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Noise Control in Sacramento County, California

HARRY SEN AND MAS HATANO

In 1976 the Sacramento County Board of Supervisors recognized the need for a noise-control program by approving local ordinances and providing funds for two persons to implement a noise-control program. This team spends most of their time in enforcement (60 percent) and land use (40 percent) activities. Details of the ordinances and the noise standards are presented. The major noise problems in the county involve transportation (highways, airports, trains, and waterways) and general complaints about loud noises (neighbors, radios, dogs, fixed mechanical sources, and so forth). Each transportation problem and the various state and federal laws that are involved are discussed. A case study is presented along with a solution to a problem of using a football stadium for rock concerts to satisfy the audience, adjacent residents, and promoters.

An overview of the noise-control activities in Sacramento County, California, is presented. These activities can provide a guide to other local agencies that wish to develop or supplement an ongoing noise-control program. The need for a noise program was recognized by the county long before any federal or state laws were enacted. Complaints about noise from such sources as barking dogs, loud radios, transformers, swimming pool pumps, air-conditioning units, and noisy neighbors were common. Usually the Sheriff or Health Department responded to the complaints with mixed results. Noise from highway traffic, aircrafts, trains, and boats generally went unabated.

In 1970 the Board of Supervisors (BOS) of Sacramento County adopted the first noise ordinance for fixed mechanical sources, which (a) provided personnel to respond to noise problems from mechanical equipment and (b) authorized the purchase of a sound-level meter. This work was assigned to the Health Department.

The California Environmental Quality Act (CEQA) was passed by the state in 1970. It was comparable to the federal National Environmental Protection Act (NEPA) passed in 1969. CEQA required that an environmental impact report (EIR) be written for all major construction projects in California that involved private or public funds. Noise was one of the many issues to be addressed.

CEQA was followed by Section 65302(g) of the state code, which required each county to adopt a noise element as part of their general plan. Interim studies were performed, which resulted in the Noise Element for the Sacramento County General Plan (NESCGP) being approved by the BOS in September 1975. This was followed by Sacramento County Code (SCC) 254 titled "Noise Control", which was approved by the BOS in June 1976. A supplement to SCC254 (numbered SCC490) was approved by the BOS in December 1981. The provisions of these documents provide the authority for responding to most noise problems in the county.

GEOGRAPHIC AND DEMOGRAPHIC DATA

Sacramento County is located in northern California (Figure 1). It covers an area of 930 $miles^2$ and has a population of 809,700. The climate is generally mild, with a mean annual temperature of 62°F. However, the summers are hot and dry with temperatures exceeding 100°F on occasion, and the winter temperatures are cold but usually greater than 32°F. Rainfall averages 18 in. per year. The terrain is generally flat and is about 35 ft above sea level.

About 35 percent of the work force in Sacramento County are public employees; 22 percent are employed in trades, 18 percent are employed in services, and the balance are employed in other categories. The percentage of public employees is high because the capitol of California is located in the city of Sacramento, which is the largest city in the county.

CURRENT PROGRAM

The goal of the county noise program, as stated in the NESCGP, is "to provide the residents of Sacramento County an environment as free as possible from unnecessary noise and to reduce the level of necessary noise in order to improve the overall quality of life in the county."

The functions of the NESCGP are to identify noise problems in the community from transportation facilities and fixed noise sources and make recommendations for land use. A chart of land use compatibility for community noise is shown in Figure 2. It is used as a tool to evaluate the noise impact, but it is not used as a standard.

In SCC254 (Declaration of Policy) the following provisions are stated:

> It is hereby declared to be the policy and purpose of this chapter of the SCC to assess complaints of noises alleged to exceed the ambient noise levels. Further, it is declared to be the policy to contain sound levels in the County of Sacramento at their present levels with the ultimate goal of reducing such levels, when and where feasible and without causing undue burdens, to meet the noise standards set forth in this chapter.

The principal element of SCC254 is the noise standards given in Table 1. Exceptions are made for noise sources such as sirens, school activities, and other events conducted under permit. The standards for mechanical equipment, pumps, fans, air-conditioning apparatus, stationary pumps, stationary cooling towers, and stationary compressors are given in Table 2.

SCC490 (supplement) specifically addresses the loud playing of radios, tape recorders, record players, or televisions outdoors on public property. It does not specifically set a noise-level standard, but it does provide for fines ranging from $50 to $250 for people who are cited.

The adoption of the NESCGP resulted in the creation of a Noise Section as part of the Environmental Health Branch of the County Health Department. The section is staffed by an industrial hygienist and a noise specialist who use four sound-level meters, three calibrators, one graphic level recorder, and one octave band analyzer. Enforcement (60 percent) and land use (40 percent) are the two primary areas of emphasis.

From the standpoint of enforcement, the section responds to all noise complaints, which range from noisy roosters in rural parts of the county to fixed mechanical sources and noisy aggregate plants. All problems to date have been resolved without taking legal action.

Surveys conducted by the Sacramento City Police and County Sheriff's Department indicate that the majority of complaints reported by citizens concern barking dogs or loud parties. These do not generate

Figure 1. Sacramento County.

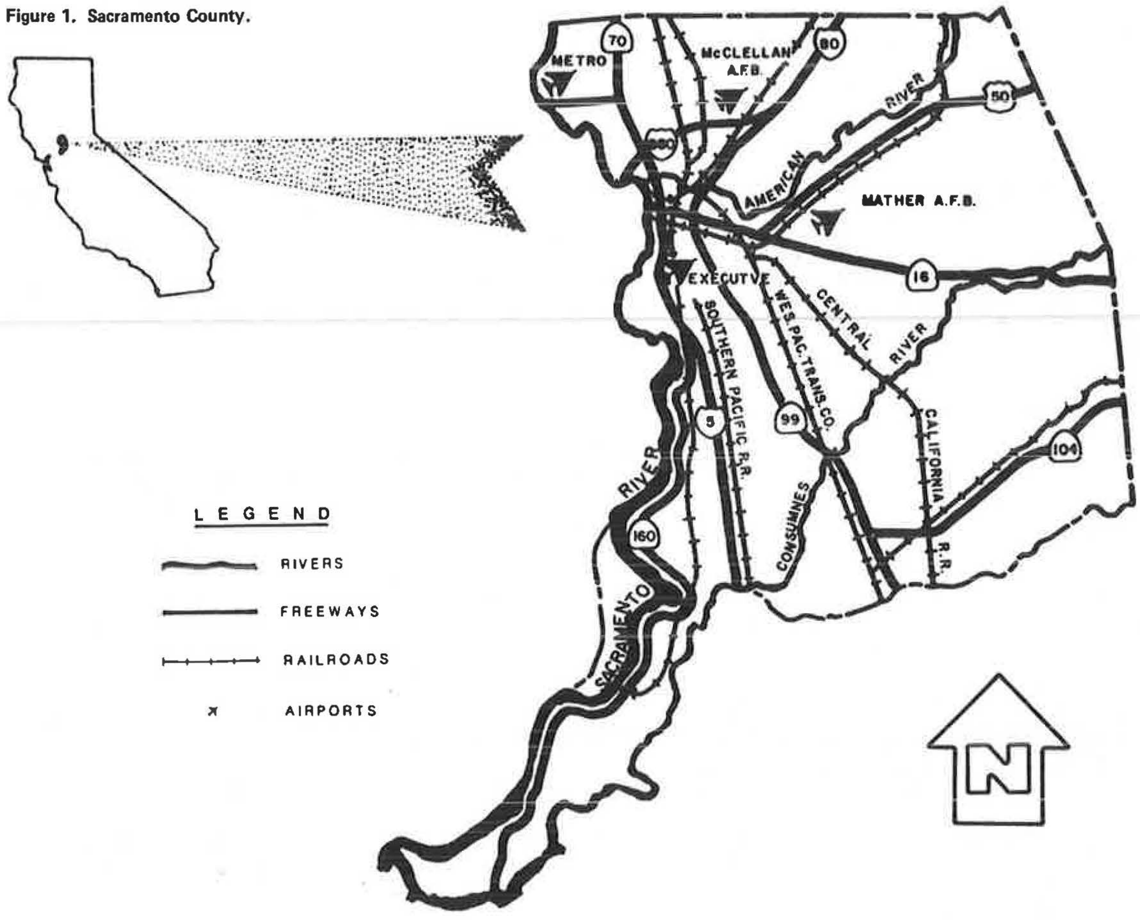
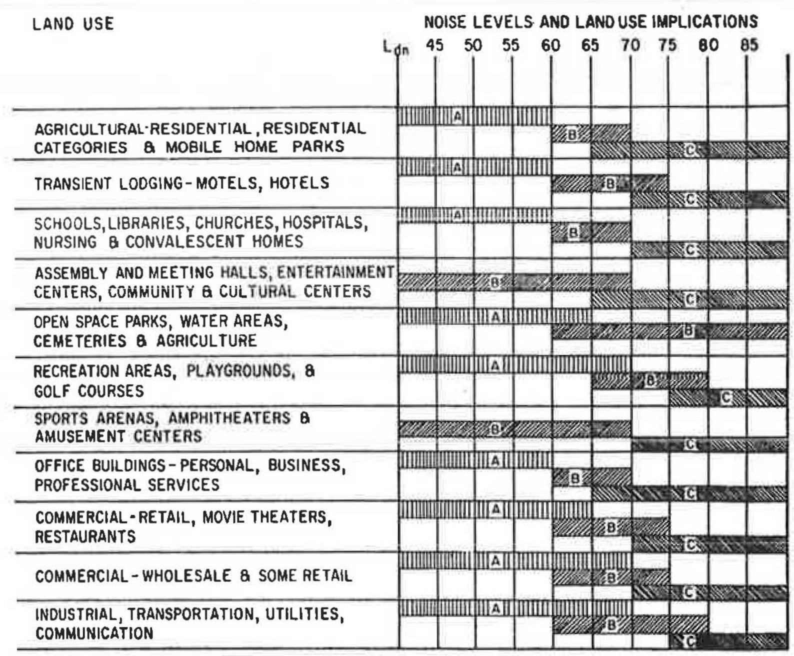


Figure 2. Land use compatibility for community noise.



A SATISFACTORY; NO SPECIAL REQUIREMENTS.

B USE SHOULD BE PERMITTED ONLY AFTER CAREFUL STUDY & INCLUSION OF PROTECTIVE MEASURES IF NEEDED.

C USE SHOULD BE DISCOURAGED. IF PERMITTED, NOISE REDUCTION MEASURES MUST BE TAKEN.

NOTE: NOISE INSULATION FEATURES FOR NEW CONSTRUCTION SHOULD BE SUCH THAT AN INTERIOR L_{dn} OF 45 dB WILL BE ACHIEVED IN AREAS WHERE PEOPLE SLEEP.

Table 1. Exterior and interior noise standards.

Cumulative Duration of the Intrusive Sound (min/hr)	Noise Level [dB(A)] Not To Be Exceeded Between 7:00 a.m. and 10:00 p.m.	10:00 p.m. and 7:00 a.m.
Exterior noise standard		
30	55	50
15	60	55
5	65	60
1	70	65
0	75	70
Interior noise standard[a]		
5		45
1		50
0		55

[a]Includes apartment, condominium, town house, duplex, and multiple dwelling unit.

Table 2. Standards for stationary equipment.

Noise Level [dB(A)]	Criteria
60	One foot inside the property line of the affected residence and 3 to 5 ft above the ground; this will be lowered to 55 dB(A) for new equipment installed 5 years later
55	Center of neighboring patio 3 to 5 ft above the ground level
55	Three feet outside living area window of closest residence

the most noise, but they appear to generate the most complaints.

Land use activities involve assistance given to subdividers, contractors, acoustical consultants, planners, and building officials. Environmental documents, plans, and other documents related to noise are reviewed. Sometimes limited studies and noise monitoring tests are performed.

The land use process in Sacramento County is as follows. The developer submits plans to the Department of Public Works. Then the plans follow one of two proposals as to the course of action taken: ministerial or discretionary.

Proposal 1: Ministerial

If the architectural plans and use conform to initial zoning, a building permit is issued without any further approval from the Zoning Administrator, Subdivision Review Committee, Planning Commission, and BOS. The noise standard is Title 25 (California Noise and Insulation Act), which specifies an interior standard of 45 dB community noise equivalent level (CNEL) for multiple housing.

Proposal 2: Discretionary

If the architectural plans and use do not conform to the initial zoning, the procedures are as follows. All projects are reviewed from the CEQA enacted in 1970 as to the type of discretionary proposal to use: (a) rezone (the EIR section of the Planning Department screens all noise-impacted projects for review by the Noise Section), (b) variance, (c) use permit, (d) development permit, (e) subdivision (all parcel map split and subdivision proposals are reviewed with input by the Noise Section), and (f) parcel map division of land in more than four lots [30 percent of the projects reviewed are affected by transportation noise sources (highway, railway, airport, and waterway)].

Recommendations made by the Noise Section have resulted in denials, extensive modifications of plans, and mitigative measures imposed on the developer. These have been generally well received by the subdivision Review Committee, Planning Commission, City Council, and BOS. The final approval on noise-impacted projects is provided by the Noise Section.

Unresolved noise problems between the county and any violator are first referred to a nine-person Hearing Board. Four members are appointed by the mayor of the city of Sacramento, subject to city council approval. Four members are appointed by the BOS, and the ninth member is appointed by the BOS and the mayor, subject to city council approval. The members are further broken down to represent the legal (1), medical (1), acoustical (1), engineering (1), contractor (2), public (2), and business (1) sectors.

If the problem cannot be resolved by the Hearing Board, it is then referred to the BOS, and finally to the courts if necessary. To date only one case has gone as far as the Hearing Board. The accomplishments of the professionals in the Noise Section testify to their ability to solve noise problems by appealing to people's sense of responsibility through persuasion and helpful advice.

HIGHWAYS

Five major freeways cross Sacramento County (Figure 1): I-5, I-80, I-880, US-50, and SR-99. In addition, there are a number of expressways, major arterials, and local streets. Traffic noise from these highways affects more people on a continuous basis than any other noise source.

The county has no direct control over the noise from vehicles, which are under the jurisdiction of the federal and state governments. Law enforcement officers can cite drivers of vehicles that exceed state vehicle noise laws, but this is seldom done.

Section 65302(g) of the Government Code requires the California Department of Transportation (Caltrans) to provide noise contour maps next to all state highways in the county. The county uses these maps to control land uses next to highways under state jurisdiction.

The state has a community noise program to retrofit noise barriers along existing freeways when traffic noise exceeds an L_{eq} of 67 dB(A). However, because of a shortage of funds, many areas that exceed the standards will not receive barriers for some time. Barriers are required on new or major highway construction projects that are federally funded.

Section 215.5 of the Streets and Highways Code allows any city or county to construct noise barriers on state rights-of-way to state standards. It also provides for reimbursement of the costs of the barriers when the project reaches the priority level for state funds. The county has not participated in this program because of a lack of funds.

Developers have constructed noise barriers in many cases to meet the state standard of 65 dB CNEL (exterior). In other cases techniques such as orientation of the houses, thicker glass, and double pane windows are other alternatives considered.

AIRPORTS

Sacramento Executive Airport

Executive Airport was built in 1930 and is located in and owned by the city of Sacramento (Figure 1). It serves as a general aviation airport for the residents of the area. Sacramento County leases and operates the airport. At one time it served interstate commercial airlines, but those aircraft now use Metro Airport (constructed in 1967), which is located in the northwest part of the county.

Urban growth (primarily residential) has surrounded the airport and created environmental, operational, development, and safety problems. Estimates indicate that existing facilities will be adequate to handle operational demand (275,000 annual takeoffs and landings) until 1985 and based aircraft demand (575) until the early 1990s. The various alternatives for the airport included no growth, controlled growth, or relocation.

The county adopted the controlled-growth master plan and land use plan for Executive Airport in April 1979. It involved items such as improved airport runways, buildings, acquisition of property, and land use.

Airport operational and noise-abatement procedures were part of the plan:

1. Operation of aircraft shall not exceed 80 dB [the effective perceived noise level (EPN)];
2. Restrict touch-and-go operations and practice instrument approaches on weekends and between 6:00 p.m. and 7:00 a.m. on weekdays; helicopter touch-and-go operations are prohibited;
3. Keep traffic pattern altitude at 1,000 ft, and at 1,500 ft for turbine-powered or large aircraft;
4. All departing aircraft shall climb on runway heading to an altitude of 600 ft before turning; and
5. Formation landings and departures are prohibited.

Sacramento Executive Airport regularly monitors noise levels to determine changes in noise contours, trends, and compliance with regulations. Executive Airport essentially complies with the California Division of Aeronautics noise standards, which are currently 70 dB CNEL, and which will drop to 65 dB CNEL in 1995.

Sacramento Metro Airport

Metro Airport was constructed in 1967 and is located in the northwest part of Sacramento County (Figure 1). It is the largest commercial airport in northern California (not including the San Francisco Bay Area) that serves major interstate airlines for passengers (3.7 million annual passengers in 1982), freight, and pilot training. A number of intrastate commuter airlines also use the airport.

The airport is generally surrounded by agricultural land. About 86 percent of the 7,800 acres owned by the airport is leased for farming. There are also gas-producing wells located on airport property that provide revenue for airport operations.

Projected growth of air travel will result in noncompliance with the California Division of Aeronautic noise standard of 70 dB CNEL, which will be reduced to 65 CNEL in 1995. Nevertheless, the noise impact will be small because of the small population involved in farming and the nearby land owned by the airport.

McClellan and Mather Air Force Bases

McClellan Air Force Base was constructed in 1938 and is located in the northern part of Sacramento County (Figure 1). It was a rural area in 1938, but by 1985 it will be completely surrounded by development. The base covers 2,593 acres and employs about 18,000 people (civilian and military).

Its mission is to provide worldwide logistic management for weapon and support systems, equipment, and commodity items. It also performs an industrial-type mission in providing maintenance, supply, and procurement-type services essential to U.S. Air Force logistics.

Mather Air Force Base was constructed in 1918 and is located in the eastern part of Sacramento County. Most of the area is undeveloped or farmland, but urban growth is beginning to approach the base. It covers 5,800 acres and employs about 7,000 people. The base mission is to train navigators, and it is part of the Strategic Air Command (SAC).

The Air Force recognized the critical nature of urban growth near airports and developed an air installation compatible use zone (AICUZ). This was the refinement of the green belt concept (1971), which specified an area of 2.5 miles from the runway ends and 1 mile on each side. The AICUZ consists of accident potential zones (APZ) and noise zones (NZ), and uses a 24-hr noise descriptor (L_{dn}). The APZ and NZ are overlaid to create compatible use districts (CUDs), which are the basic planning units of the AICUZ program.

Noise contours are drawn around the base to provide a planning and control process to restrict adjacent land to agriculture, industrial, or residential use. The role of the Air Force is to minimize the impact of its operation by planning flights to reduce noise, acquire properties adjacent to the base, and work cooperatively with the county by exchange of information. The role of the local communities is to ensure that proper land use planning is practiced.

RAILROADS

The Southern Pacific, Western Pacific, and Central Pacific railroads and the National Railroad Passenger Corporation (Amtrak) provide rail service to Sacramento. Railroad tracks cross all parts of the county (Figure 1), and trains use some tracks day and night. Most of these tracks have been in place longer than any of the freeways or airports in Sacramento County.

Railroad maintenance shops and switching yards are located within the city limits of Sacramento. The Southern Pacific (SP) shops and yard are located near the confluence of the Sacramento and American rivers. SP train noise is not a problem because of the small number of residences and businesses located nearby. In contrast, the Western Pacific shop and yards have a number of residences on both sides of the facility.

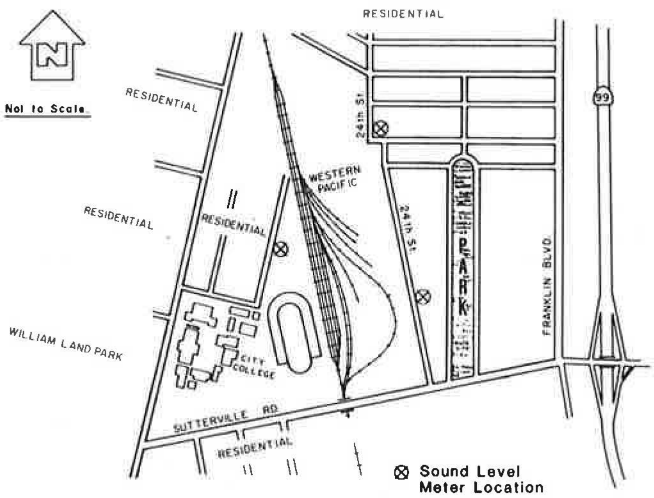
Urban growth has resulted in many developments along the railroad right-of-way and subsequent complaints about the noisy trains. The U.S. Environmental Protection Agency (EPA) has made some effort to require quieting of locomotives manufactured in future years and is looking at noise standards for yard operations.

Section 65302, which was previously mentioned for highways, requires the railroads to provide noise contour maps to the county for land use planning purposes. There have been several developers who have constructed or plan to construct noise barriers in order to develop their property. The railroads have made some efforts to control noise by scheduling train and work activities in their yards.

WATERWAYS

The western boundary of the county is the Sacramento River. It is a navigable river that flows to San Francisco Bay and is used by commercial and pleasure boats. The American River bisects the county and flows east to west and joins the Sacramento River. This is used by small private boats and by rafters. There are other rivers that are generally used by fishermen or for other recreation.

Figure 3. Plan of study site.



Noise from boats is a problem. Noise regulations of the California Department of Boating and Waterways are used by the County Sheriff's Department to control noise. They have four sound-level meters to assist them in their work.

State regulations require mufflers on all combustion engines, and noise levels from engines cannot exceed 86, 84, and 82 dB(A) before 1976, before 1978, and after 1978. Testing is performed by using SAE test J34, which requires measurements at 50 ft with the boats traveling at full throttle.

CASE HISTORY

Hughes Stadium, which has a seating capacity of more than 20,000, is located next to the campus of the Sacramento City College and is owned by the Los Rios Community College District (Figure 3). The stadium is located within the city of Sacramento in a noise-sensitized residential area, and problems have arisen because of various athletic events, rock concerts, and other activities held at Hughes Stadium. Contributing to the noise problem is the proximity of the Western Pacific railroad yards and Executive Airport.

A rock band played at Hughes Stadium on Labor Day in 1976. Noise levels at this concert were monitored at the request of the City Police Department because of previous complaints. Loudspeakers were located at the south (open) end of the stadium, and a strong prevailing wind from the south carried noise into the residential areas north of the stadium.

Noise measurements were taken at locations about 900, 1,500, and 2,600 ft from the stadium (Figure 3). Measurement periods varied from 20 min to 2 hr during the 5-hr concert. A summary of the data and the corresponding noise standards are given in the following table:

Time (min/hr)	Standard [dB(A)]	Measured Noise Levels [dB(A)] at 900 ft	Measured Noise Levels [dB(A)] at 1,500 ft
30	≤55	63-71	62-65
15	≤60	68-76	67-69
5	≤65	79-82	69-71
1	≤70	≤83	≤72

Additional measurements taken at 2,600 ft indicated ambient levels of 45 dB(A), after each performance (applause and cheers) levels of 60 dB(A), and amplified sound and music levels of 75 dB(A).

The noise data indicated that the levels may potentially be intrusive within 0.75 mile north of the stadium. Such factors as shielding, wind, ambient levels, distances, and proximity to the railroad yard or arterial streets affected the noise levels. However, the noise levels measured clearly revealed that the standards were exceeded and were a legitimate community concern. Many complaints were received by the police, stadium officials, and the Health Department. These complaints were primarily from residents north of the stadium.

There was a dilemma because stadium officials needed the revenue, rock band enthusiasts wanted loud music, and the residents wanted quiet. The county Noise Section performed a study with a local sound company. Measurements were made at peripheral sites around the stadium while the speakers were moved around the inside of the stadium. Noise levels were set at 102 dB(A) and were measured at 120 ft in front of the speakers.

The study indicated that the noise standards could be met if the speakers were placed at the north (closed) end of the stadium, directly downward, and faced the southwest. Arterial traffic noise at the south end of the stadium tended to mask some of the band noise, and the overcrossing helped to block the noise. The first row of buildings across the arterial street were businesses, which also helped minimize the noise impact.

A permit issued for the next concert stipulated that one person from the county Noise Section be stationed at the amplifier and have full control of the volume. He received instructions from a second person who had a sound-level meter and was placed near a sensitive residence. Communications between the two was by walkie-talkie.

This proved to be a workable solution for all parties, and no complaints were registered. The sound level of 102 dB(A) at 120 ft with loudspeakers placed at the north end of the stadium and facing south was a satisfactory criterion.

SUMMARY

Sacramento County has implemented a successful ongoing noise-control program that can serve as a model for city or county government. Transportation noise affects the most people and is controlled by land use planning. Noise complaints from such sources as barking dogs, loud radios, and noisy neighbors are the most common. These complaints have always been resolved by helpful advice rather than by issuing citations.

Noise Impact Analysis for a Proposed Bus Operating Base

MYLES A. SIMPSON

An evaluation was conducted of the potential noise impact for a proposed bus operating base in northern Seattle. In the analysis the impact of two alternative sites for the proposed base was examined. Both sites are located in residential areas. Thus, there was concern about the noise impact from bus traffic arriving and departing the base as well as daily operations at the base. Because of the need for buses to depart the base during early morning hours to travel to their assigned routes, of great concern was the potential impact of bus traffic on sleep disruption in neighborhoods near the base. A field noise-measurement program was undertaken to document the existing noise environment and to define typical bus passby noise levels. Based on these measurements, projections of the noise impact of buses relative to other noise sources were made. On the base noise-generating operations of particular interest include maintenance and repair activities and bus start-up and pull-out. Estimates of community noise levels for each operation were compared with noise-level limits in local ordinances to determine the extent of the potential impact of noise. For both off-base- and on-base-generated noise, mitigation measures were recommended, and estimates were made of the resulting noise-level reductions.

At the request of the municipality of Metropolitan Seattle, Bolt Beranek and Newman Inc. (BBN) conducted an evaluation of the potential impact of noise resulting from two alternative sites for a proposed bus operating base, called the North Operating Base. This evaluation was based on a review of the preliminary analysis contained in the draft environmental impact statement (EIS) for the North Operating Base (1) and its backup noise and vibration report (2).

The evaluation focused on the potential impact of buses leaving the base for their assigned routes and returning to the base, and the potential impact of maintenance and repair operations conducted at the base.

To better understand the effect of base-generated traffic on communities along the departure and arrival routes, a field noise-measurement program was undertaken. The impact assessment was then conducted based on the results of these measurements.

The paper is organized as follows. First, the measurements, impact analyses, and recommended mitigation measures are described. Second, the impact of base operations on surrounding communities, as reported in the draft EIS, is reviewed, and greater details about the mitigation measures are given. Finally, the major conclusions of the analyses are summarized.

IMPACT EVALUATION OF BASE-GENERATED TRAFFIC

Description of Proposed Operations

The draft EIS for the North Operating Base (1) indicated that there would be 616 bus trips leaving and returning to the base each day. The analysis presented in this paper is based on revised figures involving 583 bus trips in and out of the base. (Data from a June 15, 1982, memorandum from Linda Hender of Seattle Metro.)

For proposed site 1 [Aurora drive-in site (see Figure 1)], the major bus routes would be Aurora Avenue, North 145th Street, and North 130th Street. For proposed site 2 [Holyrood site (see Figure 2)], the major bus route would be North 205th Street.

Buses are scheduled to leave the base during early morning and early afternoon hours. Buses return to the base in the late morning and during the evening and night hours.

Note that the operating base is also expected to generate automobile traffic, amounting to approximately 50 percent more automobile trips per day than bus trips. However, because of the lower noise levels of automobiles compared with buses (even at the somewhat higher speeds of automobile travel), the analysis indicates that exposure to bus noise would exceed the exposure to automobile noise on all streets where the potential for noise impact might occur. Also, the base-generated automobile volume is a small fraction of existing traffic (see Figures 1 and 2). Accordingly, the analysis described in this paper focuses on the noise of bus traffic only.

Field Measurement Program

Traditionally, an analysis of the impact of traffic on a roadway is based on either the noise occurring during the peak traffic hour or during a complete 24-hr period. The proposed base-generated bus traffic will represent only a small percentage of the total daily volume of vehicles on the roadways near the proposed base sites. Further, the peak traffic hour for these roads usually occurs from either 7:00 to 8:00 a.m. or from 4:00 to 5:00 p.m., when proposed base-generated bus traffic is not expected to be high. Thus a conventional analysis would indicate that base-generated traffic will result in little or no impact on noise-sensitive land uses (residences) along the bus routes.

Nevertheless, because of the unusual distribution of base-generated traffic, and in particular the high number of buses expected to depart during early morning hours when other traffic is at a minimum, the potential for noise impact occurring during this period was a subject of concern. Although the projected number of bus operations during early morning hours is known, traffic volumes during this time of day are generally unavailable, which makes estimates of traffic noise levels inaccurate. Accordingly, a field noise-measurement program was undertaken to gather sufficient data to permit an assessment of the potential noise impact during early morning hours, as well as other times of the day.

The two major purposes of the field measurement program were to measure noise levels at selected locations to document existing conditions throughout the day and to measure noise levels of individual bus passbys because only limited data concerning bus noise levels were available.

The field noise-measurement program, as well as the subsequent analysis reported in this paper, concentrated on the noise environment along North 130th Street east of Aurora Avenue, south of proposed site 1. This street was chosen from among all the possible bus routes with residential dwellings because it had the lowest current traffic flow (which would indicate the lowest existing noise levels) and the highest ratio of proposed bus to existing traffic volumes (which would indicate the greatest potential for noise impact). Thus the analysis for this street should indicate worst-case conditions for the potential impact of bus noise on the residences along proposed bus routes for either site 1 or 2.

The first noise measurement was of the existing 24-hr noise environment. Two locations were selected for monitoring, as shown in Figure 3. At both locations the noise environment was measured with automatic noise-monitoring instrumentation for

Figure 1. Proposed site 1 showing 1980 average daily traffic volumes on the local street system.

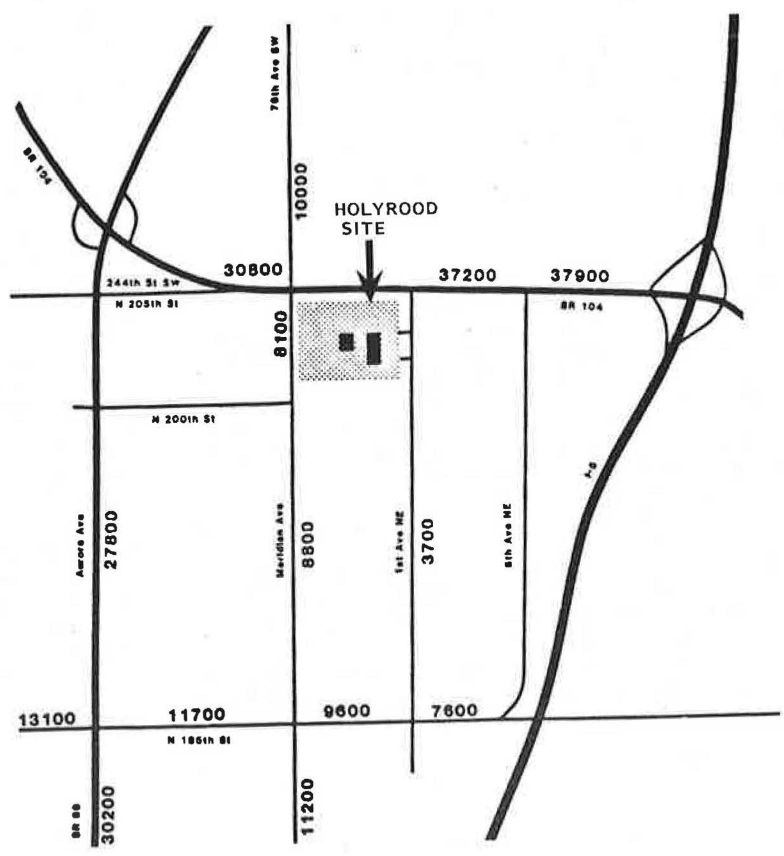


Figure 2. Proposed site 2 showing 1980 average daily traffic volumes on the local street system.

