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IMAGE-3: Computer-Aided Design for Parallel Highway Noise Barriers

WILLIAM BOWLBY AND LOUIS F. COHN

Although most state transportation agencies in the United States have constructed traffic noise barriers on new or existing highways, little attention has been given to the problem of multiple reflections between parallel barriers. That is, when barriers are on both sides of a highway, each barrier degrades the other's performance. Therefore, the money spent on the noise-abatement project may not bring the expected benefits that were sought. In other countries, especially in Japan, use of barriers with sound-absorptive faces to counteract this problem is commonplace. Much of this other multiple-reflections analysis and absorptive treatment design has been done through acoustic scale modeling. This technique, when correctly used, is generally beyond the resources of almost all U.S. transportation agencies. There has been no versatile, easy-to-use, parallel barrier analysis and design tool for American designers. The only currently available FHWA procedure, a nomograph, has many constraints that limit its usefulness. Because of a need to consider absorptive treatment for I-440 in Nashville, Vanderbilt University has developed an algorithm and computer program called IMAGE-3 for the analysis of parallel barriers. The algorithm combines the emission, propagation, and diffraction components of the FHWA traffic noise prediction model with geometrical acoustics for addressing the multiple-reflection phenomenon. The program overcomes the constraints of the parallel barrier nomograph and permits quick analysis of many situations, including different sound-absorption schemes.

Nearly 200 miles of traffic noise barriers had been constructed by state transportation agencies in the United States as of the end of 1980 (1). This total may well represent only a fraction of the total U.S. barrier program, because in 1979 the FHWA estimated that there were potentially more than 875 miles of barrier projects on the Interstate highway system (2). Much of the existing mileage and most of the potential future mileage are in urban areas, where noise barriers are often required on both sides of the highway. (This will be referred to as a parallel barrier situation.)

Theoretical and scale-modeling studies indicate that the acoustic performance of each barrier can be seriously degraded by the presence of the other wall, to the point where no noise reduction occurs, or the levels actually increase over the no-barrier condition (3-7, and paper by Hajek elsewhere in this Record). Simply put, multiple reflections reduce or eliminate insertion loss.

If unaddressed this phenomenon can have serious consequences on an agency's noise-abatement program. First, scarce financial resources are being improperly spent; each noise barrier will not reduce community noise levels as anticipated. Second, the agency will not be providing the degree of noise reduction promised to a community to meet federal regulations. [Note that abatement design criteria are given by the FHWA (8).] As a result, the agency may lose its credibility with the public. In addition, agency decision makers may lose faith in noise barriers as legitimate means for making highways compatible with their environs.

The parallel barrier multiple-reflections problem has received increasing recognition and study during the past several years. The typically mentioned method to minimize the multiple-reflection problem is the treatment of one or both of the barrier surfaces facing the highway with sound-absorbing material (4,7,9). However, only one American parallel noise-barrier project has been constructed by using such materials to reduce the multiple-reflection phenomenon (10). Other studies have suggested tilting barriers back by 10° to redirect reflection (7,9).

There are several reasons for the general lack of consideration of the parallel barrier problem nationwide.

1. Most noise-barrier acoustical designs are performed by using computer programs (11-14). Despite recent FHWA emphasis on parallel barrier analysis (7,15), none of these programs can correctly analyze such a situation. The only available tool is a nomograph (7), which is severely limited in its applicability to real-world design problems.
2. Most American noise-barrier designers were trained through an early FHWA noise-fundamentals course (16) that concentrated on single-wall analysis and design. Even in an advanced training course, first taught in late 1982, single-wall analysis was emphasized (17). [Designers, however, did receive a brief introduction to the parallel barrier nomograph during workshops for the FHWA demonstration project on highway noise analysis (15).]

3. For many reasons, including heavy project work loads, the designers often do not have the opportunity to evaluate the performance of in-place barriers to observe firsthand the degradation problem of parallel barriers (1). Lacking this feedback mechanism, the need to address the problem is often not identified.

In addition, practice and results in other countries are often contradictory; thus there is no clear sense of direction given to U.S. designers.

1. Canadian modeling indicates that multiple reflections are significant (4,18), whereas Canadian field measurements are inconclusive (19,20).
2. British field measurements indicate that multiple reflections have little effect on the noise problem (21).
3. The Japan Highway Public Corporation developed a standard absorptive noise-barrier panel that it has used on several hundred kilometers of parallel Japanese noise barriers (22). But in the past some Japanese researchers have not considered multiple reflections to be significant (note that these data are from private correspondence between S. Hattori of the Japan Highway Public Corporation and L.F. Cohn, June 7, 1982). Others, however, definitely believe the phenomenon to be extremely important (4).

Thus many American designers have been in a quandry, particularly noting the relatively low level of FHWA emphasis. Some are skeptical of the existence of a problem because of the conflicting data in the literature. Others, who are convinced of the need for parallel barrier analysis and absorptive treatment design, do not have a flexible, easily used analysis and design tool. Because most future U.S. noise-barrier construction will be in urban areas where parallel barriers may be needed and because a significant amount of work indicates that multiple reflections degrade performance, there has been a clear need to develop an analysis and design tool, along with guidelines for its application.

The development of an algorithm for parallel barrier analysis and absorptive treatment design is described in this paper. Also discussed in this paper is the implementation of the algorithm at Vanderbilt University in a computer program called IMAGE-3. Its use in an example problem is described.

PARALLEL BARRIER THEORY

There is currently only one published method in the United States for multiple-reflection analysis for highways--the parallel barrier nomograph (7). This nomograph, however, has several constraints that limit its applicability as an analysis tool and virtually preclude its use as a design tool:

1. Only one source type is used (heavy trucks),
2. The source is restricted to one position--at the midpoint of the highway canyon,
3. The barriers are equal in height,
4. The absorption coefficients are assumed to apply to the entire height of each wall,
5. The same absorption coefficient is assigned to each wall, and
6. The use of the nomograph is time consuming (another nomograph must initially be used to determine an input value, and subsequent graphs may be required).

Despite these limitations, the theory behind the parallel barrier nomograph is acoustically and mathematically correct. The nomograph was based on the work of Pejaver and Shadley (6), who used geometrical ray acoustics or image theory to describe the multiple reflections between parallel walls. Image theory has been previously used in acoustics to represent propagation in corridors (23), in rooms (24), and in walled highways (3,18). Work by Maekawa (3), Pejaver and Shadley (6), and Hajek (18) compare scale-model results with image source calculations in attempts to validate their modeling techniques. All of the results indicate satisfactory agreement between measurements and calculations for the limited cases studied. Nevertheless, it should be noted that no well-documented field validation studies can be found in the literature.

