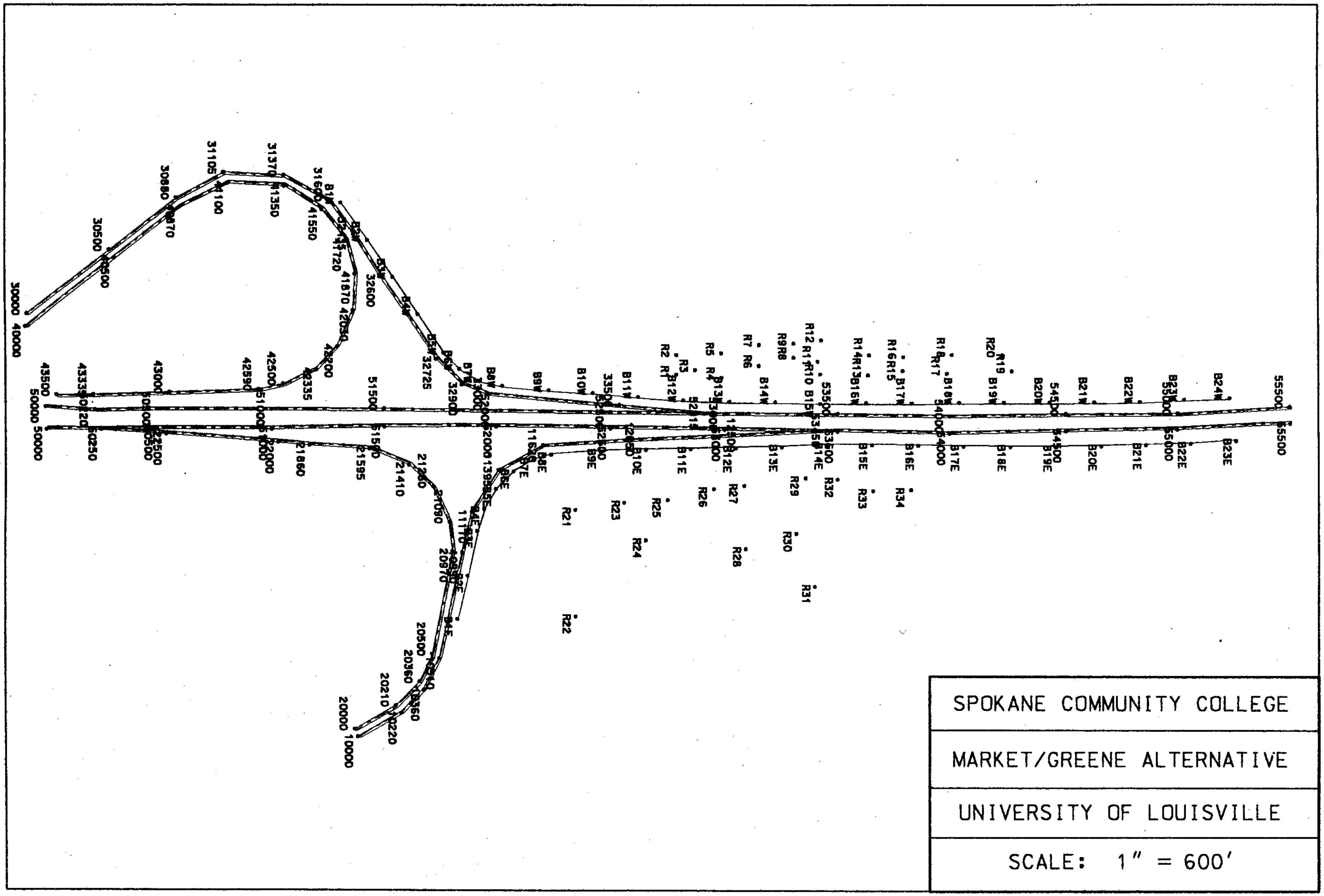
SR-405

UNIVERSITY OF LOUISVILLE

SCALE: 1" = 600'



KENT COMMONS PLAY FIELD
SR 167
UNIVERSITY OF LOUISVILLE
SCALE: 1″ = 600′


SPOKANE COMMUNITY COLLEGE
MARKET/GREENE ALTERNATIVE
UNIVERSITY OF LOUISVILLE
SCALE: 1" = 600'

