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Barrier Cost Reduction Program: A Supplement to FHWA's STAMINA Program

Grant S. Anderson and Christopher W. Menge

The barrier cost reduction (BCR) computer program has been developed to overcome significant shortcomings in current design practice for complex highway noise barriers. These shortcomings are summarized, the concept of a "balanced" noise barrier—the barrier that provides the most protection for the least cost—is discussed, and finally the BCR design process is outlined. The roles of the BCR program, the barrier designer, and the partner STAMINA program of the Federal Highway Administration are separately described. Emphasis is on designer-BCR interaction, which leads to final, balanced barrier design. Eighteen such interactions are briefly described. Finally, an application of the BCR program in the city of Baltimore, Maryland, which resulted in construction cost savings of approximately 40 percent, is described in detail. The program will shortly be documented for use by state highway agencies.

In the design of complex highway noise barriers, it is current practice to use three-dimensional computer models that take into account the full geometric complexity of the highway, the field of receivers, and the intervening terrain. Three-dimensional models that have been approved by the Federal Highway Administration (FHWA) are the TSC MOD-04 model and its successor, the STAMINA program.

Multiple computer runs are required in the design of any complex noise barrier. In practice, a particular barrier design is first suggested by hand calculations and then run on the computer. Then the process is repeated with a modified barrier design suggested by the computer output, by further hand calculations, and by the designer's intuition. Generally, three or four barrier designs are computed before computation funds, available design time, and the patience of the designer have expired. Each successive design eliminates some of the weaknesses of the previous design.

Such a process has several significant shortcomings:

1. Only a limited number of designs are generally computed. The designer-computer interaction—try, look, react, try again—is thus limited to three or four iterations. When architects later comment on the aesthetics of the resulting design, however, further computer iterations are often not possible. For this reason, the computer-assisted design is often abandoned in favor of a hand-calculated design that meets the architect's continually evolving constraints. In the same manner, computer-assisted response to neighborhood concerns is often not possible. Structural engineers also impose constraints that should require further designer-computer interactions if they are to be properly incorporated in the barrier design. In short, current practice does not allow enough computer-designer interactions to incorporate all nonacoustical constraints into an achievable and satisfactory barrier design.
2. Costs are not incorporated into designer-computer interaction. Costing is generally done after barrier design. If costs prove too high, barrier heights are often hand-adjusted downward, without computer assistance and without computer calculations of the loss in barrier protection.
3. After the barrier design is complete, some receivers remain underprotected and others overprotected. The small number of interactions does not allow "fine tuning" of the barrier design to eliminate this unevenness of protection.
4. After the barrier design is complete, the designer has no assurance whatever that the design is "balanced" —that it either (a) provides the most protection for the money or (b) is the least expensive barrier that will achieve the desired protection. In short, the design may involve very inefficient use of construction funds.

The barrier cost reduction (BCR) computer program described in this paper was developed to overcome these shortcomings. This program has been used in conjunction with the TSC MOD-04 computer program on the design of several noise barriers in the city of Baltimore, Maryland. The program will shortly be documented, and in approximately one year it will be available as a supplement to STAMINA.

This paper is meant to familiarize the reader with the underlying concepts of the BCR program and to describe its use in Baltimore.

CONCEPT OF A BALANCED BARRIER DESIGN

The BCR program guides the designer toward a balanced noise-barrier design. For a given amount of protection, a balanced barrier design has the least cost and, for a given cost, provides the most protection. These equivalent definitions of a balanced barrier design are the obvious goals of any designer. In short, a balanced design provides the most protection for the least cost.

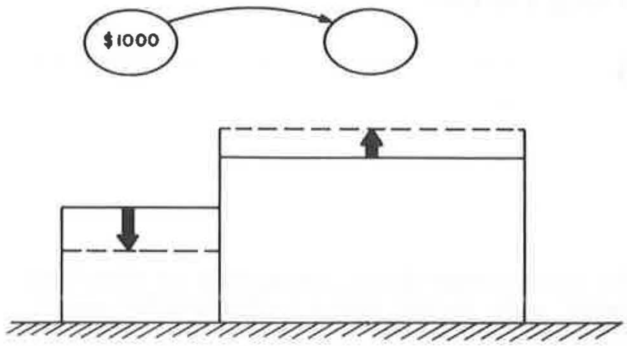
Figure 1 shows the balancing process. Shown are two barrier elements that are part of a more complex barrier system. The first estimates of barrier heights appear as solid horizontal lines in the figure.

Are these two solid-line heights properly balanced? Suppose $1000 in cost were transferred from the left-hand to the right-hand barrier element, as indicated in the figure. The net cost of the barrier has not changed. What has happened to the protection that the barrier provides? If the protection improves, then the cost transfer was a wise one and should be made. If protection decreases, then the opposite cost transfer should be made. The barrier elements are balanced only if the cost transfer produces zero change in protection.

When every pair of barrier elements has been examined and balanced in this manner, then the entire barrier design is balanced. Intuitively, there is then no further reason to transfer costs from any barrier element to any other. This intuitive balancing process is mathematically equivalent to the two alternative definitions of a balanced barrier: one that either provides the most protection for a given cost or costs the least for a given amount of protection.

Many such balanced designs are always possible: low-cost designs that provide little protection, high-cost designs that provide much protection, and many

Figure 1. Cost transfer between two barrier elements.



intermediate designs. The BCR program identifies all such balanced designs, guides the designer to a reasonable selection from among them, and computes total cost and protection for any of them.

By balancing each barrier element against all others, the BCR program also balances the larger characteristics of the barrier. It allows intelligent balance between barrier length and height, for example. It provides detailed guidance on wrapping barrier ends around noise-sensitive receivers versus increasing the barrier length parallel to the roadway. It allows a cost-efficient, balanced design where cross streets, pedestrian access routes, or ramps must penetrate a barrier. It balances the ramp noise against the main-line noise so that neither is ignored or overemphasized. In the same way, it balances local street noise against noise from the limited-access portions of a highway project.

Most important, the BCR program balances cost against acoustical performance. For example, noise barriers on structure are significantly more expensive than those on fill, especially if the structure has to be reinforced to withstand the additional wind loading. Funds can therefore be saved if structure-mounted barriers are reduced in height and fill-mounted barriers are increased in height, to compensate. To what extent is this possible? The answer depends on the full three-dimensional geometry and the details of factors such as materials cost and receiver positions.

The BCR program allows for all of these balances in the detailed barrier design. It is a balancing tool.

BCR DESIGN PROCESS

Overview

The BCR design process is an interactive process that involves the STAMINA program, the BCR program, and the barrier designer. STAMINA does all the acoustics computations. The BCR program merges STAMINA output with cost information and does the benefit/cost (B/C) arithmetic. Then the designer interacts with the BCR program to narrow in on a barrier design. BCR suggests designs, the designer chooses one, and BCR computes protection and cost. Then this interaction is repeated as often as the designer wishes, for each different barrier design.

STAMINA

STAMINA does all the acoustics calculations involved in barrier design. Therefore, as improvements to STAMINA evolve, they will automatically accrue to the STAMINA-BCR combination and will automatically be consistent with FHWA policy concerning noise computations. Currently, the accuracy of STAMINA's acoustics computations is widely accepted.

STAMINA is a three-dimensional computer model. Input consists of roadway elements, barrier elements, and receivers—all in x, y, z coordinates.

Before the development of the BCR program, each barrier element in STAMINA had one specific height. As part of the BCR development, STAMINA was modified to perturb barrier-element heights up and down—all independently—and then to recompute the acoustics for these perturbed barrier heights. For these perturbation calculations, STAMINA now requires the following additional input for each barrier element: (a) the number of height perturbations desired, (b) the incremental height of these perturbations, and (c) a "zero height" (for example, existing ground or existing parapet height). Then STAMINA outputs all the acoustical effects of these height perturbations for use by the BCR program.

BCR Program

The BCR program accepts the new STAMINA output plus the following additional information: (a) for each barrier, the type of construction material; (b) for each type of construction material, the lineal cost as a function of barrier height; (c) for each receiver, the number of people represented; and (d) for each receiver, the design noise level.

All of these additional inputs are chosen by the designer. In particular, the designer chooses his or her own cost input, so that cost calculations will incorporate the designer's own regional experience and cost-saving engineering.

With this information, the BCR program then computes a B/C ratio for each perturbation of each barrier element. With 50 barrier elements and 6 perturbed heights per element, for example, the output consists of a 50x6 matrix of B/C ratios. Computation of these ratios involves only the simplest of arithmetic and does not degrade either acoustical accuracy or the accuracy of the cost input. Figure 2 shows a sample of B/C output (since the BCR program is formulated in U.S. customary units of measurement, this figure is presented without SI equivalents).

Designer-BCR Interaction

Given this B/C output, the barrier designer chooses an initial design for further computation. Generally, the designer first chooses a balanced barrier design. Figure 2 shows one such balanced design in the form of a vertical twisted path of equal (or near-equal) values through the B/C matrix. A 55-or-56 path is shown. The corresponding barrier heights are read directly from the right-hand field of numbers in the output.

As is evident from the output, other balanced paths through the matrix exist. The 52-or-53 path, for example, would represent a balanced barrier of lower height than the one shown. This lower-height barrier would cost less and provide less protection. For the money, however, it would provide the most protection possible. The B/C arithmetic guarantees this.

Once a matrix path is chosen, the designer enters the barrier-element heights into the BCR program. Then the BCR program computes the barrier cost—both total cost and cost separately by type of construction material. In addition, the BCR program computes the resulting L_{eq} at each receiver so that the designer can judge whether enough protection has been achieved. The turnaround time for this designer-BCR interaction is approximately 10 min, in the time-shared mode. To compute the L_{eq} at each receiver, the BCR program uses the STAMINA output only, and so the accuracy of

Figure 2. Sample B/C output.

BARRIER ELEMENT	10 log (B/C)						CORRESPONDING HEIGHTS					
1	48	52	55	57	59	59	12	14	16	18	20	22
2	48	49	55	58	59	60	12	14	16	18	20	22
3	46	49	53	56	60	59	12	14	16	18	20	22
4	45	48	51	53	54	56	14	16	18	20	22	24
5	45	49	52	55	60	60	14	16	18	20	22	24
6	48	48	52	56	57	57	12	14	16	18	20	22
7	50	52	55	57	59	59	12	14	16	18	20	22
8	53	55	59	62	63	61	8	10	12	14	16	18
•			•						•			
•			•						•			
•			•						•			

the acoustics is maintained.

This designer-BCR interaction may be repeated as often as the designer wishes. He or she may ask for costs and protection for any barrier design, even for designs that are not balanced or only partially balanced. A barrier system with 50 barrier elements, each with six possible heights, could be designed in more than 10 billion ways, and any of these designs could be chosen by the designer for BCR computation.

As an example of this interaction process, the designer may first wish to protect everyone to 67 dB(A) L_{eq}. He or she tries several balanced designs to find the proper one (four tries, 40 min). But the maximum height of this balanced barrier is extreme in one place. The designer lowers the height at that place and raises it elsewhere to compensate. In other words, the designer chooses a path through the B/C matrix that is as balanced as possible but with the new height constraint. The designer then interacts with the BCR program several times to find a modified barrier that again succeeds in protecting everyone to 67 dB(A) L_{eq} (two tries, 20 min). Because of this slight unbalancing, the barrier cost will increase slightly—by the cost of imposing this height constraint for aesthetic purposes.

The following is a partial list of possible designer-BCR interactions:

1. Rebalance the barrier design so that no barrier elements are higher than 4.5 m (15 ft). How much additional money is required to satisfy this height constraint? Turnaround time is 20 min.
2. Rebalance the design, ignoring the nearby park. How much money is saved by the new barrier design? This money is then available to relocate the park. Turnaround time is 40 min.
3. Rebalance the design, ignoring the school. How much money is saved? This money is then available to noise insulate the school. This question can also be answered separately, floor by floor. Turnaround time is 20 min.
4. "Smooth out" the barrier heights along the barrier, for aesthetics. How much extra cost is incurred? How much reduction in benefit results? Turnaround time is 20 min.
5. Balance the design with only residences included, and cost this design. Do the same with only the schools and then only the parks. What are the relative costs, then, of protecting these three types of land uses? Total turnaround time is 60 min.
6. Suppose we have revised our cost estimates downward for steel barriers on structure. Rebalance the design to take this into account. The steel barriers should end up taller than before and the overall costs lower. Turnaround time is 40 min.
7. Barrier 6 is controlling costs. By overcoming some engineering problems, we can change barrier 6 from cast-in-place concrete to precast concrete. Rebalance the design. How much money is saved? Turnaround time is 40 min.
8. We can use 3:1 slopes on earth-berm barrier 15 to save land-purchase costs. This changes the unit costs of that barrier. Rebalance the design. How much money is saved? Turnaround time is 40 min.
9. To reach a protection level of 67 dB(A) L_{eq} at all receivers costs $350 000. We feel that $200 000 is our cost limit. Should the design be rebalanced with this cost constraint? What effective design noise level have we been able to achieve? Turnaround time is 20 min.
10. Instead of aiming for a given design noise level, aim for a 10-dB insertion loss at the closest receivers. Rebalance the design with this constraint. Turnaround time is 20 min.
11. Barrier 12 can be all wall, or all berm, or any proportion in between. Rebalance the design for both extremes and a selection of intermediate berm-to-wall ratios. For equal benefit, which ratio results in the lowest barrier-system cost? Turnaround time is 40 min for each wall-berm combination.
12. Barrier 6 can be changed to a more costly material that requires less maintenance. On the basis of barrier area alone, the apparent extra cost is $30 000. However, the computer will reduce this barrier height and increase the height of other, cheaper barrier segments when the design is rebalanced after the change. Rebalance the design. What is the actual extra cost? Turnaround time is 40 min.
13. Reduce all barrier heights by 0.6 m (2 ft) from the balanced-design heights. How much did noise levels increase at each receiver? How much is the cost savings? Turnaround time is 10 min.
14. Rebalance the design so that no barriers are located past station 630. How much have remaining heights increased? How much extra cost is incurred? Turnaround time is 20 min.
15. Rebalance the design so that no barriers are located past station 600 and none are higher than 4.5 m (15 ft). Can the design noise levels be met? If yes, how much extra cost is incurred over the unconstrained balance? Turnaround time is 20 min.
16. The community is insisting that we protect the cemetery to 57 instead of 67 dB(A) L_{eq}. Rebalance the design with this change in design noise level. How much extra cost is incurred? Turnaround time is 40 min.
17. The balanced barrier design leaves an isolated receiver 2 dB above its proper design noise level. In the BCR input, reduce the design noise level by 2 dB to "fool" the BCR program into an extra 2 dB of protection for this receiver. Rebalance the design. How much extra cost is incurred? Turnaround time is 20 min.
18. The effective source height of heavy trucks is lowered by regulation. Significantly lower barrier heights are then possible. The new barrier system may balance out quite differently from the higher one. Rerun STAMINA for the reduced-height trucks, and then rebalance the barrier by using the BCR program. How much money is saved? Turnaround time is 8 h. (This is the only interaction that requires a rerun of STAMINA.)

APPLICATION TO BALTIMORE

The BCR program was used to design barriers for a proposed highway through the Locust Point area of Baltimore, Maryland. Figure 3 shows the roadway plan for the proposed barrier design. All noise-sensitive receivers are to the north of the roadway, which (from left to right) is elevated about 9 or 12 m (30 or 40 ft) in the air, drops to grade, and proceeds below grade as it enters a tunnel (not shown). In addition, a north-side ramp is located about midway on the plan. The ramp complicates the design because it requires an opening in the barrier and possibly requires its own barrier, as shown.

Figure 3 also shows the adjacent land uses, which include a park quite close to the at-grade roadway, some densely populated rowhouses, a multistory school, and a church. Since the residences are on a hill, the barriers must be higher than they would otherwise have to be.

Figure 4 shows the vertical alignment or roadway

Figure 3. Example roadway plan and land use.

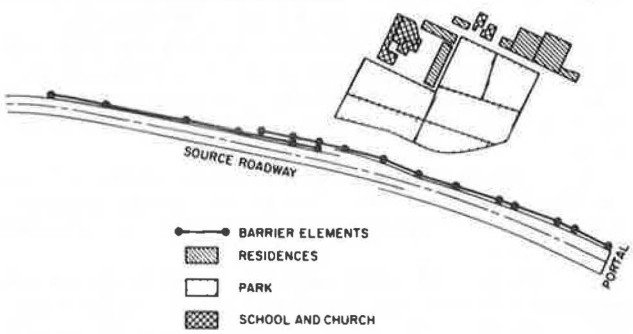


Figure 4. Vertical alignment.

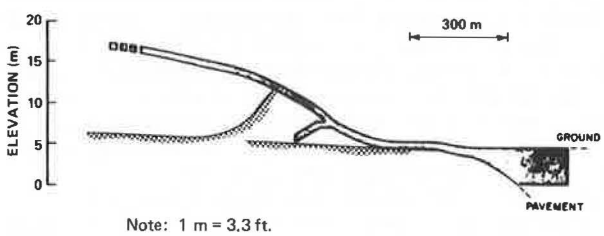


Figure 5. Compressed vertical alignment.

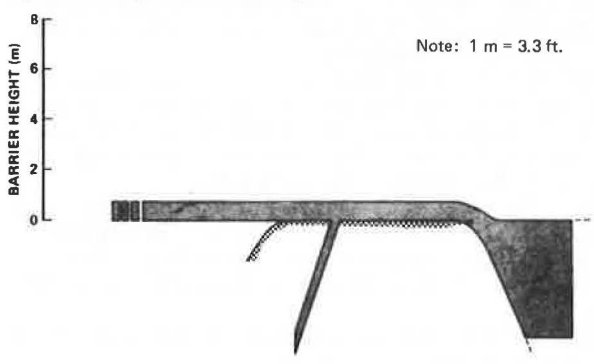


Figure 6. Initial barrier design and costs.