The basic concept in geometrical acoustics, as seen in a cross-sectional view, is shown in Figure 1. The path for the ray from the actual source, which diffracts over the top of the near wall at a diffraction angle of θ_0 to reach the receiver, is shown in Figure 1a. There is, however, a reflection of the sound from the source off the far wall that travels back across the canyon between the two walls and also diffracts over the near wall, as shown in Figure 1b. This ray has a diffraction angle of θ_1; it behaves as if it originated from an imaginary source behind the far wall and as if the far wall did not exist. If the wall is perfectly vertical, this imaginary source is located at the same distance from the far wall (w_2) and height (H_S) above the ground as the real source.

Note, however, that its diffraction angle (θ_1) is smaller than that for the actual source (θ_0), and therefore the barrier attenuation for this image source is lower. This is because the difference in

Figure 1. Parallel barrier cross section showing (a) actual source (S) ray diffracting over near wall; (b) first image source (I_1); and (c) second image source (I_2), which is an image of image source I_2'.

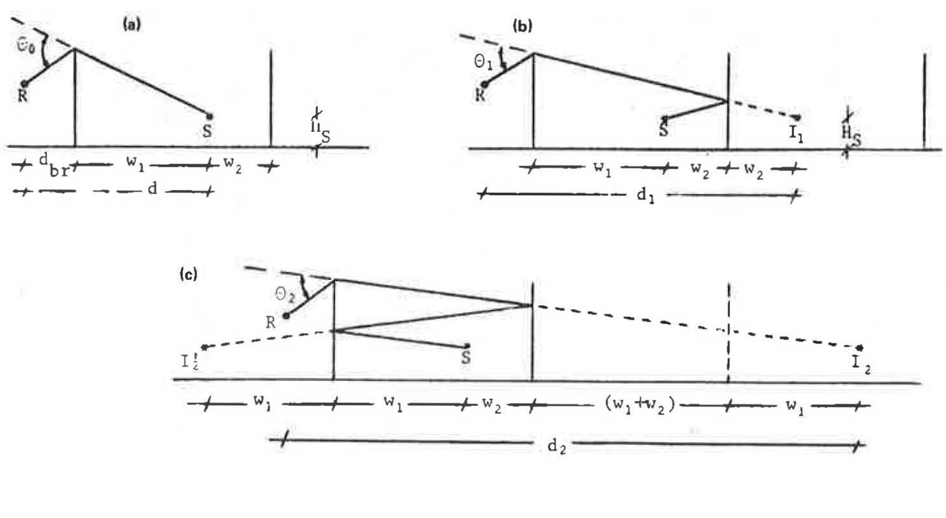
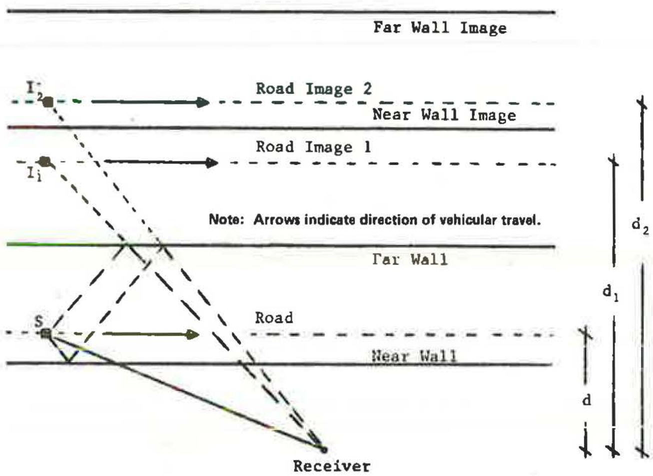


Figure 2. Plan view of parallel barriers showing reflection along the canyon for actual source (S) and first two images.



the path length is related to the diffraction angle. Thus the smaller diffraction angle for the image source results in less diffraction attenuation for the image when compared with the direct source. Nevertheless, this smaller diffraction attenuation is offset because the distance attenuation for the image source is greater than for the direct source.

The location of the second image, which first strikes the near wall and then the far wall before diffracting over the near wall, is shown in Figure 1c. The actual number of images that theoretically occur will range from zero to infinity, depending on, among other parameters, source position and wall heights.

Looking only at a cross section shows but one aspect of the multiple-reflections phenomenon. Traffic noise is generated by a series of point sources moving along a line, simulated as a line source. As shown in Figure 2, the reflections from a point source will travel down the canyon as well as across it. Thus it is necessary for image sources to be analyzed as line sources in the same manner as the actual traffic source.

One further item needs to be considered in the discussion of theory. Highway noise barriers are not, typically, perfectly reflective. A percentage of the energy of the incident ray is absorbed and the rest is reflected. This characteristic of a material is described by absorption coefficients (α) in the different octave bands, or by an average of the absorption coefficients in four octave bands, known as the noise reduction coefficient (NRC). (Note that the octave bands are centered on 250, 500, 1,000, and 2,000 Hz.) The application is that each time a ray strikes a wall, its intensity is reduced by the multiplicand $(1 - \alpha)$, which is known as the reflection coefficient.

There are several different types of absorption coefficients. The type typically reported in absorptive material product literature is known as the sabine absorption coefficient (α_{sab}), which is measured by a reverberation room standard test procedure (25). It represents an average of the absorption coefficients for rays striking the surface at all possible angles. Use of this value assumes that α is independent of the angle of incidence of the incoming ray (6). A further assumption in this work is that the reflections are specular; that is, sound energy is not scattered on striking the surface (26).

PARALLEL BARRIER ALGORITHM

The algorithm discussed in this paper was developed to overcome the constraints that limit the usefulness of the parallel barrier nomograph as a design tool; i.e.,

1. Any number of source roadways may be included in each problem analysis,
2. Each source roadway may be located anywhere within the canyon,
3. Analysis may be performed for up to three vehicle types,
4. The height of each barrier is independently variable,
5. Each barrier may be divided into three horizontal zones or sections of differing absorption coefficients (two sections allow analysis of partly absorptive walls, whereas three sections permit approximate analysis of a cross section that consists of a wall, side slope, and wall), and
6. Different absorption coefficients are allowed for each section of each wall.

Use of the algorithm directly results in

1. The hourly L_{eq} with no barriers [note that throughout this paper the term L_{eq} is used to represent the hourly equivalent sound level, commonly noted as $L_{eq}(h)$],
2. The L_{eq} with a single wall between the source and receiver,
3. The L_{eq} with both barriers, and
4. The increase in L_{eq} (i.e., the degradation of the single-wall insertion loss) caused by the presence of the far wall.