APPENDIX B
TABLES

TABLE I
OPTIMA RESULTS FOR SLANTED-TOP MODELING

Receiver Name	Insertion Loss (dBA)	
	Barrier 50 feet from road	Barrier 45 feet from road
1	7.6	7.4
2	5.8	5.9
3	5.1	5.2

TABLE II
SPOKANE COMMUNITY COLLEGE AREA
INSERTION LOSS COMPARISON BETWEEN
SINGLE BARRIER AND REFLECTIVE AND ABSORPTIVE
PARALLEL BARRIERS

U of L Receiver Name	Insertion Loss (dBA)		
	24' Single Barrier	24' Reflective Parallel Barriers NRC = 0.0	18' Absorptive Parallel Barriers NRC = 0.75
R1	9.1	7.4	7.9
R2	10.0	7.7	8.2
R3	9.8	7.9	8.4
R4	9.0	7.3	7.8
R5	10.4	8.1	8.4
R6	10.4	8.4	8.8
R7	10.7	8.1	8.5
R8	10.9	8.7	8.8
R9	11.0	8.3	8.7
R10	10.2	8.4	8.8
R11	10.8	8.7	8.9
R12	11.2	8.5	8.8
R13	10.1	8.8	8.7
R14	11.2	9.0	9.0
R15	10.5	8.6	8.9
R16	11.0	8.9	8.9
R17	9.9	8.1	8.5
R18	10.9	8.7	8.8
R19	9.6	7.7	8.2
R20	10.5	8.3	8.7
R21	10.7	7.4	8.3

U of L Receiver Name	Insertion Loss (dBA)		
	24' Single Barrier	24' Reflective Parallel Barriers NRC = 0.0	18' Absorptive Parallel Barriers NRC = 0.75
R22	8.3	2.7	5.8
R23	10.8	7.8	8.3
E23	11.6	7.3	8.0
R24	10.7	6.7	8.0
R25	10.8	7.9	8.3
E25	11.7	7.7	8.1
R26	10.7	8.1	8.5
E26	12.0	8.5	8.7
R27	10.7	8.1	8.5
E27	12.2	8.8	8.9
R28	11.1	7.1	8.2
R29	10.4	8.1	8.7
E29	12.6	9.8	9.5
R30	11.0	7.3	8.1
R31	11.2	6.6	8.2
R32	10.6	8.3	8.8
R33	11.1	8.7	9.0
E33	12.5	9.2	9.4
R34	11.1	8.7	9.1

TABLE III
FOURTH AVENUE
COMPARISON OF NOISE ANALYSIS RESULTS
1975 FHWA VERSUS 1993 WASHINGTON STATE
REFERENCE MEAN EMISSION LEVELS

U of L Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
	1975 FHWA	1993 Washington State	1975 FHWA	1993 Washington State	1975 FHWA	1993 Washington State
R41	72.9	73.0	63.2	63.1	9.7	10.0
R42	72.5	72.5	60.9	60.7	11.6	11.9
R43	71.6	71.7	62.3	62.0	9.3	9.6
R44	70.8	70.5	58.9	58.7	11.9	11.8
R45	69.6	69.4	59.6	59.3	10.0	10.1
R46	70.2	70.1	60.2	60.0	10.0	10.1
R47	70.5	70.4	60.3	60.1	10.3	10.2
R48	65.4	65.5	58.7	58.5	6.7	7.0
R49	66.8	66.9	59.6	59.4	7.2	7.6

TABLE IV
MAGNOLIA ROAD
COMPARISON OF NOISE ANALYSIS RESULTS
1975 FHWA VERSUS 1993 WASHINGTON STATE
REFERENCE MEAN EMISSION LEVELS

U of L Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
	1975 FHWA	1993 Washington State	1975 FHWA	1993 Washington State	1975 FHWA	1993 Washington State
RM1	71.7	71.5	61.1	61.0	10.5	10.5
RM2	67.4	67.6	61.1	60.9	6.4	6.7
RM3	67.9	68.1	61.3	61.1	6.7	7.0
RM4	68.4	67.9	60.1	60.0	8.3	7.9
RM5	71.4	71.3	61.0	60.9	10.3	10.4

TABLE V
KENT COMMONS PLAY FIELD
COMPARISON OF NOISE ANALYSIS RESULTS
1975 FHWA VERSUS 1993 WASHINGTON STATE
REFERENCE MEAN EMISSION LEVELS