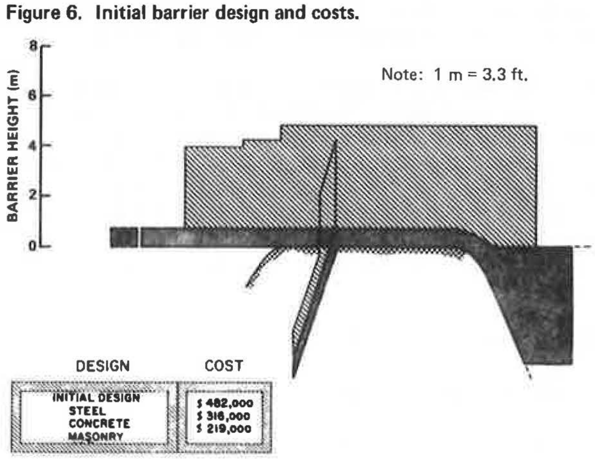


Figure 7. Balanced steel barrier design.

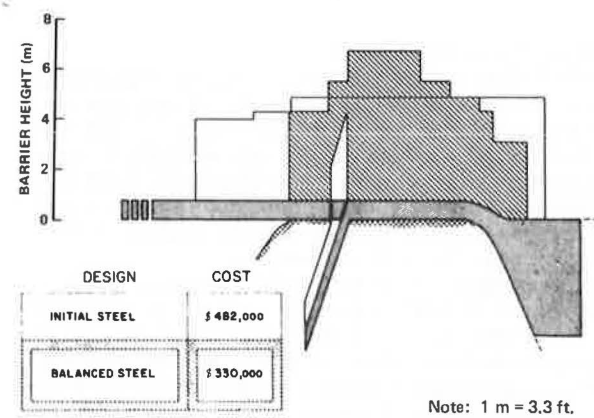


Figure 8. Balanced concrete barrier design.

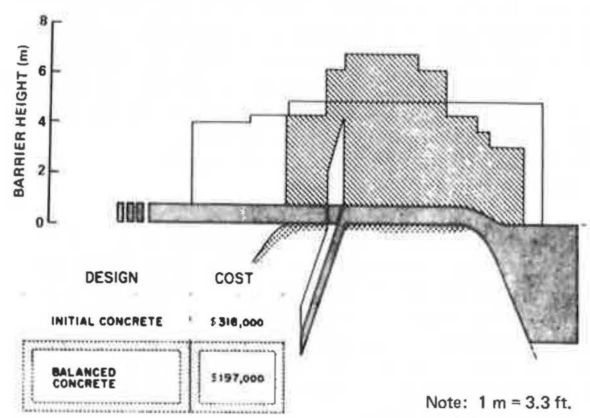


Figure 9. Balanced masonry barrier design.

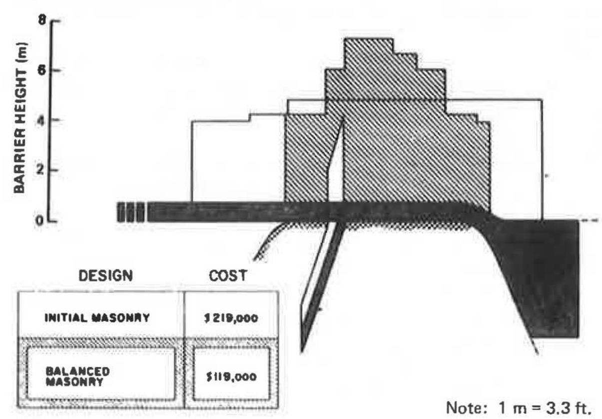


Figure 10. Steel barrier design: 6-m maximum height.

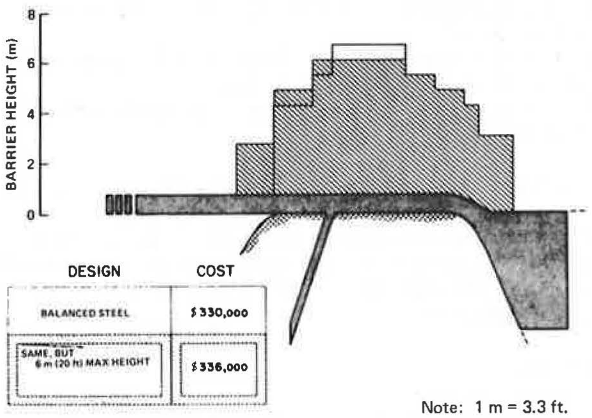


Figure 11. Concrete barrier design: 6-m maximum height.

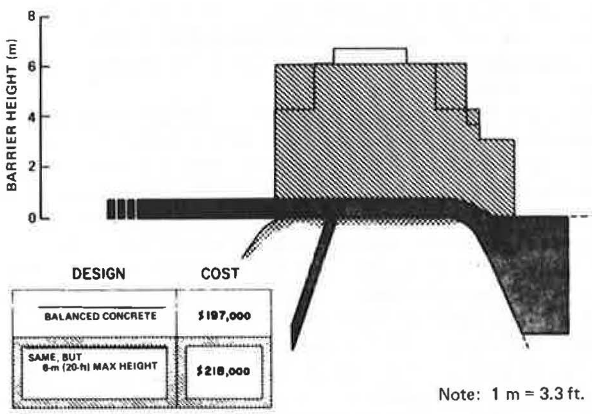
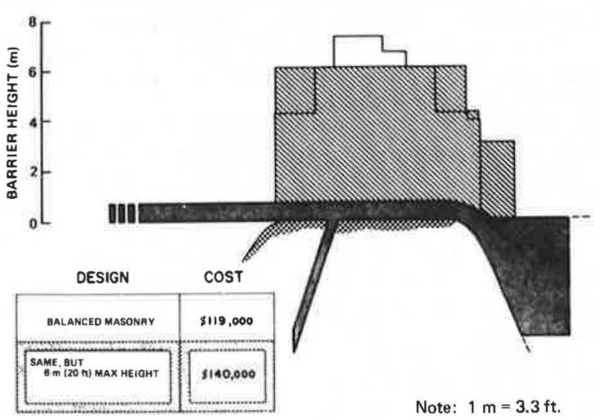


Figure 12. Masonry barrier design: 6-m maximum height.



profile. The elevation scale is exaggerated, as usual. Zero elevation equals sea level. To the left, the roadway is on structure. The ramp drops to grade. To the right, the roadway is depressed below grade. The shaded area represents the Jersey barrier on structure and grade, which merges into the retaining wall to the right.

Figure 5 is a compressed version of Figure 4. Essentially, zero represents roadway height in this figure, since the various barrier designs are placed on top of the roadway pavement. To the right, the barrier sits on grade. The scale on the left will gauge the

Figure 13. Masonry barrier design in which park is not protected.

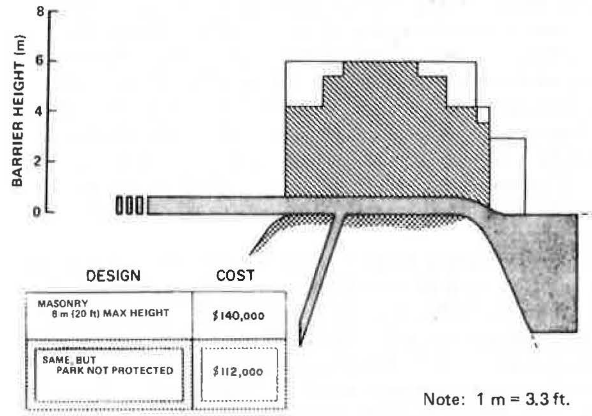
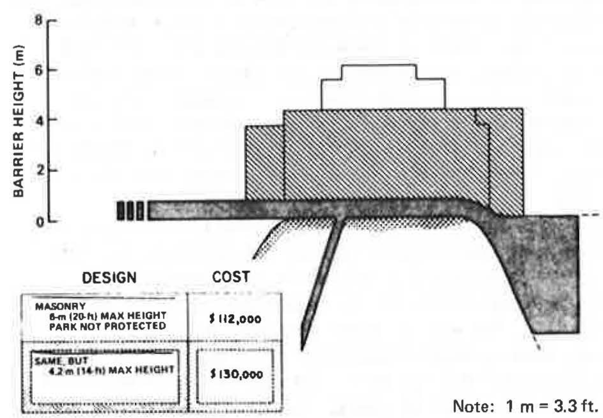


Figure 14. Masonry barrier design in which park is not protected and maximum height is 4.2 m.



various barrier heights in later figures.

The initial barrier design and costs are shown in Figure 6. This initial design involved multiple use of the FHWA barrier nomograph and the TSC MOD-04 program to produce a solution that protects all receivers. The design is a relatively uniform but noncontinuous structure; the ramp barrier penetrates the main-line barrier on the profile. Barrier height decreases on the elevated structure because, by cost intuition, these reductions had been initially entered into the TSC MOD-04 input.

The costs for this barrier were determined for three materials: steel, concrete, and masonry. However, along the elevated sections of roadway (the reduced-height elements), steel was used for all three cost estimates.

Figure 7 shows a comparison between the initial design (unshaded) and the balanced design for steel (shaded). When the BCR program balanced the initial design, a number of important things happened:

1. The dimensions of the barrier changed. The barrier length decreased and height increased, but not uniformly.
2. The ramp barrier completely disappeared because the BCR program determined that it was not necessary.
3. The barrier cost much less. The balanced barrier produced the same protection at a cost savings of $152 000.

Figure 8 shows a comparison between the concrete version of the initial design and the balanced design. Again, there are substantial cost savings and a modified barrier design. This balanced concrete barrier system is very similar to the balanced steel system; some elements are slightly taller, however, because it is less expensive to build tall concrete barriers.

Figure 9 shows the balanced masonry barrier system. This design is even taller, as well as being $100 000 cheaper than the initial masonry barrier design.

The design team looked at these designs, plus quite a few others, and determined that the balanced designs were too tall. Returning to the BCR program, the design team then imposed a 6-m (20-ft) height constraint on all elements in the balanced designs. As Figure 10 shows, the new balanced steel design is somewhat different from the first balanced design. The new design lowers the highest portion of the barrier to 6 m but increases the barrier length to the left, which results in a $6000 increase in cost.

Figures 11 and 12 show the new balanced designs and costs for the concrete and masonry barrier systems, respectively. Both of these materials cost $21 000 more than their preceding balanced counterparts because of the 6-m height constraint; these costs are still substantially lower, however, than those for the initial design. When the height constraint is taken into account, these are the cheapest and most effective barriers.

Because the new designs still seemed extreme, the design team determined that (a) the masonry barrier provides the best solution and (b) the nearby park causes the excessive barrier heights. After some negotiation, the design team decided that, if the barrier cost savings justified it, the half of the park closest to the highway might be moved. For the BCR program, this kind of change is very easy to implement and explore. The designer simply lets the nearest park receivers represent zero people. This change completely alters the B/C matrix.

Figure 13 shows the newly balanced barrier design. The overall savings for this (shaded) barrier, compared with that for the unshaded one, is $28 000, a substantial sum of money.

Many more barrier systems were investigated. Figure 14 shows one of the later design options. The height was contained to 4.2 m (14 ft), the costs went up somewhat, and the barrier was lengthened so that some of it would sit on the elevated structure.

This barrier evolution at Locust Point in Baltimore is summarized below (1 m = 3.3 ft):

Barrier Design	Material	Cost ($)
Initial	Steel	482 000
	Concrete	316 000
	Masonry	219 000
Balanced, no constraints	Steel	330 000
	Concrete	197 000
	Masonry	119 000
Balanced, 6-m maximum height	Steel	336 000
	Concrete	218 000
	Masonry	140 000
Balanced, park not protected		
6-m maximum height	Masonry	112 000
4.2-m maximum height	Masonry	130 000

From the initial masonry design to the 4.2-m-high balanced design that leaves the near portion of the park unprotected, the cost savings is $89 000.

This $89 000 savings involved the following options:

1. A cost savings of $100 000 realized by initial use of the BCR program,
2. A cost penalty of $21 000 to restrict the barrier height to 6 m (20 ft),
3. A cost savings of $28 000 because the near portion of the park is not protected, and
4. A cost penalty of $18 000 to restrict the height to 4.2 m (14 ft).

Each of these intermediate options, during the evolution of the barrier, was a balanced option. They all provided the most protection for the least cost, consistent with the constraints imposed. Each design also reduced the noise for all receivers to just below the design noise level of 67 dB(A) L_{eq}.

SUMMARY

In the design of complex highway noise barriers, it is current practice to use three-dimensional computer models. To overcome the significant shortcomings of this current practice, such as the limited number of designs, lack of cost computations, unevenness of protection, and inefficient use of construction funds, the BCR program was developed and used for barrier design in Baltimore, Maryland.

The new BCR program guides the designer toward a balanced barrier design—one that either provides the most protection for a given cost or costs the least for a given amount of protection. In the BCR design process, (a) the STAMINA program does the acoustics computations, (b) the BCR program merges STAMINA output with cost information and does the B/C arithmetic, and (c) the designer interacts with the BCR program as often as desired to narrow in on an acceptable design.

This designer-BCR interaction centers around the B/C ratios that are computed by the BCR program for each height perturbation of the barrier's many elements. The B/C ratios direct the designer toward balanced sets of barrier elements. The BCR program then computes cost and protection for any set that the designer requests. Turnaround time for this computation is only 10 min in the time-sharing mode. The designer may request that any barrier-element height combination be computed, even combinations that are not balanced or are only partially balanced.

The resulting designer-BCR interaction is extremely flexible and is capable of answering many specific design questions in short turnaround time. Such questions involve the cost and protection implications of the following factors: height constraints, elimination of receivers, modification of the design for aesthetic purposes, separate assessment of protection costs by land use, reduced costs of construction materials, changes in construction materials, the protection possible for various cost constraints, use of target insertion losses instead of design noise levels, options in berm-wall height ratios, trade-offs between construction and maintenance costs, effects of across-the-board height reductions, length constraints, length and height constraints combined, proposed changes in design noise levels, extra effort to protect isolated receivers, and lowered heavy-truck source heights.

In the design of the Locust Point barrier in Baltimore, a multitude of optional designs were investigated with the BCR program, all with only one run on the TSC MOD-04 computer program. The initial balancing reduced barrier length and increased heights, but nonuniformly. After height constraints were imposed, the barrier was rebalanced without protecting the closest portions of a nearby park. Finally, another height constraint was imposed. This process resulted in a net cost savings of 40 percent.

Attitudes Toward Noise Barriers Before and After Construction

F. L. Hall

To obtain the most reliable indication of the effectiveness of noise barriers in terms of the reactions of community residents to highway noise, comparable surveys should be conducted before and after barrier construction. Two questionnaires designed for this purpose are presented and discussed. The questionnaires are based on discussions held at the 1978 Conference on Highway Traffic Noise Mitigation and on additional field experience.

One of the concerns raised but not answered at the 1978 Conference on Highway Traffic Noise Mitigation in Los Angeles was the problem of how best to collect information on community opinion about noise-barrier effectiveness. At the conference, several state representatives reported on their experience and on the difficulties they encountered. Others voiced their concerns during formal or informal discussions. This paper attempts to summarize those concerns and, from them and our own field experiences, to suggest the most effective procedures for obtaining information on community opinion about noise barriers.

Florida experience (1) is a good example of the problems inherent in obtaining appropriate information about community attitudes when a noise barrier is built as part of the construction of a new roadway [type 1 project (2)]. In such cases, some residents may be dislocated by the construction, which makes follow-up interviews impossible. Residents who were there both before and after construction of the new road may confuse barrier and highway effects. In the worst case, they may rate the barrier negatively because the area is noisier after construction of the new road than it was before. The unavoidable difficulty is that they are being asked to compare a hypothetical situation (a new road with no barrier) with a new and possibly unpleasant situation (a new road with a barrier). In such a case, it is next to impossible to obtain valid information, since most people are not able to make such a hypothetical comparison realistically. As a result, the most practical suggestion for type 1 projects is to avoid attempting to evaluate the community's attitude toward the barrier in before-and-after terms.

For barriers built in locations where an existing highway already affects existing residences (type 2 projects), these difficulties do not exist, and it is an excellent idea to attempt to obtain information on community attitudes both before and after barrier construction. In Minnesota (3), the State Legislature has required such an evaluation of noise barriers.

The remainder of this paper deals with the problems of data collection for type 2 projects.

DATA COLLECTION REQUIREMENTS

The underlying objective of a data collection effort such as that discussed in this paper is to obtain information that accurately describes the opinions of owners of abutting property on "the effectiveness and desirability of acoustical barriers" (3, pp. 60-61). On the basis of discussions at the Conference on Highway Traffic Noise Mitigation, five specific requirements were identified to ensure that this objective is met:

1. The data should be as representative of the affected community as possible. This means that the data collection procedures should be constructed to ensure a high percentage of completed responses and that the procedures should try to minimize any bias that might be introduced by the way the questions are worded.
2. The first survey, at the inception of the project, should identify the severity of the problems caused by highway noise in the specific project areas and the potential for public participation during project design selection.
3. The second survey, after barrier completion, should obtain information that is as comparable as possible to that collected in the first survey.
4. The cost of collecting and processing the data should be kept to a minimum.
5. It should be possible to identify which person in a household answered the first survey so that the same individual can be interviewed in the second survey. This is strongly recommended, since otherwise the differences in the responses may distort the results.

In some respects, these requirements all lead to similar conclusions for the questionnaire. Keeping the questionnaire brief and asking only those questions that are essential help to keep costs low and response rates high. Personal questions, such as age, should be kept to the minimum necessary to meet requirement 5 above and should be asked only at the end of the questionnaire. Respondents sometimes refuse to participate when personal questions are asked first. When they know why such information is needed, they are more likely to provide it.