Constraints on the algorithm in its present form include the following:

1. The walls and roadway sources must be parallel to each other and to the x-axis,
2. The elevations of the wall tops and the roadways must be constant (but not necessarily equal to each other), and
3. Propagation is based on a 3-dB reduction in the L_{eq} per doubling of distance (i.e., an acoustically hard site).

This latter constraint is consistent with STAMINA 2.0, which also uses a 3-dB rate on acoustically soft sites when barrier attenuation exceeds the excess ground attenuation (11). This condition will generally apply to most receivers for which barriers are being designed because they are generally near the highway, with a low value for excess ground attenuation.

In addition to these constraints, no accomodation has been made for reflections off the ground within the canyon. Although Maekawa (3) has included three ground-reflection images in his calculations, Pejaver and Shadley (6) and Hajek (18) exclude ground reflections. Scale-modeling validation studies by each of these researchers appear to indicate that ground reflections are not significant; the question, however, warrants additional investigation.

As stated previously, the algorithm considers noise contributions to receptors outside the highway canyon from three types of vehicular noise sources (automobiles, medium trucks, and heavy trucks) traveling along a line within the canyon. It incorporates the basic emission, propagation, and diffraction algorithms in the FHWA highway traffic noise prediction model (27), thus permitting use on Federal-Aid highway project designs (8). In addition, it uses geometrical acoustics to generate image sources and absorption coefficients to reduce the intensity of each reflection.

The final form of the algorithm represents a restatement (for computational ease) of the basic equation of the FHWA model (27) with a term added for absorption. Thus the expression for the L_{eq} contribution at a receiver from the ith image source [$(L_{eq})_i$] for a particular vehicle type on a roadway is

$$(L_{eq})_i = 10 \log \left\{ 0.4735\ [(V\cdot\Delta\phi)/(S\cdot d_i)]\ [10^{(\overline{L_0})_E/10}] \left[\prod_{j=1}^{m} (1-\alpha_j) \right] \right\} - \Delta_B \quad (1)$$

where

- V = hourly volume of this vehicle type (vehicles/hr);
- $\Delta\phi$ = angle (in radians) at the receiver subtended by the endpoints of the image roadway; if $\Delta\phi$ is in degrees, the coefficient 0.4735 would be 0.008264;
- S = travel speed of the vehicles (mph);
- d_i = normal distance from the receiver to the ith image roadway (ft);
- $(\overline{L_0})_E$ = reference energy mean emission level for this vehicle type (dB), as presented in the FHWA model (27);
- α_j = absorption coefficient to be applied to the jth reflection for the ith image source; and
- Δ_B = barrier attenuation for the ith image roadway (dB), again as presented in detail in the FHWA model (27).

Note that the product expression $[\prod_{j=1}^{m} (1 - \alpha_j)]$ indicates that the intensity of the image source is reduced by the factor $(1 - \alpha_j)$ for each reflection that occurs in the propagation of the sound of this image (for j ranging from 1 to m). In this expression it is not stated that α_j will assume one of up to six values (two walls times three sections per wall), depending on where the jth reflection occurs (which section of which wall).

Also of interest in examining Equation 1 is the method for determining d_i (i.e., for locating the image source). Referring to Figure 1, the distance to the image is a function of the actual source-receiver distance, the width of the canyon, the location of the source within the canyon, and the wall off which the sound first reflects. Basically,

$$d_i = d_{br} + i(w_1 + w_2) + \begin{cases} w_2 & \text{if i is odd} \\ w_1 & \text{if i is even} \end{cases} \quad (2)$$

where

- d_{br} = distance from the receiver to the near wall;
- w_1 = distance from the source to the near wall;
- w_2 = distance from the source to the far wall; and
- i = sequential number of this image, where i = 0 is the direct source, i = 1 is the first image, and so on.

Once all of the image contributions have been computed for a particular vehicle type, the total L_{eq} is computed as follows:

$$(L_{eq})_{total} = 10 \log \left\{ 10^{(L_{eq})_{direct}/10} + \sum_{i=1}^{n} [10^{(L_{eq})_i/10}] \right\} \quad (3)$$

where $(L_{eq})_{direct}$ is the L_{eq} contribution from the actual source, and $(L_{eq})_i$ is the L_{eq} contribution from the ith image.

In a similar manner, vehicle type L_{eq} values are combined to determine the roadway L_{eq} contributions, which are, in turn, combined to determine the total L_{eq} at the receiver.

IMAGE-3

The algorithm has been programmed in FORTRAN for the Vanderbilt Computer Center DEC system 1099 computer to permit calculation of the multiple-reflection and sound-absorption effects. The IMAGE-3 program has the following features:

1. Use of Cartesian coordinates;
2. Up to six roadways may be specified per run;
3. Up to five receivers (on one or both sides of the canyon) may be specified per run;
4. The option of interactive or batch data input and file creation;
5. Capability to print out formatted input data, detailed results, and summary results;
6. Capability to print out intermediate calculations (e.g., contributions to the L_{eq} from each image); and
7. Easy file editing for reruns of problem data.

Barrier attenuation is addressed in the same manner as presented in the FHWA model (27). That is, a path length difference (δ_o) is first calculated along the normal between the receiver and the line source. Then the attenuation for the entire line source is found by numerical integration across the angle at the receiver between line endpoints by using the following approximation:

$$\delta = \delta_o \cos \phi \quad (4)$$

where δ is the path length difference at any angle off the normal line (ϕ).

The program currently does not compute sound-level contributions from beyond the ends of a barrier canyon. If a receiver under study is near the end of a barrier canyon, this flanking contribution may be easily calculated by using one of the standard methods for the FHWA model (11,12,27).

During execution, the program first computes the no-barrier and single-wall hourly L_{eq} values for a given octave band [or overall dB(A)] for a given vehicle type on a given road for a given receiver. It then locates the first image and determines if it diffracts over the near wall and if it strikes the far wall. A case where the ray misses the far wall is shown in Figure 3. The program next computes the unabsorbed, or fully reflective, contribution from this image to the total sound intensity at the receiver, determines the absorption zone on the far wall in which the reflection occurs, and reduces the source intensity accordingly. The program repeats these steps for the second image, with the additional step of determining the absorption zone on the near wall for the first bounce (see Figure 1c for an illustration of this image). This process continues for additional images until the cumulative L_{eq} increases by less than 0.1 dB or until the image does not strike the far wall on one of its bounces (as shown in Figure 3b).