U of L Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
	1975 FHWA	1993 Washington State	1975 FHWA	1993 Washington State	1975 FHWA	1993 Washington State
RK-1	69.7	68.7	61.9	61.3	7.8	7.4
RK-2	69.1	67.8	60.8	60.1	8.3	7.7
RK-3	69.4	68.2	60.1	59.4	9.4	8.9
RK-4	65.2	64.5	59.0	58.3	6.2	6.2
RK-5	69.2	68.1	59.1	58.4	10.1	9.7
RK-6	66.4	65.7	58.4	57.6	8.0	8.0
RK-7	68.6	67.4	58.1	57.3	10.6	10.1
RK-8	67.4	66.4	57.6	56.8	9.8	9.6
RK-9	68.4	67.1	58.3	57.6	10.0	9.5
RK-10	65.9	65.1	57.6	56.8	8.3	8.3

TABLE VI
SPOKANE COMMUNITY COLLEGE AREA
COMPARISON OF NOISE ANALYSIS RESULTS
1975 FHWA VERSUS 1993 WASHINGTON STATE
REFERENCE MEAN EMISSION LEVELS

U of L Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
	U of L	WSDOT	U of L	WSDOT	U of L	WSDOT
R1	67.9	66.5	59.3	58.2	8.6	8.4
R2	68.6	67.3	59.5	58.3	9.2	9.0
R3	68.5	67.1	59.3	58.1	9.2	9.0
R4	68.0	66.7	59.5	58.4	8.5	8.2
R5	68.8	67.5	59.3	58.1	9.4	9.3
R6	69.0	67.7	59.4	58.3	9.6	9.4
R7	69.0	67.7	59.3	58.1	9.7	9.6
R8	69.3	68.0	59.4	58.3	9.9	9.7
R9	69.2	68.0	59.3	58.1	9.9	9.8
R10	69.2	67.9	59.6	58.6	9.6	9.3
R11	69.3	68.0	59.4	58.3	9.9	9.7
R12	69.3	68.0	59.2	58.1	10.0	9.9
R13	69.3	68.0	59.8	58.8	9.5	9.2
R14	69.5	68.3	59.4	58.3	10.1	10.0
R15	69.3	68.1	59.6	58.5	9.8	9.5
R16	69.4	68.1	59.3	58.2	10.0	9.9
R17	68.9	67.7	59.6	58.6	9.3	9.0
R18	69.2	68.0	59.3	58.2	9.9	9.8
R19	68.3	67.0	59.3	58.3	9.0	8.7
R20	68.8	67.5	59.2	58.1	9.6	9.4
R21	69.5	68.1	59.9	58.7	9.6	9.4
R22	67.4	65.9	60.0	58.6	7.4	7.3
R23	69.5	68.2	59.9	58.7	9.6	9.5

U of L Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
	U of L	WSDOT	U of L	WSDOT	U of L	WSDOT
E23	73.5	72.2	63.8	62.5	9.7	9.7
R24	69.1	67.7	59.6	58.4	9.4	9.3
R25	69.3	67.9	59.7	58.5	9.6	9.5
E25	73.2	71.8	63.3	62.1	9.9	9.7
R26	69.1	67.8	59.5	58.4	9.6	9.4
E26	73.6	72.1	63.2	62.0	10.3	10.1
R27	69.2	67.9	59.5	58.4	9.7	9.5
E27	73.8	72.3	63.2	62.0	10.5	10.3
R28	68.7	67.4	59.0	57.8	9.7	9.6
R29	69.2	67.9	59.6	58.5	9.6	9.3
E29	74.2	72.8	63.2	62.1	11.0	10.8
R30	68.8	67.5	59.1	57.9	9.6	9.6
R31	68.0	66.6	58.2	56.9	9.8	9.7
R32	69.5	68.1	59.7	58.6	9.8	9.5
R33	69.8	68.5	59.7	58.6	10.1	9.9
E33	73.7	72.4	62.8	61.6	10.9	10.8
R34	69.8	68.5	59.6	58.5	10.2	9.9