In other respects, these five requirements are contradictory or incompatible. With regard to the procedures for administering the questionnaire, requirements 1 and 4 conflict. Door-to-door interviewing is probably most effective for the first requirement, in terms of response rate, ability to control for male and female participation, and ability to recognize and overcome misunderstandings. It is, however, the most expensive approach. One way to reduce costs is to use people already on staff. For example, the New York State Department of Transportation (NYSDOT) was able to use office secretarial staff among others in their door-to-door interviewing. An added advantage of using these people is that the same personnel will usually be available for the follow-up surveys. There has sometimes been an increase in the number of refusals to participate when men have done the interviewing, although this may not be generalizable. The expense of door-to-door interviews is usually offset by the fact that they generally achieve close to an 80 percent response rate.

Other procedures rely on mailed questionnaires that are to be mailed back, or on a mailed notice followed by a telephone call in which the actual interview is conducted, or on a telephone call alone. If the mailings are followed up with a second request, they can also obtain better than a 70 percent response rate [based on Minnesota experience (3)]. A potential difficulty with a mailed survey, however, is its inability to overcome language or literacy problems. Telephone surveys overcome these problems and often produce almost as good a response rate as door-to-door surveys. The Urban

Figure 1. Suggested questionnaire for survey before construction of a noise barrier (instructions to interviewer in italics or brackets).

Hello. I am from the (state) Department of Transportation, which is concerned about problems that may be affecting people such as yourself who live near major highways. We are actively considering solutions to some of the problems in your neighborhood. We would very much appreciate a few minutes of your time to answer the following questions.

1. What are the most important things you dislike about living in this area?

Write down the exact thing(s) said, for later coding. Probe slightly: "Is there anything else you dislike?" Focus on the residential environment of a few surrounding blocks. Whether or not road-related problems are mentioned, use the following transition phrase to move to the next question: "The Department of Transportation is particularly interested in things you dislike that may be related to living near a highway."

2. Here is a list of problems other people have mentioned. Please rate each of them with regard to how great a problem it is for you and your family while you are at home.

Read question stem at left and each response as written.

	not a problem at all	a minor problem	a moderate problem	a major problem or	an extremely bad problem?
Is highway dust and dirt	___	___	___	___	___
Is headlight glare	___	___	___	___	___
Is litter from vehicles	___	___	___	___	___
Is highway noise	___	___	___	___	___
Is vibration from the road	___	___	___	___	___
Are fumes from the road	___	___	___	___	___
Are there any other road-related problems? Name? Severity?	___	___	___	___	___

3. How often does the noise from the road interrupt you during any of the following activities?

	never	only occasionally	several times per week	several times per day	almost all the time
Conversation indoors	___	___	___	___	___
Conversation outdoors	___	___	___	___	___
Use of telephone	___	___	___	___	___
Watching television	___	___	___	___	___
Relaxing indoors	___	___	___	___	___
Relaxing outdoors	___	___	___	___	___
Sleeping	___	___	___	___	___

4. How often do you or members of your family use your yard for relaxing or playing during warm weather?

___ every day ___ once or twice a week
___ several times a week ___ less than once a week

5. a. Have you regularly been forced to close your windows because of traffic noise?

Yes___ No___

b. [If yes] How often would you say this happens?

___ once or twice a month ___ several times a week
___ once a week ___ most of the time

6. Have you made any modifications to your house or yard because of the traffic noise?

Yes___ No___ [If yes] What?

7. Are there any other problems associated with living near the highway that you would like to mention? Yes___ No___

List responses.

8. How long have you lived at this address?___________

9. Would you or other members of your household be interested in attending a public meeting about possible solutions to some of the problems mentioned earlier?

Yes___ No___

10. And now, a few questions about yourself, to assist us in contacting you personally for a possible follow-up survey.

If name is offered by respondent at this point, write it down, and do not ask remaining items.

a. Sex [Do not ask.] male___ female___
b. How old are you?___ years
c. What is your main occupation (that is, what sort of work do you do)?

____

Thank you for your assistance.

Noise Survey (4, p. 71), for example, reports a 70 percent overall completion rate in its telephone survey. In the two cities where both the telephone and door-to-door methods were used, neither was obviously better. Los Angeles gave a 10 percent better completion rate for door-to-door; Boston, a 1 percent worse rate. To select the appropriate approach in each project, a decision must be made as to what problems are likely to be encountered and what costs (in personnel time) are reasonable to overcome them.

Another way in which the requirements are contradictory becomes apparent when the first three requirements are taken together. Obviously, after barrier construction the community will be very much aware of traffic noise. For the two surveys to be comparable, the people should be equally aware of the traffic noise during the first survey. Yet to ensure such an awareness at that time would probably bias their responses to the first survey with respect to requirement 2 (identifying the severity of highway noise before construction). This difficulty can be overcome to some extent by using door-to-door or telephone interviewing, since the respondent does not need to know the final focus of the questionnaire at the start of it. Unfortunately, the mailed survey cannot overcome this problem because it cannot be assumed that people answer the questions in order. Thus, the first question in the questionnaire shown in Figure 1 should be omitted in a mailed survey. It should also be omitted in the follow-up surveys taken after barrier construction.

PROPOSED QUESTIONNAIRES

The questionnaires presented here contain a central core of questions suitable for use both before and after barrier construction. A comparison of the answers at the two times should serve as the best obtainable indicator of the barrier's effect on people. The after survey also includes some questions used in the Minnesota survey (3) that ask directly about the barrier.

The introductory paragraph for the preconstruction questionnaire (Figure 1) is kept quite brief, as would be the case for a door-to-door or telephone survey. For a mailed survey, a separate, more detailed letter of introduction should replace the introductory paragraph. For the second survey, after construction (see Figure 2), the introductory paragraph should also be brief. The first task of the introduction to the second survey is to identify the appropriate person to interview—namely, the same individual spoken to in the first survey. The second task is to introduce the survey in a manner similar to that in which the first one was introduced.

In administering the questionnaire face to face or over the telephone, it is extremely important that the same wording be used all the time, by all the interviewers, so that answers to the same exact question have been received from all respondents.

The structure of both questionnaires moves from the general to the specific. This approach has been advocated for a number of years (5) and is one that we have used quite successfully in our own work on noise effects. The first question is valuable in the before survey to ascertain how often traffic noise is volunteered as a major problem. It does not make sense to ask this question in the second survey, since people's attention will have been drawn to the highway noise by the construction of a barrier and so answers will not be comparable.

For questions 2-5 to be strictly comparable before and after construction, it is essential that both surveys be conducted at the same time of year. In the drafting of the questionnaire, those times of year when windows are normally open (when heating or air conditioning is not in use) were assumed. It is at these times of year that external noises are generally most noticeable and the barrier's effectiveness can best be judged. If the interviews are administered at some other time of year, some questions may have to be reworded. In the same way, question 4 is worded for the northern half of the

Figure 2. Suggested questionnaire for survey after construction of a noise barrier (instructions to interviewer in italics or brackets).

Hello. I am from the (state) Department of Transportation. Last year we spoke to a person in your household about problems that may be affecting people who live near highways. The person we spoke to was *(describe, from question 10 data)*. Is he/she available?

If the appropriate person is not available, try to find the best time to call back when he/she will be available.

Now that we have completed our work on the project in this area, we would like to know how the highway is affecting people here.

1. Here is a list of problems that were mentioned in last year's survey. Please rate each of them with regard to how great a problem it is now for you and your family while you are at home.

Read question stem at left and each response as written.

	not a problem at all	a minor problem	a moderate problem	a major problem or	an extremely bad problem?
Is highway dust and dirt	___	___	___	___	___
Is headlight glare	___	___	___	___	___
Is litter from vehicles	___	___	___	___	___
Is highway noise	___	___	___	___	___
Is vibration from the road	___	___	___	___	___
Are fumes from the road	___	___	___	___	___
Are there any other road-related problems? Name? Severity?	___	___	___	___	___

2. How often does the noise from the road interrupt you during any of the following activities?

	never	only occasionally	several times per week	several times per day	almost all the time
Conversation indoors	___	___	___	___	___
Conversation outdoors	___	___	___	___	___
Use of telephone	___	___	___	___	___
Watching television	___	___	___	___	___
Relaxing indoors	___	___	___	___	___
Relaxing outdoors	___	___	___	___	___
Sleeping	___	___	___	___	___

3. How often do you or members of your family use your yard for relaxing or playing during warm weather?

___ every day ___ once or twice a week
___ several times a week ___ less than once a week

4. a. Have you regularly been forced to close your windows because of traffic noise?

Yes___ No___

b. [If yes] How often would you say this happens?

___ once or twice a month ___ several times a week
___ once a week ___ most of the time

5. What effect do you think the noise barrier has had on the traffic noise you hear while you are at home?

considerable reduction	moderate reduction	slight reduction	no effect	slight increase	moderate increase	considerable increase
___	___	___	___	___	___	___

6. What effect do you feel the barrier and its associated landscaping have had on the general appearance of this residential area?

considerable improvement	moderate improvement	slight improvement	no effect	slight deterioration	moderate deterioration	considerable deterioration
___	___	___	___	___	___	___

7. Are there any suggestions you have regarding noise barriers we may build in the future in other areas, to improve their appearance or effectiveness?

Thank you for your assistance.

continent and may require rewording for the extreme south.

Questions 9 and 10 are also necessary only in the preconstruction survey. Question 9 provides information that should be of use in ensuring good participation at community meetings to plan the barrier. Question 10 provides information essential to identifying the same individual for the second survey. Based on our own experience, these three pieces of information (sex, age, and occupation) are adequate to identify the same individual for the follow-up survey. If, when the question is introduced, the respondent offers his or her name, that, of course, is adequate.

The questionnaire for the second survey (Figure 2) opens with the same four questions about the effects of the road that were asked in the first survey. In addition, three questions have been added about the barrier itself, including a final open-ended question, which can often be very helpful in identifying attitudes the other questions have missed.

The results of these two questionnaires, analyzed together, permit a thorough description of the perceived effectiveness of the noise barrier, both directly (from the last questions of the postconstruction survey), and indirectly (through changes in the degree of problems reported in the other four questions). If only the after-construction survey is used, the only kind of information that can be obtained is of the direct type, which, of course, relies on people remembering how bad the noise was before the barrier was constructed. The indirect measures of the actual effects of noise before and after construction provide a more reliable indicator of the barrier's effectiveness. If no preconstruction survey is conducted, these measures can never be obtained. A small expenditure in the early stages of the project can produce large returns later, when the effectiveness of the barrier is evaluated.

ACKNOWLEDGMENT

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REFERENCES

1. W. Lindeman. The Birth of a Barrier: A Case Study—I-275 in St. Petersburg, Florida. Proc., Conference on Highway Traffic Noise Mitigation, Los Angeles, Dec. 1978; Federal Highway Administration, 1979, pp. 19-24.
2. Federal-Aid Highway Program Manual. Federal Highway Administration, U.S. Department of Transportation, FHWA-PPM-7-7-3, Vol. 7, Chapter 7, Section 3, 1976.
3. G. P. Orlich. Community Attitudes, Before and After Barrier Construction. Proc., Conference on Highway Traffic Noise Mitigation, Los Angeles, Dec. 1978; Federal Highway Administration, 1979, pp. 60-74.
4. The Urban Noise Survey. U.S. Environmental Protection Agency, Rept. 550/9-77-100, 1977.
5. P. N. Borsky. The Use of Social Surveys for Measuring Community Responses to Noise Environments. In Transportation Noises (J. D. Chalupnik, ed.), Univ. of Washington, Seattle, 1970, pp. 219-227.

Sound-Absorption Treatments for Highway Noise Barriers

Christopher W. Menge

Various aspects of the use of roadside barriers to reduce levels of traffic noise in nearby communities are discussed. These include the need for barriers on both sides of a highway, the resulting degradation of barrier performance, and the need to incorporate sound-absorbing facings into barrier designs. A general overview of sound-absorbing materials is given, and some common misconceptions about reducing highway noise are examined.

When a highway passes through a densely populated area, noise control is often required, and barriers are frequently the only practical means of noise control. If there are residential areas on both sides of a highway, two barriers may be necessary. When two vertical barriers are used, however, the noise-reducing capability of each barrier is usually compromised.

As Figure 1 shows, the sound that emanates from passing vehicles is reflected back and forth between the barriers. Eventually, the noise spills over the tops of the barriers and travels directly into residential areas. Much of the benefit provided by using one barrier is lost when a second barrier is added because the second barrier acts as a reflecting surface and causes multiple sound reflections between the two surfaces.

In 1975, the Federal Highway Administration (FHWA) sponsored a study of the effects of multiple sound reflections in walled highways (1). The study included an acoustical scale-model analysis of the effects of barriers on both sides of a highway. The study predicted the extent to which the noise-reducing capability of an individual barrier was degraded by the addition of a barrier on the opposite side of the highway. This noise reduction was evaluated in three different "receiver zones" (see Figure 2). In zone 1 a receiver could not see the far barrier, in zone 2 a receiver could see some of the far barrier but not the source, and in zone 3 a receiver could see the source.

Figure 3 shows examples of the performance of an individual barrier and the degradation that results in each of these receiver zones from the addition of a second (far) barrier (concrete or steel barriers are assumed in these examples). In zones 1 and 2, the loss in barrier attenuation was very significant: 5-7 dB. Note that in zone 3, where the single barrier did not break the line of sight from the source to the receiver, the single-barrier attenuation was 0 dB. In this case, however, sound amplification occurred because the far barrier reflected a significant amount of sound energy toward the receiver, sound that was originally propagating away from the receiver. In this instance, the amplification could be as much as 3 dB.

The performance of a barrier can also be compromised when the two barriers overlap—for example, when a ramp joins a highway. As Figure 4 shows, when a barrier associated with a ramp overlaps the main-line barrier, sound is reflected back and forth between the barrier walls on each side of the ramp. The sound energy then propagates directly into nearby residential areas. Recent work by Bolt Beranek and Newman, Inc., for the city of Baltimore, Maryland, has shown that, when this or similar barrier configurations exist, the effectiveness of otherwise very effective noise barriers (barriers that provide 10-15 dB of attenuation) may be significantly compromised (yielding less than 10 dB of attenuation) for some residences.

RESTORING BARRIER PERFORMANCE

An effective way to prevent the degradation of performance in a two-barrier system is to make the barriers sound absorbing. If most of the sound incident on a barrier is absorbed, the remaining reflections will no longer be significant. Therefore, if the barriers are efficiently sound absorbing, the far barrier will not compromise the performance of the near barrier, and the effectiveness of an absorptive two-barrier system will be as good for both sides of a highway as a single barrier is for one side of a highway.

USE OF SOUND-ABSORBING MATERIALS TO IMPROVE BARRIER PERFORMANCE

A sound-absorbing material absorbs sound by forcing air molecules to move in and around many tiny fibers or passages. As the air molecules are forced in directions other than a straight back-and-forth motion, they lose energy, and sound intensity or sound level decreases.

Some familiar objects that are made of materials that absorb sound are thick carpeting, stuffed furniture, and heavy draperies. Fabrics are soft and fibrous, characteristics that make them excellent sound absorbers.

How much sound a material absorbs (its sound-absorbing effectiveness) is usually rated by the material's absorption coefficient α. The absorption coefficient is defined as the ratio of the sound energy absorbed by a surface to the sound energy incident on that surface. α may take on all numerical values between 0 and 1. For a perfect absorber, $\alpha = 1.0$; for a perfect reflector, $\alpha = 0$. The absorption coefficient is specified at a certain frequency or over a range of frequencies. The absorption coefficient of a material is commonly specified in octave bands, from 63 to 8000 Hz. For example, a poured-concrete surface has an absorption coefficient of 0.02 in the 500-Hz octave band; virtually all of the sound in that octave band is reflected (2). On the other hand, for a 5-cm (2-in) thick glass fiber blanket spaced 2.5 cm (1 in) away from a solid backing, $\alpha = 0.90$ in the 500-Hz octave band; therefore, 90 percent of the incident sound energy in the 500-Hz octave band is absorbed and, as a result, the level of the reflected sound is 10 dB lower than the level of the incident sound (3).

Figure 5 shows the effect of increasing absorption on the noise-reducing capability of a two-barrier system for three receivers in zones 1 and 2. This effect is shown for the 500-Hz octave band, the predominant frequency region for truck noise. At a receiver height of 4.6 m (15 ft), the height of a typical second-story window, the attenuation increases to 11 dB when $\alpha = 0.8$ from only 5 dB when $\alpha = 0.05$. The single-barrier attenuation ($\alpha = 1.0$) is 12 dB (Figure 5).

Clearly, sound-absorption treatments will improve the performance of a two-barrier system. The effectiveness of barriers with gaps in them (Figure 4) can also be restored if the propagation corridor is properly treated with sound-absorbing material. However, for outdoor use, sound-absorbing materials must withstand

Figure 1. Multiple sound reflections in a two-barrier system.

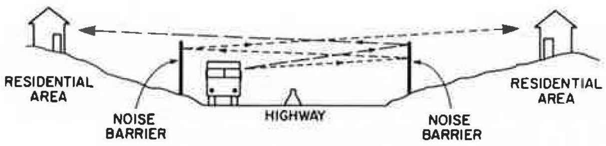


Figure 2. Receiver zones for a two-barrier system.

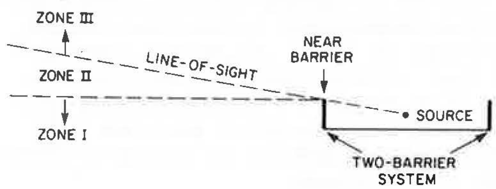


Figure 3. Degradation of sound attenuation by barrier.

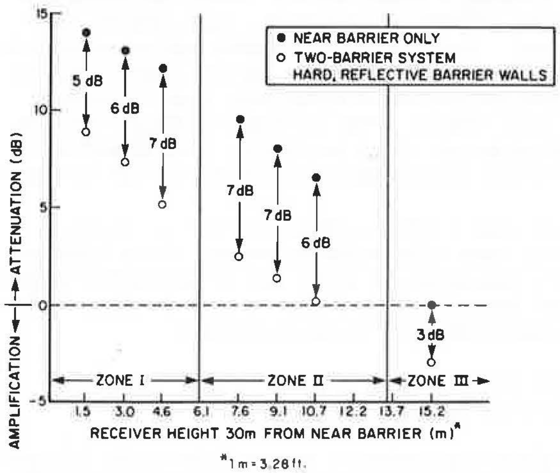
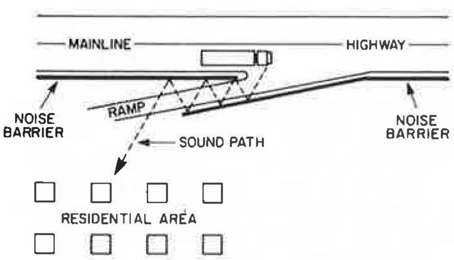


Figure 4. Sound path through overlapping barriers.