Figure 3. Noise measurement locations.

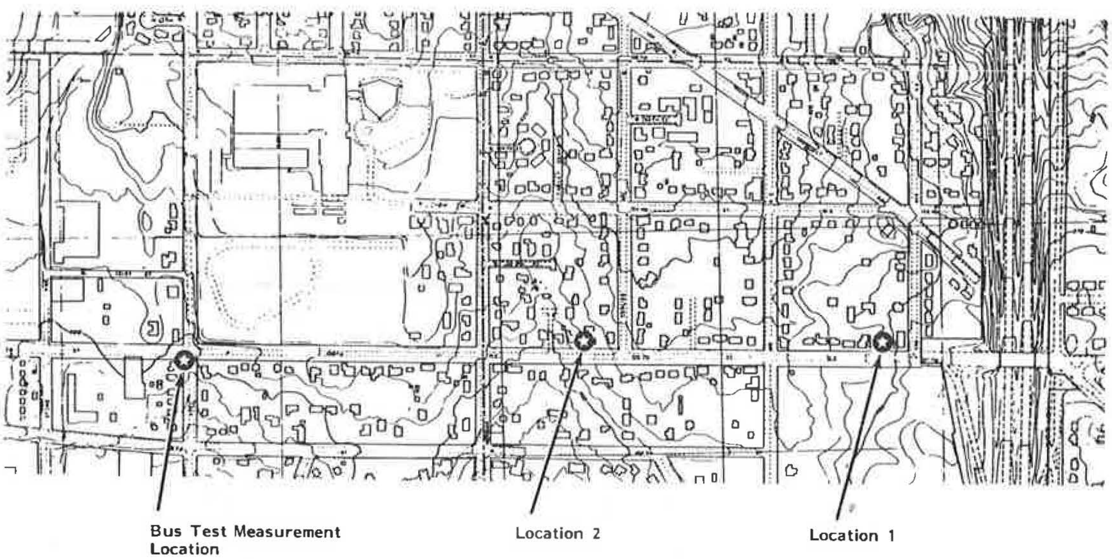


Table 1. Field measurement instrumentation.

Manufacturer	Model	Description
Noise Monitoring at Locations 1 and 2		
DAI	607P	Environmental noise analyzer
GR	9610	0.5-in. electret microphone
GR	9600	Preamplifier
B&K	UA0254	Windscreen
GR	1562A	Calibrator
Bus Measurement Recording		
Kudelski	Nagra III	Recorder
B&K	2203	Sound level meter
B&K	UA0254	Windscreen
B&K	4220	Pistonphone calibrator
B&K	4131	1-in. condenser microphone with random incidence adaptor
Bus Measurement Processing		
Kudelski	Nagra III	Recorder
DAI	607P	Environmental noise analyzer
B&K	2203	Sound level meter
B&K	2305	Graphic level recorder

a 1-day period from May 4 to May 5, 1982 (23 hr of data were acquired at each location). The two selected locations were thought to be representative of the noise environment along North 130th Street, although it is recognized that noise levels may vary from location to location, depending on proximity to other major roadways, presence of traffic signals, roadway gradients, and so forth. The locations selected were not intended to reflect the maximum or minimum exposure to noise along North 130th Street, but rather to generally be representative of conditions along the roadway.

Noise levels were monitored continuously at the selected locations with a DAI Model 607 noise monitor. (The instruments used to collect and process field data are given in Table 1.) These units sample the noise environment 8 times per second, store the measured noise levels internally, and generate a paper tape that lists hourly average sound levels as well as the statistics of the distribution of noise levels during the preceding hour. The monitors were also set up to measure and print out the noise levels of individual single events where the noise levels were greater than 75 dB(A). The units were calibrated at the beginning and conclusion of the measurement program.

Figure 4 shows the hourly average sound level measured at each location, as well as the day and night average sound level (L_{dn}), which is a measure of the 24-hr noise environment. The data in Figure 4 show that the pattern of hourly average sound levels is similar between the two locations, with the noise levels at location 1 typically 1 to 2 dB greater than those at location 2. The noise levels at both locations are fairly constant during daylight hours (8:00 a.m. to 8:00 p.m.), which indicates fairly constant traffic flow on North 130th Street during these hours. (Note that bus noise tests, to be described later, influenced the measured noise levels from 5:00 to 6:00 a.m. at both locations. Shown in Figure 4 are the measured noise levels, which include the bus passbys as well as the estimated noise levels with these bus passbys removed.)

The second set of measurements consisted of a series of planned bus passbys on North 130th Street between 5:00 and 6:00 a.m. on the morning of May 5, 1982. Noise levels were recorded at a measurement location on Ashworth Avenue, approximately 18 ft south of North 130th Street (see Figure 3). Eighteen different coaches of various types were used in the test, which involved each coach driving west past the measurement microphone, turning around, and driving back east past the measurement microphone. Nominal speed of travel was 25 to 30 mph. Because several coaches made 2 trips, a total of 25 passbys in each direction occurred during the test. The coaches selected for the test were representative of the typical mix of coaches expected to operate from the proposed operating base.

The measured bus passby noise levels were recorded on magnetic tape for later processing. The recorded noise levels were played back onto a graphic level recorder, from which the maximum noise level of each bus passby was determined. By correlating these measured noise levels with the observation log maintained in the field and the schedule of bus operations during the test, the maximum A-weighted noise level occurring during most of the passbys was determined. During the test there were occasional occurrences of multiple bus passbys; i.e., a bus heading east would pass by the measure-

Figure 4. Measured existing levels.

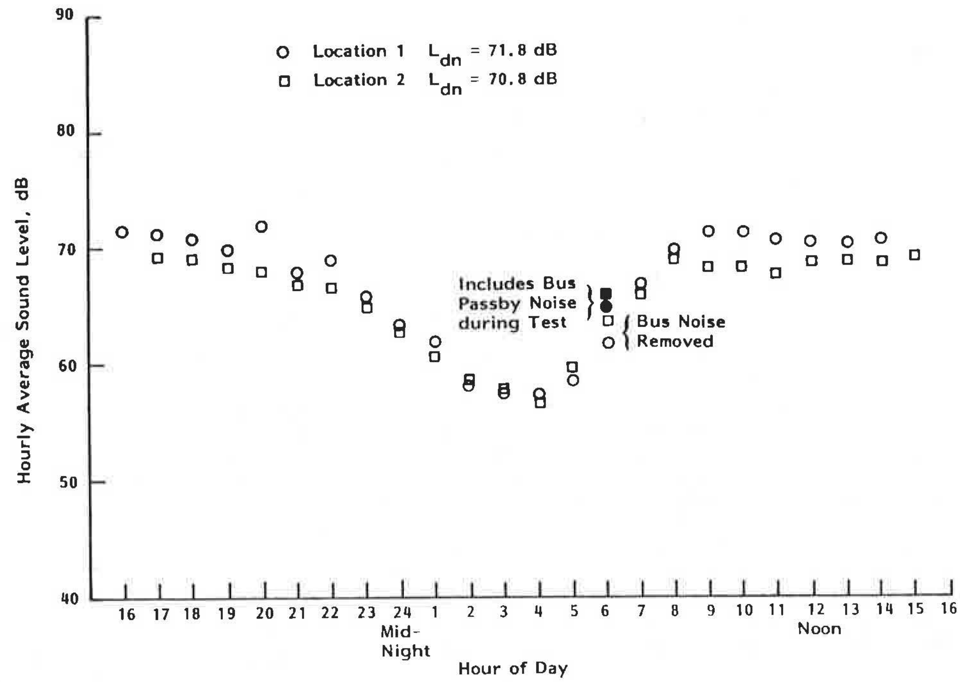


Table 2. Measured noise levels from bus passbys.

Bus Series	Bus No.	Maximum Passby A-Weighted Noise Level[a] (dB) Westbound (distance = 44 ft)	Eastbound (distance = 23 ft)	Eastbound (normalized[b])
1100	1103	79	-	-
1200	1261	-	86	80
	1268	76	75	69
	1209	78	80	74
	Avg	75	80	74
1300	1314	84	-	-
1400	1488	75	83	77
	1483	78	-	-
	1485	79	-	-
	1412	-	73	67
	1479	80	82	76
	1448	87	-	-
	1424	76	79	73
	1488	76	83	77
	1461	75	79	73
	1483	77	81	75
	1448	75	83	77
	1424	74	82	76
	Avg	77	81	75
1600	1666	79	82	76
	1668	75	81	75
	1690	-	77	71
	1668	73	78	72
	Avg	76	80	74
1700	1716	79	-	-
	1704	77	79	73
	1716	72	76	70
	1704	72	77	71
	Avg	75	77	71
Avg of all buses		77	80	74

[a]Measured with slow meter response.
[b]Normalized to 44-ft distance.

ment microphone simultaneously with a bus heading west. When this occurred, it was not possible to determine the maximum noise level of each individual vehicle.

The measured passby noise levels are given in Table 2. Note that westbound buses were approximately 44 ft from the measurement microphone, whereas eastbound buses were approximately 23 ft from the measurement microphone. In order to compare noise levels from buses traveling in both directions, the noise levels measured from eastbound buses were adjusted to reflect the noise level that would occur if these buses were traveling along the same lane at the same distance as the westbound buses, that is, at 44 ft (see the last column in Table 2). The data in Table 2 indicate that, on average, the westbound buses had noise levels that were 3 dB higher than the eastbound buses, which indicates that the driver's side is the noisier side of the bus.

The data in Table 2 also indicate that, although there may be considerable variability in the passby noise level for a given series of buses (the westbound passby levels for the series 1400 buses range from 74 to 87 dB), on average, no great variability exists among the various bus series. This may be due in part to the limited amount of data collected for some of the buses. Also note that at higher speeds greater differences between bus series may become apparent. For these tests, drivers were instructed to maintain a speed of 25 mph as they passed by the measurement location.

Note that during the passby test a variety of other vehicles traveling on North 130th Street passed by the measurement microphone. For example, during the tests a truck passed by with a maximum A-weighted sound level of 85 dB, which provided one of the highest readings during the measurement period.

The recorded bus noise levels were also played back into a DAI 607 noise-monitor unit, which provided the sound exposure level of individual events. This sound exposure level (SEL) is a useful measure of the total noise energy within each event; the summation of SELs occurring during a given time period may be used to derive the average sound level occurring during that time period. Unfortunately, because of the occurrence of simultaneous passbys (either of buses traveling in opposite directions or of several buses passing the measurement microphone in rapid sequence), it was not possible to determine the SEL of each bus passby. Nevertheless, the SEL determined by the monitor unit for a series of passbys (e.g., four buses passing by the microphone in a sequence) does have meaning and can be used as a measure of the total energy in the four passbys. The measured SEL values for all of the bus events are given in Table 3. As indicated by the data in the table, some of the SEL values refer to individual passbys, whereas some are for multiple events. Also, when nonbus events occurred simultaneously with bus events (such as a car and bus driving by simultaneously), the SEL measured by the monitor unit had not been included.

Because SEL is a measure of total energy within each signal, the individual and multiple events can be combined together to derive an energy average for all events. As indicated by the data in Table 3, the energy-averaged SEL for all the events is 82.8 dB. This averaged SEL may then be used to predict the impact of a selected number of bus passbys.

Because of the multiple occurrences of bus passbys in both directions, it was not possible to segregate the eastbound and westbound SEL values. Nevertheless, the energy-averaged SEL value may be associated with an equivalent distance appropriate to all of the passbys; for estimation of average sound levels, this equivalent distance is 30 ft. For situations of greatest concern (early morning traffic when buses are traveling in the near lane), this approach may overestimate noise levels, because included in the average are the higher noise levels of buses traveling in the opposite direction when the driver's side faces the residence.

With the value of 82.8 dB for the average sound exposure level ($\overline{SEL}$) of a typical bus passby at 30 ft, the lower curve in Figure 5 has been developed by using the following relationship:

Hourly average sound level = $\overline{SEL}$ + 10 log (number of buses per hour) - 35.6 dB.

This lower curve represents the estimated hourly average sound level along North 130th Street from projected bus trips. The average sound levels shown in Figure 5 have been adjusted to an approximate distance of 41 ft, which corresponds to the approximate location of measurement microphones at locations 1 and 2 where 24-hr data were acquired. Shown beneath the curve of the estimated bus level is the number of bus trips expected by hour of day. The upper curve is presented for comparison purposes; this curve is the lower bound of the measured hourly average sound levels shown in Figure 4 at either locations 1 or 2.

Table 3. Measured SELs from bus passbys.

Passby A-Weighted SEL at 30 ft (dB)	No. of Buses Measured	Passby A-Weighted SEL at 30 ft (dB)	No. of Buses Measured
79.7	1	84.3	1
86.4	2	81.8	1
84.9	1	78.0	1
85.3	3	84.5	1
91.4	6	85.6	2
91.9	8	80.8	1
91.5	5	84.7	4
76.4	1	89.7	4
80.8	1		

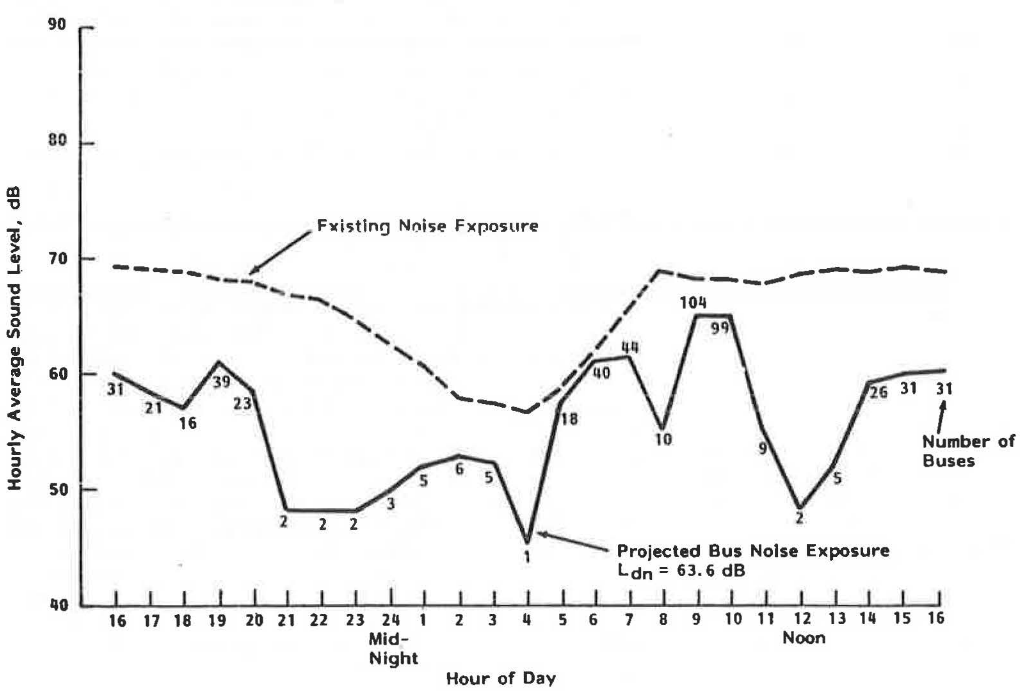
Note: The energy-average SEL of 43 bus passbys is 82.8 dB.

Analysis of Impact

Applicable regulations and criteria for judging the noise impact are described in detail in the draft EIS. For base-generated traffic, the assessment would involve comparison of projected bus levels with existing traffic levels, in light of federal compatibility guidelines related to absolute levels and U.S. Environmental Protection Agency (EPA) Region 10 guidelines about noise increases. The federal guidelines indicate that day and night levels in excess of 65 dB are unacceptable for residential land use. EPA Region 10 guidelines indicate that noise-level increases of up to 5 dB are considered slight, up to 10 dB are considered significant, and greater than 10 dB are considered serious.

On a daily basis the day and night sound level for locations along North 130th Street already places the location in an unacceptable noise envi-

Figure 5. Comparison of measured existing levels and projected bus levels.



ronment category. The projected L_{dn} value for proposed bus traffic is sufficiently low so as not to contribute to the total day and night level. On a 24-hr basis, therefore, the proposed bus operations would not affect residences along North 130th Street.

On an hourly basis, Figure 5 shows that between the hours of 4:00 and 6:00 a.m., projected hourly average sound levels of buses will be comparable to existing measured hourly average sound levels. Thus during these hours the total exposure to noise would be approximately 3 dB higher than at present. This would be categorized by the EPA guidelines as a slight impact.

Note however that there will be variations in both projected and existing noise levels from buses with locations along North 130th Street, and there may be some locations where future noise levels from buses may exceed existing levels by perhaps 2 to 3 dB. Under such conditions the increase in total noise level would likely still be less than 5 dB, and therefore would still be considered a slight impact.

One further consideration must be discussed, however. Even for those locations where future noise levels from buses will be less than existing levels, noise levels will likely be noticeable within the homes of residents. For some residents, the repeated passbys of buses may interfere with sleep. Unfortunately, the area of sleep disturbance from noise intrusions is not well understood, and there is little scientific data that provide clear guidelines concerning the impact of such noise sources, particularly when the average level is comparable to background levels. Thus even though EPA guidelines would indicate that only a slight impact might occur, and even though no specific criteria are available that can be cited as a basis on which to judge the potential for sleep disturbance, it should be recognized that during the hours of 4:00 to 6:00 a.m. such an impact on sleep might occur.

A final comparison might shed some light on this subject of sleep disturbance. The maximum sound levels and SELs measured at locations 1 and 2 during the hours of 10:00 p.m. to 7:00 a.m. are given in Table 4. The data in the table indicate those noise levels that may have been due to bus passbys as a result of the special bus noise tests conducted during that time period. Note that other sources of noise, such as other traffic vehicles normally traveling on North 130th Street, are already creating maximum levels and SELs that are comparable to and higher than noise levels that may be generated by bus passbys. Thus if these noise events are not now affecting sleep patterns, it is reasonable to expect that the projected bus passbys will not have an impact on sleep.

The impact of future bus traffic on streets other than North 130th Street will be lower than that indicated for North 130th Street. For example, projected bus operations on North 145th Street are about a third of those projected for North 130th Street, yet the traffic on North 145th Street is higher than on North 130th Street. This would tend to shift the curves shown on Figure 5 approximately 5 dB farther apart. With regard to the impact analysis for the proposed site 2, projected bus operations on North 205th Street are approximately twice that on North 130th Street; however, existing traffic flow on North 205th Street is more than twice that on North 130th Street. For North 205th Street, the two curves shown on Figure 5 would be shifted apart by approximately 1 dB.

Mitigation Measures

On the basis of the discussion in the preceding section, the only time period during which mitigation measures might be considered is the period from 4:00 to 6:00 a.m. A simple and effective way to reduce noise levels during this period would be to divert a portion of the traffic scheduled for North 130th Street to other east-west streets capable of handling the bus traffic, such as North 110th Street and North 85th Street. For example, removing half of the expected buses between 4:00 and 5:00 a.m. and between 5:00 and 6:00 a.m. would reduce hourly average sound levels by 3 dB on North 130th Street, and reducing expected buses by three-quarters would reduce hourly average sound levels by 6 dB. These changes in the pattern of hourly average sound levels are shown in Figure 6. Reducing noise levels on North 130th Street by 3 to 6 dB could well ensure that sleep disturbance is minimized.

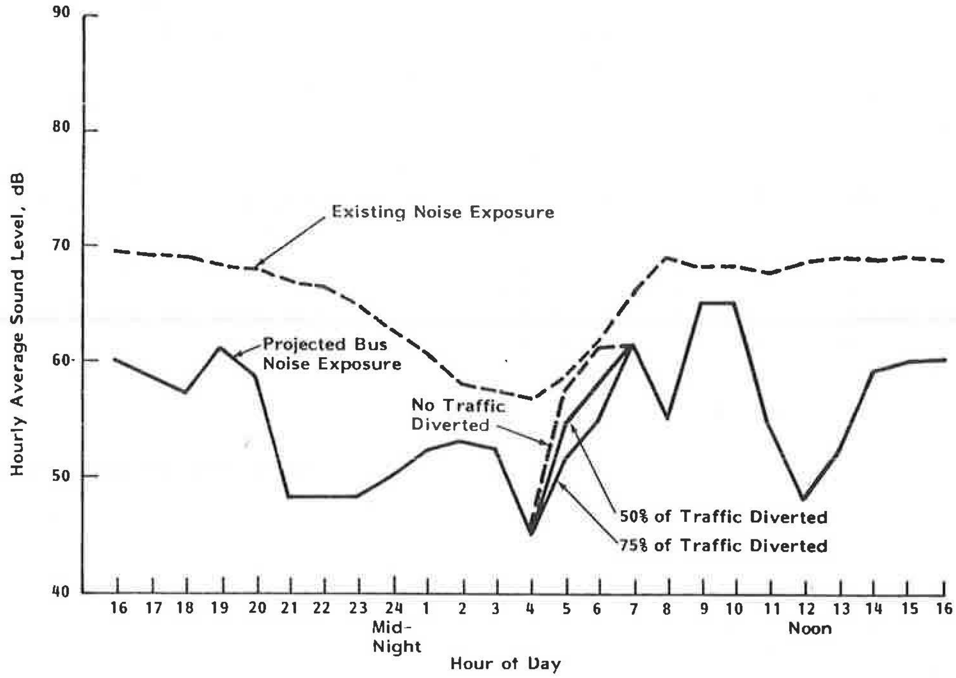
Note that the addition of bus traffic on North 110th Street or North 85th Street will likely have little effect on nearby residents because of the low level of bus traffic diverted to these streets. Also, these streets have higher traffic volumes than North 130th Street, and therefore presumably higher noise levels during the hours of 4:00 to 6:00 a.m.

Table 4. Measured night noise levels at locations 1 and 2.

Hour	SEL (dB)	Maximum A-Level (dB)	Hour	SEL (dB)	Maximum A-Level (dB)
Location 1			Location 2 (continued)		
10:00-11:00 p.m.	83.9	81.2	1:00-2:00 a.m.	83.4	80.1
	83.8	80.3	2:00-3:00 a.m.	87.4	83.4
	85.3	81.4	3:00-4:00 a.m.	84.5	79.7
11:00 p.m.-12:00 midnight	84.4	80.0	4:00-5:00 a.m.	81.3	77.5
12:00-1:00 a.m.	89.7	86.2		90.8	85.1
3:00-4:00 a.m.	86.3	80.7		84.3	79.8
	82.8	78.7	5:00-6:00 a.m.[a]	89.6	84.8
4:00-5:00 a.m.	88.0	84.0		83.5	80.1
5:00-6:00 a.m.[a]	83.4	78.4		81.9	77.9
	82.3	77.2		85.9	78.2
	84.0	79.5		85.2	82.0
	81.6	77.2		83.4	79.5
6:00-7:00 a.m.	83.8	81.2		83.3	78.8
Location 2				83.7	80.2
10:00-11:00 p.m.	82.4	78.8		94.7	86.3
11:00 p.m.-12:00 midnight	84.8	81.5	6:00-7:00 a.m.	82.1	78.7
	82.0	78.7		85.2	81.1
	83.1	79.4		87.0	82.5
12:00-1:00 a.m.	86.2	83.0		81.2	77.2

Note: Only noise signals with levels greater than 75 dB are listed.
[a]Period of bus passby test.

Figure 6. Change in projected bus levels for traffic diversion from 4:00 to 6:00 a.m.



One mitigation measure suggested early in the study was the modification of homes along North 130th Street. As discussed previously, reducing the noise level by 3 dB can be achieved by diverting approximately half of the traffic to alternate routes. Reducing the noise level by 6 dB can be accomplished by diverting three-quarters of the traffic. For the same type of reduction to be achieved by building modification, fairly significant changes to the building structure would be required. A study (3) of the costs of building modifications for noise abatement indicated that (in 1973 dollars) modifications to a single-family dwelling would cost approximately $6,000 to achieve a 5-dB reduction in noise. In 1982 dollars, this would be more than $10,000, which is clearly not a cost-effective measure in the light of the reduction in noise obtainable by simply diverting traffic. Of course, the reduction achievable through building modification does apply throughout the entire day, whereas the route-diversion mitigation measure only applies to those hours in which it is implemented.

Reduction of the noise levels of buses through source control would include replacing noisy buses with quieter models or retrofiting buses to produce lower noise levels. Consideration of this mitigation measure was beyond the scope of this study.

IMPACT EVALUATION OF BASE OPERATIONS

Proposed Operations and Their Potential Impact

The draft EIS (1) and the noise and vibration technical backup report (2) describe future base activities and provide noise-level estimates for these activities. These documents categorize activities in terms of maintenance operations, fuel and wash operations, and bus start-up operations. Although all of the assumptions and input information used to develop the noise-exposure estimates were not completely available, the projected noise-exposure levels from these various operations appear quite reasonable based on a review and analysis of the data presented in the report by Michael R. Yantis Associates (2).

The impact analysis indicates that for both proposed site 1 and proposed site 2 the noise of maintenance operations will provide the greatest impact in terms of the amount by which the Seattle and King County noise ordinance will be exceeded. For selected residential locations, the noise-level estimates are projected to exceed ordinance limits by as much as 27 to 29 dB. Bus start-up noise is the second greatest cause of concern, providing future noise levels that will exceed the ordinance by as much as 12 to 14 dB at selected locations. Fuel and wash operations will have the least potential impact at most residential locations.

Mitigation Measures

For purposes of describing measures to reduce or eliminate the potential noise impact, it is useful to categorize sources of the potential noise impact as follows: maintenance operations that occur indoors, maintenance operations that occur outside, and bus start-up operations. Indoor maintenance operations would include stalled coach tests, fast idle tests, and the use of pneumatic tools. Maintenance operations that occur outside would include the use of eductor trucks, cyclone cleaners, yard sweepers, and fuel and wash operations.

Such a breakdown is useful because the most cost-effective measure of noise control for indoor activities is clearly the closing of maintenance building doors during the times when these operations occur. Note that several of these operations occur rather infrequently, such as stalled coach tests, which are expected to occur approximately 3 times per day at less than 5 min per time. Closing doors during these intervals should not create any adverse impact on maintenance personnel inside the building.

For outside maintenance operations, including fuel and wash operations, care should be taken to schedule such activities during daytime hours. For example, one report (2) indicates that the yard sweepers will typically operate between 6:30 and 7:30 a.m. If this activity can be shifted to slightly later in the morning, the noise impact would not be as severe.

One of the major sources of noise is the eductor truck, which is used to pump out selected storage sumps on the base. This activity will occur fairly infrequently; however, when the activity does occur, the resulting noise levels will be high enough to exceed noise ordinance limits. A recommended mitigation measure will be the use of noise barrier walls to provide shielding to nearby residents. Because the exact locations of the eductor trucks have not yet been determined, it is difficult to assess the precise benefits of such walls relative to the noise produced by these trucks. It is likely, however, that the noise reduction provided by the walls for the eductor truck noise will not be sufficient to eliminate the potential noise impact. A supplementary measure would be the use of portable noise barriers, such as those used in construction work, located in the immediate vicinity of the truck to provide an extra measure of noise control. Because of the infrequency of eductor truck operations, use of such portable barriers should not have a major impact on base operations.

Even if the noise of maintenance operations were entirely controlled by closing the maintenance doors, scheduling of operations to occur during daytime periods, and using portable noise barriers, the noise of bus start-up and pull-out operations would result in noise levels in excess of ordinance limits, and at selected locations the noise of fuel and wash operations would also exceed ordinance limits. Because bus start-up operations occur throughout the base, and because these activities will occur throughout the entire 24-hr period, the use of noise barrier walls along the perimeter of the base will be an effective mitigation measure. The barriers may be contructed of wood or masonry block at an approximate height of 13 ft aboveground.

Recommended locations for such walls are shown in Figures 7 and 8. These locations have been selected primarily to minimize the impact of base activity on residential areas that surround the base. The length of wall indicated for each site in Figures 7 and 8 is greater than indicated in the draft EIS; the additional length was deemed necessary to avoid the potential for sound paths to the community around the sides of the walls.

After the operating base site is selected, and grading plans and the layout of the base are completed (for building placement, bus parking, entrance and exit locations, and so on), it would be desirable to develop more detailed and specific plans for such walls. It is quite possible that the height of the walls can be reduced, at least in selected locations, from the estimated 13 ft. The 13-ft height has been chosen as a height that, for all prediction locations used in the draft EIS, will eliminate the impact of bus start-up noise.

With implementation of the mitigation measures just described, placement of buildings on the site will not have a significant effect on the reduction of community noise levels.

CONCLUSIONS

The major conclusions resulting from the analysis described in this paper are as follows.

1. Base-generated bus traffic along North 130th Street will not affect nearby residences throughout most of the day. From 4:00 to 6:00 a.m., base-generated bus traffic will have a slight impact. During this time period the noise of bus passbys may cause sleep disturbance for some residents, although the area is already exposed to noise of comparable levels from other vehicles on North 130th Street.
2. The potential noise impact of base-generated traffic on other streets in the vicinity of proposed sites 1 or 2 will be lower than that described for North 130th Street.
3. The potential noise impact of base-generated traffic from 4:00 to 6:00 a.m. may be mitigated by diverting a portion of the bus trips to other east-west streets. For those streets selected, there should be no noise impact.

Figure 7. Recommended noise barriers, north base, site 1.

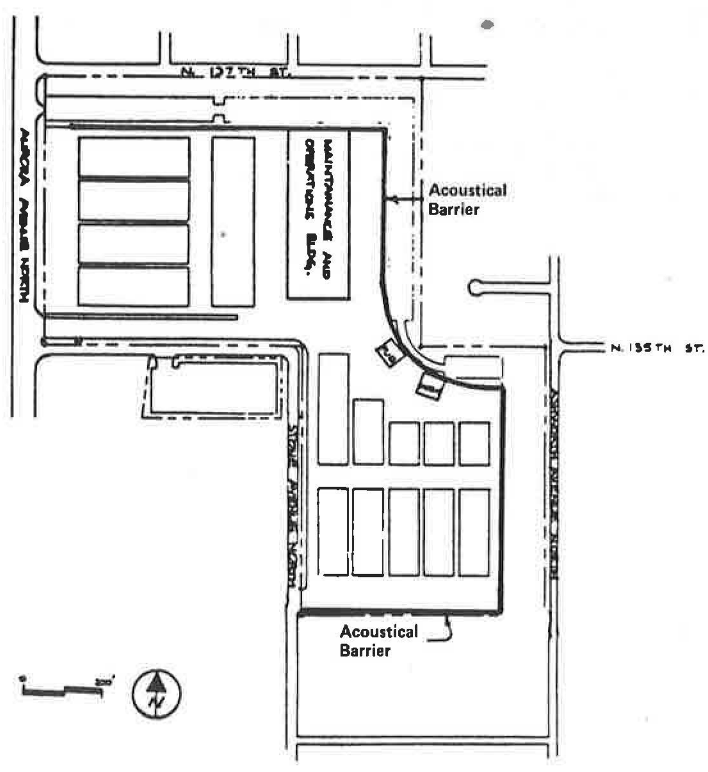
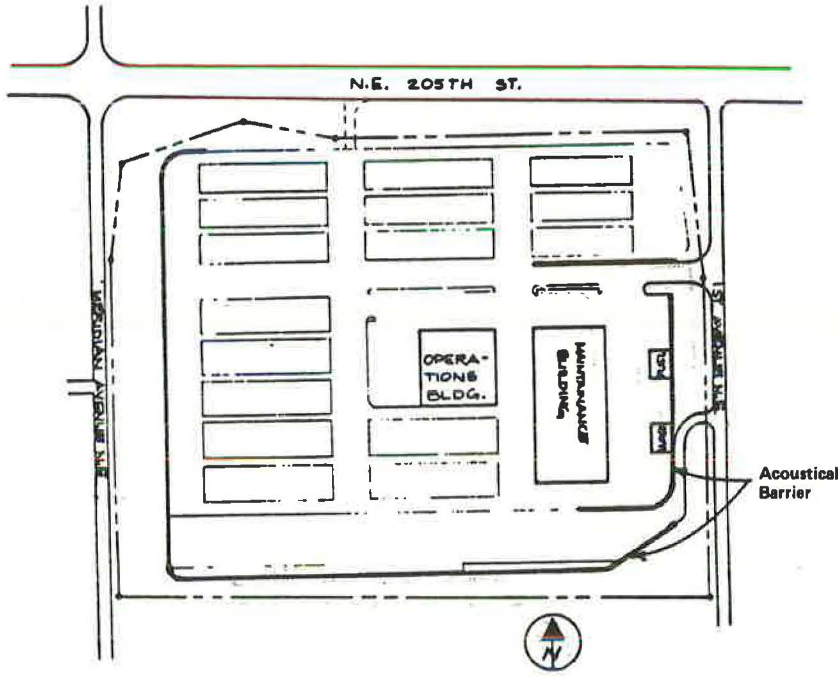


Figure 8. Recommended noise barriers, north base, site 2.