TABLE VII
FOURTH AVENUE
LINE OF SIGHT BREAKS

Barrier Section	Barrier Height	LOS Break	Barrier Section	Barrier Height	LOS Break
BFA	18'	18.0'	BFK	20'	7.7'
BFB	18'	18.0'	BFL	20'	6.0'
BFC	18'	9.1'	BFM	20'	6.1'
BFD	18'	5.7'	BFN	20'	4.9'
BFE	18'	6.1'	BFO	20'	6.6'
BFF	18'	6.3'	BFP	20'	6.5'
BFG	18'	6.5'	BFQ	20'	6.8'
BFH	18'	6.6'	BFR	20'	7.1'
BFI	18'	5.5'	BFS	20'	6.6'
BFJ	20'	6.9'	---	---	---

Note: A positive line-of-sight break is the difference in height between the top of the barrier and the line-of-sight below the barrier top. A negative line-of-sight break is the difference in height between the top of the barrier and the line-of-sight above the barrier top.

TABLE VIII
FOURTH AVENUE
COMPARISON OF NOISE ANALYSIS RESULTS
FOR U OF L VERSUS WSDOT

U of L Receiver Name	WSDOT Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
		U of L	WSDOT	U of L	WSDOT	U of L	WSDOT
R41	---	72.9	---	63.2	---	9.7	---
R42	B-7	72.5	73.2	60.9	63.6	11.6	9.6
R43	---	71.6	---	62.3	---	9.3	---
R44	---	70.8	---	58.9	---	11.9	---
R45	B-6	69.6	68.6	59.6	57.9	10.0	10.7
R46	---	70.2	---	60.2	---	10.0	---
R47	B-5	70.5	67.1	60.3	60.1	10.3	7.0
R48	---	65.4	---	58.7	---	6.7	---
R49	---	66.8	---	59.6	---	7.2	---

TABLE IX
MAGNOLIA ROAD
LINE OF SIGHT BREAKS

Barrier Section	Barrier Height	LOS Break	Barrier Section	Barrier Height	LOS Break
BM1C	20'	20.0'	BM1I	20'	8.4'
BM1D	20'	14.0'	BM2A	20'	8.9'
BM1E	20'	12.8'	BM2B	20'	9.4'
BM1F	20'	7.2'	BM2C	20'	8.9'
BM1G	20'	9.3'	BM2D	20'	10.3'
BM1H	20'	10.1'	BM2E	20'	12.6'

Note: A positive line-of-sight break is the difference in height between the top of the barrier and the line-of-sight below the barrier top. A negative line-of-sight break is the difference in height between the top of the barrier and the line-of-sight above the barrier top.

TABLE X
MAGNOLIA ROAD
COMPARISON OF NOISE ANALYSIS RESULTS
FOR U OF L VERSUS WSDOT

U of L Receiver Name	WSDOT Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
		U of L	WSDOT	U of L	WSDOT	U of L	WSDOT
RM1	C-24	71.7	72.7	61.1	62.9	10.5	9.8
RM2	C-26	67.4	69.5	61.1	63.4	6.4	6.1
RM3	C-25	67.9	74.3	61.3	67.9	6.7	6.4
RM4	C-27	68.4	66.1	60.1	59.1	8.3	7.0
RM5	---	71.4	---	61.0	---	10.3	---

TABLE XI
KENT COMMONS PLAY FIELD
LINE OF SIGHT BREAKS

Barrier Section	Barrier Height	LOS Break	Barrier Section	Barrier Height	LOS Break
BK11	19'	9.8'	BK28	19'	12.4'
BK12	19'	11.2'	BK31	19'	11.8'
BK13	19'	12.4'	BK32	19'	12.1'
BK14	19'	12.4'	BK33	19'	12.5'
BK15	19'	14.2'	BK34	19'	13.0'
BK16	19'	13.0'	BK35	19'	13.4'
BK17	19'	11.2'	BK36	19'	13.6'
BK22	19'	10.9'	BK37	19'	13.7'
BK23	19'	11.0'	BK41	19'	14.1'
BK24	19'	10.3'	BK42	19'	19.0'
BK25	19'	10.9'	BK43	19'	19.0'
BK26	19'	10.8'	BK44	19'	19.0'
BK27	19'	12.3'	BK45	19'	19.0'

Note: A positive line-of-sight break is the difference in height between the top of the barrier and the line-of-sight below the barrier top. A negative line-of-sight break is the difference in height between the top of the barrier and the line-of-sight above the barrier top.