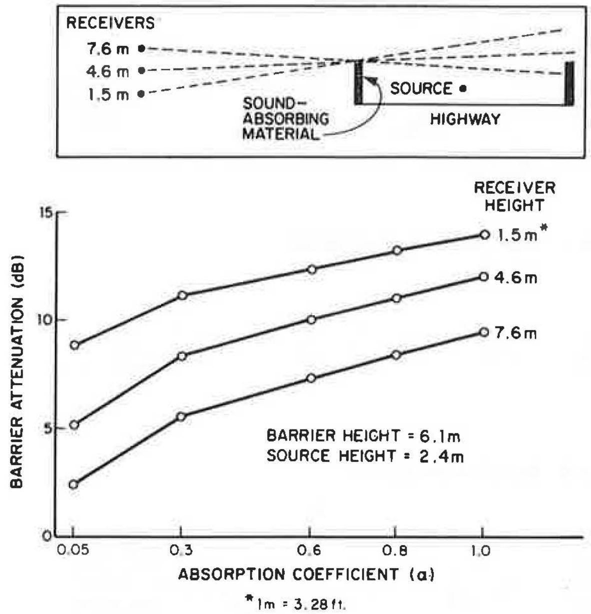


the effects of weather and dirt and must remain sound absorbing for many years. These are not trivial requirements.

SOUND-ABSORBING MATERIALS

A review of criteria for selecting sound-absorbing materials for use on highway noise barriers is given below. The characteristics of some selected materials and the reasons for rejecting other materials commonly believed to be effective for noise control are then discussed. A catalog of sound-absorbing materials and treatments for highway applications is given elsewhere (4).

Figure 5. Attenuation versus absorption coefficient for two-barrier system.



Criteria for Selecting Materials

Sound-absorbing materials should be selected to meet the following criteria (in order of importance):

1. Sound-absorbing capacity—Only materials that meet the sound-absorption criteria should be considered further. For highway barriers, it is necessary to install on the barrier surfaces sound-absorbing treatments that have absorption coefficients of 0.6 or higher. Absorption coefficients of at least 0.6 are necessary in the four most important octave bands for highway noise: 250, 500, 1000, and 2000 Hz.
2. Physical durability—Materials that meet the first criterion should have sufficient durability. In the highway environment, they will be exposed to sun, water, wind, salt, air contaminants, and temperature changes. To remain effective, they must be able to resist these elemental forces for many years.
3. Acoustical durability—Materials that have sufficient physical durability must also resist degradation of their sound-absorbing properties. Oil and dirt can clog the tiny passages between the fibers that make up sound-absorbing materials. Clogging effectively inhibits the motion of air molecules, which is the mechanism by which sound is absorbed. Since sound-absorbing barriers installed along highways have not been in use for long periods of time, little is known about the effects of highway oil and dirt on the acoustical durability of sound-absorbing materials.
4. Maintenance requirements—If the sound-absorbing capacity of a material decreases as a result of clogging, the effectiveness of the barrier will decrease. Cleaning the barrier face may restore its acoustical performance, but requirements for maintenance should be avoided if possible. In addition, the appearance of sound-absorbing barriers should not deteriorate over time, and their finishes should not require cleaning or painting.
5. Flame, fuel, and smoke ratings—Materials that meet all of the above requirements should have flame, fuel, and smoke ratings that are low enough that they can be used safely beside highways. We found only one class of materials that did not meet these criteria: Polymer

Figure 6. Covered highway.

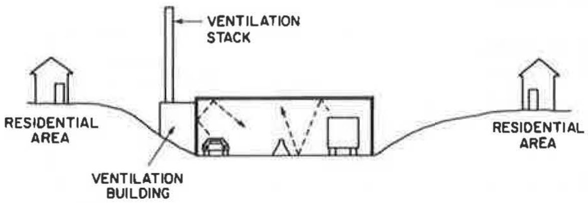


Figure 7. Earth berms as noise barriers.

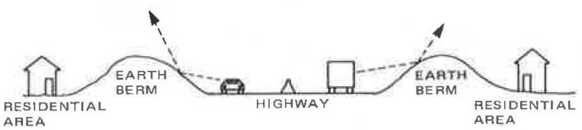
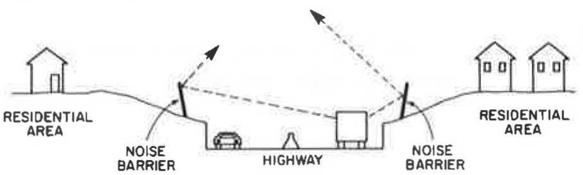


Figure 8. Sloped noise barriers.



foams produce cyanide or other highly toxic gases when burned and, although some foams are rated "self-extinguishing", they can continue to burn if fueled by other burning materials that might be present in an automotive fire. Most fabric materials, on the other hand, can be treated with flame retardants, if necessary, which would make their flame, fuel, and smoke ratings acceptable for placement near highways.

Specific Materials

Standard Effective Materials

Glass fiber, a standard material used by the construction industry, is one of the most useful and effective sound-absorbing materials for highway use. It is readily available, and its sound-absorbing properties have been extensively tested.

Several manufacturers have produced glass fiber in prepackaged assemblies for sound-absorbing panels or barriers. These integrated packages typically use two types of protective facings for the glass fiber: One is usually a perforated or expanded metal facing that protects the glass fiber from physical abuse, and the other uses a thin, waterproof plastic or mylar sheet that protects the fibers from moisture, dirt, air contaminants, and air sifting (fibers floating out into the air). Since these systems have high sound-absorption coefficients, they can be used effectively on highway noise barriers. Some of the systems have solid sheet-metal backs and so can be considered self-contained sound-absorbing barriers.

When a large system of sound-absorbing barriers is required, it may be prudent for the highway department or engineering firm to design its own sound-absorption treatment. One of the most efficient and cost-effective treatments is 5-cm (2-in) thick, low-density [approximately 24-kg/m^3 (1.5-lb/ft^3)] glass fiber batts mounted 10-20 cm (4-8 in) away from a hard, sound-reflecting barrier wall. Additional details are given elsewhere (4).

Thin Fabrics and Films

Laboratory tests have shown that some thin fabrics and films can be designed and fabricated to provide sufficient sound absorption for highway use. They must be mounted with an air space of 10-20 cm between their front face and any hard, sound-reflecting barrier wall.

Fiber density in fabrics and perforation density in films must be carefully controlled during production if the materials are to function properly. Fabrics or films specifically designed for outdoor absorptive treatments have not yet been manufactured because there has not been enough demand for them. In general, materials designed for other environments have been adapted to highway use. If the demand for sound-absorbing highway barriers increases, thin fabrics and films that maximize efficiency and minimize the quantity of material are likely to be produced.

Plantings

Dense evergreen trees, shrubs, vines, and grass are repeatedly considered as possible materials for noise abatement. They are often proposed both as sound barriers and as sound absorbers. In both cases, they exhibit such serious deficiencies that, apart from their use to meet other criteria for highway design (such as beautification and visual screening), they should not be considered to meet sound-attenuation criteria for highways.

Plants are simply unsuitable for use as sound-absorbing materials beside highways. To be effective, a plant's leaf structure would have to be similar in fineness and density to that of glass fiber. No plant with these characteristics has been identified.

ALTERNATIVES TO SOUND-ABSORBING MATERIALS

Sound-absorbing materials may be undesirable because of cost, maintenance requirements, or design constraints. There are a few alternatives to sound-absorbing materials that can be considered for particular situations.

Covered Highways

Excessive noise levels can be reduced dramatically by covering a highway (see Figure 6). However, other factors, such as cost and ventilation requirements, are usually primary considerations. A covered highway usually costs much more than even the most expensive noise-barrier design and, unless the tunnels are very short, they must be ventilated. Ventilation systems often require a high exhaust stack and additional structures to house the motors and fans. If they are not designed properly, ventilation systems can create their own noise problems.

Berms

Earth berms can be placed on both sides of a highway to act as noise barriers, as shown in Figure 7. Because of their shape, berms prevent sound from reflecting back and forth. They act effectively as single, independent barriers as long as no vertical walls are placed on top of them. However, berms have limited application as an alternative to absorptive barriers because their use requires a significant amount of right-of-way property. This alternative poses particularly difficult problems in urban areas, where space is limited.

Sloped Barriers

Figure 8 shows a configuration of sloped barriers that was recently tested in an acoustical scale-model study for the Harbor Tunnel Thruway in Baltimore (5-7). For this particular configuration—a depressed highway with residential areas on both sides—hard, reflective barriers sloping away from the highway at an angle of 10° from vertical were found to be as effective as an absorptive vertical two-barrier system.

Although very little information about the overall effectiveness of sloped barriers exists, sloped barriers should prove to be effective for configurations other than that of the Harbor Tunnel Thruway. Model studies will generally be required to determine optimal barrier locations and slopes, at least until enough data are collected to develop generalizations. For other configurations, sloped barriers may have to be higher than vertical absorptive barriers. Once the performance characteristics of sloped barriers are known, costs and installation limitations can be compared with those of absorptive two-barrier systems. Only then will the best applications for each approach be defined.

Sloped barriers, however, will not replace sound-absorbing materials in all applications. Where deep cuts require vertical walls or where space is limited, sound-absorption treatments will be the only effective means of eliminating the multiple reflections that degrade the performance of a two-barrier system.

REFERENCES

1. J. R. Shadley and D. R. Pejaver. A Study of Multiple Sound Reflections in Walled Highways and Tunnels. Bolt Beranek and Newman, Inc., Cambridge, MA, Draft Rept. 3202, Dec. 1975.
2. L. L. Beranek. Acoustics. McGraw-Hill, New York, 1954, pp. 300-301.
3. P. H. Parkin and H. R. Humphreys. Acoustics, Noise, and Buildings. Praeger, New York, 1958, pp. 309-313.
4. C. W. Menge and N. A. Powers. Sound-Absorbing Barriers: Materials and Applications. Proc., TRB Conference on Highway Traffic Noise Mitigation, Los Angeles, Dec. 1978; Federal Highway Administration, U.S. Department of Transportation, 1979, pp. 198-211.
5. C. W. Menge. Sloped Barriers for Highway Noise Control. Proc., Inter-Noise '78, San Francisco, 1978, pp. 509-512.
6. C. W. Menge. Noise Barrier Design Through Acoustical Scale Modeling, Harbor Tunnel Thruway, Baltimore, Maryland. Bolt Beranek and Newman, Inc., Cambridge, MA, Rept. 3496, Feb. 1977.
7. E. J. Miller, Jr. Case History: Noise Abatement Project, Harbor Tunnel Thruway, Highlandtown Area, Baltimore, Maryland. Proc., TRB Conference on Highway Traffic Noise Mitigation, Los Angeles, Dec. 1978; Federal Highway Administration, U.S. Department of Transportation, 1979, pp. 25-31.

Noise Barriers Adjacent to I-95 in Philadelphia

Harvey S. Knauer

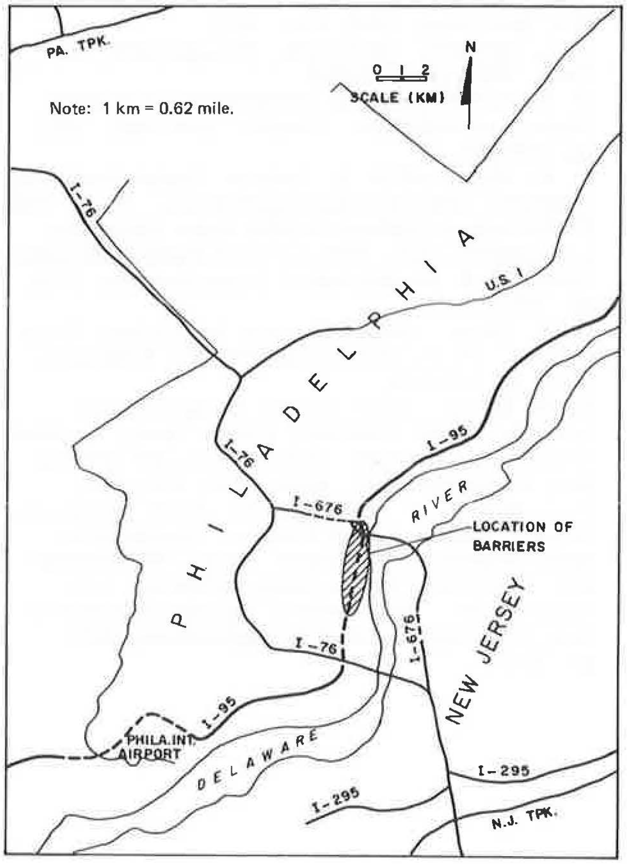
Pennsylvania's first major noise-barrier project, from inception to the later stages of construction, is described in detail. Construction of the barriers, which will total approximately 9300 m² (100 000 ft²), was mandated by the terms of a 1975 consent decree signed by the Pennsylvania Department of Transportation, the Federal Highway Administration, the city of Philadelphia, and a coalition of local community groups. Final barrier locations, types, and sizes were determined only after extensive community participation. In several instances, trade-offs were made between barrier height and the view of the historic Philadelphia waterfront. Barrier heights range from 2.4 to 8.2 m (8-27 ft). Cost varies from \$237 to \$912/m² (\$22-\$85/ft²). When the barriers are completed, noise attenuation at ground-level observation points is expected to range from 6 to 15 dB(A). The project's history, funding problems and implications, techniques of barrier analysis, implications of barrier design and community participation, barrier costs, and observation of the overall process are discussed.

In eastern Pennsylvania, the Delaware Expressway (I-95) extends in a north-south direction generally paralleling the Delaware River for approximately 80 km (50 miles). Except for a 6.4-km (4-mile) section in the vicinity of Philadelphia International Airport that has been delayed by environmental problems, all of the expressway is open to traffic. A 4.8-km (3-mile) section in Philadelphia's Center City was completed in the spring of 1979, but its opening to traffic was delayed until late August 1979 by conditions of a consent decree signed in December 1975.

The 1975 consent decree was an agreement between the Pennsylvania Department of Transportation (DOT), the Federal Highway Administration (FHWA), the city of Philadelphia, and an organization called the Neighborhood Preservation Coalition (NPC). The NPC is an organization of approximately 20 constituent community groups in the vicinity of I-95 in the city of Philadelphia. The consent decree required, among other things, that noise barriers be constructed, where feasible, before the Center City portion of I-95 became operational (see Figure 1). It also required that barrier designs be acceptable to the NPC.

Before the signing of the consent decree, the Pennsylvania DOT had performed noise-monitoring and preliminary noise-prediction analyses. Under the terms of the consent decree, the DOT was required to obtain the services of an independent noise consultant to verify the preliminary analyses and to determine recommendations regarding feasible types and loca-

Figure 1. Project location map.



tions of noise barriers. A consultant was retained and, after considerable delays, a final report was published in December 1977. The report verified previous analyses performed by the Pennsylvania DOT and recommended various noise-abatement treatments.

In a review of the report by the NPC and the DOT, the suggested solutions were found to be generally unacceptable. Many of the barriers suggested would have obstructed the adjacent communities' view of the Delaware River waterfront, and other recommendations—such as those involving building insulation and air conditioning—presented legal and long-term complications and were contrary to the terms of the consent decree.

After the rejection of the consultant's recommendations, the DOT and the NPC initiated a series of meetings with the intention of arriving at an acceptable solution that would provide the optimum in terms of both noise reduction and view. It was through approximately 30 such meetings, and 2 large, formal public meetings, that final noise-barrier location, size, and type were determined.

This paper reviews the processes of barrier design and community participation from the initiation of detailed community discussions through the later phases of barrier construction.

FUNDING PROBLEMS AND IMPLICATIONS

About a year after the signing of the 1975 consent decree, financial problems within the Pennsylvania DOT became critical. This led finally to the suspension of its Twelve-Year Capital Improvement Program in the fall of 1977 and a subsequent drastic reduction of personnel. The result was that the DOT had no funding to meet the obligations regarding noise barriers that were stipulated by the consent decree. It was not until June of 1978 that it appeared possible that some "outside" money could be obtained to match federal Interstate highway funds for barrier construction. In an unprecedented action, the Pennsylvania State Legislature, in October 1978, approved $250 000 in matching funds (transferred from revenue-sharing funding) for barrier construction. However, a requirement to award all noise-barrier contracts by June 30, 1979, was also stipulated.

TECHNIQUES OF BARRIER ANALYSIS

As mandated by the 1975 consent decree, FHWA design noise levels were the basis for the determination of acceptability. All noise receptors were classified as activity area B [70 dB(A) L_{10} exterior] and activity area E [55 dB(A) L_{10} interior], as defined by the Federal-Aid Highway Program Manual (1). Application of these design noise levels and the resultant trade-offs to provide acceptable views are discussed later.

The predicted noise levels used in the final barrier design process were generated by the FHWA Highway Traffic Noise Prediction Model (2). This model, which was described in draft form and was used with the concurrence of the FHWA division office in Harrisburg, Pennsylvania, was felt to be the most complete and acceptable technique for the project. Traffic data used in the prediction process were generated by the Delaware Valley Regional Planning Commission (DVRPC), the metropolitan planning organization for the Philadelphia metropolitan area.