4. Modification of residences along roads on which buses are scheduled to operate is not a cost-effective method of noise control.

5. The major source of noise impact resulting from on-base operations is maintenance activity, and in particular the use of eductor trucks. Bus start-up and pull-out noise is also a significant contributor to the noise impact in community areas surrounding the proposed base.

6. The potential noise impact of maintenance activities that occur inside the maintenance building can be completely mitigated by closing the building doors when these operations are under way.

7. Whenever possible, outside maintenance activities should be scheduled to occur during daytime hours.

8. When eductor trucks are used, portable noise barriers should be used to reduce the potential noise impact.

9. As an overall mitigation measure for on-base sources, and particularly for bus start-up and pull-out noise, construction of noise barrier walls along the perimeter of the operating base is recommended. A masonry block or wooden wall 13 ft high will eliminate the impact of bus start-up and pull-out noise.

10. After detailed plans for the operating base are prepared, a detailed design of the recommended noise barrier walls should be undertaken. This design would specify exact dimensions and locations to provide maximum noise reduction at the greatest cost-effectiveness.

REFERENCES

1. SEPA Draft Environmental Impact Statement/NEPA Environmental Assessment--North Operating Base. Municipality of Metropolitan Seattle, March 1982.
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Stop and Go Urban Intersection Noise

SIMON SLUTSKY, WILLIAM R. McSHANE, JOSE M. ULERIO, SEUNG HWAN LEE, AND PHILIP J. GREALY

A summary of a procedure to predict stop and go urban intersection noise is presented. A computer program that takes into account the effects of urban building structures on multiple reflection and diffuse scattering; vehicle types, mixes, and traffic signalization on microscopic traffic flow behavior; and vehicle acceleration as well as speed and type of vehicle source strength is described. The concepts used in the acoustic model are summarized, and the principal simplifying assumptions in the numerical treatment are noted. The large number of options of street geometry caused by the presence or absence of building walls on any of the eight possible wall locations resulted in considerable program complexity, which was resolved by careful program structure and logic. A typical computer input-output is presented, and some preliminary results for a single vehicle passby are presented.

Past research studies and development efforts related to noise from vehicular traffic streams have primarily focused on models to predict noise impacts from high constant-speed highways, in which the site geometry is either natural terrain or terrain modified by acoustic barrier structures. Few studies have examined the generation and propagation of traffic noise in urban environments or dealt with the impact of noise from stop-and-go traffic. The objective of this study is to develop a prediction model for traffic noise generated by stop-and-go traffic in an urban environment.

PREVIOUS WORK

The literature pertaining to the numerical treatment of acoustic propagation of sound in the presence of tall buildings lining acoustic corridors is relatively sparse, considering its environmental importance. The literature is sparse because of the mathematical intransigence of the acoustic wave equation when any realism of boundary conditions is attempted. Nevertheless, some important studies have been performed, and the following conclusions have been reached:

1. Use of geometric acoustics (ray theory) is justified, provided absorption and diffuse scattering effects are included (1-5);
2. Trapping of energy in the vicinity of the source can be significant for large wall scattering (5); and
3. Large noise reductions are encountered when sound propagates around a corner, and smaller reductions occur on crossing a street.

The most useful vehicular noise emissions data (for purposes of this study) were reported by Hillquist and Scott (6) and by Jones and Hothersall (7). The former revealed that full-throttle exhaust noise at low speeds is 15 to 20 dB more than that of the steady (cruise) condition. Also, the low-speed, full-throttle speed-noise level has a slope corresponding to 10 logV rather than 30 logV. Other investigators model the low speed-noise level as constant up to a lower limit for cruise behavior.

Jones and Hothersall established regression surfaces of sound pressure level (SPL) versus speed and acceleration for two vehicle classes (light and heavy). This work is ideal for purposes of this study, except that it does not distinguish sufficiently between vehicle types, and the confidence bands of the data are rather wide. Use of simulation techniques for steady-flow traffic noise modeling dates back to NCHRP Report 78 (8).

Favre (9) presents a simulation model for unsteady-flow traffic in which the traffic is for a one-way single lane of vehicles, no overtaking, no obstacles (pedestrians, parked vehicles), and the only traffic restraint is that due to consecutive vehicle interaction in response to a traffic light(s). The acoustic medium is assumed free space. The vehicle is defined by its position and the velocity of the vehicle in front. The noise emitted by a vehicle (assumed omnidirectional) depends on its class, velocity, and acceleration. There are two classes of vehicles: heavy and light. For heavy vehicles, the noise-emission correlations reflect only velocity, not acceleration.

Favre finds excellent agreement in the character of the measured data at an intersection and the corresponding simulated results. This agreement extends to the appearance of the acoustic amplitude pulsations that develop and to the noise statistics (L_1, L_{10}, L_{90}, L_{eq}, and speed).

Favre notes the lack of a data base on heavy vehicles and buses and the limitations that this places on his traffic simulation model.

Related studies by Diggory and Oakes (10) describe departures from free-flow traffic in the neighborhood of traffic circles. Noise is speed dependent; arrival times are defined by a random distribution function; and velocity is dependent only on position along the traffic circle. No queue formation is considered. Results of experiments were in satisfactory agreement with predictions.

Jones and Hothersall (11) use their sound level versus velocity and acceleration regressions (7) to develop a simulation for flow at traffic circles. Differences between measured and predicted values were noted and explained in terms of (a) queuing not considered, (b) ground absorption not considered, and (c) need for greater number of vehicle classes.

NETSIM (network simulation) is a microscopic traffic simulation model that was initially developed in connection with the FHWA urban traffic control system (UTCS) demonstration project. In the present context, NETSIM has the following distinct advantages:

1. It is a microscopic traffic model that is supported and promulgated by FHWA;
2. Of all traffic models, it has gained the most acceptance in the traffic engineering community and has been used by a wide variety of interested parties;
3. It is available in both full-network and single-intersection versions, with lower core requirements in the latter case;
4. It currently has data bases that allow estimates of air pollutant emissions and energy consumption as routine outputs; as such, the addition of noise-level estimates is a logical extension, which further supports this FHWA tool;
5. It has been well validated in its previous applications, and it has an associated credibility; and
6. It provides vehicle position and other characteristics that are consistent with the framework of the noise-emissions data base as defined in the contract.

The single-intersection version of NETSIM was reworked as part of this current effort, and its output files were made compatible with the needs of the noise computations program.

ACOUSTIC AND ANALYTIC PREMISES

In order to cope reasonably with complex geometry and acoustics, the following approach was taken and approximations made:

1. Geometric acoustics were assumed valid for the description and quantification of all direct and specularly reflected paths;
2. No scattering of ray paths around corners was considered; and
3. Diffuse scattering was approximated by a pair of diffuse energy-flow equations expressing a balance between upstreet and downstreet flow, absorption, and partial reemission at the walls; loss up the top of the street; and with source energy supplied by the sidewall acoustic illumination intensity.

REFLECTION FIELD

For parallel walled streets, the assumption of geometric acoustics makes possible the use of the method of images. Thus the various path ms pressure contributions for the source (of strength W) and receiver of Figure 1 can be expressed by

$$\langle p^2 \rangle/\rho c W = (1/2\pi) \sum_{n=-\infty}^{\infty} (R^{|n|}/L_n^2) \qquad (1)$$

where L_n is the length of the nth virtual ray path and R is the wall reflection coefficient. (Source doubling because of reflective pavement is assumed.)

For source and receiver in the middle of the street of width D and longitudinal separation Z,

$$\langle p^2 \rangle/\rho c W = (1/2\pi Z^2) + (1/\pi) \sum_{n=1}^{\infty} [R^n/(Z^2 + n^2 D^2)] \qquad (2)$$

This series is unsatisfactorily convergent, but for values of Z/D that are not too small, the series can be represented by an integral:

$$(\langle p^2 \rangle/\rho c W)' \cong (1/\pi Z D) \int_0^{\infty} \exp[-(\gamma Z/D)\eta]\ [d\eta/(1 + \eta^2)]\ ; \gamma = -\ln R \qquad (3)$$

This equation describes field behavior quite well.

Nevertheless, source and receiver separations are unsatisfactory in an urban environment; thus the procedure is to model the direct and first reflection paths exactly, approximate the higher-order reflections by an integral, and base that integral on source and receiver positions in the middle of the street (Figure 2).

The result is a technique whereby the integrals can be stored in the program as tables (computed only once), and the three discrete paths are represented by three simple inverse square subroutine terms. An analysis of the errors encountered in the various simplifications was made, and the errors were found to be quite negligible (a few percent).

It is unfortunate that the conceptual simplicity ends at this point and complications begin to proliferate. The first complication arises when the source and sink are on opposite sides of a cross street (Figure 3). Thus certain paths cannot cross the street, but are reflected into the side streets. Both discrete paths and integral must be modified by using blocking factors that characterize the zones of silence. The blocking factor is identically zero (no transmission) if the ray slope exceeds a limit equal to the diagonal slope across the intersection. For the integral, this slope is reflected in the limits of the integral and eliminates the infinite limit.

The situation is complicated further when the source and receiver are on adjacent cross streets. The graphical representation of ray paths between source and receiver requires the use of both virtual sources and images (Figure 4). Thus path 2-1 between virtual source 2 and virtual receiver 1 is possible as is path 1-2, but path 1-1 is marginal and path 1-0 is blocked. It is seen that each virtual receiver has a finite aperture from within which real or virtual sources may make contributions. The computational procedure in the program was to treat exactly the direct path and first reflection paths and then approximate the higher-order reflections by using the aperture restrictions in

Figure 1. Ray path between receiver and virtual sources.

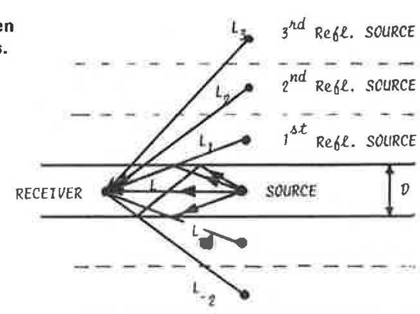


Figure 2. Treatment of higher-order reflection by integration.

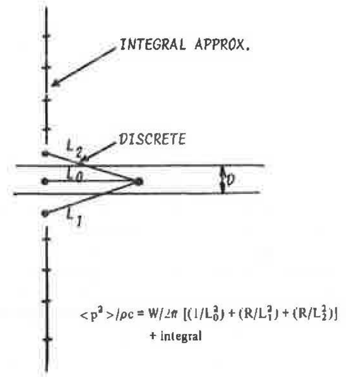


Figure 3. Treatment of contributions crossing an intersection.

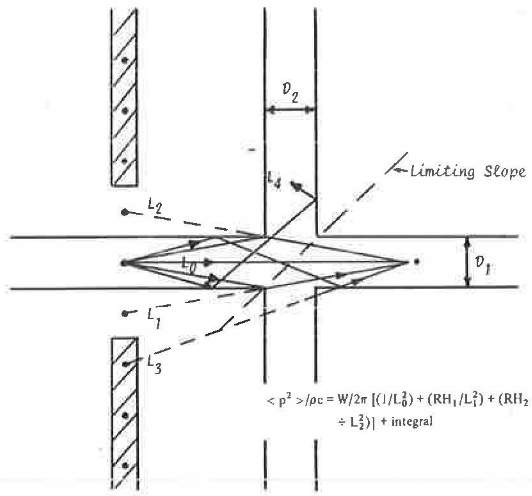


Figure 4. Treatment of contributions going around a corner.

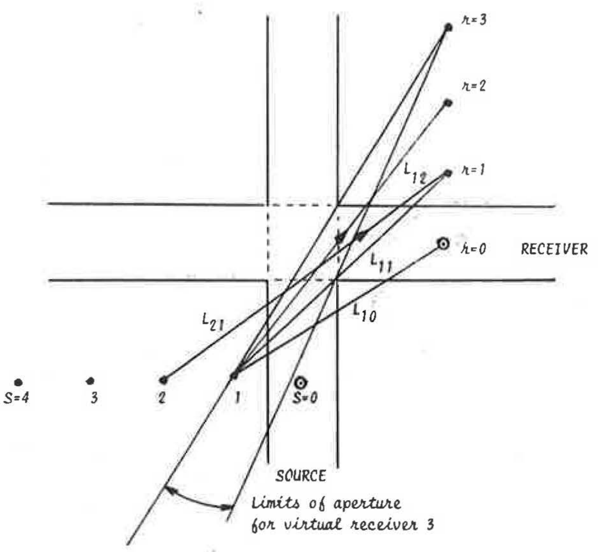
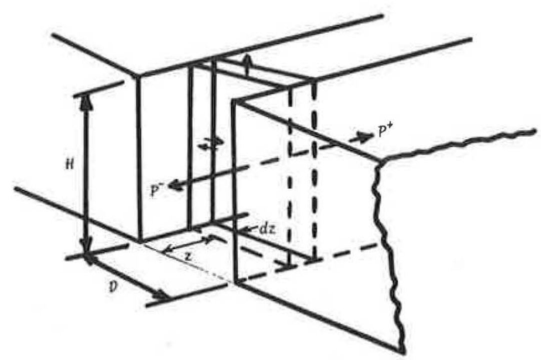


Figure 5. View looking into a walled street.



each case. The computed behavior exhibited for various source and receiver positions is extremely complex, as discussed in the following paragraphs.

The propagation characteristics of sources located in the intersection are similar to those of the (longitudinal) street crossing configuration. The principal difference, however, is that vehicle positions are not confined to a few traffic lanes, but may occupy any point of the area.

Thus the analyst is faced with a difficulty that, from a computer programming point of view, is perhaps more troublesome than any of the difficulties previously noted. That is, the streets need not each have two sidewalls, but rather, each street of any urban intersection may have two, one, or zero walls, and the one wall can be on either side. Thus, in specifying the propagation across the street or longitudinally, a choice must be made from among 16 acoustic configurations, with 16 corresponding computational programming variants. For propagation from the intersection, four variants are required, as is the case for sources on the same street. Theoretically, (3 x 16) + (2 x 4) = 56 subprograms need to be created to satisfy all configuration requirements. Fortunately, a number of subprograms are appropriate for more than one wall combination. Furthermore, the higher-order reflection tables are relevant only for the case 1 streets (walls on both sides), and here again some of the tables can be relevant in two configurations. Nevertheless, the analyst is still left with a fairly complex logic problem; i.e., to choose and generate all of the tables relevant for the intersection, and to choose the appropriate subprograms. These problems were solved by paying special attention to program control structure.

DIFFUSION FIELD

On double-walled streets the treatment of diffusion begins by using the approach taken by Davies (5). The diffusion field is assumed to consist of two power fluxes (P^+ and P^-) directed downstreet and upstreet, respectively, and each is thought of as the resultant of omnidirectional intensity fields (integrated over the respective half spheres). An energy balance equation is established over the surfaces bounded by two parallel planes cutting the street at adjacent longitudinal position coordinates Z and Z + DZ, and by the planes defined by the sidewalls, the pavement, and the roof (Figure 5). The pavement is assumed to reflect perfectly, and the roof is assumed to absorb perfectly. The sidewalls are assumed to reflect specularly, to scatter diffusely (and omnidirectionally), and to absorb the remainder of the incident intensity. All geometric and reflective parameters are assumed constant on a street. An important feature of the Davies formulation is the reemission of part of the diffuse energy incident on the walls (that is, the part that is not absorbed) as components of both upstreet and downstreet power fluxes (P^- and P^+). Thus the effect is that diffuse power is first scattered away from the source region (i.e., a section of acoustically illuminated wall), but it is then partly rescattered back toward the original source section.

The results can be expressed in the following forms:

$$dP^+/dz = -aP^+ + bP^- + \beta hI \quad (4)$$

$$dP^-/dz = aP^- - bP^+ - \beta hI \quad (5)$$

where

- a = (1/D) + (1/2H) - [(1 - α)/2D];
- b = (R + β)/2D;
- β = diffuse reflection coefficient;
- D = width of street;
- H = mean height of buildings (both sides);
- R = reflection coefficient; and
- α = 1 - R - β = absorption coefficient.

The pair of coupled equations can be treated to give uncoupled equations for P^+ and P^-:

$$d^2P^+/dZ^2 = (a^2 - b^2)P^+ - [H\beta(a + b)I] + [h\beta(dI/dZ)] \quad (6)$$

$$d^2P^-/dZ^2 = (a^2 - b^2)P^- - [H\beta(a + b)I] - [h\beta(dI/dZ)] \quad (7)$$

These equations must be solved with boundary conditions P^+ and P^- both approaching zero as Z approaches infinity, and $P^+(0)$ is an externally determined input at Z = 0 (the mouth of the street). Green's functions appropriate to the boundary conditions were then obtained.

There was interest in finding the combined flux $P^+ + P^-$ in the street because of sources in the street and in the intersection, and in the flux $P^-(0)$ issuing into the intersection as a result of the sources in the street. Therefore,

$$P(Z) = P^+(Z) + P^-(Z) \quad (8)$$

$$P(Z) = [(a + b + \theta)/(a + b)]\, Q^+e^{-\theta Z} + [(a + b)\beta h/\theta] \int_0^\infty K(z,\xi)I(\xi)d\xi \quad (9)$$

where

$$K(z,\xi) = \exp[-\theta|z-\xi|] - [b/(a+\theta)]\exp[-\theta(z+\xi)] \quad (10)$$

The power radiated out of the mouth of the street (Q^-) into the intersection is found to be

$$Q^- \equiv P^-(0) = \beta h[(a+b+\theta)/(a+b)] \int_0^\infty I(\xi)e^{-\theta\xi}\, d\xi \quad (11)$$

This analysis was carried out on the tacit assumption that there was only one semi-infinite street opening on a reservoir region. It is necessary to generalize to n streets. For example, consider four streets (n = 1, . . . , 4) emptying into an intersection. The cross-sectional area of each street will be denoted by A_1 to A_4, and the area out the top (the plan view) will be denoted by A_5. The quantity Q_1^+ is then apportioned by assuming that Q_2^-, Q_3^-, and Q_4^- are each shared proportionately to areas (A_1,A_3,A_4,A_5), (A_1,A_2,A_4,A_5), and (A_1,A_2,A_3,A_5), respectively; then

$$Q_1^+ = A_1\left\{[Q_2^-/(A-A_2)] + [Q_3^-/(A-A_3)] + [Q_4^-/(A-A_4)]\right\} \quad (12)$$

where A is the sum of all the areas bounding the intersection (see Equation 14). Q_1^+ is therefore the sum of that portion of each of the power flows from streets 2, 3, and 4 that flow into street 1. Therefore,

$$Q_n^+ = A_n \sum_{m\neq n}^{4} [Q_m^-/(A-A_m)]\,;\ n = 1,4 \quad (13)$$

$$A = A_1 + A_2 + A_3 + A_4 + A_5 \quad (14)$$

To check the results, the following requirement must be satisfied:

$$\sum_{n=1}^{5} Q_n^+ = \sum_{m=1}^{4} Q_m^- \quad (15)$$

NONREVERBERANT STREETS

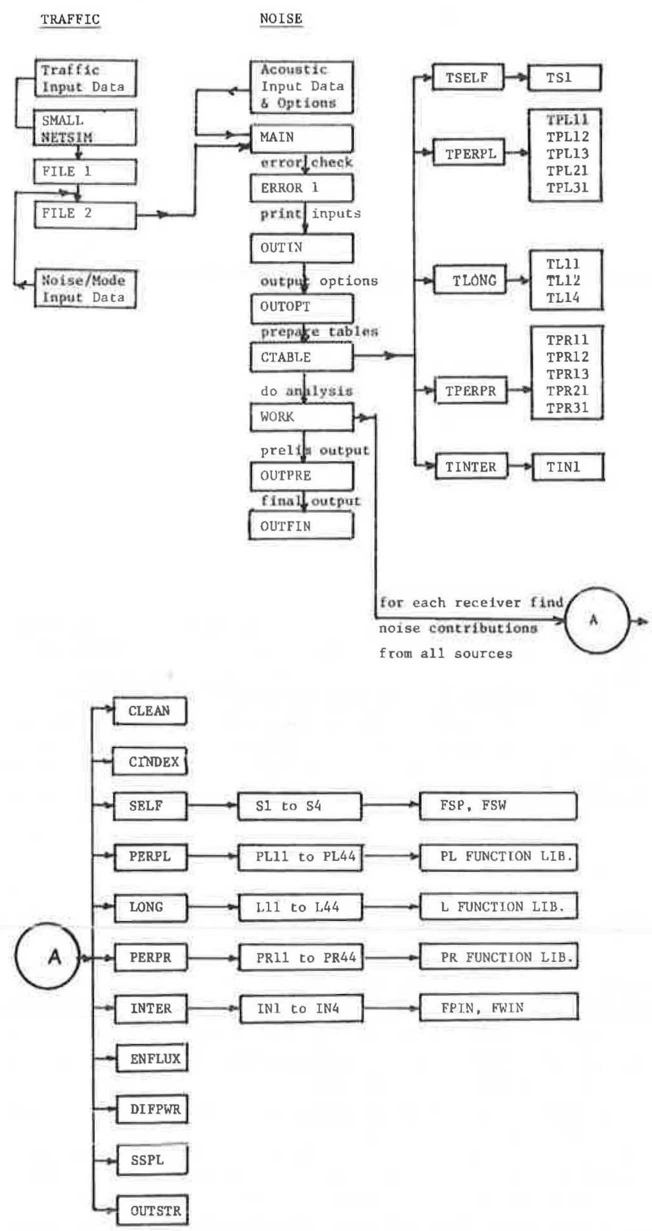
Note that in a street that does not have walls on both sides, it is not possible to create a reverberant field. Thus a street with one wall may have a single reflection of a given ray. In such a street there is no need to compute wall intensities for use as the source function of the diffuse flux-generating mechanism. Thus, in the case of a type 1 street (walls on both sides), which radiates into a street that is not type 1 (e.g., type 2, 3, or 4), the contributions of all orders of reflection on the receptor field must be evaluated, but not those on the diffusion field (i.e., type 2, 3, or 4 are uncoupled for diffusion). Similarly, it is assumed that coupling is negligible in the reverse direction (i.e., that sources located in the open spaces of type 2, 3, or 4 streets can have a negligible contribution to the diffuse field in a type 1 street). Hence the wall intensities in a type 1 street because of sources in streets of type 2, 3, or 4 are not considered. An exception is made for the intersection. In this case sources can be quite close to the target walls, and incident rays can enter at angles close to the wall normal; thus the contribution may be significant.

COMPUTER PROGRAM

The procedure followed in carrying out the numerical computations that correspond to the previous discussion is most easily described by using the program flow diagram shown in Figure 6.

The first step in the process is to prepare traffic data for SMALL NETSIM (traffic lane geometry,

Figure 6. System logic for INTERSECTION NOISE program.



volume, vehicle mix, light signal times, bus lane assignment, turn ratios, and run). The tape output is called file 1; it consists of extracted information of vehicle position, speed, and acceleration. Combined with the acceleration and velocity noise data base as input, the NETSIM program generated file 2, which contains position and sound power data for all vehicles in a form suitable for the INTERSECTION NOISE program. Inputs for this next step include building geometry and reflective characteristics (specular and diffuse reflection coefficients) as well as selecting output options. Note that the same file 2 can be used with variations on building geometry and reflection, and the same file 1 can be used to test the effect of different vehicle emission characteristics (by creating a new file 2).

The sequence of the INTERSECTION NOISE program is first to check discrepancies in input data (ERROR 1) and then to print out the input data (OUTIN). Then the output options are listed (receiver positions and number; source tabular increment; choice of L_{10}, L_{eq}; histograms at N_1 stations and time histories at N_2 stations; printout interval if greater than 1 sec); i.e., see Figures 7 and 8.

The next subroutine is CTABLE, which first decides from each street type (1, 2, 3, or 4, depending on wall configuration) and street type pair (e.g., if both streets of a pair are type 1 and are on opposite sides of the intersection) what the appropriate table-generating subroutine should be. The table entries are the higher-order contributions at each receiver station because of the unit source strength at each (tabulated) source station. The general sequence is as follows:

1. Let the first receiver street be designated NR=1;
2. Let the first source street be designated NS=1;
3. Because this is a self-noise configuration, go to the subroutine TSELF;
4. Based on whether or not street NR=1 is of type 1, go to table-generating routine TS1 (and execute) or return to CTABLE;
5. Let the second source street be NS=2;
6. Because the street pair is now perpendicular and the sound makes a left turn in moving from source to receiver, go to subroutine TPERPL; and
7. Based on the source street type (1 to 4) and receiver street type (1 to 4), go to the appropriate table-generating subroutine; but because tables are needed only if one or both streets are double walled (type 1), the number of different cases is sharply reduced; finally the appropriate table is computed, and control is returned to CTABLE.

The source index NS is taken through all these steps until all source streets (including the intersection area) are tested for choice of table type and the tables are computed.

Figure 7. Typical street configuration printout.

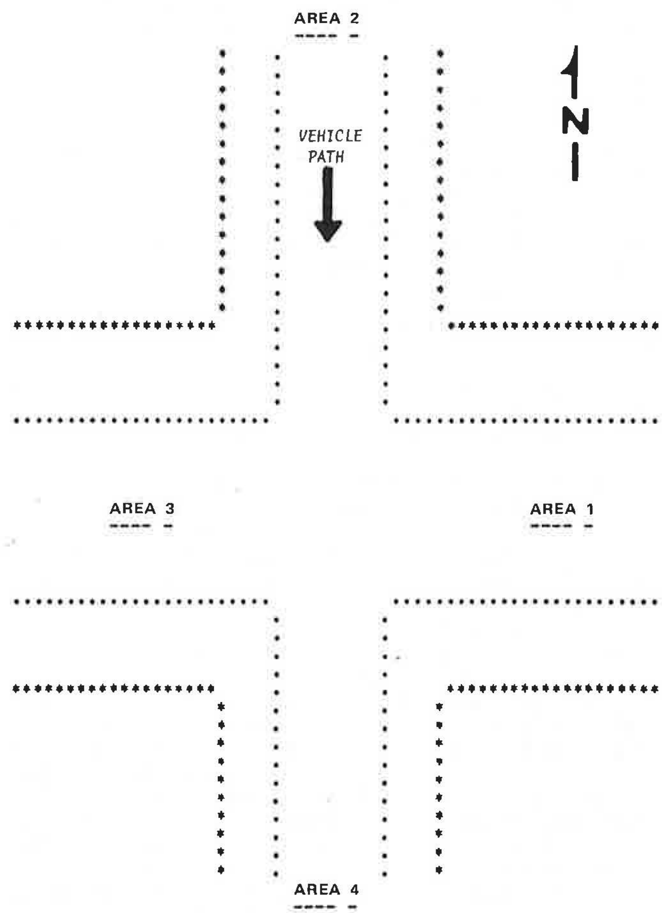


Figure 8. Printout of geometric input parameters.

STOP-GO PROGRAM : TEST RUN FOR THE VALIDATION(SITE #2 ; CASE 1)

LOCATION : 3RD AVE. AND 23RD ST.,NEW YORK(MANHATTAN), N.Y.

DATA : OCTOBER 30, 1982

AREA	LENGTH (FT)	BLDG-BLDG WIDTH(FT)	SIDEWALKS(FT) SIDE A	SIDEWALKS(FT) SIDE B	NUMBER OF LANES		NUMBER OF SIDES	HEIGHT (FT)
1	700.0	101.0	28.0	29.0	2	2	2	36.0
2	300.0	98.0	25.0	25.0	2	2	2	48.0
3	500.0	101.0	29.0	28.0	2	2	2	56.0
4	300.0	96.0	25.0	25.0	2	2	2	45.0

AREA	REFLECTION COEFFICIENT	SCATTERING COEFFICIENT	RECEIVER DISTANCES(FT) LATERAL	RECEIVER DISTANCES(FT) LONGITUD.	SOURCE DIST LONGITUD.(FT)
1	0.60	0.30	10.0	15.0	10.0
2	0.60	0.30	105.0	15.0	20.0
3	0.60	0.30	10.0	15.0	20.0
4	0.60	0.30	17.0	15.0	20.0

NOTES

1)AREA 5 IS THE INTERSECTION

2)CODES BELOW
..... IS THE CURB
(BLANK) SHOWS BUILDINGS NOT PRESENT
***** SHOWS BUILDINGS PRESENT

Next the receiver street index is stepped to NR=2, the source index to NS=1, and the cycle of tests is repeated. Thus 20 tables each of $\langle p^2 \rangle$ and wall intensity would be created if all streets had double walls, and no tables would be created if walls did not exist.

When the tabulation of the higher-order reflection terms is complete, the control is transferred to subroutine WORK. In this program the previously developed tables and the precise position and strength of each source are used to find the higher-order reflection contribution to $\langle p^2 \rangle$ and wall intensity at each receiver by interpolation. Then the exact direct and first reflection terms at each receiver due to each source are added.

The choice of computational formulas in a given street intersection depends on the type of wall geometry, and the sequence of choices is similar to that in constructing the tables.

In general, the WORK sequence is as follows.

1. CLEAN starts all working variables and steps to the next time increment.
2. CINDEX accesses file F2 for the vehicle positions and strengths for the new time and arranges them in arrays accessible to the following subroutines.
3. In WORK the first receiver street index is set (NR=1) and the first source street index is set (NS=1). This sends control to subroutine SELF.
4. SELF tests for the appropriate street type from among types 1 to 4 and sends control to the corresponding subroutine from among S1 to S4. Then the direct, first-order, and higher-order (interpolating from the tables) contributions to $\langle p^2 \rangle$ and wall intensity are computed for each receiver in NR=1 and for each source in NS=1, and the resulting array is stored. Control is then restored to WORK.
5. The source street index is stepped to NS=2, control sent to subroutine PERPL, choice made from among 16 possible street type pairs, and control sent then to the appropriate subroutine from among PL11 to PL44. The contribution to $\langle p^2 \rangle$ and wall intensity are computed for each receiver in NR=1 and each source in NS=2, and the results are added to the previously stored array.

The process is repeated in this way by stepping the source street index through to 5 (thereby calling subroutines LONG, PERPR, and INTER), and then the process is repeated for receiver streets NR=2,3,4. Control is then sent to ENFLUX (through WORK) to calculate the diffuse power flux emptied into the intersection by all streets, mixed, and reinjected into each street as Q_1^+ to Q_4^+.

DIFPWR next computes the diffuse power P in all streets. Subroutine SSPL sums the mean square pressure at each station of all streets due to the reflection and diffuse power contributions, and then it calculates the A-weighted sound pressure level. This array is stored in output storage OUTSTR, and control is returned to WORK.

At this point the WORK cycle is repeated by taking the files through the CLEAN cycle, updating the time and vehicular data, recomputing the sound pressure levels, and storing the results for the time step. The number of cycles of repetition is set by the user as an input option. After all cycles are completed, control is shifted from WORK to OUTPRE, where the output is arranged in preliminary form, and then to OUTFIN--the final output.