After completion of the calculations for all vehicle types, roads, and receivers, the program prepares the output reports, which will be described in the section on Data Output.

Figure 3. Example of far wall being too short to produce images, where (a) only the actual source (S) contributes to level at R, and (b) only the actual source and I_1 contribute to level at R.

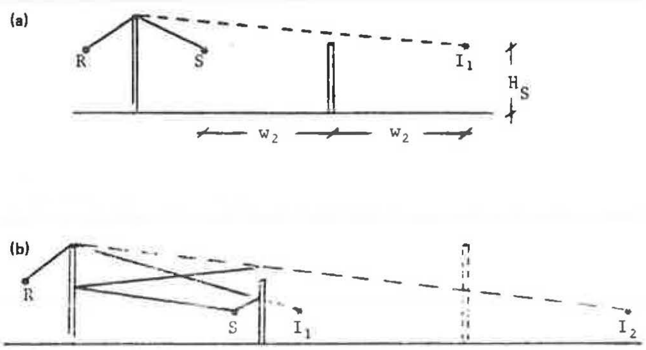


Figure 4. Three Z-coordinates are needed for each barrier to indicate the elevations of the tops of each barrier section.

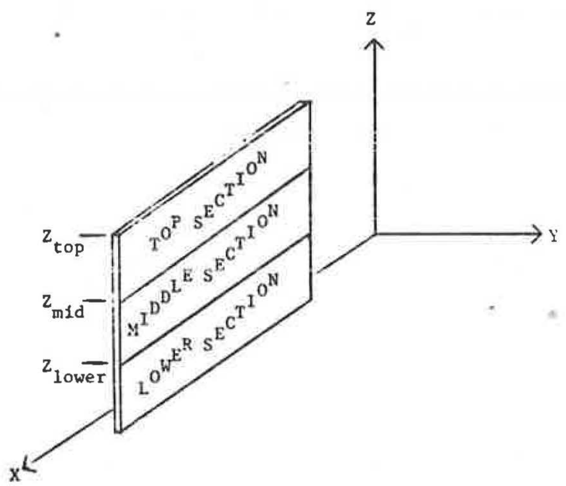


IMAGE-3 DATA INPUT

Data input is fairly straightforward. Preprinted worksheets permit the needed information to be collected before the computer terminal is used. In addition, the user can choose to have the program interactively request the data items to help ensure correct data input. The data items fall into five categories.

1. File names: If the user is interactively entering data, the program can be asked to create a file to store this input data. This file must be given a name, such as INPUT.DAT, for future access. If the user has already created an input file, the program will ask for the name of the file so its data can be read. The program also requests a name for the output file, which is the file it creates containing the results of the computer run; an example is OUTPUT.DAT.

2. Problem title: The user may provide a one-line description of the problem for easy future reference and identification of the results report.

3. Barrier data: Three types of barrier data are needed for each of the two barriers in each problem: a title, geometric data, and absorption data. The title, again, is a one-line description of the barrier for clear identification on the results report. The geometric data includes the x- and y-coordinates of each barrier endpoint and the z-coordinates of the top of each horizontal section on the barrier. As shown in Figure 4, three z-coordinates are needed to define the tops of the lower, middle, and upper sections of the wall. Also shown in Figure 4 is that the barriers need to be parallel to the x-axis. The absorption data includes, at a minimum, the NRC for each wall section. If octave band analysis is desired, absorption coefficients in the 250-, 500-, 1,000-, and 2,000-Hz bands are also needed.

4. Roadway data: Three types of roadway data are needed--a title, geometric data, and traffic data. Again the title provides a description of the output. The geometric data consist of the x-, y-, and z-coordinates of each endpoint of each road. Roads must be parallel to the x-axis and of constant (but not necessarily equal) elevation. The traffic data consist of the average speed for all vehicles and the hourly volumes of automobiles, medium trucks, and heavy trucks.

5. Receiver data: Required for each receiver are a title; the receiver's x-, y-, and z-coordinates; and an indication as to which barrier it is closer.

The interactive data input for a simple one-road, one-receiver problem is shown in Figure 5. User responses to IMAGE-3 requests are underlined. The input file subsequently created from these data is shown in Figure 6.

DATA OUTPUT

At the completion of its calculations, the program writes the results to an output file that the user can display on a terminal or have printed at the computer center.

The output consists of three parts: (a) formatted input data; (b) levels at each receiver for the no-barrier, single-wall, and multiple-reflections cases (all assuming a 3-dB drop-off rate); and (c) incremental contributions from each image to the total level at a receiver for the multiple-reflections case.

The program output for the simple problem illustrated in Figures 5 and 6 is shown in Figure 7. The formatted input data is shown in Figure 7a, and the levels at the receiver for each case are shown in Figure 7b. The upper portion of Figure 7b shows the summary of the totals at each receiver; the column labeled INCR represents the difference between the single- and double-wall cases. The lower portion of the figure gives the contributions at each receiver from each roadway (the TL line in the VT column) and each vehicle type on each roadway (the AU, MT, and HT lines in the VT column).

The image contributions for each roadway are shown in Figure 7c; for clarity, only the automobile contributions are shown. REC and RD are the sequential receiver and road numbers assigned by the program; I is the image number, where zero represents the direct ray. LEQI is the $L_{eq}(h)$ contribution from the ith image, and LEQT is the cumulative $L_{eq}(h)$ for this vehicle type on this road (the logarithmic sum of the LEQI values). ZRAY is the elevation of the last bounce off the far wall for each image before the ray returns to the near wall to be diffracted. A value of 0.00 is assigned for the zero-th image because the direct ray does not reflect off the far wall. No additional images are created when, for all vehicle types, LEQT changes by less than 0.1 dB or ZRAY exceeds the top elevation of the far wall.