The FHWA model generated exterior L_{10} noise levels for worst-case noise conditions. Exterior-interior noise-reduction values were calculated for typical buildings in the study area based on procedures outlined by Davy and Skale (3). These values, for both open and closed windows, were applied in the assessment of interior noise levels and their relationship to the 55-dB(A) L_{10} interior design noise level. Typical calculated interior noise-reduction values were 10 dB(A) (open window) and 27 dB(A) (closed window). It readily became apparent that no noise violations would be likely under closed-window conditions. Open-window conditions, however, became the most critical consideration for many receptors, particularly at upper-story levels.

BARRIER DESIGN AND COMMUNITY PARTICIPATION

Because of the critical time schedule imposed by the funding action of the legislature and the anticipated diverse desires and opinions of the various community groups adjacent to I-95, it was determined that the barriers in the Center City area would be best dealt with and constructed in four contract sections. These contract areas were finalized midway through the design process, when logical barrier-transition breaks became clear. The processes of barrier design and community participation are discussed below for each contract area.

Contract Area 1

The communities within contract area 1 (see Figure 2) consist mainly of three-story residential Philadelphia row houses that include some commercial activities in the form of ground-floor stores and restaurants. Some

Figure 2. Contract areas 1 and 2.

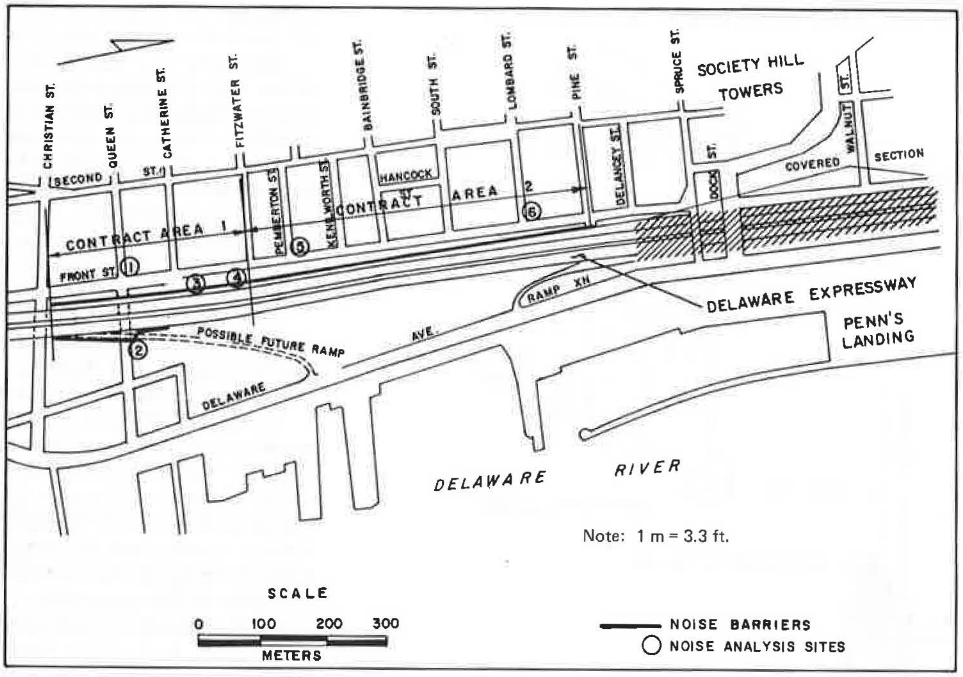


Figure 3. Post-and-panel noise barrier for contract area 1.

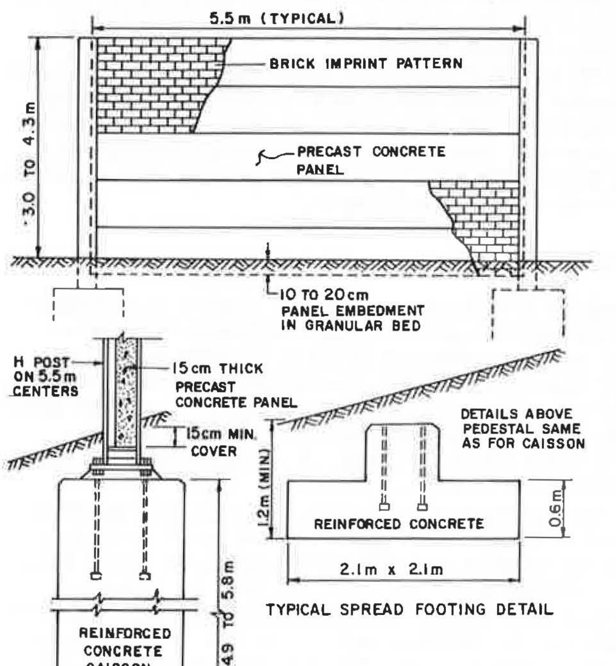


Figure 4. In-place post-and-panel noise barrier.

factories and warehouses previously existed on the land now occupied by I-95. In recent years, the area experienced extensive upgrading in which common row-houses were converted to middle- and upper-class townhouses. As a result of the construction of I-95 and the demolition of many multistory factories, the view of the redeveloped Philadelphia waterfront is now an attractive attribute of the area.

There are private residences in the area that are approximately 21-34 m (70-110 ft) from the nearest edge of the I-95 travel way. Without noise barriers, exterior L_{10} noise levels were predicted to range from 70 to 78 dB(A), and interior L_{10} open-window levels to range from 64 to 68 dB(A). In this area, I-95 makes the transition from an elevated roadway to an at-grade roadway (with respect to the adjacent residences). The roadway between Christian Street and Queen Street is on elevated fill, and the slopes are generally 2:1. I-95 crosses over Queen Street on structures and then descends toward the beginning of a cut section near Fitzwater Street.

Figure 2 shows the location of noise barriers and noise-analysis sites in this section. Except on the Queen Street structure, all barriers were constructed as precast concrete panels between steel posts (see Figures 3 and 4). The post foundations are embedded 4.9-5.8 m (16-19 ft) to withstand a 1.4-kPa (30-lbf/ft^2) horizontal force. The surfaces of the concrete panels that face the community are dyed brick red and imprinted with a brick pattern and have pointed joints in which a patented process developed by the Bomanite Corporation was used. This type of barrier was selected after extensive community participation, which included the review of many types of metal and masonry barrier materials (no communities in the area were interested in wood barriers). The brick pattern was felt to fit well with the brick buildings in the area. The post-and-panel system generally met the objective of the Pennsylvania DOT that certain barrier sections be salvageable in the event that their movement was re-

Figure 5. Steel noise barrier on structure for contract area 1.

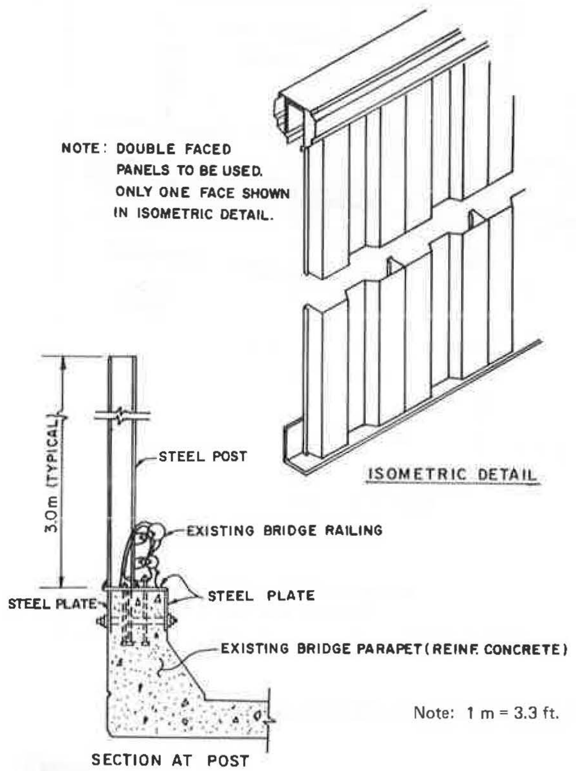


Table 1. Summary of data obtained at noise-analysis sites (L_{10} noise levels).

		Without Barriers		With Barrier	
Site*	First Floor Exterior Before Construction of I-97	First Floor Exterior	Third Floor Interior with Open Windows	First Floor Exterior	Third Floor Interior with Open Windows
1	68	71	65	62	57
2	68	70	64	62	56
3	61	78	68	68	67
4	61	78	68	71	68
5	69	74	64	67	61
6	71	72	66	64	60
7	75	71	66	Barrier not recommended	
8	71	75	68	Barrier not recommended	
9	71	74	65	60	55
10	NA	NC	58	NC	51
11	79	75	65	62	61
12	79	76	66	61	55
13	NA	74	64	63	58

Note: NA = monitored data not available; NC = value not calculated.
*For location of noise-analysis sites, see Figures 2 and 9; all sites are residences.

quired when possible future ramps were opened in the area.

The post-and-panel barriers vary in height from 3.0 to 4.3 m (10-14 ft) and are protected by steel guardrail. In steep-slope areas, the support posts are anchored to poured-concrete caissons (Figure 3). The caissons are 91 cm (36 in) in diameter. To facilitate drainage and prevent noise leakage and erosion at the base of the barrier, the bottom panels are embedded 10-20 cm (4-8 in) in a 30x60-cm (1x2-ft) stone backfill trench.

In flat-slope areas, the posts are anchored to spread footings (Figure 3). Panel embedment is similar to that for the caisson-supported design. In flat areas a drainage swale will be constructed between the barrier and the protective guardrail.

The individual panels are 15-cm (6-in) thick precast concrete. Panel lengths are generally 5.5 m (18 ft) and are in even foot-width dimensions. Panels are stepped, where required, in increments that enable coordination of the brick courses.

On the Queen Street structure, a tan-colored steel noise barrier was selected. After extensive consideration by adjacent property owners, a vertically corrugated design was selected (see Figure 5). The steel barrier, placed on top of the existing concrete parapet, is generally 3 m (10 ft) high. Metal support posts are welded to a steel seat plate that is secured to the existing concrete parapet by through bolting. Posts are generally 2.4 m (8 ft) on centers. Panels are secured to a framework attached to the posts.

All exposed steel panel surfaces are factory coated with a polyvinylfluoride film. The steel posts on the concrete panel barriers are painted with a tan-colored enamel paint that matches the color of the steel panels.

In the Fitzwater Street area, it was not feasible to construct a barrier of sufficient height to provide acceptable third-floor noise levels. However, a barrier approximately 4.3 m (14 ft) high was determined to be adequate to protect the first floor of adjacent residences. Such a barrier would partially obscure views of the waterfront from the second stories and was not acceptable to the community. After the department erected temporary test panel sections of varying heights at the site, a decision was made to construct barriers 3.0 m (10 ft) high in the Fitzwater Street area. It is predicted that this trade-off will cause first-floor exterior noise levels to exceed design noise levels by approximately 1-2 dB(A). Exterior design noise levels at all other locations are expected to be obtained by barrier implementation.

The barriers described above are predicted to reduce exterior L_{10} noise levels by 6-10 dB(A). Except in the Fitzwater Street area, where no third-floor attenuation is provided, reductions of 3-8 dB(A) are predicted for the third-story building interiors (see the data for noise-analysis sites 1-4 in Table 1).

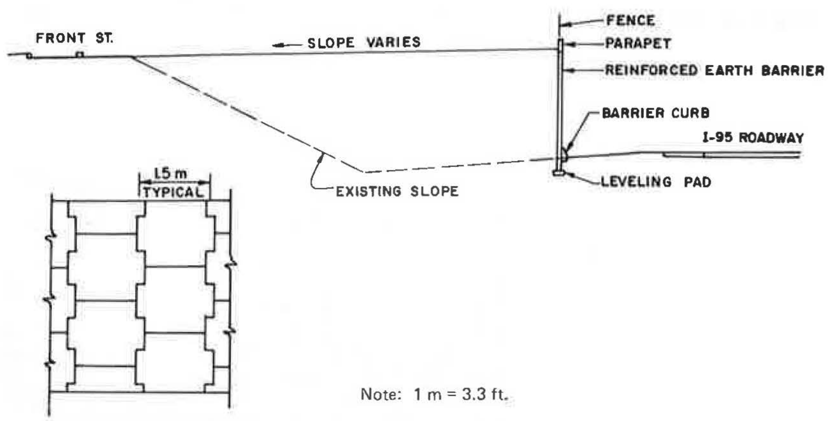
Contract Area 2

Contract area 2 communities are similar to communities in contract area 1. The residences adjacent to I-95 are approximately 36-55 m (120-180 ft) from the I-95 travel way and are elevated with respect to the highway. These residences are situated along the west side of Front Street and currently have a view over I-95 to the riverfront area. A cut slope descends from Front Street east to I-95.

Several alternative barrier locations were investigated in the earlier stages of the study. An effective barrier location would have been along the east side of Front Street at the top of the cut section. However, this location seriously obstructed the view of the riverfront and was determined to be unacceptable. Transparent barriers at this location were investigated but rejected mainly because of the fears of discoloration and maintenance considerations.

The idea of a barrier at or near the toe of the cut slope became exceedingly attractive to the community when it was determined that the area behind the barrier could be backfilled to Front Street levels and used for parking and open-space activities under a joint-use agreement between FHWA and the city of Philadelphia. A noise-barrier retaining wall was therefore designed for placement approximately 9.1 m (30 ft) from the I-95 travel way from Fitzwater Street to Pine Street (see Figure 6). The adjacent community was successful in obtaining approvals for the joint-use concept, and the city hired a consultant to prepare designs. Pennsylvania DOT engineers, in coordination with the joint-use consultant, determined acceptable top-of-barrier

Figure 6. Reinforced-earth noise barrier for contract area 2.



Note: 1 m = 3.3 ft.

Figure 7. Reinforced-earth wall under construction.

Figure 8. Joint-use area under construction behind reinforced-earth wall.

elevations that would be consistent with maintaining an acceptable view of the riverfront from Front Street.

The contract was let and awarded for the barrier wall and the joint-use project combined. The city matched FHWA funds for the joint-use items, which included sidewalks, parking areas, benches, lighting, drainage, and landscaping on top of the retained fill. The Pennsylvania DOT matched FHWA funds for the barrier wall, the retained fill, and associated drainage and utility-relocation items. The barrier contract was advertised with two alternative designs: a Reinforced Earth Company wall and an Atlantic Pipe Corporation "Doublewal" retaining wall. The contractor whose bid was accepted opted to use the Reinforced Earth Company wall.

The reinforced-earth wall is composed of a series of interlocking panels supported by metal straps that extend back from the wall into specially prepared backfill material. The friction between the straps and the backfill material is responsible for the stability of the wall. On top of the wall, a concrete parapet will be poured to a point 0.6 m (2 ft) above the backfill grade. A 1.5-m (5-ft) high decorative fence will be erected on top of the parapet. The barrier wall ranges from 2.4 to 8.2 m (8-27 ft) in height (from existing ground on the highway side of the wall to the top of the parapet) and extends for approximately 518 m (1700 ft). The barrier is protected at its highway face by a concrete Jersey barrier. Underdrains and inlets at the base of the wall are designed to provide surface and subsurface drainage. Figure 7 shows a section of the reinforced-earth wall nearing completion. Figure 8 shows a portion of the reclaimed area behind the wall that will be developed under the joint-use agreement.

Without the barrier in this area, exterior L_{10} first-floor noise levels at Front Street residences are predicted to range from 72 to 74 dB(A). The barrier is predicted to attenuate these levels by approximately 7 dB(A). Third-floor, interior, open-window L_{10} levels are predicted to be reduced by 3-6 dB(A) to levels of approximately 60 dB(A). The exceeding of the 55-dB(A) third-floor design noise level is attributable primarily to the trade-offs in barrier height required to retain a riverfront view (see the data for noise-analysis sites 5 and 6 in Table 1).

Contract Area 3

The area designated contract area 3 (see Figure 9) was originally designed to be from Chestnut Street to the Benjamin Franklin Bridge. The area adjacent to I-95 along Front Street is generally commercial from Chestnut Street to Arch Street. Some residences do exist in this area. Barrier designs were developed here because of predicted exterior L_{10} noise levels ranging from 71 to 75 dB(A). After a review by residents and businesses in this area, it was determined that no barriers were desirable. This decision was based mainly on the fact that a limited easterly view currently exists and a barrier would result in total elimination of that view. Also, the business community would lose its commercial "exposure" from vehicles traveling on I-95 if barriers were constructed.

The area between Arch Street and the Benjamin Franklin Bridge is occupied by a residential community centered around Elfreth's Alley, the oldest inhabited street in the United States. The closest traveled lane of I-95 is approximately 15.3 m (50 ft) from the end residence of Elfreth's Alley. The highway is constructed on retained fill with multilevel roadways. The retaining wall is faced with real brick (matching the color and type of the area's historic brick houses) and varies in height from 3.0 to 4.9 m (10-16 ft).

Noise levels without a noise barrier are predicted to be approximately 74 dB(A) at ground level in the Elfreth's Alley area. Third-floor levels of approximately 65 dB(A) are expected under open-window con-

Figure 9. Contract areas 3 and 4.