RESULTS FOR SINGLE-VEHICLE PASSBY

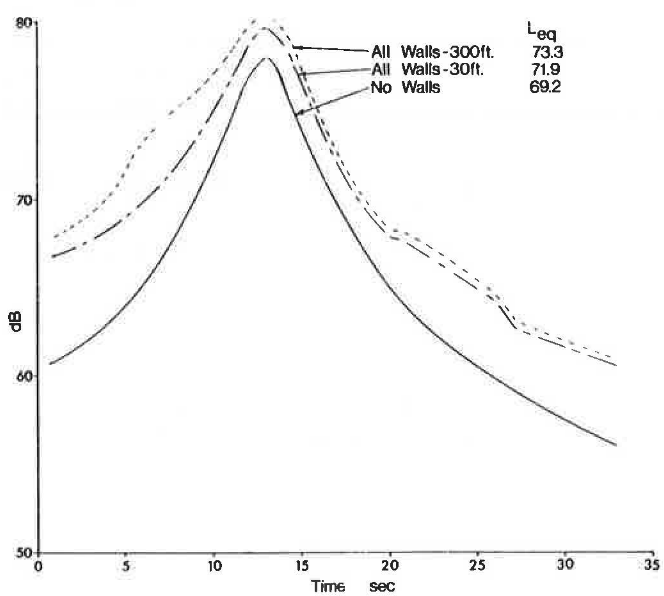
Detailed computations and analysis were carried out for the cases of a single-vehicle passby at constant speed and at constant source strength (corresponding to 80 dB at 50 ft over hard pavement). These cases were run first as an aid in debugging the system as well as for their own intrinsic interest, which is the reason for presenting them here.

The street configuration is shown in Figure 7, in which the main streets are represented by streets 2 and 4 with a width of 120 ft (building line to building line, whether or not there are walls), and the side streets are represented by 1 and 3, which have a 100-ft building-to-building width. Receivers are all located 10 ft from sides A (right side looking into the street from the intersection) at 20-ft intervals. The vehicle path is along YS = 77.5 ft in street 2, at YS = 62.5 ft in street 4, and midway between as it crosses the intersection. (The peculiar path was an inadvertent artifact of the choice of test path and is not ordinarily anticipated.) The vehicle speed was taken as 40 ft/sec, and the starting location was ZS = 560 ft into street 2.

Figure 9 shows the time history at receiver 5 in street 1 (80 ft from the boundary of the intersection) due to the cases of no walls and 30- and 300-ft-high walls lining all streets. The field of the no-walls case is exactly as anticipated for pure inverse square law propagation (without ground attenuation).

By contrast, the cases of all walls reveal interesting behavior of quite a different character. The most striking difference is the sudden transition of levels (between t = 13 and 17 sec) from values less than to values greater than the no-wall case, as well as the jumpy behavior at t = 10, 20, and 29 sec. The jumps take place each time a reflection path becomes possible or impossible. The lower-order paths produce jumps because they are always shorter than the higher-order paths and involve fewer reflective losses (at 2.2 dB per reflection for a specular reflection coefficient of 0.6). The highest levels are reached between t = 13 and 17 sec because of the direct path contribution. Note that the vehicle is still 80 ft from the intersection boundary at time t = 13 sec, but the unsymmetric configuration of both vehicle and receiver opens up the direct line-of-sight path.

Figure 9. Time history in receiver area 2 caused by source moving from area 2 to area 4.



The direct path contribution continues to rise as the vehicle crosses 90 ft through the intersection and is cut off shortly thereafter by the walls of streets 1 and 4. Between t = 18 and 28 sec, propagation from street 4 into street 1 is primarily by paths that reflect once in each street. But at time t = 29 sec that path is cut, and the higher-order (more than one in either street) reflective contributions remain. The dropoff rate for that component depends on the source and receiver positions in a quite complicated way, and the receiver level can either rise or drop as the source approaches the intersection.

Study of the numerical computations for the case of a 30-ft wall indicates that the contribution of the diffuse reflection mechanism to the final levels is of little practical significance. Thus at t = 1 sec, when the source is at ZS = 560 ft, the diffuse reflection contributes about 7 percent to the final energy (0.3 dB), and this percentage is generally less (about 0.2 dB), although values of as much as 15 percent have been noted at some source and receiver position combinations.

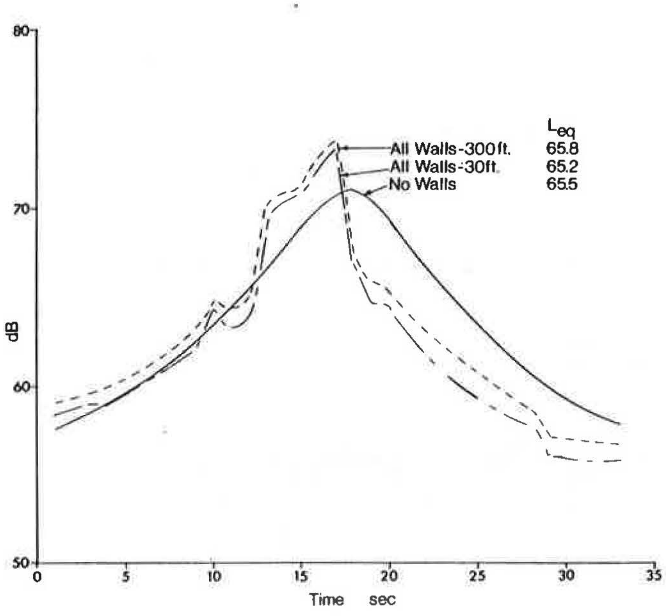
Before considering the high-wall case for the perpendicular street configuration, it is interesting to examine the case of receiver position 5 located in street 2. The results for the no-wall and 30-ft-wall cases are shown in Figure 10.

One interesting result is that the maximum levels differ by less than 2 dB between walled and no-walled configurations, but that the difference increases to about 6 dB at a distance of 480 ft on the same side of the intersection. Crossing the intersection results in a roughly 3-dB drop in levels for the walled configuration. Jumps at t = 21 and 26 sec occur because of discrete changes (gain or loss) of reflection paths. The change in slope of the curve at t = 5 sec is caused by the takeover of the higher-order reflection as the dominant contribution between t = 1 and 5 sec.

Of considerable significance is the difference in the levels on street 1 as compared with street 2; about 6.7 dB, on an energy average. The implication is that a receiver located 80 ft eastward into this 100-ft-wide sidestreet and exposed to the southbound traffic stream on the 120-ft-wide main street will be about 6.7 dB quieter on the basis of L_{eq}.

In considering the effect of high walls (300 ft), note that the effect of diffuse scattering is relatively small in the neighborhood of the maximum street levels (about 0.5 dB for the corner propagation, area 2, receiver 5; and about 1 dB for source and receiver on the same street). It appears, however, that it may reach 3.5 to 4 dB in some regions of the same street propagation, contributing 1.4 dB to the overall L_{eq} for that configuration. Of great interest is the difference in L_{eq} experienced in street 2 versus that in street 1 (7.5 dB).

Figure 10. Time history in receiver area 1 caused by source moving from area 2 to area 4.



RESULTS FOR URBAN INTERSECTION TRAFFIC

Measurements of traffic noise and traffic statistics (vehicle count by lane, type, turn frequency, bus stop characteristics, and so forth) were made at three urban intersections. The three sites, with specific details on the intersection geometrics and building configurations, are summarized as follows:

1. Site 1--Francis Lewis Boulevard and Union Turnpike, Queens, New York: no buildings or other vertical surfaces at the intersection; intersection of 2 two-way streets; and a single defined direction of travel during peak periods;
2. Site 2--Third Avenue and 23rd Street, New York, New York: buildings on all four intersection approaches ranging from three to five stories; intersection of 2 two-way streets; and a single defined direction of travel during peak periods; and
3. Site 3--Madison Avenue and 46th Street, New York, New York: buildings located on all four intersection approaches with 10 or more stories; intersection of 2 one-way streets; and a single defined direction of travel during peak periods.

Figure 11. Hourly traffic volumes and vehicle classification counts: validation of site 2.

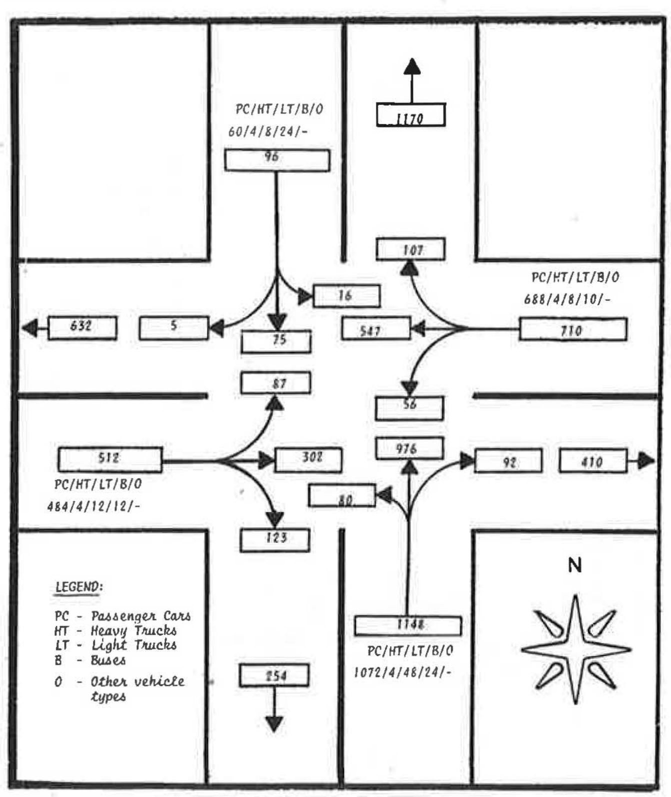


Figure 11 shows an example of the type of traffic data required (as collected for site 2), and Figure 12 shows a layout of intersection geometry and microphone placement.

Figure 13 shows a time history at site 2 for three traffic cycles for microphone M2. These data were taped in the field and reduced by playback to a microcomputer system. Figure 14 is a time history of the output from the corresponding INTERSECTION NOISE program. Note that the lack of detailed correspondence between the measured and predicted histories is no cause for concern, because subsequent sections or cycles of the actual time history differ from each other by as much. Of greater significance are the histograms of Figures 15 and 16. It is interesting that all of the actual noise-level histograms show sharp lower-level cutoffs, which correspond to a constant ambient background.

Finally, the data in Table 1 summarize the actual and predicted noise levels for the three evaluation sites. The actual values of L_{eq} and L_{10} are generally greater than the predicted values by about 2 dB(A) for microphone positions that involve bus acceleration (R1 and R2) and by about 0.7 dB(A) for sites at 200 ft from the position of the bus stop.

Figure 12. Validation of site 2: Third Avenue and 23rd Street.

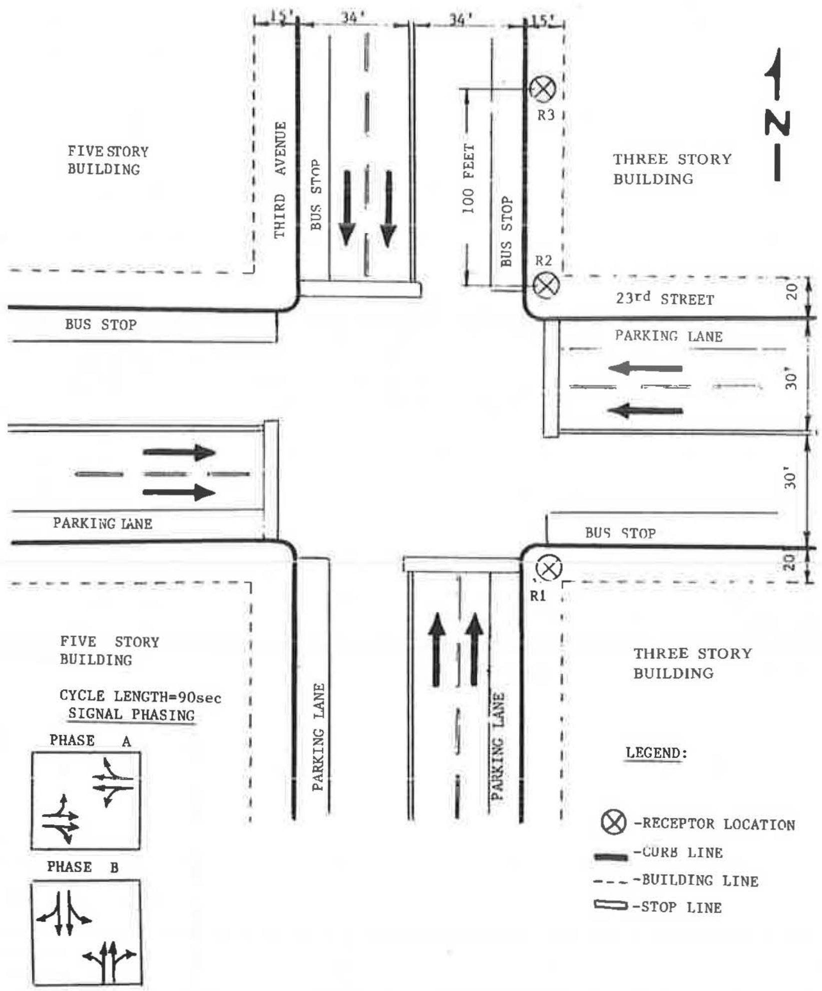


Figure 13. Time history of actual noise levels at receptor location 2.

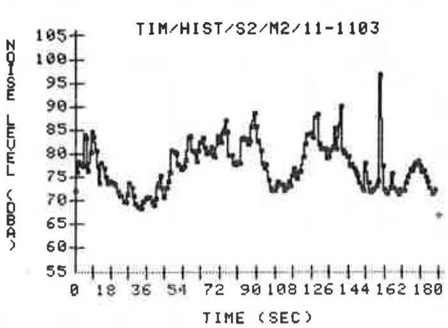


Figure 14. Time history of predicted noise levels at receptor location 2.

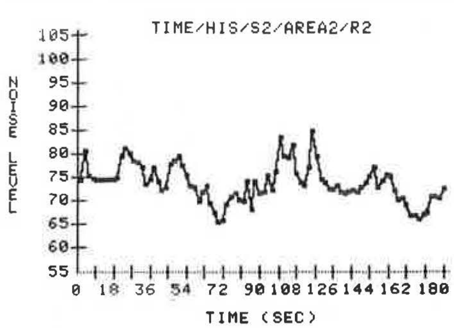


Figure 15. Histogram of actual noise levels at receptor location 2.

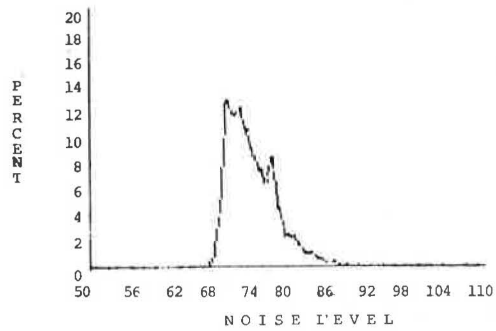


Figure 16. Histogram of predicted noise levels at receptor location 2.

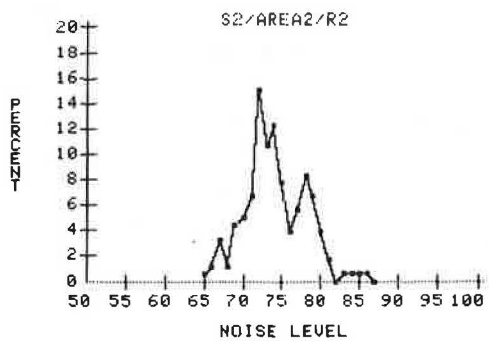


Table 1. Summary of actual and predicted noise levels at evaluation sites.

	Noise Level [dB(A)]					
	L_{eq}		L_{10}		Standard Deviation	
Location	Actual	Predicted	Actual	Predicted	Actual	Predicted
Site 1						
R1	72.8	68.5	74.4	70.0	3.2	4.5
R2	71.5	69.4	74.0	71.5	3.6	4.5
R3	69.6	69.2	72.6	69.0	3.5	4.8
Site 2						
R1	76.3	77.1	79.1	80.6	3.9	4.7
R2	78.6	76.0	80.0	78.7	3.9	3.9
R3	75.9	75.2	79.0	78.5	4.6	4.1
Site 3						
R1	79.4	77.0	81.5	79.3	5.2	6.8
R2	77.1	79.0	78.8	79.0	4.0	5.9
R3	77.2	77.9	80.1	78.8	4.3	6.5

ACKNOWLEDGMENT

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Statistical Comparison of STAMINA 1.0 and STAMINA 2.0/OPTIMA for a Typical Barrier

LOUIS F. COHN, CHARLES F. RIDDLE, AND WILLIAM BOWLBY

The FHWA has produced several computer versions of its highway noise-prediction model, including STAMINA 1.0 and STAMINA 2.0/OPTIMA. These two versions are nearly identical mathematically, but STAMINA 2.0/OPTIMA has several new features designed to enhance accuracy and, more importantly, to lead to better barrier designs. The results of a simultaneous application of STAMINA 1.0 and STAMINA 2.0/OPTIMA for the same barrier, which is located on I-65 immediately north of the proposed I-65/I-440 interchange in Nashville, are reported. Basic statistics are used to evaluate differences between program output. Also, the nonoptimized final barrier design for STAMINA 1.0 is compared with the optimized STAMINA 2.0/OPTIMA barrier design in terms of cost. Although all the results of an in-depth research endeavor are not reported in this paper, two significant conclusions are demonstrated for this application. First, STAMINA 1.0 and STAMINA 2.0 produced basically equivalent results, which is to be expected. Second, the optimization process produced a significant reduction in expected barrier costs based on cost data contained in OPTIMA.

During the past 2 years researchers have been involved in designing a comprehensive noise barrier system for the 8-mile I-440 project in suburban Nashville. For the first section of the project (approximately 3 miles), the STAMINA 1.0 (1) computer program was used to predict noise levels and to design barriers. The remaining sections have been studied by using the STAMINA 2.0/OPTIMA (2) package. One unique part of the project was analyzed with both versions of STAMINA. The purpose of this paper is to discuss the similarities and differences observed by this dual analysis.

Currently, the literature on highway noise does not contain a comparative study of STAMINA 1.0 and STAMINA 2.0, although a report by Anderson et al. (3) does examine comparative data from preceding models. Thus one objective of this paper is to include a documented study of one location where both programs were used to confirm several assumptions. The first assumption is that the basic prediction aspects of the models give the same results. This is significant because many highway projects in the United States have been studied by using both programs for one reason or another. Although it is expected that the STAMINA 1.0 and 2.0 programs should give the same results, there are enough differences between the two programs that a comparison is appropriate. The second assumption to be confirmed is whether the balanced approach to barrier design (OPTIMA) will produce significant savings when compared with the traditional STAMINA 1.0 approach. The savings are determined by using the cost data contained in OPTIMA, which are based on actual barrier costs per linear foot in various height zones.

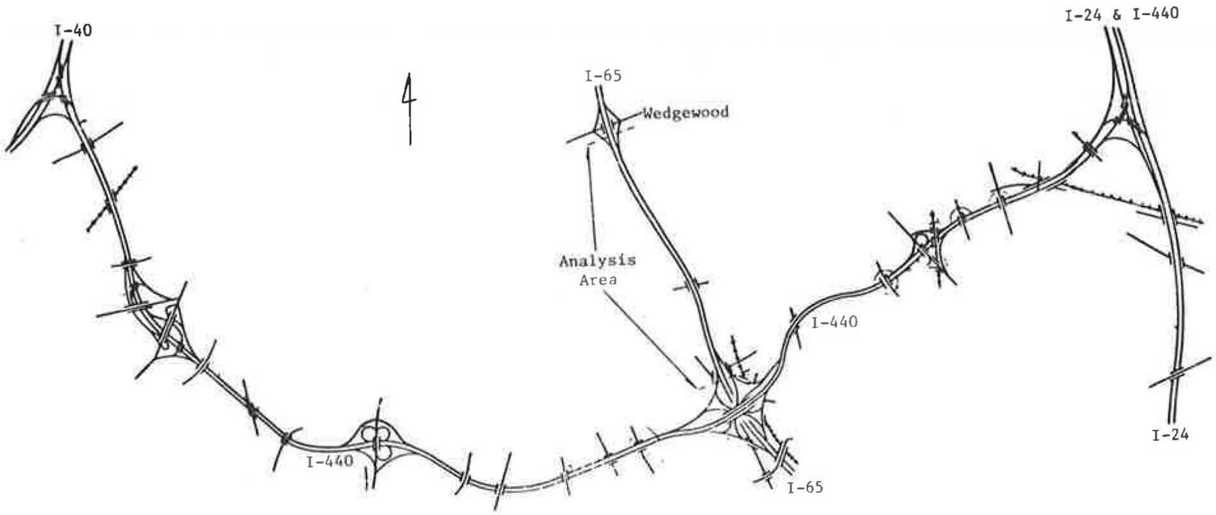
It is not the intent of this paper to report the results of a long-term, intensive research study aimed at model validation or the determination of barrier cost. Rather it is meant to illustrate, for at least one application, that the two programs are equivalent and that OPTIMA can be a money-saving tool. It is also not the intent of this paper to draw any conclusions concerning the effectiveness or cost parameters used in OPTIMA.

The section analyzed with both methods was located on I-65 immediately north of the I-65/I-440 interchange. The limits of the sections were Wedgewood Avenue (1 mile north of I-440) and the northern portion of the interchange (see Figure 1). Thus the study area was approximately 1 mile long. Barriers were considered on the west side of I-65 only, or adjacent to the southbound lanes. Fifty single-family homes were classified as first- or second-row receivers, along with one school and a five-unit apartment building. The existing portion of I-65 is slightly depressed for the major portion of the project area, and slightly elevated for the rest. Construction plans call for the addition of one travel lane in each direction, as well as ramps at the I-440 interchange.

DIFFERENCES BETWEEN STAMINA 1.0 AND STAMINA 2.0

Although the basic emission, propagation, and diffraction algorithms remain unchanged between the two

Figure 1. Location of study area in Nashville.



programs, there are several significant improvements to STAMINA 2.0 when compared with STAMINA 1.0 (2):

1. Time-sharing nature,
2. Input format,
3. Barrier height changes,
4. Barriers on elevated structure,
5. Revised alpha factor operation,
6. Shielding factors,
7. Noise level output format,
8. Acoustics output,
9. A-weight sound level only,
10. No receiver sound level criterion, and
11. Input parameter capabilities.

Each of the improvements is discussed in the user's manual (2); therefore these discussions will not be repeated here. Suffice it to say that several of the improvements will result in slightly different equivalent sound level (L_{eq}) values at the receivers, even before the optimization process. These include numbers 4, 5, and 6 from the aforementioned list.

Of particular significance is improvement 5--revised alpha factor operation--which allows for a certain degree of excess ground-attenuation effect in the presence of barriers. Recall that STAMINA 1.0 completely eliminates excess ground attenuation whenever a barrier penetrates (or nearly penetrates) the plane between the roadway segment and the receiver. This changes the propagation rate from 4.5 dB(A) per distance doubling (soft site) to 3.0 dB(A) per distance doubling (hard site), on the assumption that the diffracted source has been elevated to the top of the barrier and is therefore less susceptible to excess ground attenuation. This process may result in higher-than-actual levels, because in low barrier cases excess ground attenuation is still a significant factor.

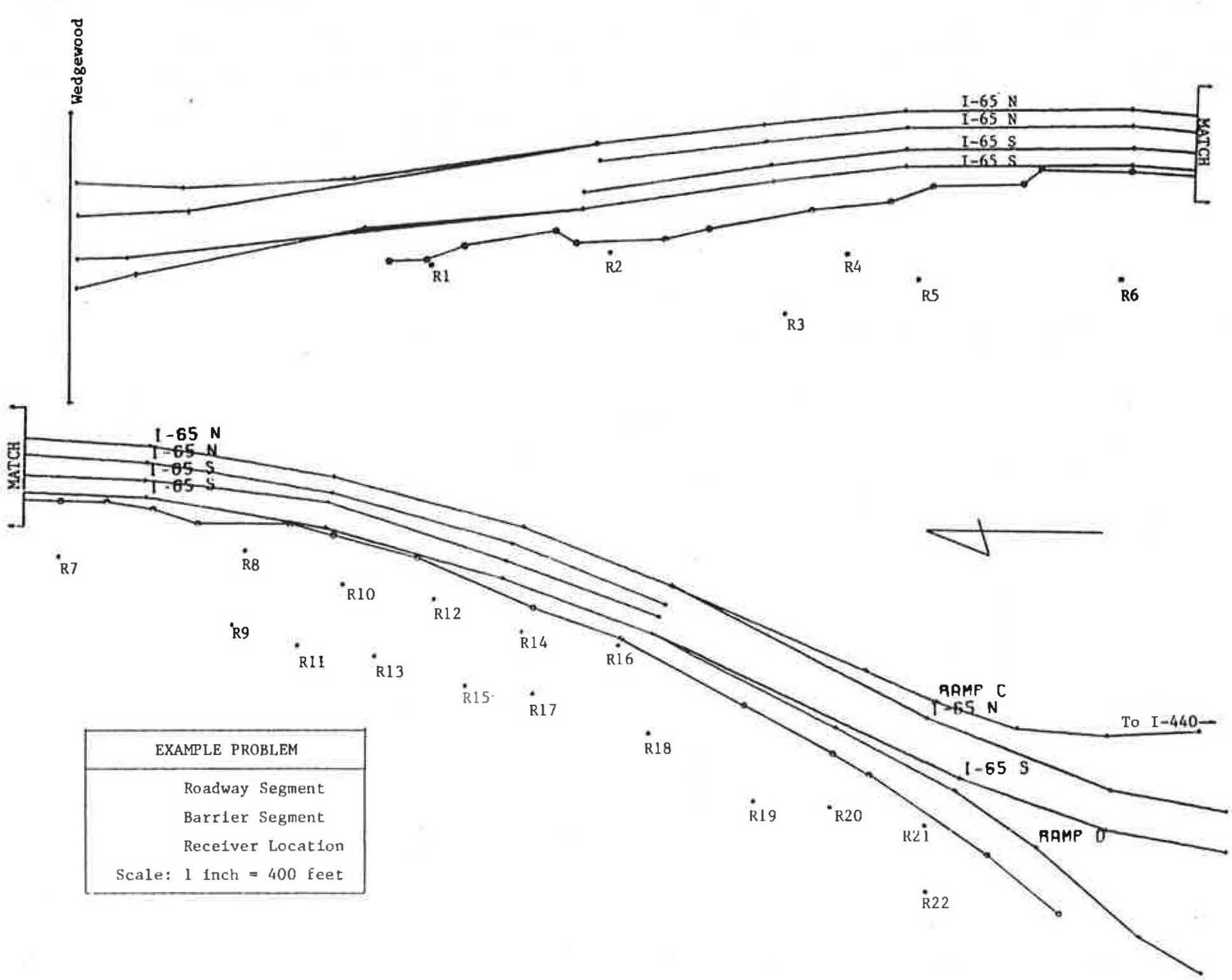
On the other hand, STAMINA 2.0 computes both barrier attenuation and excess ground attenuation, and stores only the larger of the two. Thus the barrier takes effect only when its diffraction attenuation overcomes the excess ground attenuation (2). Although this does not perfectly simulate the physical phenomenon, it is clearly an improvement over the STAMINA 1.0 consideration of ground attenuation. It should be evident that for low barriers, STAMINA 2.0 will produce slightly lower values than STAMINA 1.0.

ANALYSIS

Fifteen receiver locations were examined by using each program, with an additional seven being examined with STAMINA 2.0 only. Figure 2, which is a plan view plot generated by the Vanderbilt VUPLOT (4) interactive computer graphics package, shows the locations of the receivers in relation to I-65. First-row receivers include R1-R8, R10, R12, R14, R16, and R18-R22.

The analysis process was as follows. STAMINA 1.0 was run without any barriers, and then it was rerun several times with different barrier configurations,

Figure 2. Plan view of analysis area.



until the final STAMINA 1.0 barrier was developed. This barrier represented the most efficient design obtainable from STAMINA 1.0 to meet the 67-dB(A) goal. This final STAMINA 1.0 barrier was then entered into STAMINA 2.0 to obtain a cost value from OPTIMA and to compare what should be equivalent scenarios. Thus the initial STAMINA 2.0 barrier should provide the same results as the final STAMINA 1.0 barrier. OPTIMA was then used to the fullest extent possible to produce the most efficient barrier meeting the 67-dB(A) goal.

In summary, the following values were generated and compared:

STAMINA 1.0	STAMINA 2.0/OPTIMA
No barrier	No barrier
Final barrier	Initial barrier
Final barrier	Optimized barrier

RESULTS

The results for each receiver, including those 15 for which both programs were used, are given in Table 1. It would be expected that the most likely candidate for similarity would be a comparison of the no-barrier cases. This is the situation, as shown in Figure 3. For all 15 receivers, the difference in the means is 0.3 dB(A). The standard deviation around that differnce in means is small--0.5 dB(A). A paired t-test was performed to confirm that this difference is not statistically significant. The conclusion drawn at this point is that STAMINA 1.0 and STAMINA 2.0 produced the same results, at least for one scenario. This should be reassuring to the analyst who may find it necessary to switch programs midway through a project.

The differences between what are also two identical situations--the final STAMINA 1.0 barrier and the initial STAMINA 2.0 barrier--are shown in Figure 4. The difference in the means for the two programs is also adequately small in this comparison--1.5 dB(A), with a standard deviation about the mean of only 0.6 dB(A). In every case STAMINA 1.0 is higher than STAMINA 2.0. The paired t-test confirmed this difference to be statistically significant. That STAMINA 2.0 consistently predicted slightly lower results can be explained by the ability of the program to consider the larger excess ground attenuation in lieu of diffraction attenuation in those appropriate situations. As mentioned earlier, STAMINA 1.0 will completely neglect ground attenuation when a barrier is present.

A conclusion may be drawn at this point: The differences in the means between these two computer versions of the FHWA model are quite small when considering both propagation and barrier attentuation. Even though the difference in the means may be statistically significant, the slightly lower values obtained from STAMINA 2.0 are explainable by improvements in that program.

Because the two programs produce similar values, the next comparison is of the best barrier each could produce. A representation of such a comparison is shown in Figure 5, which is the final STAMINA 1.0 barrier versus the optimized STAMINA 2.0 barrier. The results are virtually identical, with the difference in the means being only 0.1 dB(A) with a standard deviation of 0.7 dB(A). This is to be expected because the goal for each design was the same--67 dB(A) at the critical receivers.

Figure 6 is included to visually summarize the differences in predicted values for both versions of STAMINA for the 15 receivers. Note that satisfactory agreement is obtained.

The two barriers represented in Figure 5 performed equally well in terms of final noise levels at the receivers. The only difference is that the STAMINA 1.0 barrier represents the best efforts of an experienced group of noise analysts in determining the design. The STAMINA 2.0 barrier, on the other hand, represents use of the effectiveness and cost-balancing approach that is integral to OPTIMA. Cost data for each of these barriers were obtained by running OPTIMA for the initial STAMINA 2.0 barrier (equivalent to the final STAMINA 1.0 barrier) and the optimized STAMINA 2.0 barrier; the material

Table 1. Test results.