EXAMPLE PROBLEM

A problem taken from the absorptive noise-barrier

Figure 5. Sample interactive data input.

```
.RUN IMAGE3

IS THE INPUT TO IMAGE FROM A DATA FILE (ENTER DSK:)
OR FROM THE TERMINAL (ENTER TTY:) ?  TTY:

DO YOU WANT TO STORE THE INPUT DATA IN A FILE? (Y=YES,N=NO)
Y

ENTER THE NAME OF THIS FILE;
MAXIMUM OF 10 (6.3) CHARACTERS, DEFAULT = INP.PBI :  INPUT.DAT
ENTER PROBLEM TITLE:
SAMPLE INTERACTIVE INPUT FOR IMAGE3
ENTER TITLE FOR BARRIER # 1
BARR1: NEAR WALL
FOR BARRIER # 1
ENTER X(PT 1), X(PT 2), Y, Z(LOWER), Z(MIDDLE), Z(TOP)
-1000 1000 0 15 15 15
ENTER TITLE FOR BARRIER # 2
BARR 2: FAR WALL
FOR BARRIER # 2
ENTER X(PT 1), X(PT 2), Y, Z(LOWER), Z(MIDDLE), Z(TOP)
-1000 1000 100 12 12 12
ENTER 1 FOR DBA ANALYSIS ONLY; 5 FOR DBA AND 250, 500, 1000 & 2000 HZ
1
ENTER NRC FOR BARRIER # 1, SECTION # 1
(SECTION: 1=BOTTOM, 2=MIDDLE, 3=TOP)
.05
ENTER NRC FOR BARRIER # 1, SECTION # 2
(SECTION: 1=BOTTOM, 2=MIDDLE, 3=TOP)
.05
ENTER NRC FOR BARRIER # 1, SECTION # 3
(SECTION: 1=BOTTOM, 2=MIDDLE, 3=TOP)
.05
ENTER NRC FOR BARRIER # 2, SECTION # 1
(SECTION: 1=BOTTOM, 2=MIDDLE, 3=TOP)
.05
ENTER NRC FOR BARRIER # 2, SECTION # 2
(SECTION: 1=BOTTOM, 2=MIDDLE, 3=TOP)
.05
ENTER NRC FOR BARRIER # 2, SECTION # 3
(SECTION: 1=BOTTOM, 2=MIDDLE, 3=TOP)
.05
ENTER NUMBER OF ROADWAYS (MAX=6)
1
ENTER TITLE FOR ROAD # 1
ROAD IN CENTER OF CANYON
FOR ROAD # 1
ENTER X(POINT 1), X(POINT 2), Y(BOTH POINTS) AND Z(BOTH POINTS)
-1000 1000 50 0
ENTER SPEED AND HOURLY VOLUMES OF AUTOS, MED. TRKS. AND HVY. TRKS. FOR
  ROAD # 1
55 1111 222 33
ENTER NUMBER OF RECEIVERS (MAX=5)
1
ENTER TITLE FOR RECEIVER # 1
VANDY
ENTER X,Y,Z FOR RECEIVER # 1
-100 -100 5
WHICH BARRIER IS CLOSEST TO RECEIVER # 1? (ENTER 1 OR 2)
1
DO YOU WANT PROGRAM TO USE 0.1 DB CUT-OFF? 1=YES 2=NO
1
ENTER NAME FOR OUTPUT FILE;
MAXIMUM OF 10 (6.3) CHARACTERS, DEFAULT = OUT.PBO :  OUTPUT.DAT
```

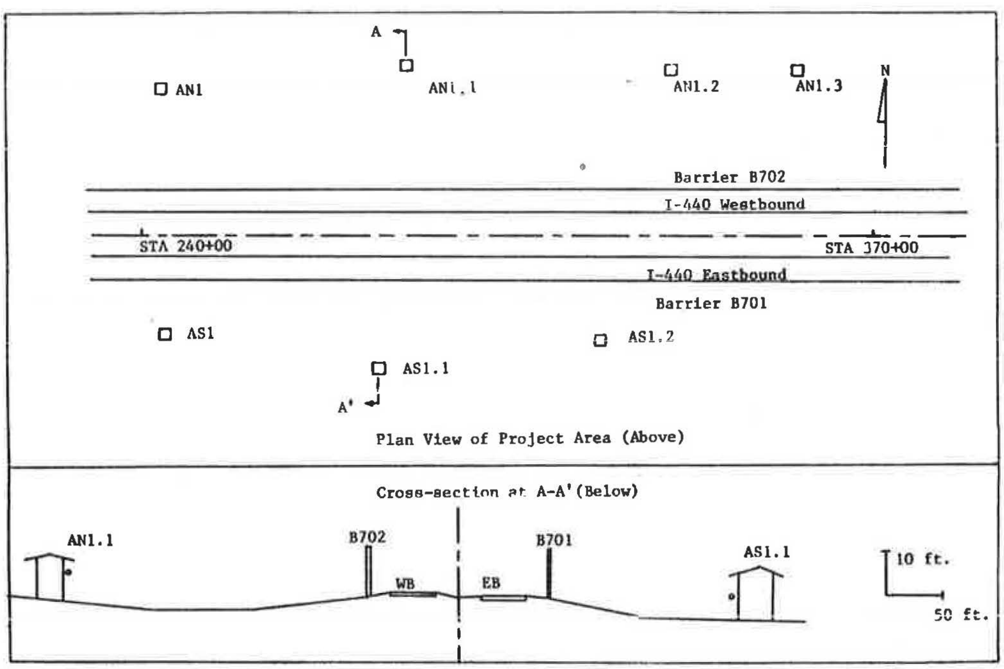
Figure 6. Sample input data file.

```
.TYPE INPUT.DAT



SAMPLE INTERACTIVE INPUT FOR IMAGE3
BARR1: NEAR WALL
 -1000.000, 1000.000, 0.0000000, 15.00000, 15.00000, 15.00000
BARR 2: FAR WALL
 -1000.000, 1000.000, 100.0000, 12.00000, 12.00000, 12.00000
 1
 5.000000E-02
 5.000000E-02
 5.000000E-02
 5.000000E-02
 5.000000E-02
 5.000000E-02
 1
ROAD IN CENTER OF CANYON
 -1000.000, 1000.000, 50.00000, 0.0000000
 55.00000, 1111.000, 222.0000, 33.00000
 1
VANDY
 -100.0000, -100.0000, 5.000000
 1
 1
```