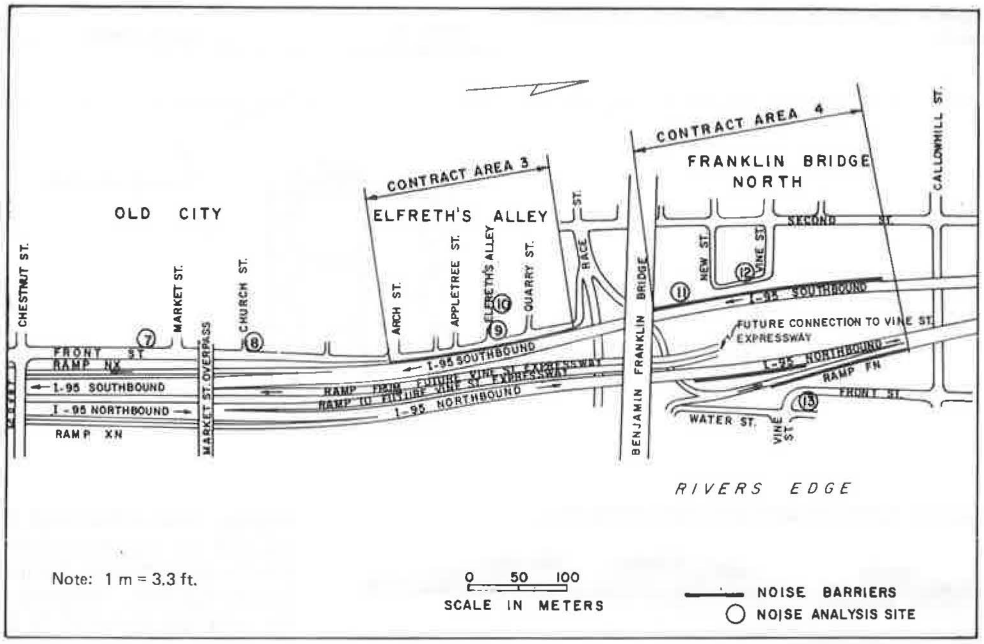


Figure 10. Reinforced concrete noise barrier and absorptive surface treatment for contract area 3.

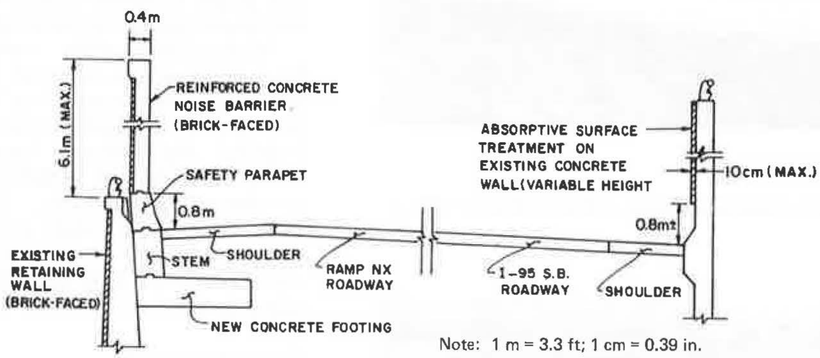
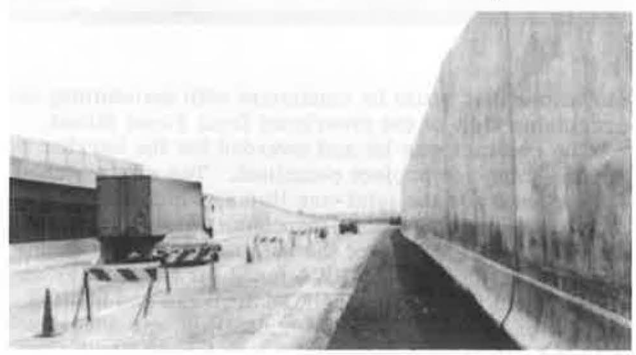


Figure 11. Brick-faced concrete barrier under construction at Elfreth's Alley.

Figure 12. Highway side of brick-faced concrete barrier.



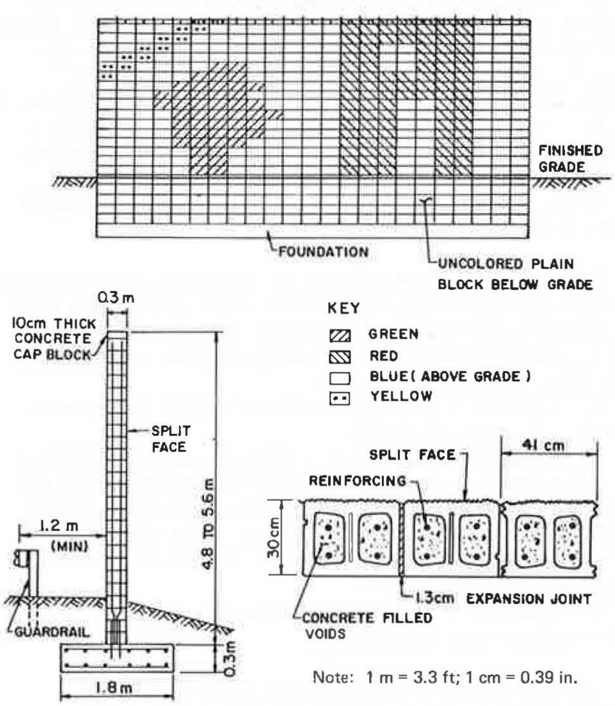
ditions. To reduce these levels to the design noise level, a barrier wall approximately 6.1 m (20 ft) high was determined to be required. In this area, view was not a factor and the community insisted on no compromise regarding noise abatement. Therefore, a wall of the required height was constructed (see Figure 10).

Many aesthetic treatments were discussed. The community finally insisted on a real-brick-faced wall between concrete columns, the color and texture of the brick matching that of the brick on the existing retaining wall. The wall was designed as a poured reinforced concrete wall with brick facing. Because of the height of the barrier, it could not be supported structurally on the existing retaining wall. Therefore, an independent footing on the highway side of and adjacent to the existing retaining wall was designed. This required reduction of the usable existing shoulder from 3.0 to

2.4 m (8-10 ft). The wall was formed in the shape of a Jersey barrier at the shoulder grade point. Figures 11 and 12 show the barrier adjacent to Elfreth's Alley nearing completion.

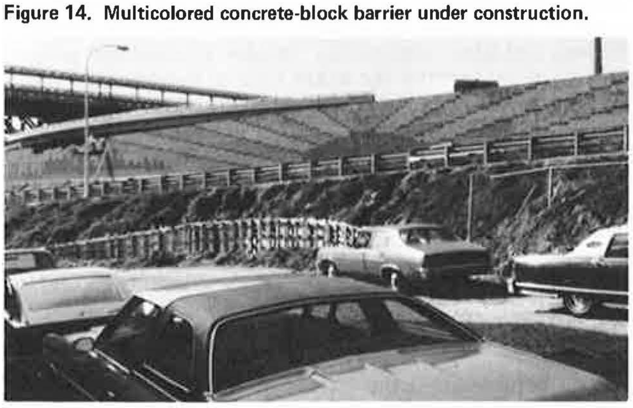
A reflection chamber was created between the new barrier and an existing retaining wall on the east side of the I-95 southbound lanes. It was determined that absorptive treatment of the existing east retaining wall was necessary if the new noise barrier were to produce the required noise attenuation. It was predicted, by means of techniques described in the FHWA Noise Barrier Design Handbook (4), that without such absorptive treatment the maximum effectiveness of the new noise barrier would be degraded by about 5-6 dB(A). The absorptive surface treatment was designed to be constructed of a perforated metal-face panel with the sound-absorbing filler material. A minimum sound-absorption coefficient of 0.90 for the 125- through 8000-Hz octave bands and a minimum noise-reduction coefficient (NRC) of 0.95 were required. The panels were required to have a factory-applied coating similar in type and color to the metal barrier walls in contract area 1 (see the data for noise-analysis sites 7-10 in Table 1).

Figure 13. Reinforced multicolored concrete-block barrier for contract area 4.



Note: 1 m = 3.3 ft; 1 cm = 0.39 in.

Figure 14. Multicolored concrete-block barrier under construction.



Contract Area 4

Contract area 4 is situated to the north of the Benjamin Franklin Bridge and contains residences on both sides of I-95. The community is currently undergoing change via the rehabilitation of older buildings to residential dwellings. Without any barriers, exterior L_{10} noise levels were predicted to range from 74 to 76 dB(A) at the first-floor levels. Interior L_{10} open-window levels of 64-66 dB(A) were predicted.

To provide abatement of noise levels at the third-floor level equal to the 55-dB(A) design noise level, it was determined that barriers as high as 6.1 m (20 ft) would be required. Such barriers would significantly affect the view, and so, with the approval of the community, heights were lowered to the 3.0- to 4.3-m (10- to 14-ft) range. This trade-off still permitted the exterior design noise levels at the first floor to be obtained [61- to 63-dB(A) levels with barriers] but resulted in third-floor, interior, open-window L_{10} levels that exceeded the 55-dB(A) design noise levels by 1-5 dB(A).

The community in contract area 4 included an active artistic element. This group was interested in having the barriers express architecturally the history of the area. After a review of many barrier-material options, they indicated their approval of a concrete block wall of varying colors. Their ideas materialized into barriers in which multicolored concrete blocks were used to form a mural design (see Figures 13 and 14). The actual designs were determined by the community and incorporated into the construction plans. The barriers are constructed of 20x40x30-cm (8x16x12-in) nominal precast concrete blocks, in red, blue, yellow, green, and white, laid in a specific pattern. The blocks are split faced on the community side. Plain uncolored blocks are used below grade. The wall is reinforced with concrete-filled voids and is on a continuous 0.3x1.8-m (1x6-ft) reinforced concrete footing. Some stepping of the wall was required for the barrier along ramp FN, and this was done in one-block increments.

Since the blocks are colored throughout, a mirror-design image appears on the highway side and is there-

Table 2. Summary of noise-barrier costs.

Contract Area	Total Contract Award Cost ($)	Barrier: Item	Barrier: Area (m^2)	In-Place Barrier Cost ($): Per Square Meter	In-Place Barrier Cost ($): Total
1	773 783	Steel	271	391	105 967
		Post and panel	1563	237	370 216
2	2 341 022		3533	364	1 287 381
3	1 305 363	Brick-faced concrete	1214	912	1 107 786
		Absorptive treatment	181	323	58 590
4	793 365		2590	241	623 828

Note: 1 m^2 = 10.76 ft^2.

fore visible to motorists. The Pennsylvania DOT had initially considered stuccoing the highway side because of concern about distraction to drivers. Some states, however, are using walls that have a design on the highway side. For this reason, it was decided to allow the design to remain visible on the highway side and to attempt a future evaluation of its effect on motorists.

Noise-analysis data for sites 11-13 are given in Table 1.

BARRIER COSTS

Table 2 summarizes noise-barrier costs by contract area. Costs for the total awarded contracts plus the prices for the barriers alone are indicated. In-place barrier costs include all items needed to construct the barriers (material, excavation, formwork replacement of disturbed areas, and any required structure modifications) but exclude such items as maintenance of traffic, mobilization, and guardrail. The prices reflect the influence of union labor and the Philadelphia labor market. The post-and-panel barriers (contract area 1) and the reinforced-concrete-block barriers (contract area 4) both cost approximately \$237/m^2 (\$22/ft^2), which indicates consistency of price for free-standing barriers. The price of \$363/m^2 (\$33.85/ft^2) for the reinforced-earth wall in contract area 2 included the cost of backfill material. The high price of \$912/m^2 (\$84.74/ft^2) for the reinforced concrete brick-faced barrier in contract area 3 is attributable to complicated excavation (which required sheeting), forming, shoulder removal and replacement, and brick-facing operations. The majority of the \$323/m^2 (\$30/ft^2) cost for the absorptive barrier in contract area 3 is attributable to the requirement of using steelworker and carpenter crews for erection. Structure modifications and limited quantities of material caused the costs for the steel barrier in contract area 1 to be higher than anticipated.

OBSERVATION OF DESIGN AND COMMUNITY-PARTICIPATION PROCESSES

As stated previously, the determination of the various barrier recommendations was the result of extensive community participation. The finalization of barrier locations, types, and sizes was considered a major accomplishment in itself in light of previous relations between the community and the state DOT. Agreements were reached in numerous meetings held in the area, usually in the homes of community leaders. Most of these meetings were held at night and were attended by two or three representatives of the Pennsylvania DOT and two or three community leaders. The early meetings involved informal discussions of noise models, noise theory, and noise effects. Alternative locations for noise barriers were discussed extensively, and major consideration was given to the issue of the view provided. In one area, temporary barriers were erected to aid the community in making its decisions about barrier height.

Many samples of barrier materials were shown to the community representatives prior to their selections. Barrier materials, locations, and heights agreed to by the community leaders and the department were presented as joint recommendations at two large public meetings. These meetings consisted of an initial 2-h informal display period in which individual questions were answered on a one-to-one basis. A short 30- to 45-min formal joint presentation by a representative of the Pennsylvania DOT and a community leader followed. Slides of various barrier types were included in this presentation. After a short recess, a general question-and-answer period was held, and this was followed by another one-on-one question-and-answer period. To aid in citizens' understanding of noise levels, an audiovisual tape of traffic on a local expressway was played back in the presence of a sound meter. The volume was adjusted to varying noise levels, depending on the level a particular individual was interested in hearing. The noise meter made it possible to approximate L_{10} noise levels. The video portion of the demonstration enabled participants to experience the noise fluctuations caused by approaching and diverging truck and automobile traffic.

Each participant in the meeting was asked to complete a questionnaire indicating his or her feelings about the barrier recommendations presented, barrier materials, associated improvements, and noise-view trade-offs. Results of the questionnaires were reviewed by the community leaders and Pennsylvania DOT personnel before formalization of the final barrier recommendations.

In the design and award process, the four contracts were let in the following ways:

1. Contract 1 was let as a performance specification. Heights and locations of barriers were given along with required transmission loss values [20 dB(A)], surface type, gloss requirements on metal barriers, wind load, and other design constraints.
2. Contract 2 allowed the use of either of two proprietary barrier designs.
3. Contract 3 was let as a cast-in-place reinforced concrete barrier designed by the Pennsylvania DOT but allowed the contractor to submit an alternative design that used reinforced concrete block. The absorptive surface treatment in this contract was let as a performance specification.
4. Contract 4 was let for a specific design, and no alternatives were allowed.

The performance specification process has the advantage of a slight saving in design time and theoretically increases competition. It places much more responsibility on the engineer during the review process and makes the writing of specifications more critical and time consuming. It also creates the possibility of not getting the exact type of method that the community and the state DOT desired. Usually, selection of a barrier was based on the community's review of the product of a specific barrier manufacturer. Because of the inability to specify a particular product, the DOT had no assurances that the low bid would contain the product that they had seen and on which their recommendations were based. Fortunately, this problem did not materialize in contract area 1, and both the steel and concrete barrier have been provided by the suppliers whose materials were selected in the review process.

It is believed that the letting of contract 2 with two alternative proprietary methods was an overall advantage in keeping the bid prices as reasonable as possible. On contracts 3 and 4, there were felt to be no acceptable alternative means of letting the contracts.

EVALUATION OF BARRIER EFFECTIVENESS

The Pennsylvania DOT intends to evaluate the effectiveness of the barriers after their completion. It was possible to monitor noise levels at several locations before barrier construction and after I-95 was opened to traffic. Noise monitoring at these locations was conducted simultaneously with traffic counting and speed monitoring, both of which were recorded by vehicle class and direction of flow. These speed and volume data were then input into the FHWA Highway Traffic Noise Prediction Model. The model predicted values 1-2 dB(A) higher than the actual monitored values. At site 9 (Figure 10), noise levels, traffic volumes, and traffic speeds were monitored simultaneously at ground level and upper stories with the barrier completed but without the absorptive surface treatment on the opposite wall. This monitoring was limited because of construction activity in the area. However, when the traffic volume and speed data were input into the FHWA model, the predicted noise levels generated were several decibels lower [3dB(A) at an elevation equivalent to top-of-barrier elevation and 5 dB(A) at ground-level-observer elevation] than the actual monitored noise levels, which indicates that reflection is likely to be a significant factor in this area. Because of the limited data, any conclusive determination of actual reflection must await further monitoring and analysis. Evaluation of the effectiveness of all of the noise barriers discussed here is expected to be completed in mid-1980.

SUMMARY

At this point, Pennsylvania's first major noise-barrier project can be termed successful. Through the late stages of construction, no major insoluble problems have emerged. Much experience has been gained in both the design and citizen-participation processes. To advance in 12 months from a stage at which there was no consensus among the many affected community groups to the construction stage was thought by many to be impossible, particularly in light of previous relations between the community and the Pennsylvania DOT. The experience gained in this process will be invaluable in future noise-barrier projects in Pennsylvania.

ACKNOWLEDGMENT

Completion of the noise-barrier project described in this paper was possible only through the dedicated efforts of the many Pennsylvania DOT and FHWA personnel involved. Special thanks go to Frank Sorrentino, Lin Chen, John Hanosek, and Carmine Fascina and to the members of the district contract management, plans, and construction units of the Pennsylvania DOT. The administrative and legal direction necessary for the completion of this project were provided by Robert Rowland, Philip Amos, and Robert Raymond.

REFERENCES

1. Federal-Aid Highway Program Manual. Federal Highway Administration, U.S. Department of Transportation, Vol. 7, Chapter 7, Section 3, May 1976.
2. FHWA Highway Traffic Noise Prediction Model. Federal Highway Administration, U.S. Department of Transportation, draft, Dec. 1977.
3. B. A. Davy and S. R. Skale. Insulation of Buildings Against Highway Noise. Federal Highway Administration, U.S. Department of Transportation, Rept. FHWA-TS-77-202, 1977.
4. M. A. Simpson. Noise Barrier Design Handbook. Federal Highway Administration, U.S. Department of Transportation, Rept. FHWA-RD-76-58, Feb. 1976.

Effectiveness of Noise Barriers Along the Capital Beltway (I-495) in Northern Virginia

Robert E. Armstrong

A recent Federal Highway Administration study of the effectiveness of three noise barriers along I-495 in northern Virginia is described. The study sites included (a) an earth berm, (b) a metal wall on an earth berm, and (c) a concrete wall on an earth berm. The study results, though limited in scope (no statistical analysis was performed), support conclusions reached in other studies that have attempted to validate the Federal Highway Administration's Highway Traffic Noise Prediction Model: The model provides an accurate estimate of (a) levels of unshielded traffic noise close to the roadway (7.5-15 m) and (b) levels of shielded traffic noise behind noise barriers. In addition, the results confirm that the noise barriers studied have reduced the level of traffic noise by at least 50 percent.