Receiver No.	Noise Levels [dB(A)] No Barrier STAMINA 1.0[a]	STAMINA 2.0[a]	Final Barrier, STAMINA 1.0[b]	Initial Barrier, STAMINA 2.0[b]	Optimized Barrier, STAMINA 2.0
1	76	76	66	64	67
2	74	74	67	65	67
3	69	68	64	62	63
4	71	71	67	65	67
5	70	69	67	66	67
6	70	69	65	64	65
7	73	73	68	67	67
8	75	75	67	66	66
9	-	69	-	65	65
10	-	74	-	68	67
11	-	66	-	62	62
12	75	75	68	67	67
13[c]	66	65	63	62	62
14	75	74	64	63	65
15	-	65	-	63	63
16	80	80	66	64	67
17[c]	71	71	65	64	65
18	-	67	-	64	66
19	74	74	67	66	67
20	-	72	-	65	66
21	77	77	67	64	67
22	-	69	-	63	66

[a]See Figure 3.
[b]See Figure 4.
[c]Second row receivers, with 4 dB(A) manually subtracted from the STAMINA 1.0 results.

Figure 3. Comparison of no-barrier cases: STAMINA 1.0 versus STAMINA 2.0/OPTIMA.

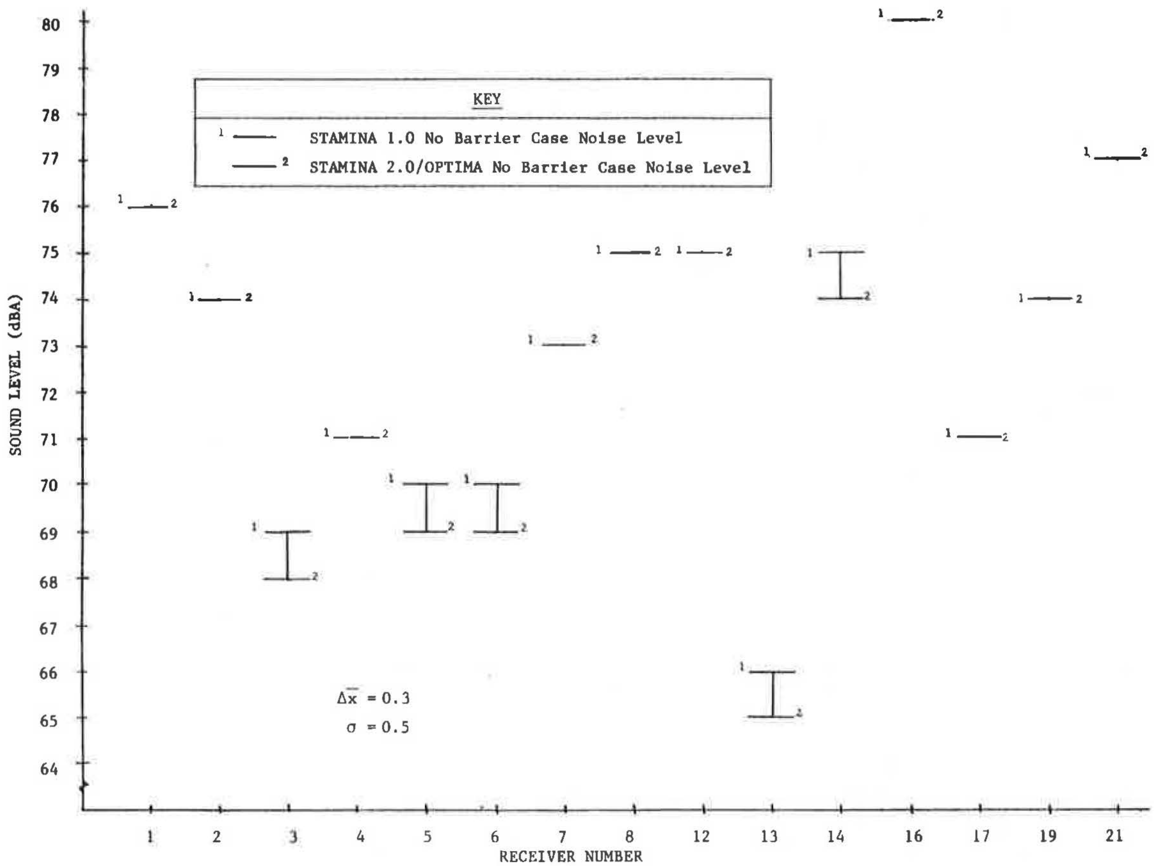


Figure 4. Comparison of final STAMINA 1.0 barrier versus initial STAMINA 2.0/OPTIMA barrier.

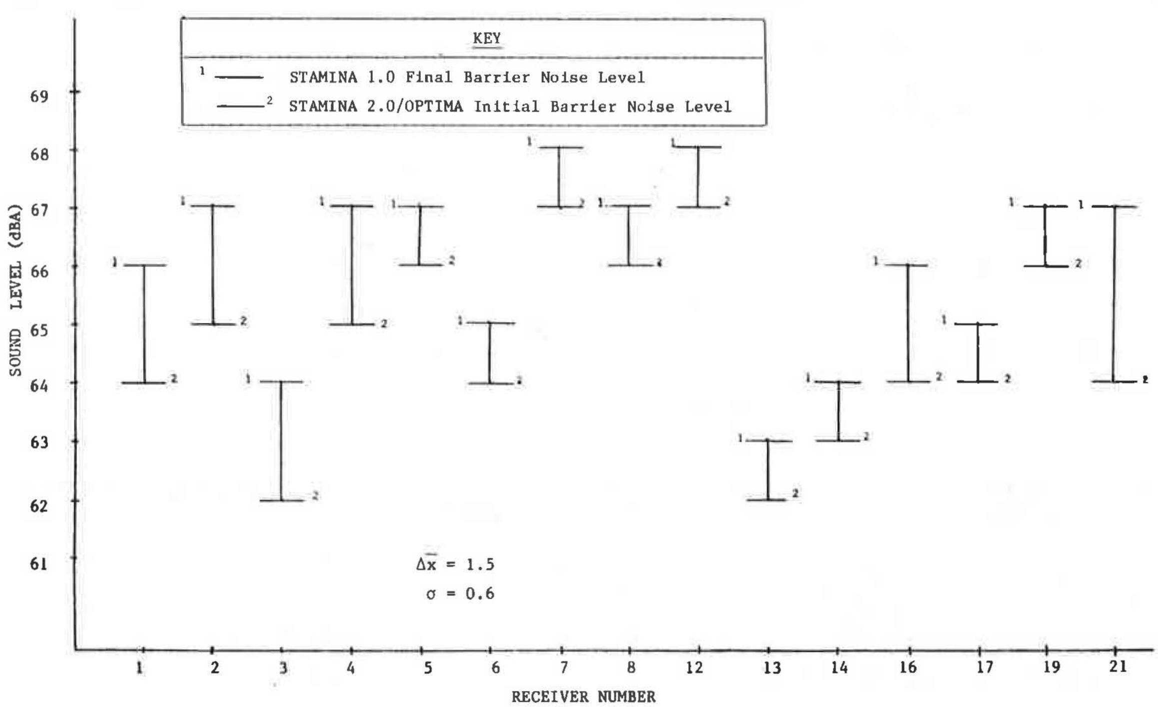


Figure 5. Comparison of final barrier cases: STAMINA 1.0 versus STAMINA 2.0/OPTIMA.

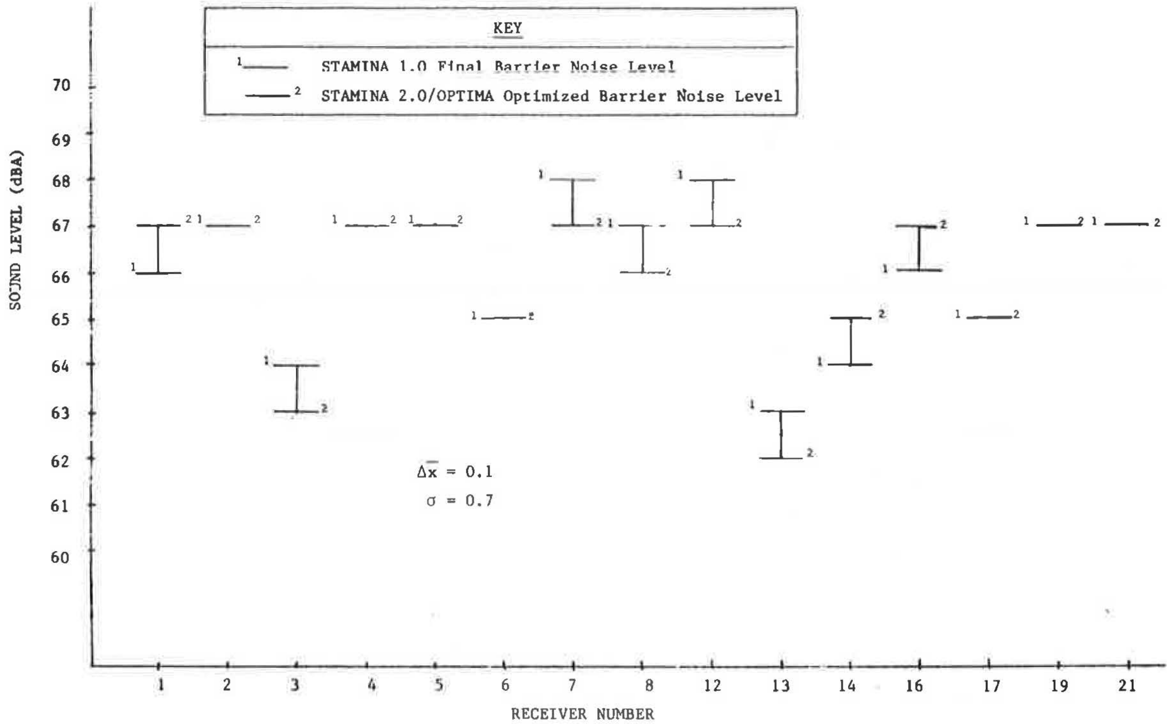
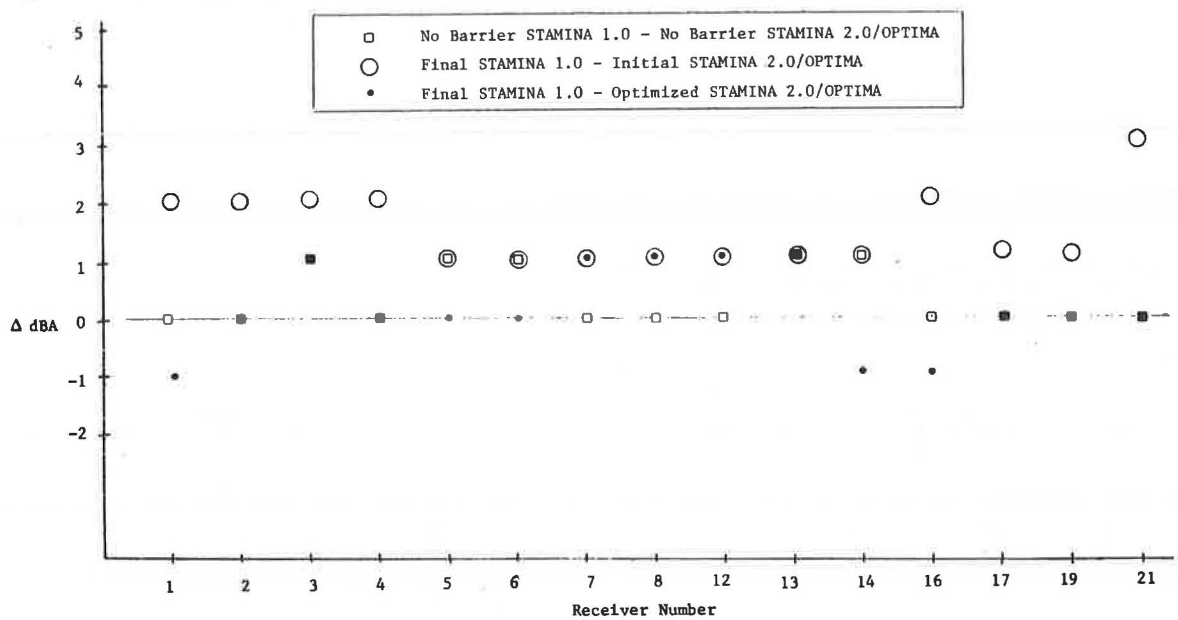


Figure 6. Differences in noise levels for three cases of STAMINA 1.0 and STAMINA 2.0/OPTIMA.



used for the barrier was concrete. The results of this exercise are as follows:

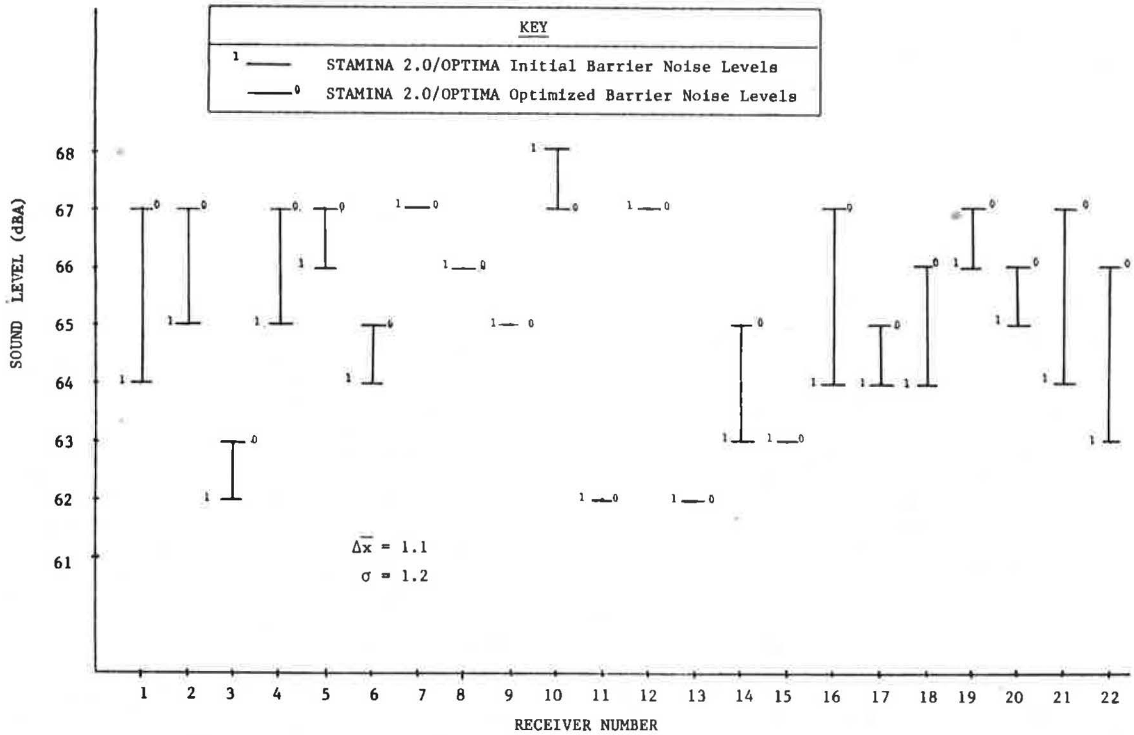
Item	Cost ($)
Best STAMINA 1.0 barrier	389,132
Optimized STAMINA 2.0 barrier	247,379
Savings	141,753

(Note that the STAMINA 2.0 barrier produced a savings of 36 percent.)

The costs for both barriers were obtained by using the data contained in OPTIMA (1981 version) for concrete barriers. Taken from the OPTIMA code, these costs are as follows:

Barrier Height (ft)	Cost ($) per Linear Foot
1	9.80
5	41.50
10	81.50
15	139.00
20	183.70
25	228.30
30	277.00
35	311.20

Figure 7. Comparison of intital STAMINA 2.0/OPTIMA barrier versus optimized STAMINA 2.0/OPTIMA barrier.



The final barrier heights for each barrier ranged from 12 to 18 ft, and the STAMINA 1.0 barrier had a higher proportion in the 15- to 18-ft range. The STAMINA 2.0 barrier had a slightly less-consistent top elevation than the STAMINA 1.0 barrier because of the fine-tuning optimization process. However, its top-elevation consistency was no worse than the barrier being constructed on the I-440 main line. The I-440 barriers are given a thorough review concerning top-elevation consistency for esthetic purposes.

The conclusion is that STAMINA 2.0/OPTIMA saved 36 percent of the cost of the concrete barrier with little sacrifice in performance. Comparing the results obtained from the initial and optimized STAMINA 2.0 barriers allows for the quantification of this sacrifice. Such a comparison is shown in Figure 7. The difference in the means (i.e., the average increase at each of the 22 receivers) is 1.1 dB(A), with a standard deviation of 1.2 dB(A). This increase occurs because the STAMINA 1.0 best effort (equivalent to the initial STAMINA 2.0) is not balanced in its distribution of effectiveness, and thus it represents a slight overkill. Note that the sacrifice in performance is minimal, especially when compared to a 36 percent savings in cost for this application.

CONCLUSIONS

As expected, the highway noise-prediction computer programs STAMINA 1.0 and STAMINA 2.0/OPTIMA produced adequately similar results for the equivalent scenarios on this project. More importantly, it has been demonstrated that when properly used, the OPTIMA concept will produce significant savings over the best efforts of an experienced analyst who uses only STAMINA 1.0. There are savings because the analyst is able to use an effectiveness and cost-balancing approach as a guide to the best barrier design. As always, engineering judgment is recommended in barrier design. The analyst should never blindly follow numbers without thoroughly validating their accuracy and reasonableness.

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Arizona's Experience with a Construction Noise-Abatement Incentive

G. BRUCE KAY

Most of the efforts to reduce highway noise impacts have focused on protecting the public from present and future traffic noise. People have progressively become aware that highway construction operations can also generate a great deal of irritating noise, particularly if such operations occur during hours when people are more sensitive to noise. Most construction noise analyses justify the impacts as temporary inconveniences and try to establish limits on hours of operation. Such limits were not possible in the administration of pavement grinding contracts on an urban freeway in Phoenix. The reasons for the problems encountered in setting and enforcing noise-level limits for nighttime construction operations are discussed. A noise-abatement incentive was established to encourage potential bidders to silence noisy construction equipment, specifically the grinding machines. The formula used to establish monetary awards was developed with the intent of compensating the contractor for initial muffling efforts, and rewarding him for innovations to further reduce noise impacts. An account is given of the first contract that used the noise-abatement incentive, the resulting reductions in noise levels, and the reactions of the contractor and residents.

Most of the efforts to reduce highway noise impacts have focused on protecting the public from the effects of traffic noise. The temporary impacts of highway construction noise on the public, although potentially greater than traffic noise, have routinely been held subordinate to the long-term benefits of the final product. The public, however, is currently more vocal in objecting to invasions of privacy. Consequently, many projects are scheduled for times when conflicts are minimal or contain provisions for reducing the chances of environmental impact.

The Interstate system in Phoenix, as in most cities, is paved with portland cement concrete (PCC). This pavement is durable, rigid, and resistant to wear from high volumes of traffic. When it begins to show stress, some form of rehabilitation or reconstruction is necessary.

A technique for rehabilitation was developed, which evolved from grooving projects in the early 1960s, by which surface irregularities could be leveled out and the pavement grooved in one operation. The term grinding was adopted for the operation. Grinding is now considered to be an economic alternative to repaving or reconstruction, and it can extend the life of a roadway by 10 years or more.

Pavement grinding in Phoenix is subject to some unique restrictions. Contractors in the Southwest prefer to grind in the winter and at night to reduce the effects of heat on the equipment. Project managers share that opinion because of the reduced nighttime traffic involved. Contractors thus have greater flexibility and better quality control for grinding and related work.

Conversely, residents adjacent to the freeway are generally more sensitive to occurrences at night. They are exposed to the combination of freeway traffic changes and the grinding operation from 10:00 p.m. to 6:00 a.m. for periods of 2 days to 2 weeks. The new noises are much harder to get used to than customary freeway traffic. Nevertheless, complaints are uncommon, primarily because most people still have a tolerant attitude. When one individual complains, a reasonable explanation usually alleviates his concern. If a group of concerned or affected residents complain, the agency may have to make an effort to reduce the noise impacts and still maintain the unusual construction schedule. Above all, complaints have to be responded to in a positive manner.

HISTORY OF GRINDING IN PHOENIX

In the winter of 1974-1975, the Environmental Planning Services of the Arizona Department of Transportation (ADOT) was requested to study the noise levels emitted by equipment used in the state's first grinding project on I-17, Phoenix's Black Canyon Freeway south of Thomas Road (Figure 1). Monitoring of noise levels indicated that an upper noise-level limit could be specified in future contracts. It was believed that potentially sensitive areas should not be exposed to unreasonably high noise levels. Consequently, an upper limit of 86 dB(A) L_{max} at a distance of 50 ft was set for all grinding activity before 11:00 p.m., and 82 dB(A) L_{max} between 11:00 p.m. and 6:00 a.m. The equipment, when properly serviced, was capable of maintaining these levels. Examination of the specifications in other states verified that 86 dB(A) or less generated few complaints. It was not recognized at the time that there were as many designs of grinding and grooving operations and equipment as there were contractors (Figures 2 and 3). A few companies designed cutting heads and blades, but generally the equipment was built and maintained by the contracting companies. The noise emissions of machines could differ by several decibels.

A project covering the northbound lanes of I-17 was initiated some years later. The same contractor, with essentially the same set of grinders in a deteriorated condition, stated that any additional shielding of the engines to bring the levels within specifications would contribute to further deterioration. Consequently, the limit was relaxed to 86 dB(A) L_{max} for each piece of equipment for the entire nighttime operation. Project managers believed that noise complaints could be handled with little difficulty. It was believed that by the time complaints were fielded, the equipment would have left a specific area.

The project proceeded smoothly during the first 8 months, with a few complaints from residents. But during the next month residents west of one 0.25-mile segment were not satisfied with the usual response and complained to ADOT management, the state Department of Health Services, and ultimately to the Governor's office. Subsequently, ADOT was asked to reduce the potential noise impacts of future projects.

The noise complaint would not have become a problem if the breakdowns and delays associated with several unexpected factors had not occurred. The equipment was in need of repair and modification. The concrete on the Black Canyon Freeway was composed of extremely hard aggregate, and the design of the diamond blades was not adequate for this project. The rate of grinding was much slower than the normal 10 to 15 ft per minute. Furthermore, the pavement deflections were so great in this section that repeated passes over large areas were required.

ADOT continued to receive inquires from the complainants after project completion, and in response more stringent noise-level limits were developed.

Figure 1. Vicinity map.

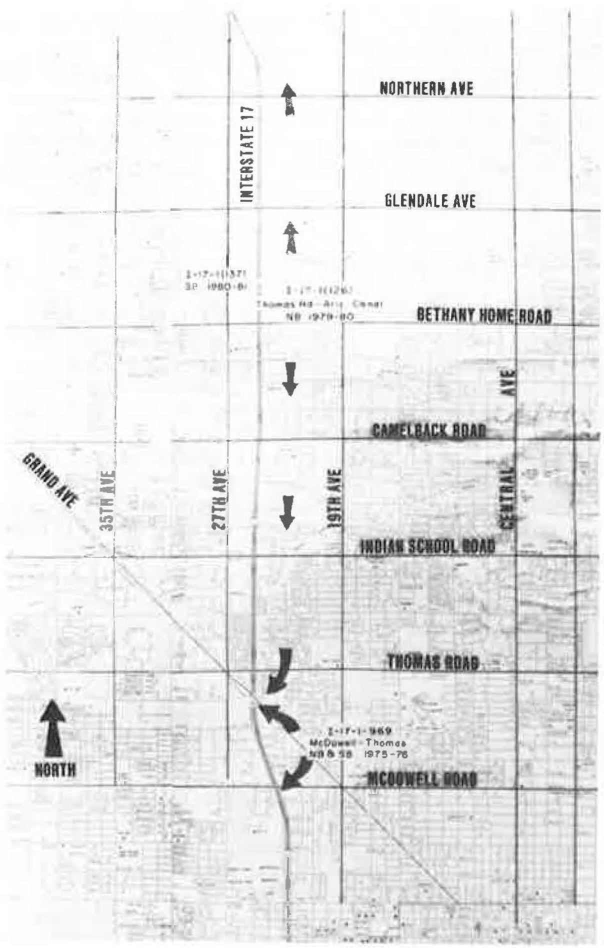


Figure 2. One manufacturer's model of a pavement grinder.

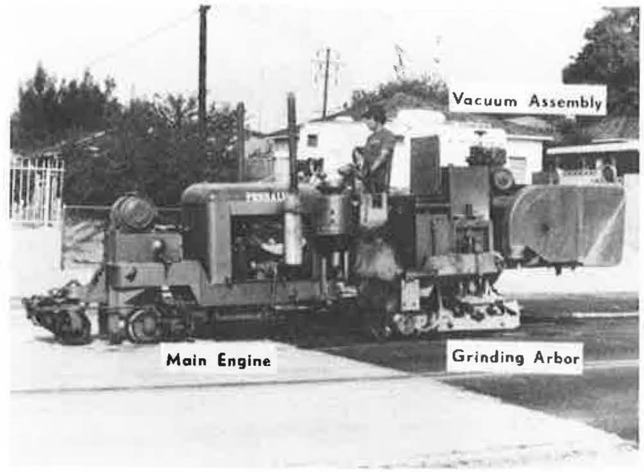
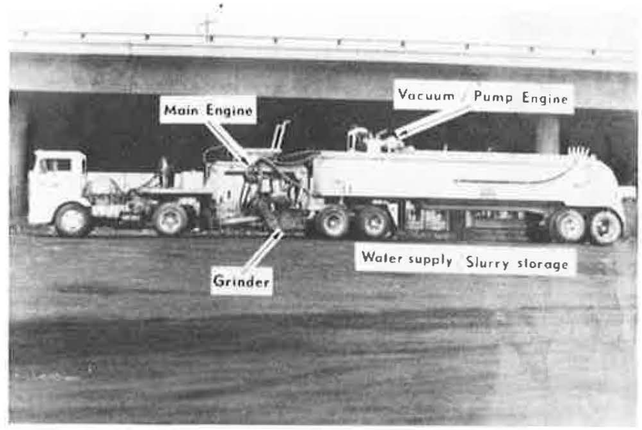


Figure 3. Model of grooving equipment.



In a prebid conference for the following project on the southbound lanes, several contractors threatened not to bid if the specifications on noise levels were maintained or tightened. ADOT management suggested that a provision for monetary incentives for noise abatement be studied. Following FHWA concurrence, manufacturers and contractors were contacted to try to understand their positions and to inform them of the proposed efforts. Their input was mixed, obviously, but overall there was approval of the incentive concept. Their technical comments were considered in the development of the incentive.

EVALUATION OF MITIGATION MEASURES

The main concern at ADOT was to significantly reduce the noise impacts at residential properties, or at least to be able to inform residents that measures were taken to reduce noise impacts. Also, ADOT wanted to offer a monetary value that was an incentive for the potential contractors to experiment with noise-reduction techniques. The Department started with a baseline L_{max} of 86 dB(A) at 50 ft, and considered graduating payments for each decibel reduction from that level.

The first step was to identify the primary noise sources and the potential for retrofitting silencers. These sources consist of (a) the 250- to 400-hp air- or water-cooled diesel engines used to power the drive train and the arbors (cutting heads), (b) the generally smaller air-cooled diesel engine used to operate the slurry vacuum and blower system, (c) the vacuum and blower system, and (d) the arbors (grinding heads) in contact with the pavement. The typical locations of these components are shown in Figures 2 and 3.

In the case of the engines, premanufactured mufflers for engine exhausts were found to be readily available. In addition, modification of the fans and shrouding of the engines (Figure 4) could provide additional reduction if needed.

The vacuum and blower noise levels were also reducible with the addition of mufflers (Figure 5). Manufacturers claimed significant insertion losses ranging up to 30 dB for the middle frequencies. The primary noise stems from the intake and the discharge of high volumes of air to the atmosphere.

The noise levels generated from the actual grinding, done with an arbor (Figure 6), cannot be distinguished from the other sources. Furthermore, many machines are equipped with shrouds of heavy fabric to retain the water and slurry within the limits of the vacuum inlets. These shrouds are effective shields.

It was estimated that noise levels could be reduced to 80 or 81 dB with the full complement of silencers. This value was not calculated; it was measured by one equipment manufacturer at its plant.

With silencing of the sources, further reduction

Figure 4. Front and rear views of a typical noise-insulated diesel engine.

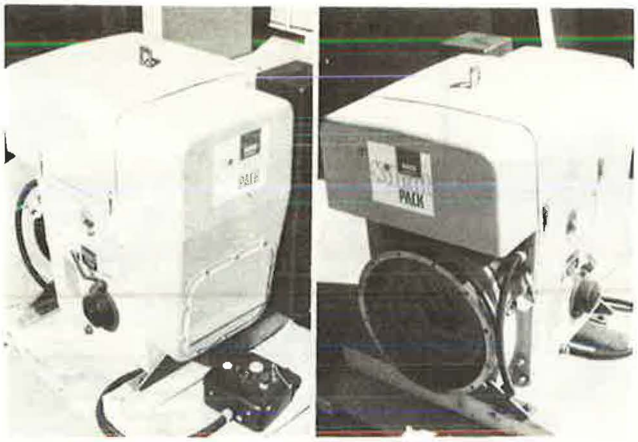


Figure 5. Typical silencer installed on rotary positive blowers or vacuums.

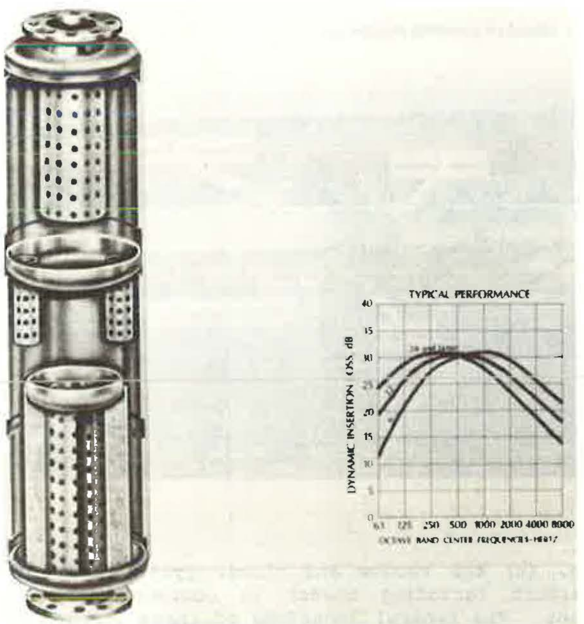
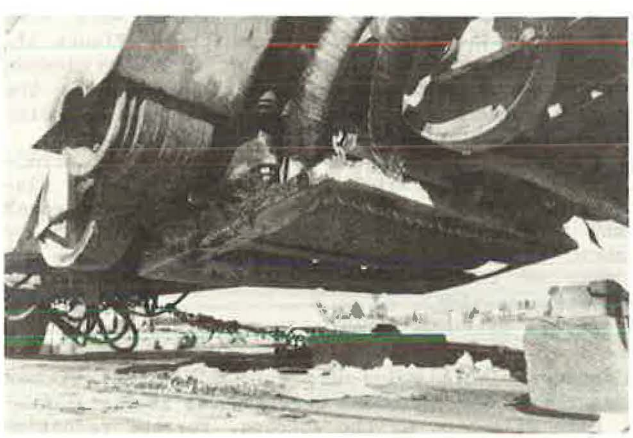


Figure 6. Grinding arbor—a cutting wheel composed of diamond chips embedded in steel disks.



was considered possible by inserting a portable barrier of some type between the source and any sensitive receivers. The manufacture of such a barrier was believed to be possible by using a 20- to 30-ft-long metal frame fitted with lead-loaded vinyl curtains suspended from a height of 10 ft or more. An efficient barrier would provide a 10- to 13-dB insertion loss. However, because of end effects, it was predicted that a resultant reduction of 6 to 7 dB would occur at the ends of the barriers (Figure 7).

THE FORMULA AND ITS APPLICATION

A monetary incentive formula was derived to provide about-even compensation for the cost of engine muffling and modifications and larger payments for efforts to further reduce noise levels at the source or in the transmission path. The formula was designed to be applied for the duration of the project, with payments calculated monthly, taking into account the number of grinders used and the incremental percentage of work completed. If equipment deterioration resulted in higher noise levels, this procedure would lower the monthly payment. If the 86-dB(A) limit was exceeded, the violating equipment would be shut down until repaired or modified.