TABLE XII
KENT COMMONS PLAY FIELD
COMPARISON OF NOISE ANALYSIS RESULTS
FOR U OF L VERSUS WSDOT

U of L Receiver Name	WSDOT Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
		U of L	WSDOT	U of L	WSDOT	U of L	WSDOT
RK-1	---	69.7	---	61.9	---	7.8	---
RK-2	NR	69.1	69-71	60.8	62	8.3	7-9
RK-3	NR	69.4	69-71	60.1	62	9.4	7-9
RK-4	---	65.2	---	59.0	---	6.2	---
RK-5	NR	69.2	69-71	59.1	62	10.1	7-9
RK-6	---	66.4	---	58.4	---	8.0	---
RK-7	NR	68.6	69-71	58.1	62	10.6	7-9
RK-8	---	67.4	---	57.6	---	9.8	---
RK-9	NR	68.4	69-71	58.3	62	10.0	7-9
RK-10	---	65.9	---	57.6	---	8.3	---

*NR=NEAREST RECEIVERS

TABLE XIII
SPOKANE COMMUNITY COLLEGE AREA
LINE OF SIGHT BREAKS

Barrier Section	Barrier Height	LOS Break	Barrier Section	Barrier Height	LOS Break
B1E	20'	20.0'	B20E	20'	20.0'
B2E	20'	-2.9'	B7W	20'	20.0'
B3E	20'	12.1'	B8W	20'	20.0'
B4E	20'	12.2'	B9W	20'	20.0'
B5E	20'	11.9'	B10W	20'	15.4'
B6E	20'	12.5'	B11W	20'	15.1'
B7E	20'	11.7'	B12W	20'	14.2'
B8E	20'	13.4'	B13W	20'	0.4'
B9E	20'	12.0'	B14W	20'	14.3'
B10E	20'	10.7'	B15W	20'	14.2'
B11E	20'	-4.0'	B16W	20'	14.3'
B12E	20'	12.4'	B17W	20'	15.5'
B13E	20'	13.1'	B18W	20'	16.4'
B14E	20'	13.4'	B19W	20'	17.1'
B15E	20'	16.7'	B20W	20'	18.2'
B16E	20'	16.5'	B21W	20'	16.0'
B17E	20'	18.0'	B22W	20'	20.0'
B18E	20'	20.0'	B23W	20'	20.0'
B19E	20'	20.0'	---	---	---

Note: A positive line-of-sight break is the difference in height between the top of the barrier and the line-of-sight below the barrier top. A negative line-of-sight break is the difference in height between the top of the barrier and the line-of-sight above the barrier top.

TABLE XIV
SPOKANE COMMUNITY COLLEGE AREA
COMPARISON OF NOISE ANALYSIS RESULTS
FOR U OF L VERSUS WSDOT

U of L Receiver Name	WSDOT Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
		U of L	WSDOT	U of L	WSDOT	U of L	WSDOT
R1	---	67.9	---	59.3	---	8.6	---
R2	---	68.6	---	59.5	---	9.2	---
R3	---	68.5	---	59.3	---	9.2	---
R4	---	68.0	---	59.5	---	8.5	---
R5	---	68.8	---	59.3	---	9.4	---
R6	---	69.0	---	59.4	---	9.6	---
R7	---	69.0	---	59.3	---	9.7	---
R8	---	69.3	---	59.4	---	9.9	---
R9	---	69.2	---	59.3	---	9.9	---
R10	---	69.2	---	59.6	---	9.6	---
R11	---	69.3	---	59.4	---	9.9	---
R12	---	69.3	---	59.2	---	10.0	---
R13	---	69.3	---	59.8	---	9.5	---
R14	---	69.5	---	59.4	---	10.1	---
R15	---	69.3	---	59.6	---	9.8	---
R16	---	69.4	---	59.3	---	10.0	---
R17	---	68.9	---	59.6	---	9.3	---
R18	---	69.2	---	59.3	---	9.9	---
R19	---	68.3	---	59.3	---	9.0	---
R20	---	68.8	---	59.2	---	9.6	---
R21	---	69.5	---	59.9	---	9.6	---
R22	---	67.4	---	60.0	---	7.4	---
R23	---	69.5	---	59.9	---	9.6	---