Figure 7. Sample output file.

```
(a)
                              IMAGE-3
    A FORTRAN PROGRAM FOR STUDYING MULTIPLE REFLECTIONS AND ABSORPTION
                   FROM PARALLEL HIGHWAY NOISE BARRIERS
             VANDERBILT UNIVERSITY, SEPT. 1982, VERSION NO. 3.08

  SAMPLE INTERACTIVE INPUT FOR IMAGE3
                                                 Problem Title
 BARRIERS:
  BARR1: NEAR WALL
  BARR 2: FAR WALL

   BARRIER POINT      X          Y        Z-BOT    Z-MID    Z-TOP
      1      1     -1000.0      0.0      15.0     15.0     15.0
      1      2      1000.0      0.0      15.0     15.0     15.0
      2      1     -1000.0    100.0      12.0     12.0     12.0
      2      2      1000.0    100.0      12.0     12.0     12.0

   ABSORPTION COEFFICIENTS: BARRIER  SECTION  NRC  250  500  1000 2000
                              1        1     0.05 0.00 0.00 0.00 0.00
                              1        2     0.05 0.00 0.00 0.00 0.00
                              1        3     0.05 0.00 0.00 0.00 0.00
                              2        1     0.05 0.00 0.00 0.00 0.00
                              2        2     0.05 0.00 0.00 0.00 0.00
                              2        3     0.05 0.00 0.00 0.00 0.00
 ROADS:
  ROAD IN CENTER OF CANYON

     ROAD  POINT      X         Y         Z        SPD.  #CARS   #MT    #HT
      1      1     -1000.0     50.0      0.0      55.  1111.   222.    33.
      1      2      1000.0     50.0      0.0      55.  1111.   222.    33.

 RECEIVERS:
  VANDY

   RECEIVER           X     Y     Z
      1            -100. -100.    5.

(b)        *** PARALLEL BARRIER ANALYSIS RESULTS ***

           SAMPLE INTERACTIVE INPUT FOR IMAGE3
                                                 Problem Title
        TOTALS:
          REC.                    LEQ (DBA)
                     NO BARR   ONE WALL  MUL.REFL.    INCR.
           1          70.5       57.4      61.5        4.2

         RECEIVER: 1

         RD VT                    LEQ (DBA)                      # REFL.
                     NO BARR   ONE WALL  MUL.REFL.    INCR.

          1 TL        70.5       57.4      61.5        4.2
          1 AU        64.3       49.6      55.2                     4
          1 MT        68.0       54.2      59.0                     3
          1 HT        63.6       52.7      54.9                     1

(c)
                                  AUTOMOBILES
                     REC RD  I   LEQI   LEQT   ZRAY
                      1  1   0  49.64  49.64   0.00
                      1  1   1  49.47  52.57   5.00
                      1  1   2  48.17  53.92   9.00
                      1  1   3  46.84  54.69  10.71
                      1  1   4  45.58  55.20  11.67
```

Figure 8. Plan view and cross section for example problem.



analysis on I-440 in Nashville is used to illustrate program use. The plan and cross-section views of the analysis area are shown in Figure 8. In a typical study the analyst would work with plots created by the Vanderbilt VUPLOT graphics package, which was developed to plot STAMINA 2.0 data (28). Note that at this site houses are on both sides of the highway, which is on fill, and that the noise barriers are just off each outside shoulder. The two barriers being analyzed, labeled B701 and B702, are on the south and north sides of I-440. This section of the barriers runs from station 321+00 to station 334+00. B701 was designed to be 10 ft high by using STAMINA 2.0/OPTIMA, and B702 was designed to be 11 ft high. Two receivers--AS1.1 and AN1.1--were chosen for the analysis.

The results of two computer runs are presented for this problem. The first run is for the fully reflective case [using an NRC of 0.05 for both walls, which is typical of concrete (7)]; the second run is for an absorptive case that uses an NRC of 0.65 for B701, while leaving the NRC of B702 at 0.05. For the example problem, each direction of I-440 was modeled as a separate roadway. The results of the cases are summarized in Table 1, and the IMAGE-3 input and output data for each case are shown in Figures 9-12.

Referring to the data in Table 1, note the columns under OPTIMA. The $L_{eq}(h)$ and insertion loss (IL) values resulted from a single-wall optimization that used the OPTIMA program where the design goal was to reduce levels below 67 dB(A) while trying to achieve a 5 dB(A) insertion loss without pushing costs too high.

The next three columns represent the results of the fully reflective parallel barrier case. The multiple reflection increases are 3.9 and 4.7 dB(A) for each receiver. When added to the OPTIMA L_{eq} values, they give new L_{eq} values of 67.1 and 69.4, and reduce the IL values to 0.4 and 0.0 dB(A).

The last three columns give the results of fully absorbing B701 with an NRC of 0.65. The multiple-reflection degradations were reduced to 2.7 and 1.6 dB(A) for each receiver. For receiver AN1.1 the absorption changed the degradation by 3.1 dB(A), but for receiver AS1.1 the change was only 1.2 dB(A). This difference makes sense intuitively because the absorptive wall (B701) is the far wall for receiver AN1.1, whereas it is the near wall for AS1.1. Ex-

Table 1. Results for example problem.

	Noise Level [dB(A)]							
	OPTIMA[a]		IMAGE-3, Reflective			IMAGE-3, Barrier B701, Absorptive		
Receiver	L_{eq}	IL	INCR	L_{eq}	IL	INCR	L_{eq}	IL
AS1.1	63.2	4.3	3.9	67.1	0.4	2.7	65.9	1.6
AN1.1	64.7	4.7	4.7	69.4	0.0	1.6	66.3	3.1

[a]These values are not part of the IMAGE-3 results. They were obtained from the OPTIMA program by using a 4.5-dB(A) drop-off rate for the no-barrier situation.

Figure 9. Input data for example problem: both walls reflective.

```
                         IMAGE-3
A FORTRAN PROGRAM FOR STUDYING MULTIPLE REFLECTIONS AND ABSORPTION
            FROM PARALLEL HIGHWAY NOISE BARRIERS
         VANDERBILT UNIVERSITY, SEPT. 1982, VERSION NO. 3.08

 EXAMPLE PROBLEM WITH BOTH BARRIERS FULLY REFLECTIVE (NRC=0.05)

BARRIERS:
 BARRIER B701: HEIGHT FROM STA 321 TO 334  IS 11 FT.
 BARRIER B702: ON NORTH SIDE; HEIGHT IS 10 FT.

  BARRIER POINT     X        Y       Z-BOT    Z-MID    Z-TOP
     1      1     2400.0     0.0     511.0    511.0    522.0
     1      2     3700.0     0.0     511.0    511.0    522.0
     2      1     2400.0   160.0     511.0    511.0    521.0
     2      2     3700.0   160.0     511.0    511.0    521.0

  ABSORPTION COEFFICIENTS: BARRIER   SECTION  NRC  250  500  1000 2000
                              1         1     0.05 0.00 0.00 0.00 0.00
                              1         2     0.05 0.00 0.00 0.00 0.00
                              1         3     0.05 0.00 0.00 0.00 0.00
                              2         1     0.05 0.00 0.00 0.00 0.00
                              2         2     0.05 0.00 0.00 0.00 0.00
                              2         3     0.05 0.00 0.00 0.00 0.00

ROADS:
 RD-1: EASTBOUND I-440
 RD-2: WESTBOUND I-440

   ROAD  POINT     X        Y        Z       SPD.   #CARS    #MT     #HT
    1      1     2400.0    40.0    510.0     55.   3332.    186.    186.
    1      2     3700.0    40.0    510.0     55.   3332.    186.    186.
    2      1     2400.0   120.0    511.0     55.   3332.    186.    186.
    2      2     3700.0   120.0    511.0     55.   3332.    186.    186.

RECEIVERS:
 AS1.1: ON THE SOUTH SIDE NEAR BARRIER B701
 AN1.1: ON THE NORTH SIDE NEAR BARRIER B702

  RECEIVER          X     Y     Z
     1            2820. -230.  510.
     2            2870.  370.  515.
```