The formula used on the project is as follows:

$$G = HC/D \quad (1)$$

where

$H = F(86 - A)^{1.5}/10^{1.5}$,
A = average decibel reading for all grinders used for 60 percent or more of the current month,
C = square yards of completed ground PCC pavement per month,
D = total square yards of PCC pavement in bidding schedule,
F = total maximum incentive part in bidding schedule (see Table 1),
G = total payment for each month,
G (TOT) = sum of all G's, and
H = noise-abatement incentive payment (see Table 1).

The values of payments for noise levels sustained over a project are given in Table 1. The exponent applied was derived empirically, with the assumption that an average of three machines would be used on a project. The exponent gave H values, or payments, that should compensate for the costs of retrofitting noise sources and would provide greater payments for further reductions.

The data in Table 2 give an example, not related to the project, of how the formula is used. Payments are made monthly and are based on the measured area of pavement grinding completed for that period, its relative ratio to the total area in the contract, and the arithmetic average of the noise levels of all grinders used during that period. The product of H--the payment amount for the average level and the fraction of work completed--is the monthly payment.

MEASUREMENT AND MONITORING OF EQUIPMENT

To control the application of the incentive formula, measurement and monitoring procedures had to be specified. The major features of the specification included the following:

1. Definition of the grinder to include all related equipment, including water trucks;

Figure 7. Plan view of Black Canyon Freeway showing the relative position of the points of maximum exposure to the noise levels with and without a portable barrier.

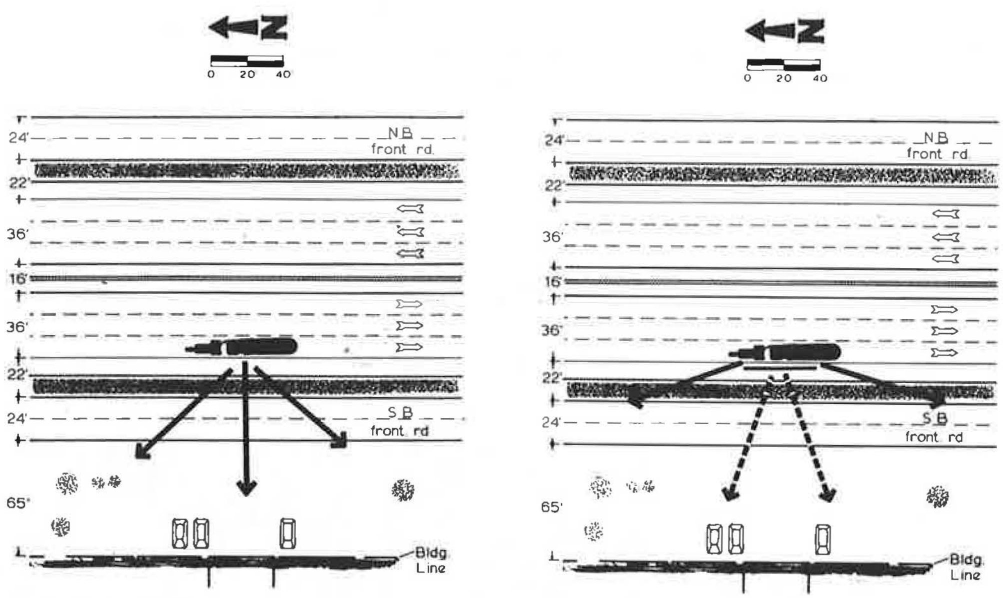


Table 1. Noise-abatement incentive payment levels.

A [dB(A)]	H[a]($)	A [dB(A)]	H[a]($)
86 -½	0	80 ±½	23,238
85 ±½	1,582	79 ±½	29,283
84 ±½	4,472	78 ±½	35,777
83 ±½	8,217	77 ±½	42,690
82 ±½	12,684	≤76 ±½	50,000
81 ±½	17,678		

[a]F = $50,000.

Table 2. Example of how noise-abatement incentive payments would be made.

Month	C (yd^2)	C/D	A	H($)	G($)
1	16,625	0.125	84.8	1,582	198
2	13,300	0.100	76	50,000	5,000
3	19,950	0.15	78	35,777	5,367
4	26,600	0.20	79.7	23,238	4,648
5	16,625	0.125	80	23,238	2,905
6	16,625	0.125	77.1	42,690	5,336
7	11,970	0.09	76.4	50.000	4,500
8	11,305	0.085	75	50,000	4,250
Total	133,000	1.0			32,204[a]

Notes: For definition of column headings, see Equations 1 and 2.
D = 133,000 yd^2, and F = $50,000.
[a]$32,204 = G(TOT).

2. Position of the measurement point at 50 ft from the path of the grinding equipment (this distance satisfied the goal of monitoring the hard sites over most of the project);
3. Recording of the maximum level and location of equipment relative to the microphone position, with the requirement that the equipment be in the production mode;
4. Provision for the engineer to monitor noise levels at any time in the project;
5. Provision for retesting any grinder if monitoring indicated that a change in levels had occurred;
6. Physical conditions of the measurement and monitoring area, i.e., flat terrain with no obstruction or reflective surfaces not related to the project; and
7. Specifications for the sound-level measuring equipment; i.e., the reference to American National Standards Institute (ANSI) standards for type 1 or type 2 meters.

IMPLEMENTATION OF THE INCENTIVE

The initial use of the incentive came in October 1980. The advertising phase did not elicit prebid responses to the specification for noise-level limits or to the incentive amount, which was set at a maximum of $50,000. ADOT was restricted from using the specifications to suggest abatement measures, primarily because of concerns for liability if they were unsuccessful.

The national exposure that the previous contract received prompted one equipment manufacturer to conduct research into the design of the diamond cutting blades for the highly resistant aggregates used in Phoenix's local concrete. They went to the expense of having slabs of local concrete shipped to their plant for extensive testing. In addition, the grinding subcontractor, whose equipment was manufactured by the same company, shipped three grinders to the plant to have them retrofitted with silencing devices. By project start-up, two machines were in production, and initial measurements were conducted.

The objective of the ADOT research was to record the maximum noise level of each grinder as it passed by 50 ft from the primary microphone. This maximum level occurred when the noisiest components were directly in front of the microphone. In the operating mode the average speed of the equipment was 7 to 10 ft per minute, which allowed time for recording. Freeway traffic was detoured onto a parallel street 0.5 mile from the facility for a 1-hr period.

The equipment used for measurement included a B&K type 2218 precision integrating sound level meter with an accessory dc strip-chart recorder, and a BBN model 640 programmable noise analyzer with digital printout of the statistical distribution of noise levels, programmed to update data every minute. One microphone was mounted 50 ft from the near edge of the equipment, and another was placed on a tripod in the frontage road about 75 ft from the equipment. A third meter, a Pulsar model 40, was supplied to the project engineer for use in monitoring noise levels during the project. Its accuracy was verified concurrently with the initial measurements.

Five months later ADOT was asked to measure noise levels of a third grinder that had been shipped to the project. This was accomplished with a 10-min shutdown of frontage road traffic. On the same night, measurements of the other grinders were conducted by using the B&K meter and strip-chart recorder under frontage road traffic. The test revealed that a minimum level could be attributed to the grinder; the frontage road traffic, 20 ft west of the microphone position, raised the level 6 to 10 dB. Traffic flow was intermittent because of signalization at a nearby interchange, and the quiet gaps were long enough to identify grinder noise levels. This finding was significant because it could reduce the time and personnel needed for the precision measurements. The specification requiring measurement at 50 ft restricted the measurement of noise levels when the equipment was in the inside lane, where the 50-ft position was on or inside the right-of-way fence, as shown in Figure 7. Obviously, if the same distance was maintained for the other lanes, the conflicts with traffic would become greater. The only alternative was to record levels from positions in the neighborhood area and adjust back to 50 ft with a point-source factor, i.e., 6 dB per double distance.

This alternative was confirmed with a third measurement. A microphone was located adjacent to the frontage road at 90 and 99 ft from each of two grinders that were operating in different lanes. When an adjustment was applied to 50 ft, the readings were consistent with previous measurements.

A fourth measurement was done in late May when the contractor was using only one machine. The contractor was finishing the last mile of the project. An increase in noise level had been reported by the project supervisor.

RESULTS AND CONCLUSIONS

The initial measurements described in the preceding section were applied to the incentive formula. The original two grinders each had an L_{max} of 82 dB(A) at 50 ft. The incentive would provide a total payment of $12,684 if the average was maintained throughout the project. The third grinder also had an L_{max} of 82 dB(A) when it was first brought onto the project. Late in the project the contractor reduced his force to one grinder used on the last mile. Its noise level deteriorated to 84 dB(A).

The contractor finished the grinding phase on time, and no penalties were applied to the incentive award. Total payment for noise abatement was approximately $11,500. The contractor reported that the cost to retrofit the three grinders was $11,700. However, at least some measures used were required to meet the 86 dB(A) specification. The original equipment, when used in a project in Georgia, was measured at 95 dB(A) and greater. The net reduction, with retrofitting, was 13 dB or more.

The reduction measures were reportedly simple to install and easily changed if necessary. The exhaust system was modified, and mufflers were installed on both engines (Figure 8). The large diesel engine was fitted with insulated cowling (see Figure 9). The cooling fan was modified by revising rotation direction and changing its speed. Silencers were installed on the vacuum and blower assembly (Figure 10), and small shields were installed on the equipment near the smaller engine.

The deterioration in noise level noted late in the project was because of a reduction in efficiency of the vacuum system. A few leaks developed in the separator (shown in Figure 10), and the speed of the small diesel had to be raised to compensate for the loss of pressure. This deterioration began in the

Figure 8. Main engine with modified exhaust mufflers.

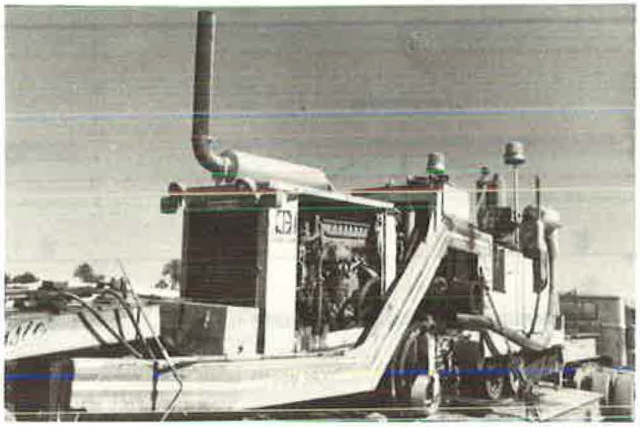


Figure 9. Insulated panel for main engine, lined with 1-in.-thick foam rubber.

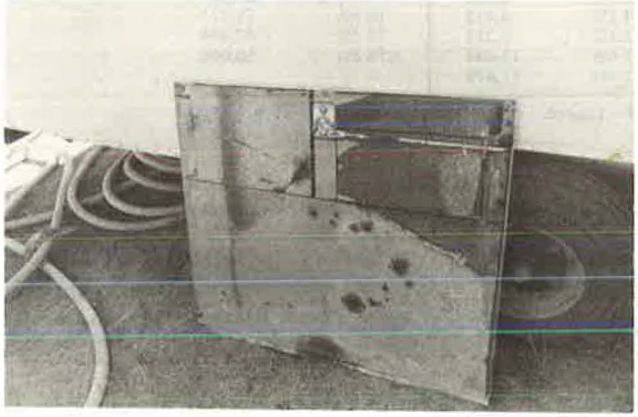
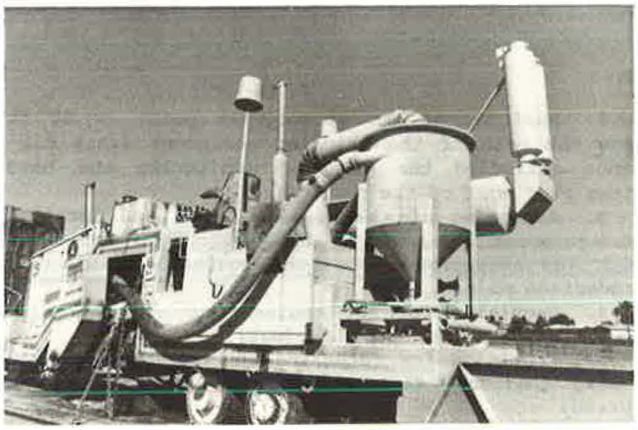


Figure 10. Vacuum and pumping system with exhaust silencers on right rear; separator is on left rear.



last 2 weeks, and its effect on residents was minimal.

Complaints were minimal throughout the 8 months of the project. The affected residents discussed earlier did not have time to complain. The grinding phase sped through their 0.25-mile segment in three nights. Other complaints received by project personnel concerned noise from other equipment used in peripheral phases of the project, i.e., power concrete saws used to clean joints and jackhammers used in patching damaged slabs. Their noise levels were less than those of the grinders.

It was believed that the lack of complaints was due in part to a significant reduction in noise levels of more irritating frequencies, even though the capability of verifying this information with instrumentation did not exist. The accessory equipment (jackhammers) had a noise impact because of their inherently higher frequencies. Furthermore, the diesel engines used on the previous contract emitted a pronounced whine, whereas the later engines and exhaust systems did not. Apparently the dampening effects of the retrofitting were significant.

The effects of the devices on overall performance of the equipment were negligible. The contractor was 5 weeks behind schedule when the first mile was completed, and delays were attributed to complications not related to the retrofitted equipment. Adjustments were made to the grinding process, design of blades, and a few other mechanical deficiencies. The project was finished on schedule. Naturally, the speed of production was a benefit to the residents.

The primary goals of reducing the inherent noise levels and reducing complaints were achieved. ADOT hopes to continue offering the same noise-abatement incentive on future sensitive projects, assuming the monetary award can be maintained at an attractive value.

Several factors that cannot be controlled may affect this decision. Larger-scale projects may require larger fleets of equipment. Overall noise levels may be more difficult to maintain at limits less than 86 dB(A). Retrofitting major components may be more expensive, and incentive payments may not be attractive enough. Larger fleets also mean more noise sources to monitor.

When compared with earth-moving equipment, the grinders are actually quite small. Most are designed to process a path width of 3 ft. However, some manufacturers are now testing machines with two arbors designed to grind 6 ft or more in one pass. The power supplies are much larger than those used in Arizona. Thus the potential for more intrusive noise is higher. Problems in attracting this more productive equipment may be encountered because of noise-level restrictions.

Obviously, future use of the incentive will have to be dealt with on a project-by-project basis. Sensitive areas will require protection, whereas other areas may not require any limits on noise levels. However, Arizona intends to protect people from excessive construction noise and will encourage innovations in noise reduction. In the near future ADOT hopes to set the primary noise-level specification to a more restrictive limit than 86 dB(A).

The need for more data on activities of other contractors is evident. The ability to sample more equipment is limited by the type of equipment that enters the state. ADOT needs input from other agencies that are collecting construction noise data of any kind. Considering the future of new highway construction versus rehabilitation and maintenance in sensitive urban areas, the need for noise abatement on construction projects may become much more important.

ACKNOWLEDGMENT

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Notice: Opinions expressed herein are those of the author and do not reflect Arizona Department of Transportation policy.

Procedure to Evaluate Transit Noise Abatement and Cost-Effectiveness: The PEACE Program System

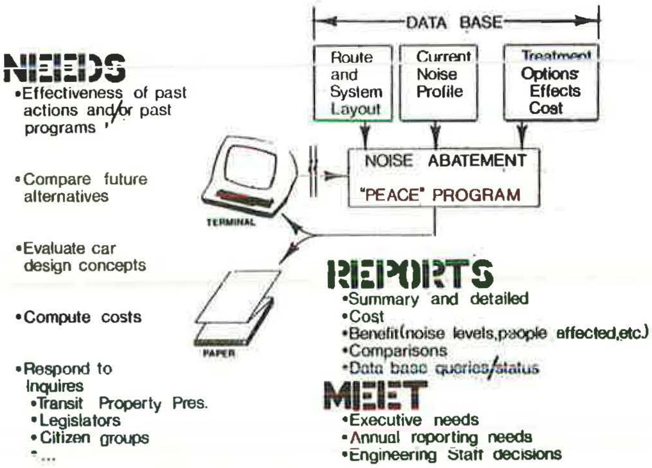
WILLIAM R. McSHANE, JOSE M. ULERIO, AND SIMON SLUTSKY

The procedure to evaluate transit noise abatement and cost-effectiveness (PEACE) program system was developed as a tool that rail transit operators and others could use to evaluate the noise performance of their system and to explore the cost and effectiveness of candidate noise-treatment plans. The system uses three input data bases: (a) system description, (b) noise profile, and (c) treatments and costs. It is designed so that the latest state of the art in noise descriptions and in treatment technology can be incorporated, and that future developments can be added. It is also designed for use on large properties. The PEACE system is implemented as a set of three computer programs: a preprocessor, a main program, and a postprocessor or report generator. The system can be used to evaluate proposed treatment sets, to investigate the potential of hypothetical treatments or of new car designs, and to check a number of what-if questions. The development work was done with close interaction with a major rail transit property (New York City Transit Authority), which plans to use the PEACE system in its work.

The procedure to evaluate transit noise abatement and cost-effectiveness (PEACE) was developed under contract to the U.S. Department of Transportation (DOT) to allow rail transit operators and other interested parties to

1. Systematically determine and review the noise levels on the system;
2. Systematically catalog the abatement measures

Figure 1. Capabilities of the PEACE noise-abatement system.



that are available, in terms of effectiveness and cost, so that they are available for inspection, review, and use;

3. Evaluate the effectiveness and cost of alternative treatment plans (total or partial); and

4. Document the results in ways that can be understood and that will allow people to evaluate the effect of changing some costs, assumptions, or values.

The PEACE program system is implemented as a set of three computer programs that allow the user to

1. Establish and check a data base on the system, which consists of three sections: description of the physical system, noise profile and characteristics, and treatment options and costs (this program is called PREPEACE);

2. Apply treatment sets (actual or candidate) to the described system to evaluate their effectiveness; alternatively, the noise characteristics of system components or treatments can be varied to gauge the impact of such changes (this program is called PEACE); and

3. Generate reports on the changes and costs (this program is called POSTPEACE).

The capabilities of the program system are shown in Figure 1.

The program system can generate seven major reports:

Report	Contents
1	Tabulation of treatments made
2	Cost report
3	Rider environment
	Noise levels by route
	Summary of all routes
4	Station environment
	In order by station number
	Sorted by noise metric
5	Community environment: block by block
	In order by input order
	Sorted by noise metric
6	Community environment: sensitive receptors
	In order by input order
	Sorted by noise metric
7	Summary
	Treatments
	Benefits
	Costs

The station and community reports can be tabulated in sorted order by any one of three noise indices. The station report can also be sorted by local jurisdiction (i.e., county, borough) and then by noise index within the local jurisdiction.

OVERVIEW

The PEACE program must be viewed as nothing more than a bookkeeper that allows the user to collect certain information to evaluate the actual impact of one or more treatments, applied to one or more sections of the system. More specifically, the certain information can be categorized into three data bases.

1. The system, which includes types of track and right-of-way, types of cars, definition of routes, and so on. The definition of routes includes time and speed between stations, cars assigned, persons traveling, and other relevant information.

2. The system noise profile, which includes the noise levels of various cars on different types of track or right-of-way, the effect of speed, and the relative contribution of various sources and paths.

3. Abatement, which is the effectiveness of various candidate treatments and the cost of the treatments.

It must be recognized that there are three principal sections to the rail transit noise environment: rider (i.e., the levels to which the transit riders are exposed while traveling in the train), station (i.e., the levels to which those in the stations are exposed), and community (i.e., the levels to which community residents and others are exposed). Further, there are four areas in which treatments can be made: car, right-of-way (ROW), station, and community. The system noise must thus be characterized in such a way that the effect of a treatment in any of these areas can be assessed in all three environments. The effect can be summarized as follows:

Area of	Affected Environment		
Treatment	Rider	Station	Community
Car	Yes	Yes	Yes
ROW	Yes	Yes	Yes
Station	--	Yes	--
Community	--	--	Yes

Not all treatments will affect all environments, even when a yes is indicated in the preceding table. For instance, car window and door seals would affect only the rider environment.

Examples of treatments in each area are as follows: car--true wheels, air condition; ROW--weld rail, place barrier; station--acoustic ceiling, treat walls; and community--double-glazed windows, acoustic treatment of ceilings in rooms. Note that the community treatments are at the sound receptor. The impact of other treatment areas on the community environment is a different aspect and one of greater priority in the present context.

The following should also be noted.

1. Station treatments are those physical treatments to the station or in the station itself, such as acoustic ceilings, wall treatments, and between-track barriers. As such, it is unlikely that the rider in the car will be noticeably affected. Certainly, residents in the community would not be affected by such treatments in any significant way.

2. Community treatments are those physical treatments performed at the receptors, such as double-glazed windows in a building or room acoustic treatment. Yet these treatments at the receptors

are often not within the purview of a transit property, and they are also considered by many to be "closing the barn door after the horse has escaped".

There are several distinct measures of effectiveness (MOEs) that can be considered. Those used in the PEACE program fall into three categories:

1. MOE X--the basic measure of effectiveness is the equivalent noise level (L_{eq});
2. MOE Y--the energy to which a single individual is exposed, which is essentially L_{eq} + log T, where T is the appropriate exposure time; and
3. MOE Z--the energy to which all involved people are exposed, which is essentially L_{eq} + log T + log PPL, where PPL denotes people.

In each environment the actual event over which L_{eq}, T, and PPL are defined is appropriately selected. For instance, for in-train noise, the basic event is the trip from one station to the next. For station noise, it is the passage of one train, either express or local. (The latter would include an arrival and a departure, the former simply a passby.)

The user has the opportunity to specify a set of treatments and the set of reports that should be generated to document the impact and cost. Figure 2 shows that PEACE is, in effect, a tool to systematically access and use the key data bases already cited.

It should be noted that all MOEs are based on expected or average values.

KEY PEACE COMPUTATION

In each of the noise environments the total noise level is described as the sum of several sources, each of which is speed dependent of the form

$$L_i = A_i + B_i \log(\mathrm{SPD}) \quad (1)$$

where SPD is the train speed, the subscript i denotes the ith source, and the constants A_i and B_i are associated with the specific source. The several sources are then added according to the usual relation

$$\hat{L}_{eq} = \hat{L}_{eq}(\mathrm{SPD}) = \log \sum_i 10^{L_i/10} \quad (2)$$

Typical values for the in-train noise of a particular car model are shown in Figure 3. By using Equations 1 and 2, the following computations can be made:

$\hat{L}_{eq}$(30 mph) = 97.3 dB(A).

$\hat{L}_{eq}$(40 mph) = 102.1 dB(A).

$\hat{L}_{eq}$(50 mph) = 106.3 dB(A).

Based on detailed measurements in at least one study (1) and insights gained from other studies (2,3), it is also possible to estimate the significance of different noise paths into the car (or other environment). At 30 mph, the total contribution along different paths in the preceding figure might be as follows:

Path	Noise [dB(A)]
1	90.5
2	94.5
3	84.0
4	83.9
5	88.6
6	78.4
7	79.8
Σ	97.3

Thus the contribution of each source along each path can be estimated, as shown in Figure 4. [Note that

Figure 2. Using the PEACE program system.

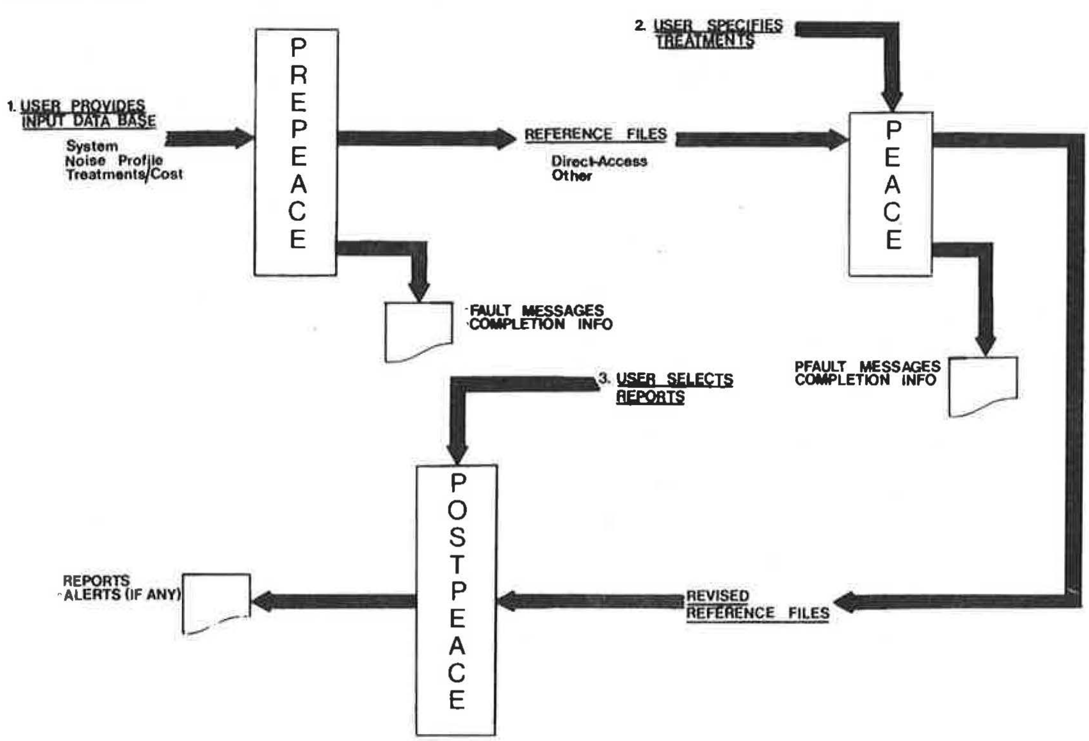


Figure 3. Typical values for in-train noise of a particular car model.

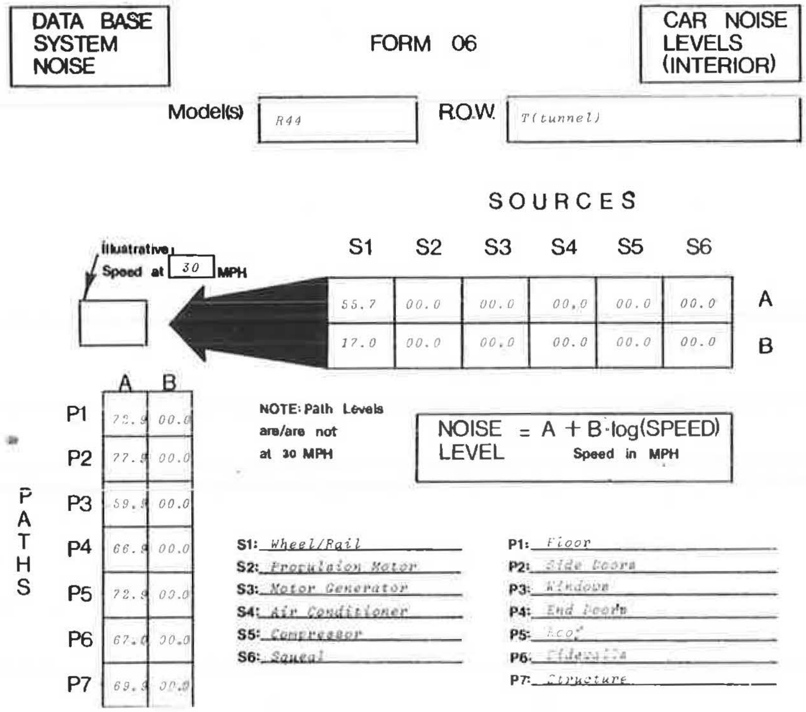
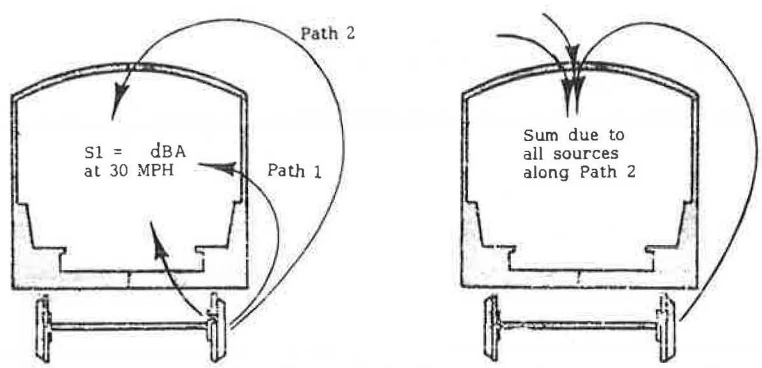


Figure 4. Contribution along sources and paths.



(A) The noise due to Source 1 at 30 MPH

(B) The noise passing thru Path 2 from all souces

SOURCES

	Total	S1	S2	S3	S4	S5	S6
	97.3	94.5	93.9	78.0	72.0	62.0	-
PATHS P1	90.8	87.7	87.1	71.2	65.2	55.2	-
P2	94.5	91.7	91.1	75.2	69.2	59.2	-
P3	84.0	81.2	80.6	64.7	58.7	48.7	-
P4	83.9	81.1	80.5	64.6	58.6	48.6	-
P5	88.6	85.9	85.3	69.4	63.4	53.4	-
P6	78.4	75.7	75.1	59.2	53.2	43.2	-
P7	79.8	77.0	76.4	60.5	54.5	44.5	-

(c) The Estimated Distribution of Noise at 30 MPH the noise levels cited are those measured at the standard receptor (e.g., in the car), not the absolute level at the source point.]

The essence of the key PEACE computation is that each treatment typically decreases one or more sources or decreases the transmission of one or more paths. Thus either one column or one row (or more of each) must be decreased entirely, and the sum must be recomputed.

The advantages of PEACE are that it (a) accesses the treatment data base for a treatment of interest, (b) accesses the noise profile data base for the present condition (such as in Figure 4), (c) computes the effect of applying the treatment, and (d) accesses the data bases as needed to generate required reports. Its principal advantage is that it will do the computations that would otherwise be too cumbersome and would limit the investigations a person could do in a practical amount of time. In particular, the changes to the source and path distribution from specified treatments require much computation. PEACE is intended to allow the user to focus on options, not computations.

THE PREPROCESSOR: PREPEACE

The PREPEACE program checks for faults in the user's input data and creates the necessary files for the other programs in the PEACE program system. The files that go into the PREPEACE program constitute three data bases: system, noise profile, and treatment and costs. The eight input files are as follows:

Data Base and Name	Input File
System	
Basic numbers and names	1
Station information	2
Route information	3
Community block by block for outdoor link	4
Car assignments	5
Noise profile	
System noise levels	6
Treatment and costs	
Treatment information	7
Cost data	8

The input data are checked extensively, and FAULT messages are printed to alert the user that there is something wrong or unusual in the input data. These are not error messages generated by the computer's operating system, but true data checks generated by the PREPEACE program.

It is neither feasible nor desirable to attempt to explain each of the inputs in this paper. This is better explained in a user's guide (4), which is accompanied by a volume of programmer's aids (5). However, it may be relevant to provide some highlights, in the following subsections.

System Data Base

The system must be defined in the most basic sense. Starting with a route map, all stations are code-numbered and all routes are identified, as shown in Figure 5. The track types are classified, and trackage is grouped into collections that would be treated together if any ROW treatments are to be done. Some of the basic numbers for the case study on the New York City Transit Authority (NYCTA) are shown in Figure 6. The sources and paths are those shown in Figure 4, but here they are for each distinct environment--rider, station, and community.

By using the basic structure of the system, each station and route is defined, as is the community (block by block). The typical definition of one route--the train travels from one station to another, covering a certain distance in a certain time, with a certain peak sustained speed--is shown in Figure 7. The track group (i.e., tunnel, concrete roadbed), the ROW group for potential treatment, and the passenger load are also defined.

