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

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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.

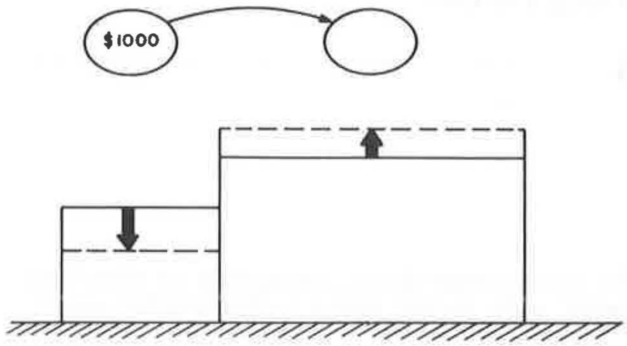
Figure 1 shows the balancing process. Shown are two barrier elements that are part of a more complex barrier system. The first estimates of barrier heights appear as solid horizontal lines in the figure.

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.

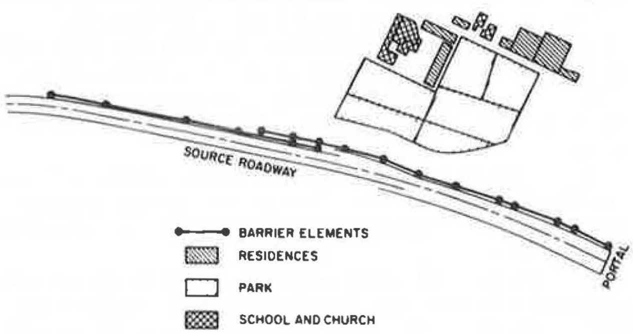
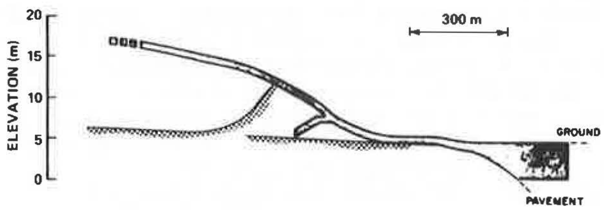
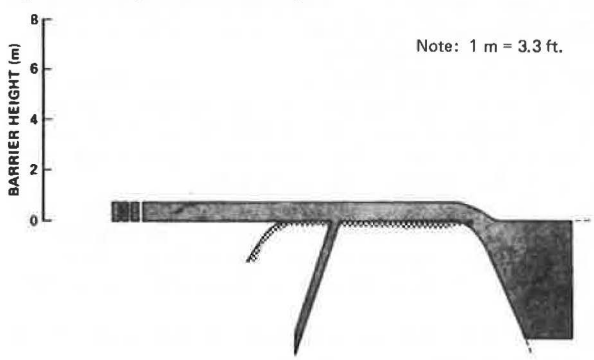


Figure 4. Vertical alignment.



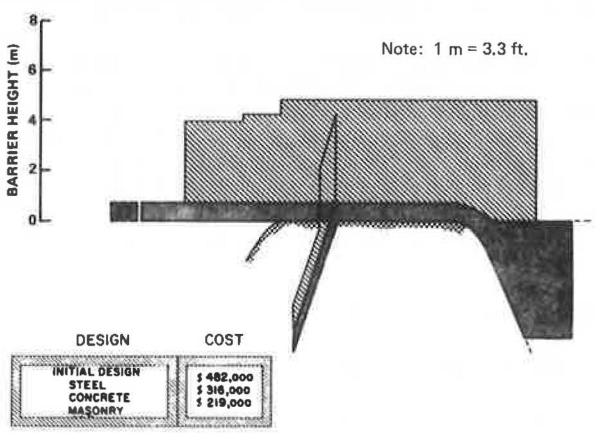
Note: 1 m = 3.3 ft.

Figure 5. Compressed vertical alignment.



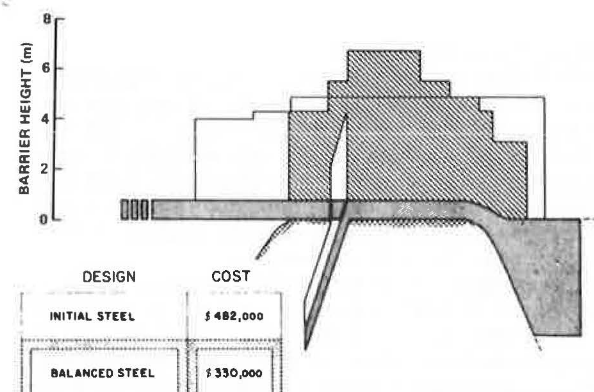
Note: 1 m = 3.3 ft.

Figure 6. Initial barrier design and costs.



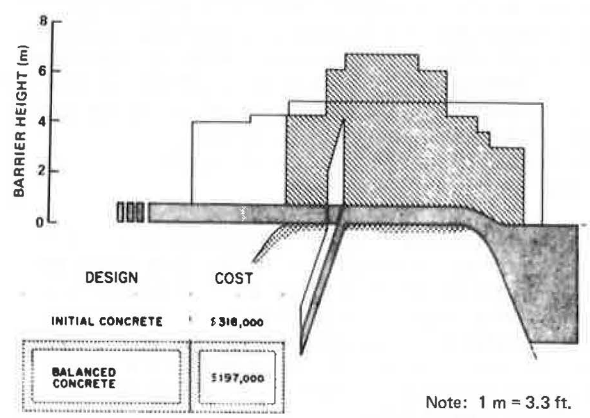
Note: 1 m = 3.3 ft.