U of L Receiver Name	WSDOT Receiver Name	L_{eq} (dBA) No Barrier		L_{eq} (dBA) Barrier		Insertion Loss (dBA)	
		U of L	WSDOT	U of L	WSDOT	U of L	WSDOT
E23	---	73.5	---	63.8	---	9.7	---
R24	---	69.1	---	59.6	---	9.4	---
R25	---	69.3	---	59.7	---	9.6	---
E25	---	73.2	---	63.3	---	9.9	---
R26	---	69.1	---	59.5	---	9.6	---
E26	---	73.6	---	63.2	---	10.3	---
R27	---	69.2	---	69.5	---	9.7	---
E27	---	73.8	---	63.2	---	10.5	---
R28	---	68.7	---	59.0	---	9.7	---
R29	---	69.2	---	59.6	---	9.6	---
E29	---	74.2	---	63.2	---	11.0	---
R30	---	68.8	---	59.1	---	9.6	---
R31	--	68.0	---	58.2	---	9.8	---
R32	---	69.5	---	59.7	---	9.8	---
R33	---	69.8	---	59.7	---	10.1	---
E33	---	73.7	---	62.8	---	10.9	---
R34	---	69.8	---	59.6	---	10.2	---

TABLE XV
FOURTH AVENUE
COMPARISON OF BARRIER TYPES

Barrier Type	Dominant Barrier Design Height	Average Insertion Loss (dBA)	Cost	Added Maintenance	Improved Aesthetics
Conventional	20'	10.4	$538,700		
Absorptive T-top	15'	11.0	$554,400	YES	YES
Y-top	18'	10.7	$697,500	YES	YES
Slanted-top	20'	10.4	$722,500	NO	YES
Single-wall Absorptive	17'	10.8	$493,400	YES	YES

Note: Eight barrier sections (BFA-BFI) are 2 feet lower than the remaining ten barrier sections (BFJ-BFS).

TABLE XVI
MAGNOLIA ROAD
COMPARISON OF BARRIER TYPES

Barrier Type	Dominant Barrier Design Height	Average Insertion Loss (dBA)	Cost	Added Maintenance	Improved Aesthetics
Conventional	20'	9.7	$361,700		
Absorptive T-top	13'	10.4	$330,000	YES	YES
Y-top	18'	10.4	$471,000	YES	YES
Slanted-top	20'	9.7	$485,200	NO	YES
Single-wall Absorptive	16'	10.4	$314,700	YES	YES

TABLE XVII
KENT COMMONS PLAY FIELD
COMPARISON OF BARRIER TYPES

Barrier Type	Dominant Barrier Design Height	Average Insertion Loss (dBA)	Cost	Added Maintenance	Improved Aesthetics
Conventional	19'	9.4	$711,700		
Absorptive T-top	11'	10.2	$590,300	YES	YES
Y-top	16'	10.0	$843,200	YES	YES
Slanted-top	19'	9.4	$954,700	NO	YES
Single-wall Absorptive	14'	10.1	$572,300	YES	YES

TABLE XVIII
SPOKANE COMMUNITY COLLEGE AREA
COMPARISON OF BARRIER TYPES

Barrier Type		Dominant Barrier Design Height	Average Insertion Loss (dBA)	Cost	Added Maintenance	Improved Aesthetics
1. Neighborhood Side						
Conventional		20'	9.5	$994,100		
Absorptive T-top		13'	10.6	$907,000	YES	YES
Y-top		18'	10.3	$1,294,400	YES	YES
Slanted-top		20'	9.5	$1,333,500	NO	YES
Single-wall Absorptive		16'	10.3	$864,900	YES	YES
2. Spokane Community College Side						
Conventional		20'	9.7	$1,173,500		
Absorptive T-top		13'	10.4	$1,070,700	YES	YES
Y-top		18'	10.3	$1,527,900	YES	YES
Slanted-top		20'	9.7	$1,574,000	NO	YES
Single-wall Absorptive		16'	10.2	$1,020,900	YES	YES
1. & 2. Both Sides of Market/Greene Alternative						
Reflective Parallel	1.	24'	8.3	$1,193,000		
	2.	24'	7.8	$1,408,000		
Absorptive Parallel	1.	18'	8.6	$1,312,300	YES	YES
	2.	18'	8.5	$1,549,000	YES	YES