One key input is the car assignment of which car models travel on which routes. In the NYCTA application, there are at least 24 distinct routes and 21 distinct car models. Noise levels vary according to car model and track type, and track types vary from route to route.

Noise Profile Data Base

The concept of the noise profile, which is described in terms of sources and paths, has been previously discussed and shown in Figures 3 and 4.

The basic noise event is the motion or arrival of a train. The levels produced are a function of the car model(s), the speed, and the ROW type or the station noise group type. The noise generator can simultaneously affect up to three environments: rider, station, and community.

The noise profile data base contains the description of each impact as a function of the relevant parameters, much akin to Figure 3.

The special power of the PEACE program system is that it can combine the system and noise profile

Figure 5. Illustration of a route map.

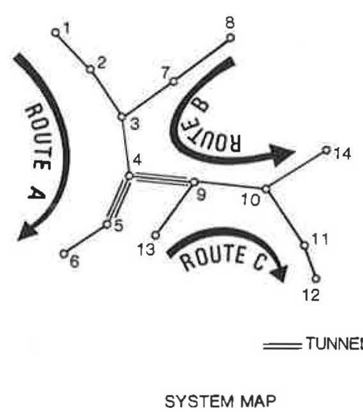


Figure 6. Organization of first section of input one.

```
THIS IS INPUT ONE...BASIC NUMBERS AND NAMES
        TYPE ONE        NUMBER OF CAR MODELS                   21
                        NUMBER OF ROUTES                       24
                        NUMBER OF TRACK GROUPS                 18
                        NUMBER OF STATIONS                    471
                        NUMBER OF STATION GROUPS(NOISE)         5
                        NUMBER OF STATION GROUPS(PHYSICAL)     38

        TYPE TWO           NUMBER OF SOURCES
                                     RIDER                      6
                                     STATION                    2
                                     COMMUNITY                  2

                           NUMBER OF PATHS
                                     RIDER                      7
                                     STATION                    2
                                     COMMUNITY                  2

        TYPE THREE         TREATMENTS TO
                                     CAR                       19
                                     RIGHT-OF-WAY              12
                                     STATION                    8
                                     COMMUNITY LOCATIONS        8
```

Figure 7. Input three (routes) and type two data (general organization).

TYPE TWO...DETAILED ROUTE INFORMATION

ROUTE NUMBER/NAME = A TRAINS= (04 06 08 10 12)

FROM LINK	TO LINK	DIST (MI)	TT (MIN)	SPD MPH	TG	O/O	OTHER ROUTES	GRROW	CAR-TRIP PK	CAR-TRIP OFF	PPL/CAR PK	PPL/CAR OFF
001	002	0.42	1.5	25.2	02	100		47	100	100	200	040
002	003	0.59	2.0	23.6	02	100		47	100	100	200	040
003	004	0.51	1.5	30.6	02	100		47	100	100	200	040
004	005	0.34	1.5	20.4	02	100		47	100	100	200	040
005	006	0.48	2.5	14.7	02	100		47	100	100	200	040
006	007	0.33	1.0	39.6	01	100	AA,B	[illegible]	[illegible]	[illegible]	[illegible]	040
007	008	0.39	1.0	46.8	01	100	AA,[illegible]	61	100	100	200	[illegible]
008	009	0.43	1.5	25.8	01	[illegible]	[illegible]C	60	100	100	200	040
009	010	0.51	1.5	30.[illegible]	[illegible]	100	CC	60	100	100	200	040
10	011	0.53	1.[illegible]	[illegible]								
[illegible]	[illegible]	[illegible]	[illegible]	22.0	14	100	CC	60	100	100	200	040
998												

ROUTE NUMBER/NAME = AA TRAINS= (04 06 08 10 12)

FROM LINK	TO LINK	DIST (MI)	TT (MIN)	SPD MPH	TG	O/O	OTHER ROUTES	GRROW	CAR-TRIP PK	CAR-TRIP OFF	PPL/CAR PK	PPL/CAR OFF
006	007	0.33	1.0	39.6	01	100	A,B	1	100	100	200	040
007	008	0.39	1.5	23.4	01	100	A,B	1	100	100	200	040
008	009	0.43	1.5	25.8	01	100	A,B	1	100	100	200	040
009	010	0.51	1.5	30.6	11	100	A,B	48	100	100	200	040
010	011	0.53	1.5	31.8	11	100	A,B,CC,D	49	100	100	200	040

Notes: TG = Track Group

% = Percent (i.e. %) of that link which is of the specified track group

GRROW = Grouped Right-of Way . . . if a right-of-way treatment is applied, it is applied to all trackage within the specified group right-of-way(s).

Figure 8. Input seven: treatment effect.

101 R46 (X)FOLLOWS ( )SAME AS

R	-10	0	0	0	0	0	0	0	0	0	0	0
S	-10	0	0	0	0	0	0	0	0	0	0	0
C	-10	0	0	0	0	0	0	0	0	0	0	0

system data bases to effortlessly produce computations of expected noise levels--computations that would otherwise consume many months of effort on a large system.

For those interested in potential treatments, the data base can be modified to investigate how useful a specific treatment would be. This is actually what the second program in the PEACE program system does.

Based on the best available state of the art (1,2), six noise sources and seven paths have been defined for the rider environment in the NYCTA case study. In other environments or in other applications, the user may elect to use fewer of each. The PEACE program system can handle lesser numbers, but note that the treatments cannot be more detailed in their effect than the detail the sources and paths allow.

Treatment and Cost Data Base

The treatment and cost data base must provide the following information:

1. Treatments that are available;
2. The impact each has on the noise condition;
3. Prohibitions or restrictions on use (if any), including prohibitions on joint use; and
4. Dollar costs and benefits associated with each treatment in unit terms (per car, per track mile, and so forth).

The treatments must be defined in terms of the A coefficients of the sources or paths in each appropriate environment, for as many sources or paths as appropriate to the specific treatment.

In Figure 8, treatment 101, as applied to the R46, has the following (hypothetical) effects on the noise impact of the R46:

1. Source 1 in the rider environment (wheel and rail noise, from Figure 3) is decreased by 10 dB(A) in its impact on the rider,
2. Source 1 in the station environment (also wheel and rail noise) is decreased by 10 dB(A) in its impact on the station occupant, and
3. Source 1 in the community environment (also wheel and rail noise) is decreased by 10 dB(A) in its impact on the community resident or transient.

Note that this example is only illustrative.

The effectiveness of treatments may be similarly defined for other treatments to cars, ROW, stations, or community. In the case of treatments to the community, note that

1. The treatment effectiveness does not depend on any transit characteristic, because it is a treatment to the receptor (for instance, it might be double-glazed windows, with air conditioning, which affects a certain path to the community receptor, perhaps a classroom), and
2. Treatments to community sites affect only one environment, the community; thus there is one defining environment, not three.

In addition to defining the treatments, the user may define that certain treatments may not be applied if other treatments have already been applied.

The other major part of this data base is the cost information. This input is designed to be especially user friendly, going far beyond the headings that are built into the data bases, so that the user can recall what the information is without reference to any supporting manuals (see, for instance, the headings in Figures 6 and 7). The cost data file is organized to meet the needs of a user with little interest in combining cost elements, computing average or annualized costs, or any other preliminary work-up. For each treatment, the user need only

1. Identify the various costs and savings that result from the application of the treatment; these may be thought of as subcosts or component pieces;
2. Identify the initial cost and savings, the useful life, and the discount rate (interest) for each such capital cost or savings; the initial cost or savings is a unit cost per car, per track mile, or other appropriate unit; and
3. Identify the cost and savings annually on a unit cost basis for each such maintenance or operations cost or savings.

The POSTPEACE program uses this information in computing the cost report, which displays both annual cost and yearly outlays in several formats. A representative section of the input the user must provide as part of the data base is shown in Figure 9. The various cost units used in creating the data base are given in Table 1.

Two special cases exist: (a) for certain capital cost and savings items there may be an up-front outlay that does not easily enter the average unit

Figure 9. Input eight: cost information.

```
TREATMENT 101    CAPITAL COST          RESILIENT WHEELS
            $       4800 INITIAL COST PER CAR        TOTAL  0 UNITS
                      10 YEARS USEFUL LIFE
                      10 PERCENT DISCOUNT RATE

TREATMENT 101    CAPITAL SAVINGS       STANDARD WHEEL
            $       1800 INITIAL COST PER CAR        TOTAL  0 UNITS
                     6.6 YEARS USEFUL LIFE
                      10 PERCENT DISCOUNT RATE

TREATMENT 101    MAINT   SAVINGS       REDUCED TRACK MAINT
            $       1700 ANNUAL COST  PER TRMI
                     000 NUMBER OF EVENTS, IF KNOWN

TREATMENT 101    MAINT   SAVINGS       REDUCED WHEEL TRUEING
            $        150 ANNUAL COST  PER CAR
                     000 NUMBER OF EVENTS, IF KNOWN

TREATMENT 102    CAPITAL COST          RING DAMPED WHEEL
            $       3700 INITIAL COST PER CAR        TOTAL  0 UNITS
                       6 YEARS USEFUL LIFE
                      10 PERCENT DISCOUNT RATE

TREATMENT 103    CAPITAL COST          TUNED DAMPED WHEELS
            $       6000 INITIAL COST PER CAR        TOTAL  0 UNITS
                     6.6 YEARS USEFUL LIFE
                      10 PERCENT DISCOUNT RATE

TREATMENT 104    CAPITAL COST          CONSTRAINED LAYER DAMPING
            $       4800 INITIAL COST PER CAR        TOTAL  0 UNITS
                     6.6 YEARS USEFUL LIFE
                      10 PERCENT DISCOUNT RATE

TREATMENT 105    CAPITAL COST          DAMPING ALLOY WHEELS
            $       7200 INITIAL COST PER CAR        TOTAL  0 UNITS
                      05 YEARS USEFUL LIFE
                      10 PERCENT DISCOUNT RATE

TREATMENT 106    CAPITAL COST          RESILIENT TREADED WHEELS
            $       7200 INITIAL COST PER CAR        TOTAL  0 UNITS
                      05 YEARS USEFUL LIFE
                      10 PERCENT DISCOUNT RATE
```

Table 1. Permitted unit costs.

Treatment	Permited Units in Dollars per	Code	Notes
Car	Car	CARb	
	Wheel	UNDR	8 wheels per car[a]
ROW	Track mile	TRMI	Indoor or outside[b]
	Side mile	SDMI	For outside barriers[b]
	Wall mile	WALL	For tunnel walls
	Slot mile	SLOT	For barriers between tracks [N tracks might have (N-1) slots]
Station	Track mile	TRMI	
	100 linear ft of wall	WALL	
	Slot mile	SLOT	For barriers between tracks [N tracks might have (N-1) slots]
	1,000 ft^2 of ceiling	SPOT	Note 1,000 ft^2[c]
	Mile of underside	UNDR	Platform underside
Community	Track mile	TRMI	
	Side mile	SDMI	For outside barriers
	Slot mile	SLOT	For barriers between tracks [N tracks might have (N-1) slots]
	Building or block	SPOT	Literally, a spot improvement
Special	Unit	UNIT	If per unit is literally specified, then (a) if capital item, the number of special purchase units must be specified; or (b) if maintenance or operations item, the number of annual events must be specified.

[a]This use is discouraged; compute costs on the basis of per car if possible.

[b]TRMI and SDMI are the only logical units for spot applications of ROW treatments, and are intended to improve community spots.

[c]With proper modification of input two (width of platforms by station group physical, covered to width over tracks), this can be changed to handle 100 ft^2 of space over tracks.

cost, such as the purchase of one welding train, and (b) for certain maintenance, operating cost, and savings items the user may wish to specify the annual number of events and units to which the treatment is performed. Some ways of handling an increased wheel trueing schedule may be best handled by this latter approach.

THE MAIN PROGRAM (PEACE)

Given the data bases and files established by PREPEACE, the user may wish to select a set of treatments, apply them to the system, and determine the cost and effectiveness of that set.

The PEACE program applies the treatments that the user selects. It keeps track of the total effect of all applied treatments in each detailed area (car model and grounded ROW combinations, stations, and so forth) in terms of sources and paths. The POSTPEACE program combines these with the noise profiles of input six to get a net effect (see section on Applications). The relative strengths in the noise profile are extremely important in determining the result. Consider the following simple example, with only two sources:

Case	Source	Noise Profile [dB(A)] Level	Treatment	Net	After
1	1	90	-10	80	90.4
	2	90	0	90	
2	1	93	-10	83	83.6
	2	75	0	75	

In both cases the before level is 93 dB(A).

The PEACE program can be used in a number of ways.

1. Apply it to a set of files to produce a before-and-after condition, and then run POSTPEACE to evaluate the effect of the candidate set of treatments.
2. Apply it to several duplicates of the same set of files by using different candidate sets of treatments. In this way different candidate sets of treatments can be compared.
3. Change one or more source files by selective use of PREPEACE to change the car assignment, car fleet, treatment effectiveness, or other data base elements. Run PEACE on the original set and the revised set to obtain comparative information.
4. Run PEACE sequentially on the same data set by using different treatment plans (incremental or phased). Run POSTPEACE between these runs. In this way an estimate of the cumulative effect can be obtained.

In each application the PEACE program generates a set of FAULT messages, which inform the user if the specified treatments are (a) invalid treatment numbers, (b) prohibited, (c) already used, or (d) otherwise undesirable or infeasible.

THE POSTPROCESSOR (POSTPEACE)

The POSTPEACE program is the report generator, which works off the files created by PREPEACE and modified by PEACE.

The inputs to POSTPEACE are shown in Figure 10. The user may select any or all of the seven standard reports, including any or all options to sort within reports 4, 5, and 6.

The treatment report is a straightforward summary of all treatments that have been applied by the user, including mileages treated, total number of cars, and so forth.

The cost report provides annualized costs by treatment, treatment areas, and total, as shown in Figure 11. It also provides yearly costs over a 50-year period, showing the recurring cost and savings explicitly. Thus a capital item with a 10-year

Figure 10. Specifying reports on POSTPEACE.

POSTPEACE PROGRAM
JULY 1982 VERSION

	CHOOSE	NAME	NO SORT	BORO SORT	SORT BY MOE 1	SORT BY MOE 2	SORT BY MOE 3
REPORT 1	--(X)---	TREATMENTS	.	.	.	.	.
REPORT 2	--(X)---	COSTS	.	.	.	.	.
REPORT 3	--(X)---	ROUTES	.	.	.	.	.
REPORT 4	--(X)---	STATIONS	(X)	(X)	(X)	( )	( )
REPORT 5	--(X)---	COMMUNITY(ALL)	( )	.	( )	( )	( )
REPORT 6	--(X)---	COMMUNITY(SENS.RECEP.)	( )	.	( )	( )	( )
REPORT 7	--(X)---	SUMMARY	.	.	.	.	.

Figure 11. Report 2 (costs): annual cost by treatment.

REPORT TWO.....ANNUAL COST BY TREATMENT

TREATMENT	COST	LESS SAVING	NET ANNUAL COST
101	798366.	-503525.	294840.
126	81566.	0.	81566.
151	172954.	-21508.	151446.
176	23988.	-2983.	21005.

SUMMARY BY TREATMENT AREAS

	COST	LESS SAVING	NET ANNUAL COST
TREAT CARS	798366.	-503525.	294840.
TREAT R.O.W.	81566.	0.	81566.
TREAT STATIONS	172954.	-21508.	151446.
TREAT COMMUNIT	23988.	-2983.	21005.
TOTAL	1076872.	-528016.	548856.

useful life will show up as a cost in years 1, 11, 21, 31, and 41.

The noise level reports (reports 3, 4, 5, and 6) show the before and after noise levels with differences, if there is any change; otherwise only the existing levels are shown. Each report has three measures of effectiveness by which the user may evaluate the site. The measures for the station environment are given in Table 2. The report format is shown in Figure 12.

The report format for a route is shown in Figure 13. Note that station names are given, and that noise from station to station is indicated. Route summary statistics are also provided.

The summary report gathers the route statistics into one place and provides a summary of how many routes, stations, and community blocks were improved by how many decibels, and how many people were beneficially affected. This information was designed for summaries to upper-level management.

APPLICATIONS

Based on the interactions with NYCTA and the Transportation Systems Center during the course of development of the PEACE program, a number of enhancements were worked into the PEACE program system.

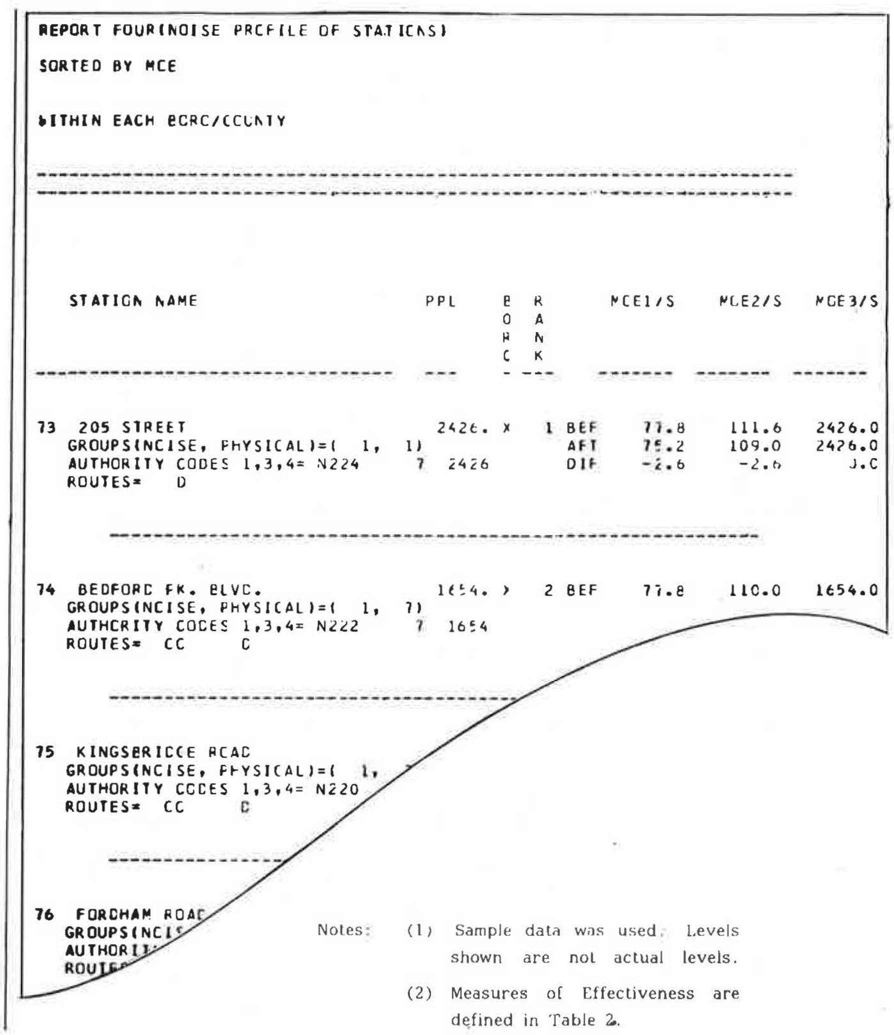
1. Cost reports must be in terms of actual annual expenditures as well as annualized costs, which are relevant in engineering economics and related analyses, but are not directly useful in budgeting.

2. ROW sections between stations are not necessarily uniform. Indeed, three or more distinct track groups might be encountered between two stations. Further, the existing NYCTA data base does not allow easy retrieval of such information; therefore, reasonable judgments were needed for a first system definition. However, the format of the forms had to accommodate the situation, and the program had to be coded with cognizance of such aspects.

Table 2. MOEs for the station environment.

Measure	Formula	Meaning
MOE 1/S	L_{eq}	Noise level if express present; otherwise local
MOE 2/S	L_{eq} + 10 log (expected exposures)	Total energy exposure due to express and local activity, based on annual turnstile counts and expected exposures per person
MOE 3/S	Annual turnstile counts	In thousands

Figure 12. Report four (stations).



Notes: (1) Sample data was used. Levels shown are not actual levels.

(2) Measures of Effectiveness are defined in Table 2.

Figure 13. Report three (routes).

ROUTE A WEIGHTED FOR ALL CARS ACTUALLY ON ROUTE
THERE ARE 344 CARS ON THIS ROUTE

		MOE1/R			MOE2/R			MOE3/R		
		BEFORE	AFTER	DIFF	BEFORE	AFTER	DIFF	BEFORE	AFTER	DIFF
1,	207 STREET	79.	79.	0.0	99.	99.	0.0	143.	143.	0.0
2,	DYCKMAN - 200 STREET	79.	79.	0.0	100.	100.	0.0	143.	143.	0.0
3,	190 STREET	82.	82.	0.0	101.	101.	0.0	145.	145.	[illegible]
4,	181 STREET	77.	77.	0.0	97.	97.	0.0	141.	[illegible]	[illegible]
5,	175 STREET	75.	75.	0.0	97.	97.	[illegible]	[illegible]	[illegible]	[illegible]
6,	168 STREET	87.	84.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0
7,	163 STREET	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	146.	146.	0.0
8,	155 STREET	[illegible]	[illegible]	0.0	97.	97.	0.0	141.	141.	0.0
9,	145 [illegible]	83.	83.	0.0	102.	102.	0.0	146.	146.	0.0
10,	[illegible]-WAVECREST	78.	78.	0.0	99.	99.	0.0	143.	143.	0.0
[illegible]	90 STREET-HOLLAND	81.	81.	0.0	101.	101.	0.0	145.	145.	0.0
[illegible]	BEACH 98 STREET-PLAYLAND	79.	79.	0.0	99.	99.	0.0	143.	143.	0.0
[illegible]	BEACH 105 STREET-SEASIDE	79.	79.	0.0	100.	100.	0.0	143.	143.	0.0
65,	BEACH 116 STREET-ROCKAWAY PARK									

SUMMARY FOR THE ABOVE ROUTE= A FOLLOWS...

	BEFORE	AFTER	DIFF
ROUTE LEQ	82.	82.	-0.
ENERGY EXPOSURE ONE PERSON	120.6	120.1	-0.5
ENERGY EXPOSURE ALL PERSONS	164.4	163.9	-0.5

Notes: (1) Sample data was used. Levels shown are not actual levels.
(2) MOE1/R is L_{eq}.

3. When considering prohibitions, the program must distinguish between absolute prohibitions and currently preferred or property-specific prohibitions.

These enhancements are only illustrative of the smaller but key issues that were identified because of the periodic interactions. Six major points stand out as prime and decisive results from the interaction process.

1. Extensive error checking of the user-provided data is needed both for out-of-range values and internal consistency.
2. The program should be a program system, consisting of a preprocessor, main program, and postprocessor.
3. The input data should be minimized so that (to the maximum extent possible) summary tables required should be generated by the preprocessor, not the user, and that noise profiles that are indistinguishable (e.g., car model X appears comparable to car model Y) are cross referenced rather than input twice as two independent pieces of information.
4. The property (and most users) view the use of PEACE in the user-specification mode as the proper approach. That is, the user selects and specifies a set of candidate treatments, which the program evaluates as to costs and benefits, and reports accordingly.
5. Because many persons must contribute small individual pieces to the data base, it is best--indeed it is imperative--to make reasonable assumptions on any missing or difficult portions of the three data bases. Users can and will react to the propriety of these assumptions much better than they will act in assembling the information initially.
6. The format of making data files self-documenting is vital and greatly appreciated.

Each of these points has been incorporated into the PEACE design.

It must be recognized that the typical user is under many obligations and works with scarce resources of time and personnel. Thus it is difficult to create a major, detailed, precise base on trackage, costs, or some other aspect unless the end product can be "felt". This is particularly true for personnel not directly connected with noise problems. It is much better to expect reaction and appropriate detail when everyone can better appreciate the sensitivity of the possible answers to specific data inputs.

By the end of the initial development of the PEACE program, the following uses of the PEACE results were identified by the NYCTA Environmental Staff Division:

1. Even the basic existing summary of noise levels by routes and stations will allow the Division to readily respond to internal inquiries and to citizen complaints;
2. The tabulation of the treatment data base will provide an identification of options and a synthesis of the state of the art;
3. The actual operation of the PEACE program will allow evaluation of (a) past program efforts and (b) alternate future abatement scenarios; and
4. The actual operation of the PEACE program will allow scenarios proposed by any other party to be identified and will enable better information to exist when legislation, mandates, and regulations are considered.

In addition, the possible educational and training aspects of using the PEACE program on a specific property must be considered.

Other applications of the program system include the following.

1. An agency might use PEACE to explore sensitivities, namely what-if questions: What if a given benefit is -10 dB(A) and not -15 dB(A)? What if one action is taken rather than another?
2. An agency might use PEACE to determine whether a potential treatment would have major benefit to a system if it had its anticipated characteristics (or some lesser ones). Thus it could be used to assess candidate demonstration treatments.
3. Similarly, an agency can attempt to identify what characteristics a treatment should have, thus better directing its identification process.
4. PEACE can be used as a training tool in a deployment activity in addition to the other applications cited.

Certainly, further applications will be identified as user experience is gained.

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Effects of Parallel Highway Noise Barriers

J.J. HAJEK

The effects of opposing, parallel highway noise barriers have been analytically quantified by using principles of geometrical acoustics; they also have been compared with measured data. The evaluation was performed both for residential areas outside barrier walls and roadway areas between barrier walls. According to analytical results, the effect of parallel barriers can be substantial in residential areas. Under certain conditions the existing preconstruction sound levels can actually be increased (rather than reduced) by erecting vertical, sound-reflecting parallel barriers. However, direct field verification of the calculated results was difficult. In roadway areas the change of sound environment between parallel barriers could be verified by direct field measurements. The comparison of the measured and calculated results indicated that the method of using image sources to account for sound reflections is applicable for describing highway noise reverberation. It is postulated that this technique should also be applicable for estimating sound levels in residential areas. Results also suggest that the driver's perception of other vehicles on the road can be affected by parallel barriers.

The objective of the work reported in this paper was to obtain a better understanding of the effect of multiple reflections caused by parallel highway noise barriers. Opposing barriers, or highway cuts with retaining walls on both sides, can give rise to multiple reflections. The resulting reverberation field within barrier walls can significantly affect sound levels both within and outside (behind) barrier walls.

The Ontario Ministry of Transportation and Communications (MTC) has been retrofitting existing freeways with noise barriers since 1977. To date about 35 km of noise barriers have been built and about 60 percent of them are parallel to other barriers, thereby rendering the single-barrier situation atypical.

In spite of their frequency of occurrence, the treatment of parallel barriers is ambiguous. Although the role of multiple sound reflections between opposing barriers has been entirely discounted by some investigators (1), others have considered it to be highly significant (2). At any rate, the effect of parallel barriers has not yet become a part of common highway noise-prediction methods (3,4).

Parallel barriers can affect the sound environment in two distinct areas: (a) in the residential area outside barrier walls, and (b) in the roadway area within barrier walls. Both areas were investigated separately by using analytical methods based on geometrical acoustics and by direct field measurements.

RESIDENTIAL AREA

Analytical Investigation

A number of theories can be used to describe a reverberant field in enclosed or semienclosed spaces: wave-reflection theory, diffuse-field theory, and application of geometrical acoustics based on image theory. The geometrical acoustics method was used in this study because of its simplicity and reported reliability (5,6). To obtain a numerical solution, several assumptions were required.

1. Only specular reflection exists with no incident sound power scattering. Loss of sound energy because of reflections off the wall surfaces is acounted for by an absorption coefficient.
2. The absorption coefficient does not depend on angle of incidence (i.e., absorption coefficient is the same for all reflections) and is constant over the entire frequency range of highway noise that contributes significantly after A-weighting is applied.
3. The walls are high enough relative to source wavelength and the position of the source and the receiver aboveground to enable application of geometrical acoustics.
4. The contributions of real and image sources are added incoherently.
5. The source exhibits a uniform directivity pattern.

The frequency of the traffic noise source used in the analysis was 500 Hz because this frequency often dominates A-weighted traffic noise spectra. This choice allows the calculated sound levels to be considered as being in dB(A). The height of the source was assumed to be 1.5 m above the pavement surface, which corresponds to a highway traffic flow that contains about 10 percent trucks.

To include the effect of multiple reflections, a number of image roadways were constructed and included as input to a highway noise-prediction program STAMINA 1.0 (7). The program automatically accounts for distance attenuation (including atmospheric absorption) and barrier diffraction attenuation of sound emitted by the original as well as by the image roadways, thereby reducing the problem to a series of single-barrier situations. The method of constructing image sources (image roadways) is shown for the first two reflections in Figure 1.

Note that the program STAMINA 1.0 has been updated and reissued as STAMINA 2.0 (8). Nevertheless, none of the changes incorporated into STAMINA 2.0 (namely, the condition that the loss of excess ground attenuation from the erection of a barrier must not exceed barrier diffraction loss) affects the reported results. In other words, STAMINA 2.0 results would be the same as those obtained by STAMINA 1.0.

The number of reflected waves originating from image sources that can reach a receiver depends on the receiver location, the relative heights of the opposing barriers, and the source height. Although an infinite number of reflections exist for receivers located in the region below the barrier top ($h_r < h_b$ in Figure 1), provided that the far wall--the wall farthest from the receiver--is equal to or higher than the near wall, only the first 15 images were included in the analysis for practical purposes.

The effect of the number of reflections (image sources) included in the analysis is shown in Figure 2 for a barrier geometry used subsequently for more detailed analysis. The parallel barrier degradation shown on the ordinate of Figure 2 is the reduction in the single-barrier insertion loss because of the presence of the opposite barrier. Ground cover is considered to be acoustically hard. According to the data in Figure 2, the degradation asymptotically increases as more reflections are accounted for and as the distance from the barrier increases. The contribution of the omitted reflections (reflections 16 to infinity) to the parallel barrier degradation was found to be smaller than 10 percent of the contribution provided by the first 15 reflections. This applied even for highly reflective barrier surfaces and for large distances behind the barrier.

The number of reflections used in the analysis of receivers located above the barrier top ($h_r > h_b$) ranged from 0 to 15. To be included in the calculation, the reflected wave must have reached the opposite barrier at least 0.6 m below the barrier top, which corresponds roughly to the wavelength of the 500-Hz source. This is a conservative assumption to account for the effect of barrier edge where a part of the sound energy is diffracted and scattered over the top of the opposite barrier.

The reflected waves are also attenuated by absorption of barrier surfaces. For the image sources, the original sound power of the source was reduced in proportion to the cumulative multiple-reflection coefficient α_M, which is defined as follows: $\alpha_M = (1 - \alpha)^j$, where α is the simple absorption coefficient (assumed identical for both barrier surfaces), and j is the number of reflections.

Results

The degradation effect of parallel barriers is shown in Figure 3 by using attenuation contours developed for 4.5-m-high barriers that are 36.5 m apart. The insert in Figure 2 shows a cross-section sketch of the barriers. This example may correspond to a six-lane freeway situated on flat terrain. The sound-absorption coefficient of barrier surfaces was assumed to be 0.05; i.e., the barriers were reflective. The contours in Figure 3 were developed for

Figure 1. Construction of image sources.