Figure 7. Balanced steel barrier design.



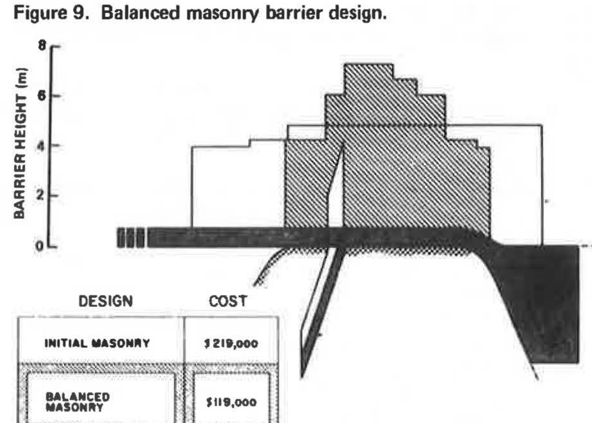
Note: 1 m = 3.3 ft.

Figure 8. Balanced concrete barrier design.



Note: 1 m = 3.3 ft.

Figure 9. Balanced masonry barrier design.



Note: 1 m = 3.3 ft.

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

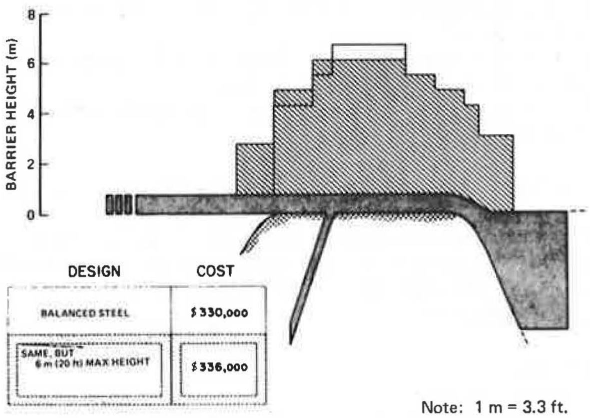


Figure 11. Concrete barrier design: 6-m maximum height.

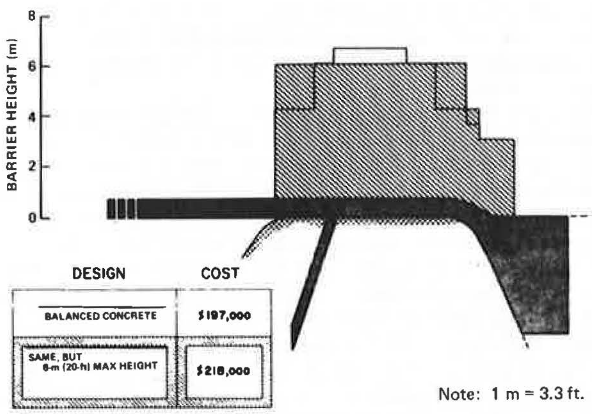
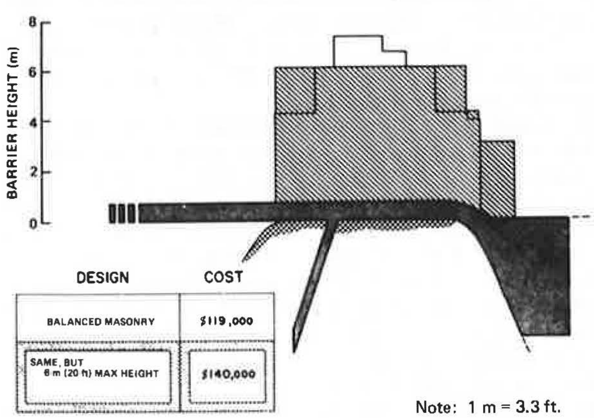


Figure 12. Masonry barrier design: 6-m maximum height.



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.

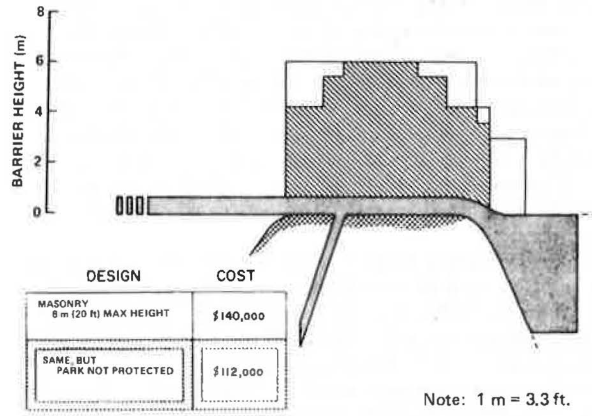
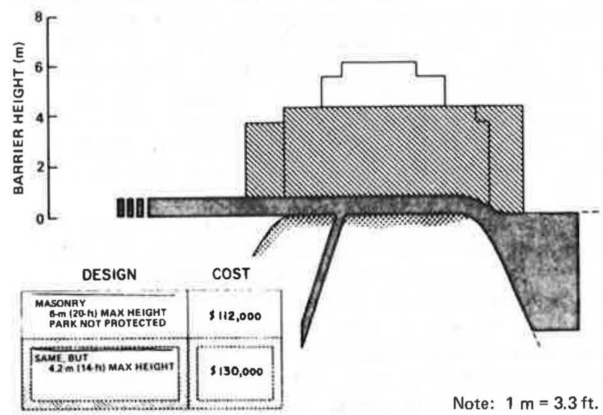


Figure 14. Masonry barrier design in which park is not protected and maximum height is 4.2 m.



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.