The use of noise barriers to reduce the impact of traffic noise on communities adjacent to highways has increased dramatically in recent years. Highway agencies across the nation are spending considerable time and money on planning, designing, and constructing these barriers on both new and existing highways. Experience has shown that noise reductions in excess of 10-15 dB are very difficult to achieve. Even after this range of reduction has been achieved by constructing a barrier, residents close to roadways are often exposed to noise levels that exceed 65 dB(A). It has been hypothesized that many people who complain of poor barrier performance are reacting to the fact that even a good barrier does not eliminate all traffic noise.

This report presents the results of a field study undertaken by the Federal Highway Administration (FHWA) to determine the effectiveness of different types of noise barriers found along the Capital Beltway (I-495) in northern Virginia. The study was conducted partly in response to citizen complaints that barriers along the beltway did not reduce highway traffic noise.

In the past several years, FHWA has developed methodologies to measure and predict levels of traffic noise and design noise-abatement measures. The most common method for assessing how well prediction methods accomplish their purpose is to compare predicted levels of traffic noise with levels measured in the field. The study reported in this paper involved the use of these methods.

The procedures used in the study are readily available to state highway agencies and interested individuals. The measurement procedures used are described in an FHWA interim report (1) (procedures presented in the interim report for measuring barrier insertion loss are being validated and were not used in this study, but procedures found in the report for taking sound-level measurements were used). The prediction procedures used are described in another FHWA report (2).

MEASUREMENT PROCEDURE

The effectiveness of a noise barrier is determined by measuring or calculating its insertion loss—that is, the noise reduction provided by a barrier at any given point. Numerically, this measurement is equal to the difference in sound levels at a given point with and without a barrier. The ideal would be to measure sound level before and after the construction of a barrier, under identical conditions. Unfortunately, this is often not possible, and so it becomes necessary to calculate the "before" sound level by using an analytical highway traffic noise prediction model. Since the noise barriers evaluated in this study were already in place, STAMINA, a computerized version of the FHWA Highway Traffic Noise Prediction Model, was used to calculate before sound levels.

Before using the FHWA model to make predictions and calculations, a user should evaluate how well the model simulates real-world conditions. Adjustments to the model may be necessary. To do this, the noise emission model and a combination of the emission model, the propagation model, and the barrier attenuation model can be checked simultaneously by comparing calculated sound-level values with measured values. If this comparison shows close agreement between the values, no adjustment to the model is necessary and the before sound level can be calculated.

In this study, measurements of existing sound levels were taken in front of, above, and behind the noise barriers. Two sets of measurements were taken at each study site. One microphone position varied between the two sets. At each microphone position, sound levels were recorded every 10 s by using type 1 sound-level meters; 100 samples were taken, and a 95 percent confidence level for the data was obtained.

During each set of measurements, vehicles traveling in each direction were counted and classified into categories of automobiles, medium trucks, and heavy trucks. In one location, traffic was recorded for only one direction because only one direction of the travel lanes was contributing to the noise being measured. Average speeds for automobiles and trucks were determined separately by using radar equipment.

STUDY SITES

In order to evaluate different types of barriers in the I-495 corridor, three sites were chosen for the study. Figure 1 shows the geographic location of the sites, which can be described as follows:

1. Site A—metal wall on earth berm, located 7.6 m above the roadway on Leesville Boulevard (see Figures 2 and 3);
2. Site B—earth berm alone, located 5.1 m above the roadway on Helena Drive (see Figures 2 and 4); and
3. Site C—concrete wall on earth berm, located 5.3 m above the roadway on Cabin John Road (see Figures 5 and 6).

Table 1 gives data on microphone positions and traffic volume and speed for each site.

DATA PROCESSING PROCEDURES

As previously stated, barrier effectiveness is determined by measuring insertion loss, which is numerically equal to the difference in sound levels at a given point

Figure 1. Location of I-495 study sites.

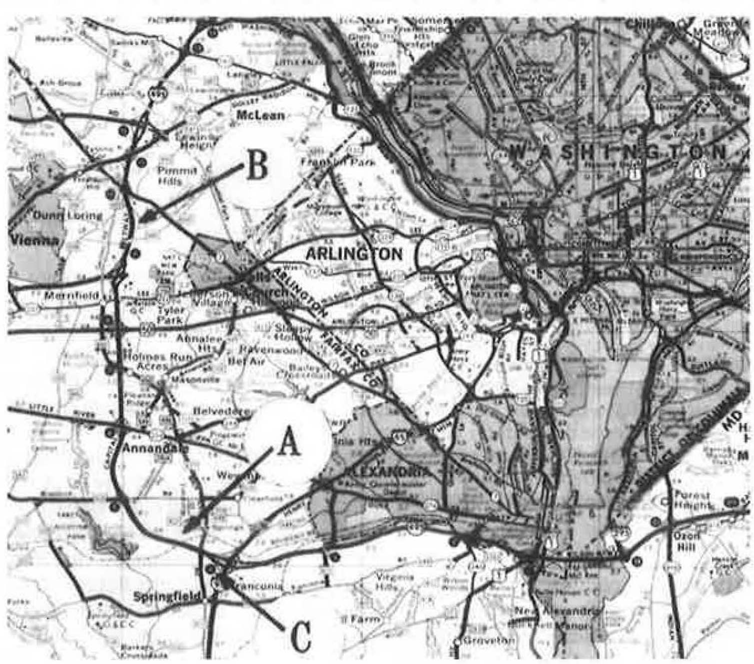


Figure 2. Cross sections and sound levels for sites A and B.

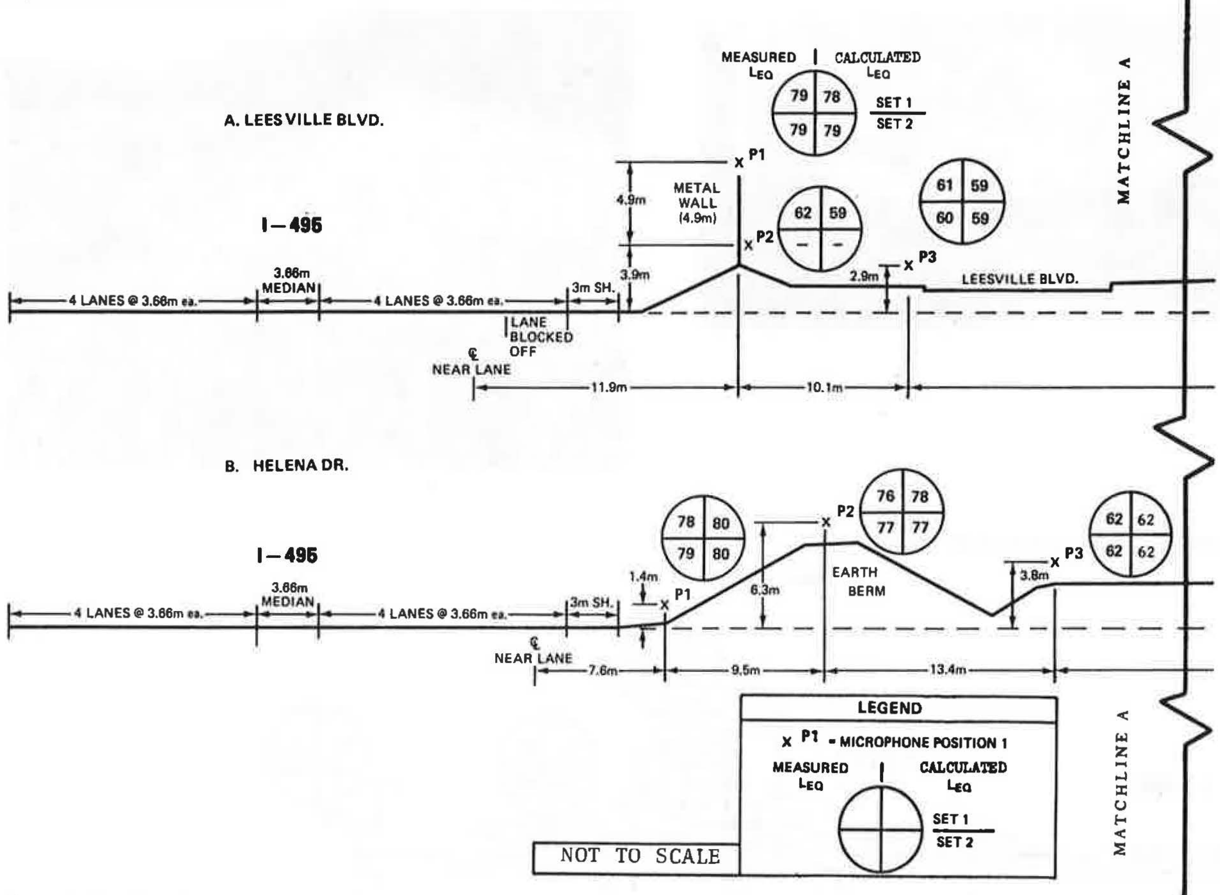


Figure 2. Continued.

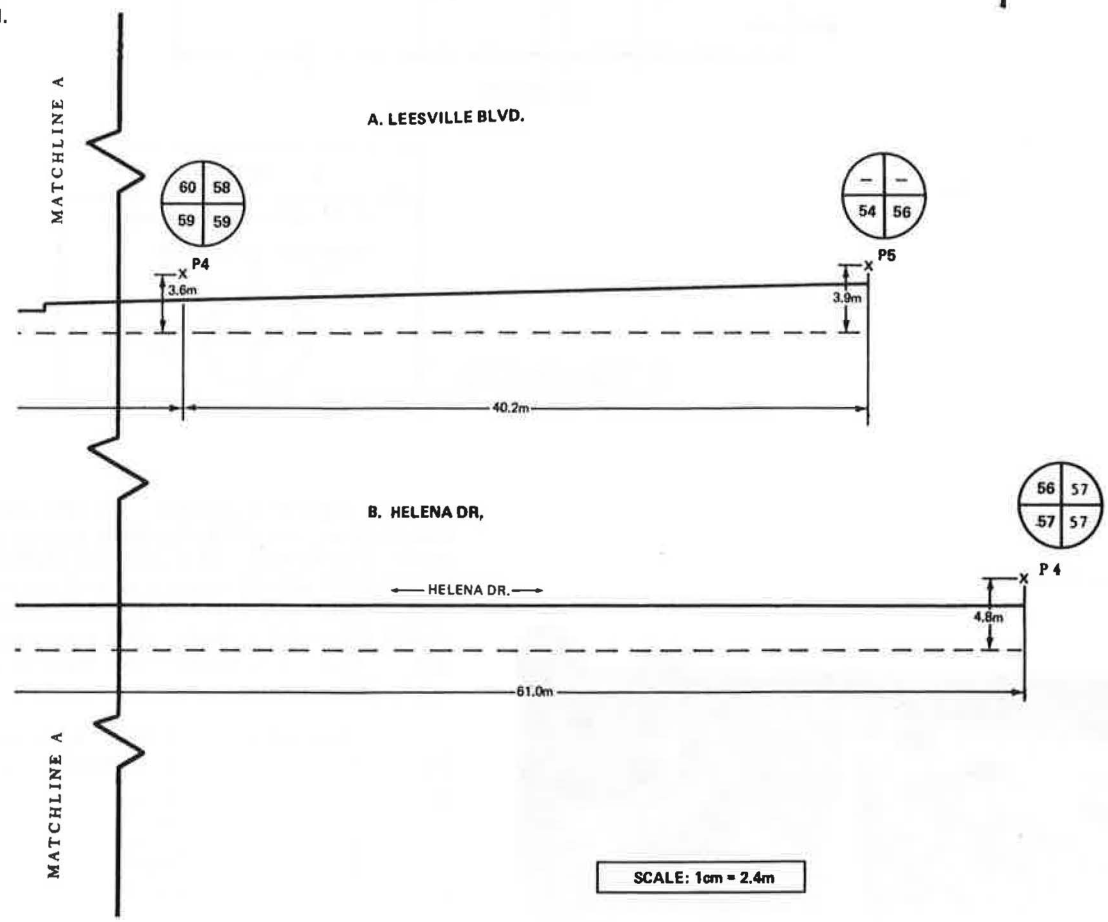


Figure 3. Site A.

Figure 4. Site B.

Figure 5. Cross section and sound levels for site C.

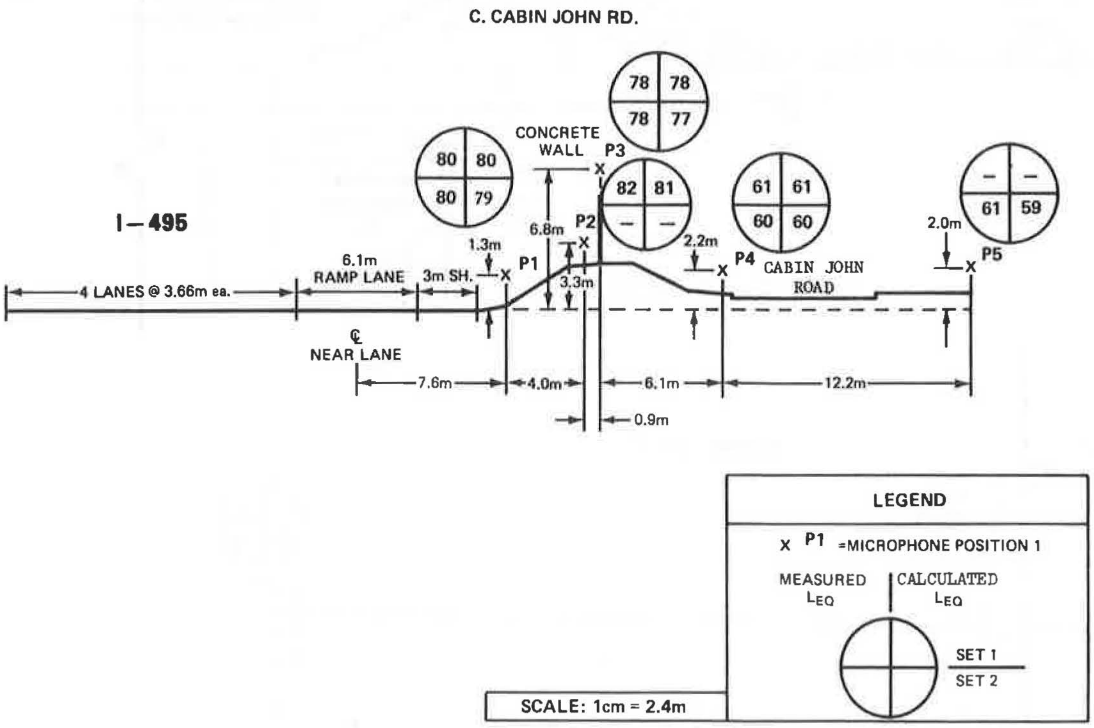


Figure 6. Site C.

with and without a barrier. By using the procedure outlined above, the FHWA highway traffic noise prediction model (STAMINA) was found to be sufficiently reliable to calculate before sound levels at the study sites. The values given in Table 2 support this finding, as do the values given in the table below (the amounts by which calculated L_{eq} values were less than or more than measured values):

Site	Measurement Set	Difference Between Calculated and Measured L_{eq} (dB)
A	1	-1 to -3
	2	-1 to +2
B	1	0 to +2
	2	0 to +1
C	1	0 to -1
	2	0 to -2

Table 1. Microphone positions and traffic characteristics for study sites.

Site	Measurement Set	Distance (m) from Centerline of Near Lane to: Barrier	Microphone Position: P1	P2	P3	P4	P5	Daily Traffic Volume[a]: Automobiles	Trucks: Medium	Trucks: Heavy	Average Speed (km/h): Automobiles	Trucks
A	1	11.9	11.9	12.2	22.0	42.1		4380	312	340	83.2	83.2
	2	11.9	11.9		22.0	42.1	82.3	4476	400	392	83.2	81.6
B	1	17.1	7.6	17.1	30.5	91.5		4528	288	340	84.8	78.4
	2	17.1	7.6	17.1	30.5	91.5		4184	268	364	83.2	75.2
C	1	12.5	7.6	11.6	12.5	18.6		3112	172	256	84.8	81.6
	2	12.5	7.6		12.5	18.6	30.8	2640	172	192	81.6	78.4

[a]During field measurements.

Table 2. Calculated and measured sound levels.

Site	Measurement Set	Sound Level by Microphone Position [dB(A)]: P1 Calculated	P1 Measured	P2 Calculated	P2 Measured	P3 Calculated	P3 Measured	P4 Calculated	P4 Measured	P5 Calculated	P5 Measured
A	1	78	79	59	62	59	61	58	60		
	2	79	79			59	60	59	59	56	54
B	1	80	78	78	76	62[a]	62	57[a]	56		
	2	80	79	77	77	62[a]	62	57[a]	57		
C	1	80	80	81[b]	82	78	78	61	61		
	2	79	80			77	78	60	60	59	61

[a]Calculated sound levels reduced by 3 dB(A) because of added attenuation caused by earth berm.
[b]Calculated sound level includes reflections from wall.

Table 3. Before (calculated) and after sound levels.

Site	Measurement Set	Sound Level by Microphone Position [dB(A)]: P1 Calculated	P1 Measured	P2 Calculated	P2 Measured	P3 Before	P3 After Calculated	P3 After Measured	P4 Before	P4 After Calculated	P4 After Measured	P5 Before	P5 After Calculated	P5 After Measured
A	1	78	79	59	62	74	59	61	71	58	60			
	2	79	79			75	59	60	72	59	59	68	56	54
B	1	80	78	78	76	73	62[a]	62	67	57[a]	56			
	2	80	79	77	77	73	62[a]	62	66	57[a]	57			
C	1	80	80	81	82		78	78	75	61	61			
	2	79	80				77	78	74	60	60	71	59	61

[a]Calculated sound levels reduced by 3 dB(A) because of added attenuation caused by earth berm.

Table 4. Insertion loss.

Site	Measurement Set	Insertion Loss by Microphone Position [dB(A)]: P3 Calculated	P3 Measured	P4 Calculated	P4 Measured	P5 Calculated	P5 Measured
A	1	15	13	13	11		
	2	16	15	13	13	12	14
B	1	11	11	10	11		
	2	11	11	9	9		
C	1			14	14		
	2			14	14	12	10

The STAMINA model is based on a reference energy mean emission level, to which adjustments are made to account for traffic flows, varying distances from the roadway, finite-length roadways, and shielding.