Figure 10. Output for example problem: both walls reflective.

```
*** PARALLEL BARRIER ANALYSIS RESULTS ***

 EXAMPLE PROBLEM WITH BOTH BARRIERS FULLY REFLECTIVE (NRC=0.05)

TOTALS:
 REC.                     LEQ (DBA)
          NO BARR   ONE WALL   MUL.REFL.   INCR.
  1         73.0      63.0       67.0       3.9
  2         72.6      64.6       69.3       4.7


 RECEIVER: 1

 RD VT                    LEQ (DBA)                  # REFL.
          NO BARR   ONE WALL   MUL.REFL.   INCR.

  1 TL      70.7      59.9       63.9       4.0
  1 AU      65.6      50.8       57.6                  20
  1 MT      63.7      50.3       56.2                   8
  1 HT      67.6      58.8       61.6                   3

  2 TL      69.1      60.1       64.0       3.9
  2 AU      64.0      52.7       58.3                  20
  2 MT      62.1      51.8       56.8                   7
  2 HT      66.1      58.4       61.3                   2


 RECEIVER: 2

 RD VT                    LEQ (DBA)                  # REFL.
          NO BARR   ONE WALL   MUL.REFL.   INCR.

  1 TL      68.7      61.0       66.1       5.1
  1 AU      63.6      53.7       59.9                  20
  1 MT      61.7      52.9       58.5                  20
  1 HT      65.6      59.2       63.8                  20

  2 TL      70.3      62.0       66.4       4.4
  2 AU      65.2      52.6       59.8                  20
  2 MT      63.3      52.3       58.4                  20
  2 HT      67.3      61.0       64.4                  20
```

Note that #REFL currently whows the# of possible reflections, not the number at which the 0.1 dB LEQT increment cut-off causes calculations to stop.

```
                      AUTOMOBILES
REC RD  I   LEQI    LEQT    ZRAY
 1  1   0  50.76   50.76    0.00
 1  1   1  51.07   53.93  515.14
 1  1   2  50.14   55.44  516.67
 1  1   3  47.87   56.14  518.80
 1  1   4  47.03   56.65  519.18
 1  1   5  45.14   56.94  519.91
 1  1   6  44.42   57.18  520.08
 1  1   7  42.05   57.34  520.45
 1  1   8  42.22   57.47  520.55
 1  1   9  40.86   57.56  520.77
 1  2   0  52.69   52.69    0.00
 1  2   1  52.04   55.39  513.20
 1  2   2  49.61   56.41  518.00
 1  2   3  48.68   57.08  518.62
 1  2   4  46.56   57.45  519.68
 1  2   5  45.78   57.74  519.90
 1  2   6  44.04   57.92  520.37
 1  2   7  43.36   58.07  520.48
 1  2   8  41.89   58.17  520.74
 1  2   9  41.29   58.26  520.81


 2  1   0  53.75   53.75    0.00
 2  1   1  53.37   56.57  512.20
 2  1   2  51.38   57.72  517.00
 2  1   3  50.55   58.48  517.62
 2  1   4  48.64   58.91  518.68
 2  1   5  47.90   59.24  518.90
 2  1   6  46.28   59.46  519.37
 2  1   7  45.64   59.63  519.48
 2  1   8  44.24   59.76  519.74
 2  1   9  43.65   59.86  519.81
 2  1  10  42.42   59.94  519.98
 2  2   0  52.56   52.56    0.00
 2  2   1  53.09   55.84  515.29
 2  2   2  52.21   57.41  516.56
 2  2   3  50.09   58.14  518.33
 2  2   4  49.29   58.68  518.65
 2  2   5  47.51   59.00  519.26
 2  2   6  46.81   59.25  519.40
 2  2   7  45.30   59.42  519.71
 2  2   8  44.68   59.57  519.79
 2  2   9  43.36   59.67  519.97
 2  2  10  42.80   59.76  520.02
```

Figure 11. Input data for example problem: barrier B701 absorptive.

```
                              IMAGE-3
A FORTRAN PROGRAM FOR STUDYING MULTIPLE REFLECTIONS AND ABSORPTION
                FROM PARALLEL HIGHWAY NOISE BARRIERS
          VANDERBILT UNIVERSITY, SEPT. 1982, VERSION NO. 3.08

 EXAMPLE PROBLEM WITH BARRIER B701 FULLY ABSORPTIVE (NRC=0.65).

BARRIERS:
 BARRIER B701: HEIGHT FROM STA 321 TO 334  IS 11 FT.
 BARRIER B702: ON NORTH SIDE; HEIGHT IS 10 FT.

  BARRIER POINT      X         Y       Z-BOT    Z-MID    Z-TOP
     1       1    2400.0      0.0     511.0    511.0    522.0
     1       2    3700.0      0.0     511.0    511.0    522.0
     2       1    2400.0    160.0     511.0    511.0    521.0
     2       2    3700.0    160.0     511.0    511.0    521.0

  ABSORPTION COEFFICIENTS: BARRIER  SECTION   NRC   250  500  1000 2000
                              1        1      0.65 0.00 0.00 0.00 0.00
                              1        2      0.65 0.00 0.00 0.00 0.00
                              1        3      0.65 0.00 0.00 0.00 0.00
                              2        1      0.05 0.00 0.00 0.00 0.00
                              2        2      0.05 0.00 0.00 0.00 0.00
                              2        3      0.05 0.00 0.00 0.00 0.00

ROADS:
 RD-1: EASTBOUND I-440
 RD-2: WESTBOUND I-440

    ROAD  POINT     X         Y        Z        SPD.   #CARS    #MT     #HT
     1      1    2400.0     40.0    510.0      55.   3332.    186.    186.
     1      2    3700.0     40.0    510.0      55.   3332.    186.    186.
     2      1    2400.0    120.0    511.0      55.   3332.    186.    186.
     2      2    3700.0    120.0    511.0      55.   3332.    186.    186.

RECEIVERS:
 AS1.1: ON THE SOUTH SIDE NEAR BARRIER B701
 AN1.1: ON THE NORTH SIDE NEAR BARRIER B702

  RECEIVER          X      Y      Z
     1           2820.  -230.   510.
     2           2870.   370.   515.
```