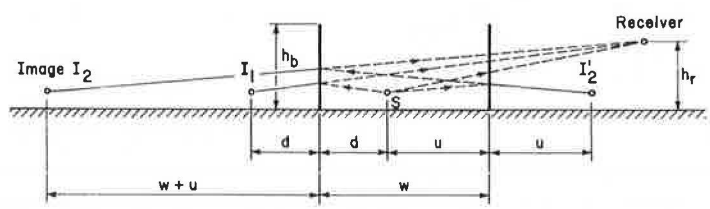
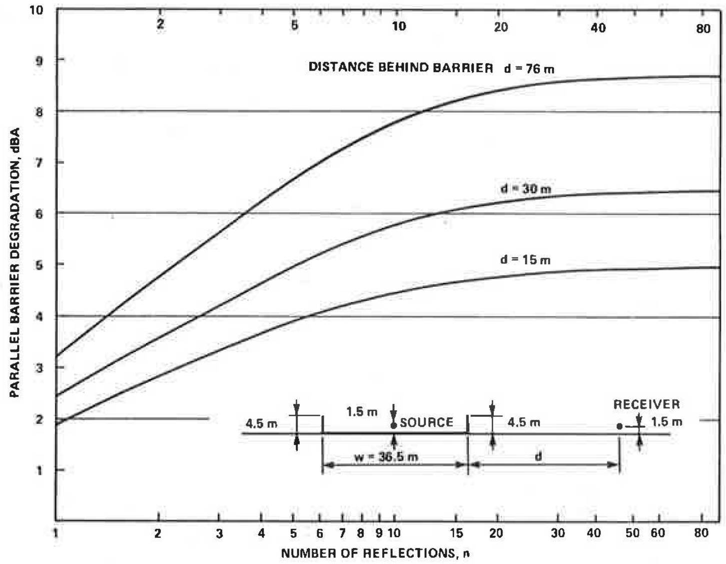
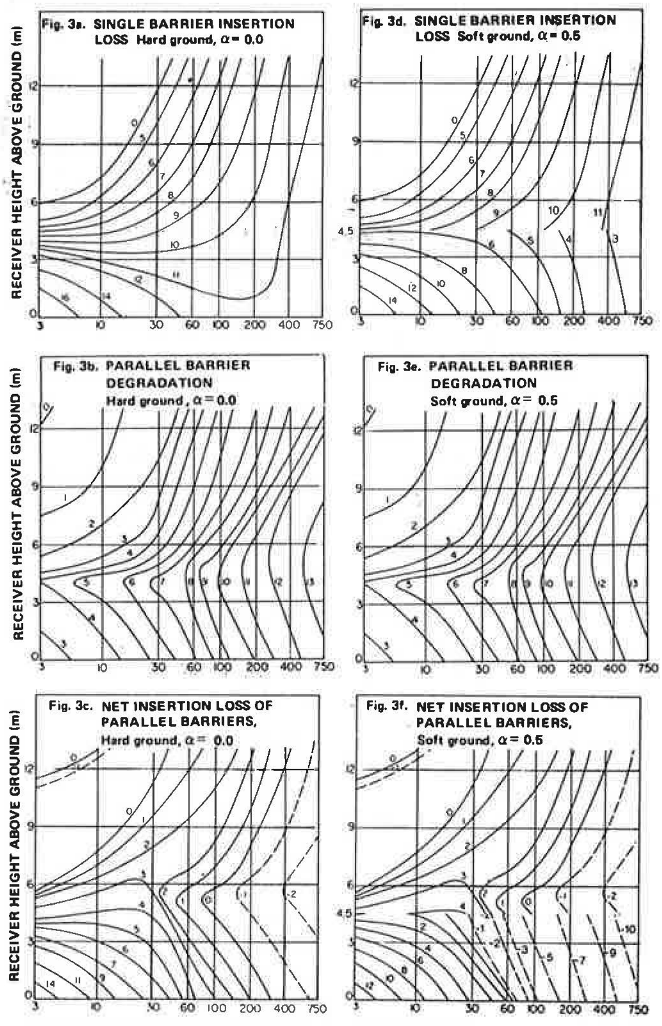


Figure 2. Parallel barrier degradation versus number of reflections.



Note: Height of barriers = 4.5 m; distance between barriers, w = 36.5 m; receiver is 1.5 m above the ground plane and distance d behind the barrier; sound-absorption coefficient of barrier surfaces, α = 0.05.

Figure 3. Barrier attenuation contours [dB(A)], showing the effect of parallel barriers.



Note: Height of barriers = 4.5 m; distance between barriers = 36.5 m; sound-absorption coefficient of barrier surfaces = 0.05; source height = 1.5 m.

two ground cover types between the highway and the receivers:

1. Acoustically soft, absorptive ground--α = 0.5 [α is defined in the FHWA model (3)], which corresponds to the before-barrier sound-attenuation rate of approximately 4.5 dB(A) per distance doubling; and
2. Acoustically hard ground--α = 0.0, which corresponds to the before-barrier attenuation rate of 3.0 dB(A) per distance doubling; when the barrier is in place, the program STAMINA 1.0 assumes an attenuation rate of 3.0 dB(A) per distance doubling, regardless of the prebarrier ground type, because of the apparent shift of the noise source to the top of the barrier (as discussed previously, the same assumption would be used by STAMINA 2.0 because the barrier diffraction attenuation exceeded the excess ground attenuation).

For each ground type, isodecibel contours show (a) the single-barrier field insertion loss [Δs (Figures 3a and d)]; (b) its degradation because of the erection of the opposite barrier [Δd (Figures 3b and e)]; and (c) the net field insertion loss for a parallel barrier situation [Δs - Δd (Figures 3c and f)].

Although the isodecibel lines that show the insertion loss of a single barrier on the hard ground (Figure 3a) are smooth, the corresponding lines for a single barrier on soft ground (Figure 3d) exhibit a distinct discontinuity for receivers 4.5 m aboveground. This is the result of the recommendation in the FHWA model (3) that hard ground be used (α = 0) whenever the line of sight (a direct line between the noise source and the receiver) averages more than 3 m aboveground. Considering the source height of 1.5 m, the switch from the hard to the soft ground occurs at the receiver height of 4.5 m. Consequently, Figures 3a and d are identical for all receivers more than 4.5 m aboveground.

The assumed change in ground attenuation whenever the average propagation height exceeds 3 m results in a considerable jump in the insertion loss. For example, according to the data in Figure 3d, a 3-dB(A) insertion-loss contour is changed, at the height of 4.5 m, into an approximately 11-dB(A) contour. It has been proposed to replace the abrupt change in the excess ground attenuation at the 3-m height by a more gradual function that incorporates both the height aboveground and the distance between the source and the receiver (4,9).

Note that the parallel barrier degradation shown in Figures 3b and e is independent of the ground cover behind the barriers. Thus Figures 3b and e are identical.

The predicted degradation of the single-barrier attenuation from the erection of the opposite barrier is quite dramatic, particularly when the ground between the highway and the observer is absorptive. For example, the data in Figure 3f indicate that no net insertion loss is produced by the 4.5-m-high reflective barriers for receivers approximately 50 m behind the barrier at 1.5 m aboveground. Furthermore, at a distance of approximately 200 m behind the barrier at 1.5 m aboveground, the net field insertion loss is negative, which indicates a predicted increase of about 6 dB(A) over the condition with no barriers. The net insertion loss of the reflective parallel barriers situated on hard ground (Figure 3c) is equally affected by the presence of the opposite barrier. However, the net insertion loss is considerably higher than for the barriers on soft ground because of the higher single-barrier insertion loss. Nevertheless, Figure 3c indicates no net insertion loss for receivers approximately 300 m behind the barrier at 1.5 m aboveground.

It should be pointed out that the degradation effect of opposite barriers can be considerably reduced or eliminated by using barriers with sound-absorptive surfaces or by inclining barrier surfaces by 3° to 10° away from the highway (10).

Field Measurements

Even though the potential degradation effect of reflective parallel barriers is considerable, it is still difficult to verify the degradation by direct field measurements. The degradation effect of parallel barriers increases with distance (Figure 2). However, at larger distances behind the barrier, where the degradation effect reaches measurable proportions (i.e., 3 or 4 dB), sound levels are usually quite low [often in the 55 to 60 dB(A) range] and can easily be influenced by highly variable community noise sources (such as local traffic or children playing) and by weather-related factors (such as wind speed and direction).

In recent studies in which the field acoustical performance of parallel highway noise barriers was evaluated (11-13), it was found that the effect of parallel barriers may not be as significant as the application of geometrical acoustics would suggest. This has been attributed to various causes, namely,

1. The presence of large reflecting surfaces at these sites (houses, parapet walls, highway vehicles) before as well as after barrier construction;
2. Relatively low barrier height at certain locations (about 3 m) and large distances between them; and
3. Difficulties in accurately measuring insertion losses when sound levels are also influenced by community noise.

Thus more carefully designed and executed field studies are required.

ROADWAY AREA

The sound field between barrier walls can be assessed more easily than sound levels in residential areas. The influence of community noise sources and reflective surfaces from outside the barrier walls is insignificant. Analytical modeling is simplified, and calculated results can be readily verified by simultaneous measurements of sound levels at a location between walls and at a corresponding location without walls. The understanding of the sound environment between barrier walls enables (a) better understanding of the sound field behind barrier walls where residences are located, (b) evaluation of the reverberant sound field between walls as it affects driver perception of other vehicles on the roadway, and (c) assessment of design variables such as sound-absorptive treatment and wall geometry.

Analytical Investigation

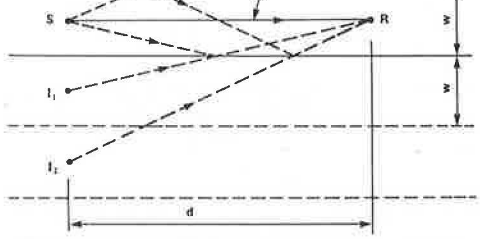
Analytical evaluation of the sound environment in the roadway area (between barrier walls) was based on the same method and assumptions as those used for the residential area (i.e., geometrical acoustics, source frequency of 500 Hz). Also, the effect of sound scattering and the resulting diffuse field were not included in the analyses. Their contribution to the multiple-reflection field formed by plain walls, the height of which is considerably smaller than the distance between them, would be negligible (14).

As shown in Figure 4, the walled highway was represented as a channel between two infinite sound-reflecting planes. In the center of the channel is a single point source (S), which emits sound energy at a constant rate and frequency spectrum. Sound waves can reach a receiver (R) both directly and after one or more reflections off side walls. These reflections can be represented by two infinite sets of image sources, each situated on one side of the channel. The space within the channel is referred to as the reverberant field. The corresponding space not bounded by the channel walls is referred to as the free field.

The objective of the mathematical model was to obtain a difference between the free-field and reverberant-field sound levels. For this reason, several factors that affect only the total sound energy or its time variation, but do not affect the difference between sound energy in the reverberation and free fields, were not included in the model. These factors are

1. Contributions from pavement (ground plane) reflections [the omission of pavement reflections is considered negligible because the pavement reflections would exist in both fields; a perfectly sound-absorbing ground was assumed in the subsequent calculations; therefore the same results (i.e., difference between the two fields) would be obtained for a perfectly reflecting ground];

Figure 4. Construction of image sources.



Note: Image sources exist in two discrete pairs, e.g., I_2 = image source for the second reflection and the first pair, and w = distance between walls; d = distance from source to observer.

2. The effect of the source motion on the sound radiation [an excellent discussion of this topic can be found in Lansing (15)]; and

3. Effect of retarded time, i.e., time at which the observed sound was emitted by the source (sounds traveling on different propagational paths would not reach the receiver simultaneously; however, the total sound energy reaching the receiver over a period of time is not affected).

The total sound intensity at the receiver (Itot) can be obtained by adding sound intensity reaching the observer directly (Iff) and sound intensity reaching the observer after one or more reflections (Irev). The increase in sound intensity level (ΔL) caused by reflections can be expressed as

$$\Delta L = 10 \log (Itot/Iff) \qquad (1)$$

where ΔL is the difference between total sound intensity and free-field sound intensity (dB); and Itot is the total sound intensity (watts/m^2); i.e., Itot = Iff + Irev, as previously defined.

Equation 1 was expanded and modified to include an infinite number of reflections that exist for the configuration of Figure 4 and to include sound attenuation due to atmospheric absorption. Assuming spherical spreading and a perfectly absorbing ground, the following equation (16) is derived:

$$\Delta L = 10 \log \left(1 + 2d^2\, 10^{Ed} \sum_{n=1}^{\infty} \left\{ (1-\alpha)^n / [d^2 + (nw)^2] \right\} \cdot [1/10^{E\sqrt{d^2+(nw)^2}}] \right) \qquad (2)$$

where

- d = straight-line path length between the source and the receiver (m),
- E = atmospheric absorption coefficient (0.001 772 dB/m),
- n = number of reflections (n = 0,1,2,3...),
- α = sound-absorption coefficient (identical for both barrier surfaces), and
- w = distance between parallel walls.

Mathematical Modeling

It is assumed in Equation 2 that the source and the receiver are located on the path the source travels. However, for short distances between the source and the receiver, Itot depends on the position of source and receiver in relation to boundaries. For this reason, Equation 2 was modified to distinguish the receiver location from the source path (see Figure 5), and the numerical solution was computerized.

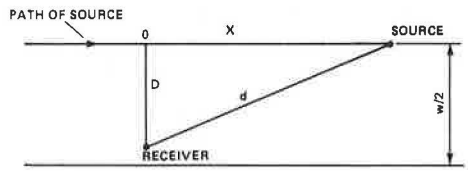
Typical single-point source passby curves calculated for the free field and for the reverberation field are shown in Figure 6. In the case of the reverberation field, the distance between the two barrier walls was 30 and 60 m. Also shown is the effect of atmospheric absorption, which becomes noticeable only for greater distances from the source.

The difference between sound levels in the reverberation and free fields is independent of the sound power of the single-point source (Equation 2). Moreover, it is also independent of the number of single-point sources, provided that their number, intensity, and position relative to the walls are the same for both fields. Thus, by integrating the sound energy of the single-point source passby curves in the reverberant and free fields, and then calculating the difference between them, the difference in sound energy between the two fields for the total traffic flow (ΔL_{eq}) can be obtained.

The difference between sound energy levels in the reverberation and free fields (ΔL_{eq}) was evaluated over an integral of distance rather than time (16). Thus the influence of the width as well as length of the reverberation field could be directly quantified.

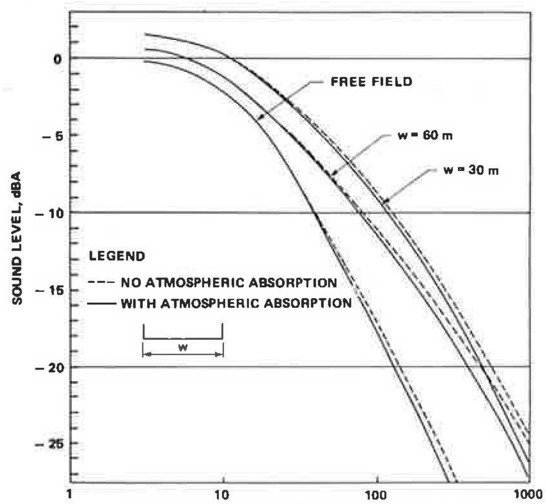
Some of the results are shown in Figure 7, which relates L_{eq} to the distance between walls and to the sound-absorption coefficient of the walls. It is apparent that the sound-absorption coefficient

Figure 5. Parameters for calculating passby curves.



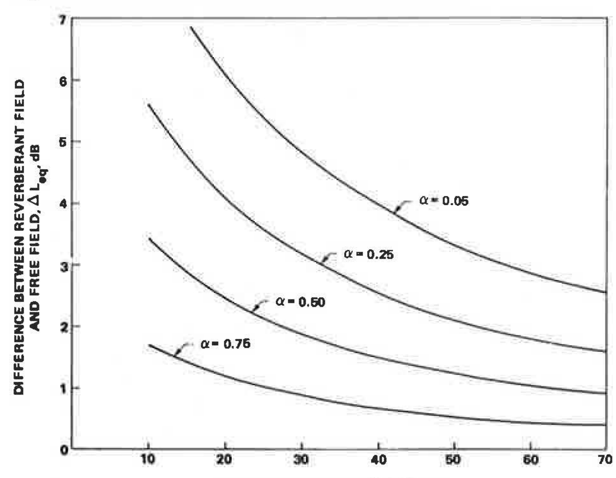
Note: D = distance of closest approach, d = actual path length distance between source and receiver.

Figure 6. Single-point source passby curves.



Note: Absorption coefficient of walls, α = 0.05; distance to closest approach, D = 13.0 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m.

Figure 7. Increase of sound levels in reverberation field.



Note: Sound-absorption coefficient of walls (α) varies; distance to closest approach, D = 13.0 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m; length of reverberation field, X = 1500 m.

(α) is an important parameter that influences sound energy build-up within walls. For example, ΔL_{eq} for partly sound-absorbing walls (α = 0.5) at 10 m apart is similar to ΔL_{eq} for sound-reflective walls (α = 0.05) at 50 m apart. The sound energy build-up within walls can also influence sound levels outside of them, or behind barrier walls or retaining walls.

Experimental Results

To verify the mathematical model, two types of full-sized experiments were conducted: (a) measurements of passby curves of single vehicles, and (b) measurements of total highway traffic flow.

Comparison of Passby Curves of Single Vehicles

Passby curves of single vehicles were measured along a relatively flat six-lane freeway (Highway 409) by using two heavy diesel trucks. The trucks passed by two adjacent receivers at a constant speed of 80 km/h; the first receiver was located within a reverberation field formed by two 6-m-high retaining walls approximately 1500 m long, and the second receiver was located in a free field with no reflecting surfaces, such as houses or parked vehicles, within a 90-m radius. The retaining walls were of untreated concrete with a coefficient of absorption (α) estimated at 0.05. A schematic diagram of the experimental setup, including a cross section of the reverberant field, is shown in Figure 8.

Measured time histories for both free and reverberant fields are compared with calculated time histories for a typical passby test in Figure 9. The measured sound levels in this figure are dB(A) levels; the calculated sound levels are for a frequency of 500 Hz. The data in Figure 9 indicate extremely close agreement between the measured and calculated time histories, disregarding considerable fluctuations of measured values. The fluctuations are a result of ground interference, wall scattering, turbulence, and other factors that were not included in the model.

In addition to the time histories, which are somewhat difficult to evaluate because of instantaneous fluctuations, maximum sound levels were also evaluated. The average measured difference between maximum sound levels emitted by the test trucks in the reverberation and free fields was 4.8 dB(A). The corresponding calculated difference was 3.3 dB(A).

Comparison of Total Traffic Flow

Experimental measurements of the total traffic flow were conducted on the same site along a six-lane freeway (see Figure 8), and on an additional site along an eight-lane freeway [Queen Elizabeth Way (QEW)], by using a procedure similar to that used for the single-vehicle measurements. The length of the reverberation field at the QEW site was approximately 400 m. Two microphones were used simultaneously--one located within a reverberation field and the second in a free field. Traffic flow volume, composition, and speed; pavement type; distance between receiver and traffic lanes; and other factors were identical at both locations. Consequently, the difference between the sound levels obtained at the two locations could be attributed solely to the effect of parallel reflecting walls.

Results were expressed by the highway traffic noise descriptors L_{eq}, L_{10} (sound level exceeded 10 percent of the time), L_{50}, and L_{90}. Results for the six-lane freeway are given in Table 1.

The data in Table 1 indicate that noise descriptors related mainly to peak sound levels (L_{10} and L_{eq}) are not as affected by the reverberation field as noise descriptors related mainly to average and background sound levels (L_{50} and L_{90}, respectively).

For example, the difference between the reverberant and free fields was about 3 dB(A) in terms of L_{eq} levels, whereas the corresponding difference in terms of L_{90} levels was about 8 dB(A). This is not surprising, considering the passby curves shown in Figures 6 and 9. For a single-vehicle passby, the difference between sound levels in the reverberant and free fields increases with the distance

Figure 8. Schematic diagram of measurement setup, Highway 409.

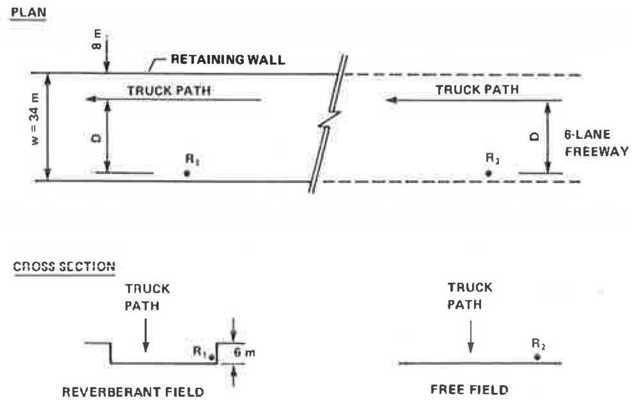
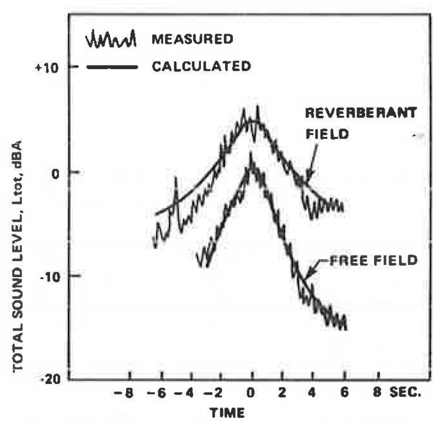


Figure 9. Comparison of measured and calculated passby curves.



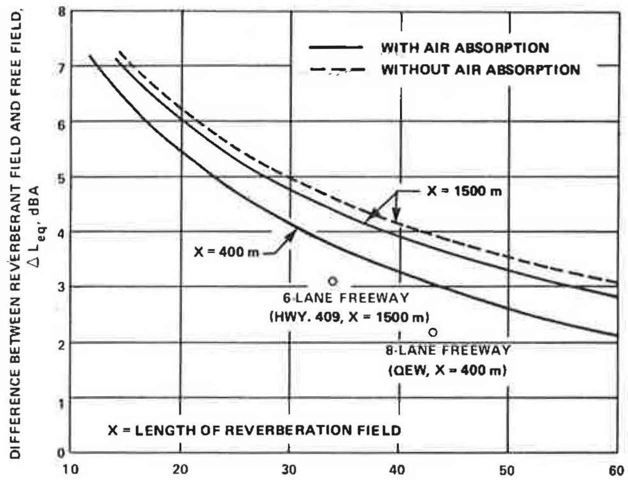
Note: Conditions are as follows: speed of test vehicle = 80 km/h; distance to closest approach, D = 24.7 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m; length of reverberation field = 1500 m, and its width, w = 34 m; sound-absorption coefficient of walls, α = 0.05.

Table 1. Comparison of sound environment measured in reverberation and free fields, Highway 409.

Item	Sound Descriptor			
	L_{eq}	L_{10}	L_{50}	L_{90}
No. of measurements[a]	11	11	11	11
Avg difference between reverberation field and free field [dB(A)]	3.07	4.44	6.74	8.32
Standard deviation of differences between reverberation field and free field [dB(A)]	1.32	1.23	1.35	1.52

[a]All measurements were 20 min in duration on Highway 409.

Figure 10. Comparison of measured and calculated differences between reverberant and free fields.



Note: Calculations based on sound-absorption coefficient of walls, α = 0.05; distance to closest approach, D = 13.0 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m.

between the source and the receiver. This tends to affect background levels more than peak levels.

The changes in the reverberant sound field cannot be characterized only by an average increase in sound levels. The time distribution of sound levels is also changed because peaks and background levels are increased at different rates. This is important when considering a driver's perception of other vehicles on the road. When the peak sound levels of individual vehicles are increased, they may be perceived by a driver as being closer than they actually are. However, the increase in the peak level is masked by an even higher increase in the background levels. Thus the driver's hearing perception of the distances between vehicles on the road is affected. The actual perception of the driver depends also on the sound levels emitted by the driver's own vehicle, its sound insulation characteristics, the density and composition of traffic flow, and other variables.

The calculated and measured differences between sound levels in the reverberant and free fields for the two freeways are compared in Figure 10. The comparison is in terms of L_{eq} levels. The measured differences are lower than the calculated ones by about 1 or 2 dB(A). Considering approximations and assumptions used in the mathematical model, this is quite a reasonable agreement. Discrepancies could arise, for example, from a nonuniform directivity pattern of highway vehicles, shielding by highway vehicles, the reflection-scattering process, and experimenal error.

CONCLUSIONS

The case of parallel highway noise barriers may actually represent a typical case of barrier arrangement because, at least in Ontario, noise-sensitive land uses exist more often on both sides of expressways rather than on a single side only. Nevertheless, the effects of parallel barriers are not as well understood as those of single barriers. The following conclusions are drawn.

1. According to analytical results, the impact of parallel barriers on the residential area can be substantial and can result in higher sound levels for a parallel barrier installation than for a free-field situation. This is particularly pronounced in the case of barriers situated on an acoustically soft ground.

2. Field measurements revealed little effect from parallel barriers. It was hypothesized that the presence of large reflecting surfaces such as houses (both before and after barrier construction) can mask the degradation effect of erecting additional reflecting surfaces (i.e., barriers). This, together with the influence of community noise sources and weather-related factors, makes field verification of the degradation effect difficult.

3. In the roadway area (within barrier walls), a close agreement was obtained between predicted and measured sound levels. Predictions were based on geometrical acoustics that used image sources to account for multiple reflections; these predictions could be verified by field measurements.

4. Because the image-source theory provides reliable results for the sound field within barrier walls, it is postulated that it may also provide reliable results when applied to the sound field outside the walls in the residential area, where verification by direct field measurements is difficult.

5. In the roadway area the background sound levels are significantly increased because of multiple reflections. This can affect the drivers' perception of distances between vehicles on the road.

6. In view of the potential extent of parallel barrier installations and their effects, research should be continued, with emphasis on full-scale testing.

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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'.

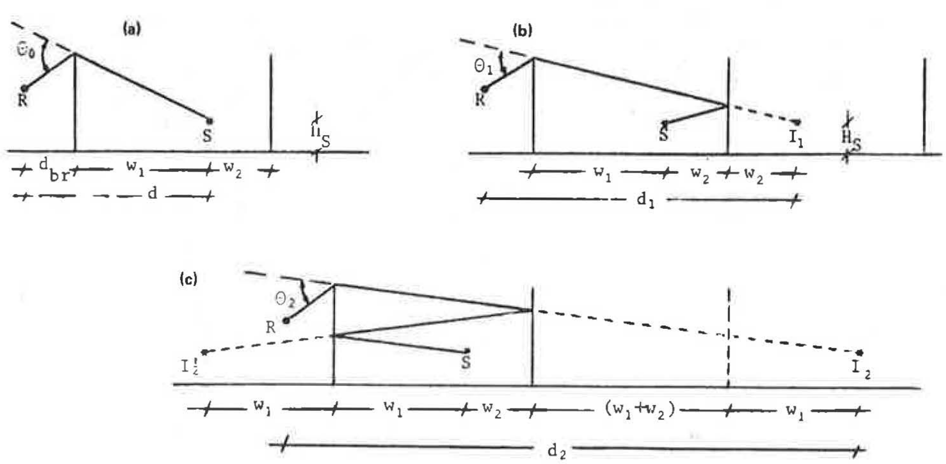
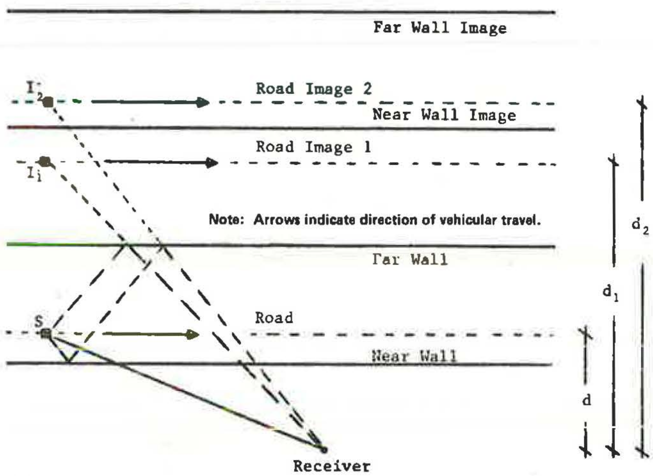


Figure 2. Plan view of parallel barriers showing reflection along the canyon for actual source (S) and first two images.



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

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

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,

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

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:

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

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:

$$\delta = \delta_o \cos \phi \tag{4}$$

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.

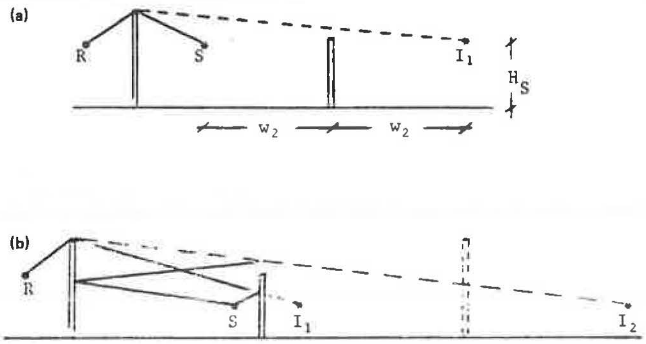


Figure 4. Three Z-coordinates are needed for each barrier to indicate the elevations of the tops of each barrier section.

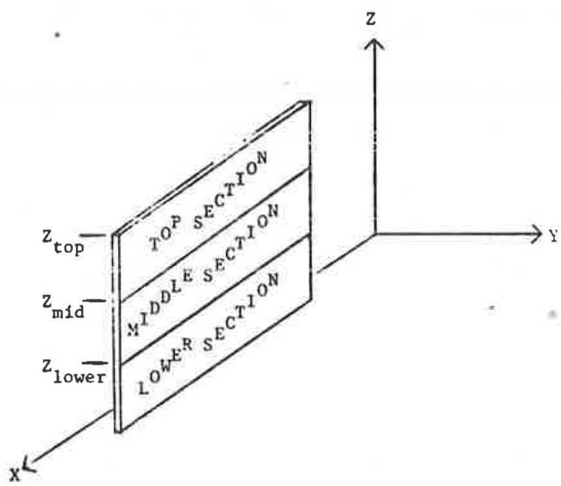


IMAGE-3 DATA INPUT

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
```

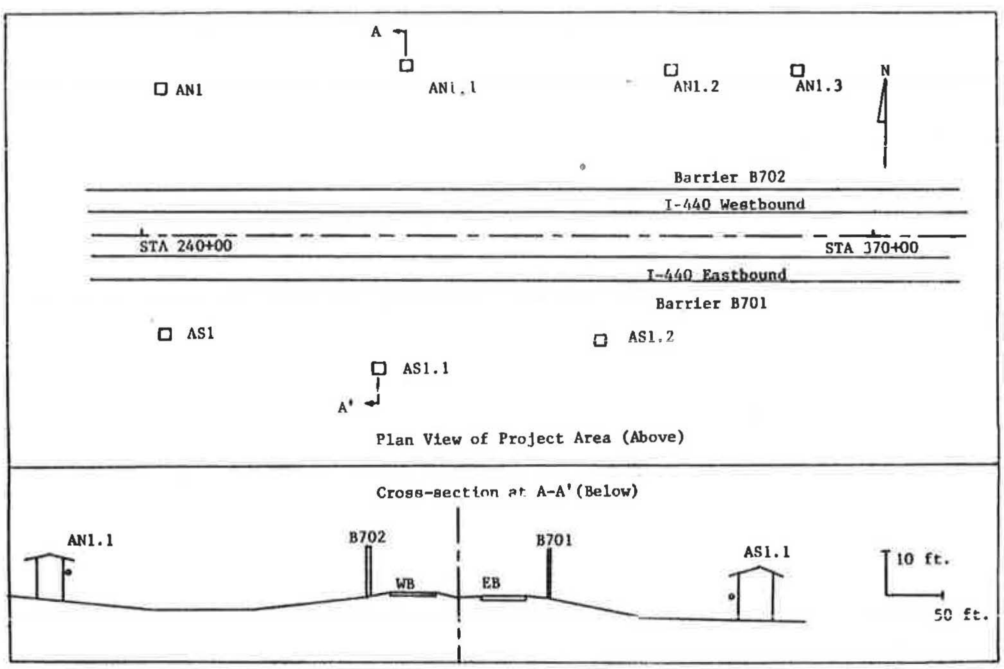
Figure 6. Sample input data file.

```
.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.Ø5	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	Ô.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) NO BARR	ONE WALL	MUL.REFL.	INCR.	# REFL.
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) NO BARR	ONE WALL	MUL.REFL.	INCR.	# REFL.
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

REC	RD	I	LEQI	AUTOMOBILES 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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