Since the installation of a noise barrier at a site negates any attenuation attributable to such factors as grass or shrubs, a propagation loss factor of 3.0 dB/doubling of distance was used in all calculations involving barriers. A manual reduction of 3 dB(A) was made for the sound levels calculated behind the earth berm at site B because past studies have indicated that earth berms provide approximately 3 dB(A) more noise attenuation than do barrier walls. Since all the sites were covered with grass and small shrubs, a propagation loss factor of 4.5 dB/doubling of distance was used to calculate the before sound levels. This results in a more conservative barrier insertion loss than would assumption of a 3.0-dB factor, since the calculated before sound levels are lower. Table 3 gives values for the calculated (before) and measured sound levels at the study sites.

ANALYSIS OF RESULTS

Table 4 gives the insertion losses determined for each study site. An insertion loss of 10 dB(A) is usually achievable with barriers of reasonable height and length; a 15-dB(A) insertion loss is much more difficult to obtain. A review of the values in Table 4 shows that insertion losses at the I-495 study sites range from 9-15 dB(A). It can be seen that the barriers at the study sites are producing acceptable insertion losses, reducing loudness at the sites by at least a half [10 dB(A)].

All three types of barriers appear to be performing well. Because of differences in site geometry, barrier design, and traffic conditions, it is not possible to say that one barrier type is performing better than another. However, the study data do support the position that earth berms provide approximately 3 dB(A) more attenuation than barrier walls.

CONCLUSIONS

Although this study was limited in scope (no statistical analysis was performed), the results support two conclusions that have been reached in other studies that have attempted to validate the FHWA Highway Traffic Noise Prediction Model:

1. The FHWA model provides an accurate estimate of the unshielded traffic noise levels close to the roadway (7.5-15 m). This is essentially a test of the vehicle emission data used in the model.

2. The FHWA model provides an accurate estimate of the shielded noise levels behind noise barriers. This is a test that involves the emission model, the attenuation rate with distance propagation loss, and the barrier attenuation model.

In addition, the results confirm that the noise barriers studied are effective in reducing levels of traffic noise.

REFERENCES

1. Sound Procedures for Measuring Highway Noise. Federal Highway Administration, U.S. Department of Transportation, Interim Rept. FHWA-DP-45-1, May 1978.
2. FHWA Highway Traffic Noise Prediction Model. Federal Highway Administration, U.S. Department of Transportation, Rept. FHWA-RD-77-108, Dec. 1978.

Systematic Method for Prioritizing Barrier Retrofit Projects for Highways

Louis F. Cohn

Because there is no standardized method for prioritizing highway noise-barrier retrofit projects, states that have such programs have had to develop their own. The methods of four states that have established ongoing noise-barrier retrofit programs—Minnesota, Maryland, Connecticut, and California—are examined. A comprehensive method developed by the New York State Department of Transportation (NYSDOT) is analyzed in detail. The seven-phase New York procedure relies heavily on field reconnaissance. A preliminary listing of potential projects is developed by computer analysis early in the process, and this listing is then refined several times as new information is gathered. The final outcome of the method is a list by NYSDOT region that shows potential projects by L_{10} "zone" [zone 1 for L_{10} values greater than 80 dB(A), zone 2 for values of 75-80 dB(A), and zone 3 for values of 70-75 dB(A)] and indicates a cost/benefit surrogate per project site. The cost/benefit surrogate selected is square meters of barrier required versus number of receptor units protected.

In 1967, New York became the first state to consolidate its highway, rail, aviation, and waterway responsibilities into one agency, the New York State Department of Transportation (NYSDOT). Since that time, NYSDOT has been a leader in developing many of the analytical tools now in use in the transportation profession, in areas as diverse as traffic safety research and transportation planning techniques.

One area in which NYSDOT has chosen not to be in the forefront, however, is the construction of noise-barrier systems on existing highways (retrofit). There are several reasons for this decision. First and most important, as the federal retrofit program was maturing into full implementation, the state of New York was entering an extended period of fiscal restraint. During the years 1975 and 1976, the state governmental structure was close to economic chaos as a result of the imminent default of New York City. Default was averted, but the whole experience created cutbacks and delays in many state programs. Once economic recovery was under way, NYSDOT became committed to a new program of high-yield capital construction that could be used to stimulate the state economy. In FY 1977/78, NYSDOT's highway construction budget exceeded $700 million, nearly double previous levels (1). This type of emphasis was not conducive to the implementation of noise-barrier retrofit projects, which require considerable planning but add little to the capital program.

A second major reason for the conservative efforts of NYSDOT in this area is that the potential for overcommitment is so great. New York State, with its population of nearly 20 million, has more than 2260 km (1400 miles) of highways designated as Interstates. Preliminary field studies have indicated that there are hundreds of potential sites for noise barriers in the state and that the associated cost is in the scores of millions. As a result, NYSDOT administrators have required an assessment of the magnitude of retrofit cost before approving a major program.

Last, in New York only a minimal number of complaints about excessive highway noise levels have been received from residents adjacent to highways. The two exceptions to this are in Westchester and Duchess Counties in the vicinity of I-684 and I-84 and in the Buffalo area along I-290 (the Youngmann Expressway). In the Westchester County situation, the residential properties are typically so large and population densities so low that using barriers to reduce noise is generally not cost-effective.

The Youngmann Expressway in Buffalo, on the other hand, does present an excellent opportunity for noise reduction. The area adjacent to the highway has generated many complaints, and the NYSDOT regional office in Buffalo has responded with a comprehensive recommendation for noise abatement. The project has progressed through the design phase and is ready for letting. The NYSDOT main office in Albany, however, has decided to hold the project until the potential long-term implication of barrier retrofit on the NYSDOT program can be assessed. The main office's Environmental Analysis Bureau (EAB) has been given the responsibility for making this statewide assessment and to do it in such a way as to minimize further delay to the Youngmann Expressway project.

This paper documents the method adopted by EAB to evaluate the 2260 km of Interstate highways in New York for noise-barrier retrofit.

FEDERAL NOISE REGULATION

The federal regulation dealing with highway noise is found in the Federal-Aid Highway Program Manual (2). Section 3y of the regulation defines a type 2 project as "a proposed Federal or Federal-aid highway project for noise abatement on an existing highway (located on a Federal-aid system) which does not include construction or reconstruction of a highway section (or portion thereof)". Initiation of such projects is a strictly voluntary undertaking by the state highway agencies. Section 12 indicates that federal participation with respect to funding is to be the same as that for the federal-aid system on which the project is located; for projects on the Interstate highway system, this means that the federal share is 90 percent and the state share is 10 percent. Because the Interstate system has the highest ratio of federal funding, it contains nearly all of the retrofit projects initiated by the states.

ALTERNATIVE METHODS OF PRIORITIZING RETROFIT PROJECTS

Before analyzing the NYSDOT approach, it would be helpful to discuss the prioritizing methods now in use in other state highway agencies that are active in barrier retrofitting. Four states have been selected on the basis of diversity in technique: Maryland, Minnesota, Connecticut, and California. Each uses mathematical formulas that produce numerical ratings for potential noise-barrier sites, but the amount and type of input parameters vary widely.

The Maryland method involves the tabulation of "points" per site based on several factors. According to information provided by the Environmental Section of the Maryland State Highway Administration, five points are awarded for each year of development since the highway was opened and, for structures such as residences, schools, and churches, points are awarded as follows:

Type of Facility	L_{10} Noise Level [dB(A)]	Points Awarded per Facility
Residence	71-75	1
	76-80	3
	>80	9
School	71-75	10
	76-80	30
	>80	90
Church	71-75	3
	76-80	9
	>80	27

In Minnesota, the formula is somewhat more complex:

$$NER = (HE/RL) \times RAR \quad (1)$$

where

NER = noise exposure rating,
HE = number of first-row homes exposed,
RL = residential length (km), and
RAR = relative annoyance rating.

RAR is determined by first calculating L_{10} values from the highway and then using the axiom that a 10-dB(A) increase results in a doubling of loudness. For an L_{10} of 60 dB(A), RAR = 1.0; for an L_{10} of 70 dB(A), RAR = 2.0; and for an L_{10} of 80 dB(A), RAR = 4.0. The Minnesota DOT has determined NER values for 167 sites in the Minneapolis-St. Paul metropolitan area (3).

The Connecticut DOT has a prioritizing method that is more complex than either the Maryland or Minnesota methods. In Connecticut, each potential project is assigned a project priority rating number (PPRN), which is the ratio of a benefits factor (BF) and the total project cost times 1000. The value for BF is determined by

$$BF = (PI \times N_b \times SF) + 1/3\,(PI \times N_a \times SF) \quad (2)$$

where PI is the project effectiveness index, a surrogate for L_{10}, and SF is a sensitivity factor. An L_{10} value of 60 dB(A) has a PI of 3.33 and, for each 10-dB(A) increase in L_{10}, PI increases by a factor of 3. The parameters N_b and N_a are the number of receptor units expected to receive benefit. The subscripts denote whether the receptors were constructed before or after the highway. N is determined by multiplying four factors: number of families per facility, number of days of use per week, number of hours of use per day, and number of months of use per year. Based on the land use categories used in the Federal-Aid Highway Program Manual (2), SF is 1.5 for category A receptors (where serenity and quiet are of extraordinary significance) and 1.0 for category B receptors (residences, schools, churches, hospitals, and the like) (4).

As part of the formal prioritizing process, each of these state highway agencies completes a more thorough analysis of abatement potential for projects that receive the highest ratings. Included in these analyses are extensive measurement programs, citizen participation, and material selection.

The approach of the state of California to retrofit prioritizing differs from the other methods discussed in that it simply relates abatement costs, abatement potential, and number of dwelling units linearly (5). Cases in which the receptors were constructed before freeway route adoption receive the highest priority. The California method relies heavily on visual inspection and existing noise measurements. A unique feature of this method is that it is fully implemented in a decentralized format by district personnel (6).

The concept of using formulas to arrive at numerical ratings for potential noise-barrier projects has the advantage of depoliticizing the selection process. This may or may not be an important consideration, depending on the circumstances. The disadvantages of such a system include the amount of time and effort required to develop the necessary data base, the potential error in numerical assignment and L_{10} determination, and the obviously diverse assumptions that can be made about annoyance. It is likely, for example, that the priority lists of the four states mentioned here would be quite different if they were recompiled by using one another's formulas. In addition, numerical ratings make it difficult to be re-

Table 1. NYSDOT method for prioritizing barrier retrofit projects.

Phase	Process	Output
1	Analysis of all eligible roadway sections	Statewide Interstate system in segments
2	Computer analysis of Interstate segments by using conservative assumptions	Preliminary L_{10} values for each segment and elimination of segments where 70 dB(A) L_{10} is not exceeded
3	Initial field reconnaissance of still eligible sites	Elimination of sites where topography and/or receptor density is not conducive to retrofit
4	Final field reconnaissance and gathering of site-specific data on topography and receptor density	Data necessary to refine computer analysis of predictions and determine cost/benefit surrogate
5	Noise-level measurement survey	Validation of refined predictions and further modification of list
6	Preparation of final listing	List of potential projects for each NYSDOT region by L_{10} zones [sound-level categories ranging from 70 to 85 dB(A)], indicating cost/benefit surrogate per project site
7	Summation of statewide lists	Total potential costs for retrofitting all feasible projects in state

sponsive when necessary to the often legitimate political considerations that arise.

NYSDOT SYSTEMATIC METHOD

As implied earlier, the NYSDOT method of prioritizing noise-barrier retrofit projects was developed under a different set of circumstances than those that prevailed in Maryland, Minnesota, Connecticut, and California. Whereas those states evolved statewide retrofit programs, the New York EAB was given a mandate to produce its program in a very short period of time so as not to further delay the Youngmann Expressway project. In addition, the EAB staff was required to operate with personnel shortages left over from the days of fiscal crisis. Under these constraints, it would not have been feasible to produce the amount of input data needed for an elaborate formula method. Fortunately, the method developed by NYSDOT does not require such data because it relies heavily on field reconnaissance activities.

The NYSDOT method (see Table 1) consists of seven phases that are designed to continuously eliminate projects from the initial listing of all segments on the Interstate system. The initial list, produced in phase 1, was determined by analysis of the 1979 estimate for completing the Interstate system in New York State (7). This document presents a segment-by-segment data bank for each Interstate route. Among other things, this data bank shows milepost numbers, number of lanes, right-of-way width, and traffic projections. The output from phase 1 was a listing of 601 Interstate highway segments, each of which was a potential retrofit project. These 601 segments represented the entire 2260 km (1400 miles) of Interstate highways in New York State.

Threshold values for volumes of traffic that would generate 70 dB(A) L_{10} or more at typical right-of-way widths were determined by using a noise-level-prediction program (8), and in phase 2 the list was pared down to 219 segments. Since all topography was assumed to be level and each segment was assumed to be infinitely long, these predictions were quite conservative in nature. The output for this phase attached a predicted L_{10} value to each segment, and for the first time the list exhibited a priority structure. The total investment in effort to this point in the study was four person days plus keypunching.

The two-man EAB staff then began a field reconnaissance of all the areas in order to eliminate those segments that were obviously unsuitable for retrofit because of topographical problems or lack of receptor density. The output of this phase (phase 3) was a different type of list. No longer working with segments whose average length was greater than 3.2 km (2 miles), the field reconniassance produced a list for each of the 10 regions of NYSDOT that showed individual potential projects. For example, the Albany region had 10 specific project possibilities, and the Syracuse region had 9. Statewide, 93 sites were identified, including 32 in the New York City metropolitan area. In addition to the Interstate system, the Long Island Expressway was field reconnoitered during this phase, and many kilometers of good sites were cataloged. However, because the expressway is on the primary urban system and not the Interstate, the state funding share would be too large in relation to that for the other projects. The Long Island Expressway sites will therefore receive a lower priority unless special legislation is enacted that places the expressway on the Interstate system or the 90 percent federal funding is otherwise provided for. The total staff commitment to phase 3 was approximately five person weeks.

Phase 4 involved a revisit to each of the rest of the sites on the list for the purpose of gathering first hand the topographical data necessary to determine barrier height and refine the computer predictions. In addition, land use and receptor data were obtained visually. The output from this phase included a projected barrier height needed for line-of-sight breakage [3, 4.5, or 6 m (10, 15, or 20 ft)], precise barrier termini, and number of receptor units to be protected. This information makes it possible to develop a cost versus benefit surrogate. Square meters of barrier required versus receptor units protected was chosen. It should be noted that, although no specific target insertion loss was selected, the NYSDOT policy is to always achieve complete line-of-sight breakage with a 3.6-m (12-ft) truck stack. In most cases this supplies adequate insertion loss. The manpower investment for phase 4 was 10 days for the upstate sites; phase 4 activities for the New York City area sites will not be completed until early 1980.

The only portion of the study to be delegated to regional personnel was the gathering of noise measurements and truck counts at each potential site (phase 5). These data were compared with the predicted values from earlier phases, and modifications to the L_{10} values were made where necessary.

By using the data obtained in phases 1-5, a list is developed for each NYSDOT region that shows each site with its associated L_{10} zone and cost/benefit surrogate (square meters of required barrier versus benefited receptor units). Rather than placing too much emphasis on the actual L_{10} value determined, more flexibility is allowed by indexing the site to an L_{10} zone. Zone 1 sites have L_{10} values greater than 80 dB(A), zone 2 sites values of 75-80 dB(A), and zone 3 sites values of 70-75 dB(A). By using these lists, the regional offices of NYSDOT can design their own retrofit strategies based on available funds, complaints received, and other considerations. Once the region decides to initiate a particular project, it will of course perform extensive and detailed measurement and prediction analyses. When the downstate field reconnaissance is completed in early 1980, it will be possible to determine total square meters of barrier required for all potential projects statewide. It will then be a relatively easy matter to estimate total costs for the entire program.

CONCLUSIONS

There are obviously several approaches a state highway agency could take in developing a statewide program for noise-barrier retrofit. The systematic method developed by NYSDOT is one that is designed for the needs of that particular agency. Because NYSDOT is highly decentralized with strong regional offices, it was felt that some main office control was required. This control was provided for by using the main office's Environmental Analysis Bureau to develop priority lists for the regions. However, the lists are compiled in such a format (L_{10} zones) that NYSDOT regions are still provided adequate flexibility.

REFERENCES

1. News Release. New York State Department of Transportation, Albany, No. 77-234, May 20, 1977.
2. Federal-Aid Highway Program Manual. Federal Highway Administration, U.S. Department of Transportation, Vol. 7, Chapter 7, Section 3, May 14, 1976.
3. Noise Exposure Study. Minnesota Department of Transportation, St. Paul, Rept. MNHWS-180-73-3, April 1973.
4. J. B. Pulaski. Connecticut's Highway Noise Abatement Program. Proc., TRB Conference on Highway Traffic Noise Mitigation, Los Angeles, Dec. 1978; Federal Highway Administration, U.S. Department of Transportation, 1979.
5. F. J. Weidler. Caltrans Freeway Traffic Noise Abatement Program in the Los Angeles Area. Proc., TRB Conference on Highway Traffic Noise Mitigation, Los Angeles, Dec. 1978; Federal Highway Administration, U.S. Department of Transportation, 1979.
6. R. Olson and others. Noise Barrier Selection on State Highways in the San Francisco Bay Area. Proc., TRB Conference on Highway Traffic Noise Mitigation, Los Angeles, Dec. 1978; Federal Highway Administration, U.S. Department of Transportation, 1979.
7. 1979 Estimate of the Cost of Completing the National System of Interstate and Defense Highways in the State of New York. New York State Department of Transportation, Albany, Aug. 1978.
8. HUSH003: A Computer Program for Predicting Highway Traffic Noise Levels. New York State Department of Transportation, Albany, Jan. 1979.