Figure 12. Output for example problem: barrier B701 absorptive.

```
*** PARALLEL BARRIER ANALYSIS RESULTS ***

 EXAMPLE PROBLEM WITH BARRIER B701 FULLY ABSORPTIVE (NRC=0.65).

TOTALS:
 REC.                      LEQ (DBA)
               NO BARR   ONE WALL   MUL.REFL.    INCR.
  1             73.0       63.0       65.7        2.7
  2             72.6       64.6       66.2        1.6

 RECEIVER: 1

 RD VT                      LEQ (DBA)                      # REFL.
               NO BARR   ONE WALL   MUL.REFL.    INCR.

  1 TL          70.7       59.9       62.5       2.6
  1 AU          65.6       50.8       55.0                    20
  1 MT          63.7       50.3       54.0                    20
  1 HT          67.6       58.8       60.9                     3

  2 TL          69.1       60.1       62.9       2.8
  2 AU          64.0       52.7       56.2                    20
  2 MT          62.1       51.8       55.1                    20
  2 HT          66.1       58.4       60.9                     2

 RECEIVER: 2

 RD VT                      LEQ (DBA)                      # REFL.
               NO BARR   ONE WALL   MUL.REFL.    INCR.

  1 TL          68.7       61.0       62.8       1.8
  1 AU          63.6       53.7       56.0                    20
  1 MT          61.7       52.9       54.9                    20
  1 HT          65.6       59.2       60.9                    20

  2 TL          70.3       62.0       63.5       1.4
  2 AU          65.2       52.6       55.4                    20
  2 MT          63.3       52.3       54.6                    20
  2 HT          67.3       61.0       62.0                    20
```

			AUTOMOBILES		
REC	RD	I	LEQI	LEQT	ZRAY
1	1	0	50.76	50.76	0.00
1	1	1	51.07	53.93	515.14
1	1	2	45.80	54.55	516.67
1	1	3	43.53	54.88	518.80
1	1	4	38.35	54.98	519.18
1	2	0	52.69	52.69	0.00
1	2	1	52.04	55.39	513.20
1	2	2	45.27	55.79	518.00
1	2	3	44.34	56.09	518.62
1	2	4	37.89	56.16	519.68
2	1	0	53.75	53.75	0.00
2	1	1	49.03	55.01	512.20
2	1	2	47.04	55.65	517.00
2	1	3	41.87	55.83	517.62
2	1	4	39.96	55.94	518.68
2	1	5	34.89	55.98	518.90
2	2	0	52.56	52.56	0.00
2	2	1	48.76	54.07	515.29
2	2	2	47.87	55.00	516.56
2	2	3	41.41	55.19	518.33
2	2	4	40.62	55.34	518.65
2	2	5	34.50	55.37	519.26

amination of the image contributions portion of the output in Figure 12 confirms this intuitive judgment: for REC 1 (AS1.1), the first images (I=1) for each road are off the reflective far wall; thus they have high LEQI values. However, for REC 2 (AN1.1), the first (and subsequent) images have LEQI values substantially attenuated compared with LEQI for the actual source (I=0).

MODEL VALIDATION

IMAGE-3 has been tested against several other published methods, and its results have been compared with other published data with satisfactory results. The no-barrier and single-wall calculations agree within 0.1 dB(A) of those from the FHWA STAMINA 2.0 and SNAP 1.1 prediction programs (11,12).

The multiple-reflections algorithm has been checked against example problems by using the FHWA parallel barrier nomograph (7) with excellent agreement. Of course, the nomograph requires the walls to be of equal height and hence does not permit checking of several of the geometric features of IMAGE-3. These were checked by hand calculation.

IMAGE-3 was also compared with Menge's scale-modeling work on the Baltimore Harbor Tunnel Thruway (5) with satisfactory results. (Note that IMAGE-3 does not simulate the barriers on the cross streets passing over depressed roadways that Menge included in his scale-model study.)

APPLICATIONS

This algorithm and the IMAGE-3 program were specifically developed as real-world applications tools. As stated earlier, no flexible method, other than scale modeling, exists for analyzing situations with parallel barriers and designing absorptive treatments.

The direct application of this work will be for noise-barrier designs on urban highways. At Vanderbilt University several parallel barrier situations proposed on I-440 are being studied. The extent of the multiple-reflections problems are being quantified, and alternative designs to overcome the problems are being examined. These alternatives include increasing the height of one or both walls, treating sections of one or both walls with absorptive material, or both. The cost of each alternative is also considered. The most cost-effective alternative will then be incorporated into the abatement design.

Parallel barrier analysis and absorptive treatment design are interactive processes between the FHWA STAMINA 2.0 and OPTIMA programs (11) and IMAGE-3. This process involves several steps. First, single-wall heights on each side of the highway are determined and optimized by using STAMINA 2.0 and OPTIMA. Then these single-wall geometries are input to IMAGE-3 to determine multiple-reflection degradations in single-wall performance.

At this point two directions may be taken. First, OPTIMA can be rerun to reoptimize single-wall heights to account for the degradation and to obtain revised cost estimates. The new wall heights may then be input to IMAGE-3 to determine the new effect on receiver sound levels. This process may be continued until the original design levels are met at each receiver. At this point the total cost of this increased wall height alternative is available from the OPTIMA runs.

The second direction involves analyzing the application of different commercially available sound-absorption systems to one or both walls. The sound-absorption coefficient data on these products are entered into IMAGE-3 to determine the effect of each system on receiver levels. By varying the extent of coverage and type of material, several different paths to achieving the original design goals may be reached. System costs may be determined and then compared with each other and with the extra height alternative. The most cost-efficient solution may then be chosen.

SUMMARY

Multiple reflections between parallel highway noise barriers, an area of previous neglect in the United States, has been the subject of increased interest during the past several years. However, the only available tool to U.S. designers--the FHWA parallel barrier nomograph--is time consuming and limited in usefulness as a real-world design aid.

To overcome the limitations, and because of a need to analyze parallel barrier situations on I-440, Vanderbilt University has developed IMAGE-3. This computer program combines the basic sound emission, propagation, and diffraction algorithms of the FHWA traffic noise prediction model with a multiple-reflections algorithm based on geometrical acoustics. The program permits analysis of a wide variety of nonsymmetrical parallel barrier cross sections and allows testing of full and partial sound-absorption schemes during the design process.

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