pleasing vista of the school's property for motorists along I-95 and effectively protects the school population from elevated noise levels. From this standpoint, in addition to the cost and performance data acquired, the Archbishop Keough transparent noise barrier should be considered a successful project.

REFERENCES

1. Bolt, Beranek, and Newman, Inc. Feasibility of Polycarbonate Sheet in Highway Noise Barriers. Fanwall Sales Corporation, Framingham, MA, Feb. 1978.
2. B.J. Chapman and R.M. Smith. Weathering Durability of Bus Passenger Shelter Glazing Materials. California Business and Transportation Agency, Sacramento, DMT-063, April 1980.

NJ-18 Freeway and Rutgers University Classrooms: Unique Construction Noise Mitigation Experience

DOMENICK J. BILLERA AND BRUCE C. CUNNINGHAM

This paper presents the identification and solution of a severe construction noise problem at Rutgers University classrooms created by the NJ-18 Freeway. The design, construction, and testing of sealed, modular metal walls attached to the buildings, which have sound-absorbing properties and window panels, are discussed.

The purpose of this report is to relate the knowledge and experience the New Jersey Department of Transportation has gained in the design and construction of a unique solution to a severe noise problem at a construction site. Our solution to mitigate construction noise impacts at university classrooms adjacent to the NJ-18 Freeway project was to attach a sound-absorbing, sealed, and ventilated wall with windows onto the affected buildings.

The NJ-18 Freeway extension project in New Brunswick is a 2.3-mile, six-lane roadway that will extend from the existing interchange at New Street along the Raritan River on the filled bed of the Delaware Raritan Canal. It will pass three Rutgers University dormitory buildings and Buccleuch Park. It will then cross the river into Johnson Park and terminate at River Road (see Figure 1). The 1972 noise impact study predicted a significant noise impact of L_{10} 77 dB(A) to the three Rutgers University river dormitories from traffic in the design year.

To mitigate this impact and also to replace land taken from Johnson Park by the project, a landscaped deck cantilevered over the roadway was proposed that was predicted to provide approximately 21 dB of noise attenuation. This deck will pass the three dormitory buildings between two access ramps for an uninterrupted 1530 ft. The estimated cost of the deck alone is $12 million. The total project cost is estimated to be $47 million.

Before construction on the project could begin, the transportation department was required to perform a construction noise study (1). This study determined that, for the three-year construction period, noise impacts would be significant and would range from L_{eq} 75 dB(A) to 86 dB(A) in the 25 classrooms and four seminar rooms that occupy the basement levels of the dormitory buildings. These high noise levels result from construction activity within 40 ft of the buildings. Ironically, one of the noisiest construction periods was found to be during the construction of the cantilevered deck, which is intended to be a noise-abatement measure.

Once the problem was identified, 13 alternative schemes were developed for dealing with the construction noise problem. These schemes were then presented to the Federal Highway Administration (FHWA) and Rutgers University officials, and an agreement on a single scheme was negotiated.

DESIGN

Three criteria were used to assess the impact of construction noise on the classrooms. The first criterion was the overall hourly L_{eq}. Although FHWA does not specify a noise level for construction, the L_{eq} was used to determine the degree of noise attenuation for all the abatement measures considered.

The speech interference level (SIL) was one criterion selected for impact assessment (2). It is defined as the arithmetic average of the sound levels in the 500 Hz, 1 kHz, and 2 kHz octave bands. These bands are used because nearly all the information contained in speech is distributed between 200 Hz and 6 kHz. The SIL is also easily determined. The table below relates SIL, distance from speaker to listener, and intelligibility for face-to-face communication. For the lecture environment in the classrooms, an SIL of 35 dB was the design goal.

Voice Level	SIL	Distance from Speaker to Listener (ft)	Intelligibility
Normal	40	16	Possible
Raised	50	8	Possible
	60	3	
Loud	70	1	Possible
Very loud	80	1	Possible
Shout	90	0.5	Possible
Maximum vocal effort	100	1	Difficult

Another approach used for impact assessment was the noise criteria (NC) for the classrooms (3). These are a set of curves of sound pressure level versus frequency, based on the averaged opinions of a large group of people (see Figure 2). The distribution of sound pressure level with frequency was adopted because it was judged to be the least objec-

Figure 1. NJ-18 Freeway extension project.

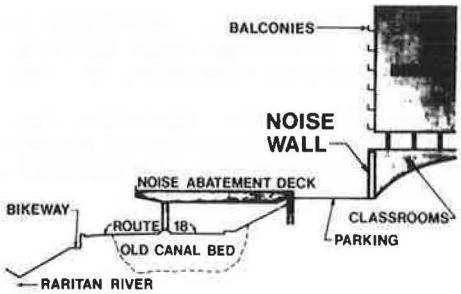
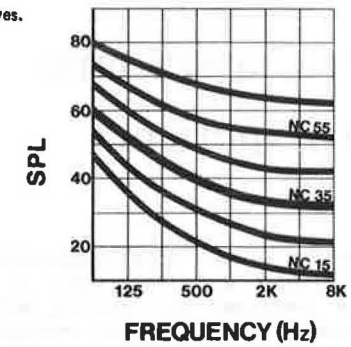


Figure 2. NC curves.



tionable. The list below shows the suggested NC values for various activities. To determine the NC value, an anticipated sound distribution is compared with the standard NC curves. An NC number is assigned to the sound that corresponds to the nearest NC curve that lies entirely above it. The design goal for the classrooms was an NC value of 35.

NC	Application
25	Recording studio
30	Theater
35	Classroom
40	Office
45	Department store
50	Typing pool
60	Light industry
70	Heavy industry

The use of these three criteria required the estimation of the overall construction noise levels. The hourly L_{eq} noise levels were calculated by using the design plans, a preliminary construction schedule, and the anticipated equipment types as input to Equation 1 (4,5).

$$L_{eq(h)} = 10 \log \sum_{i=1}^{n} UF_i \times N_i \times (10^{L_p/10})_i \times (D_o/D)_i^2 \quad (1)$$

where

UF = usage factor for a piece of equipment expressed as the ratio of time in use to time on the job,
N = number of similar pieces of equipment,
L_p = maximum noise level of equipment,
D = distance between equipment and the dormitory buildings, and
D_o = 50 ft.

As a result of our calculations, we estimate that the hourly L_{eq} noise levels will range from 75 dB(A) to 86 dB(A) at the river dormitories during the anticipated three-year construction period.

The construction noise levels were further broken down into octave band levels shown in Figure 3 in order to use SIL and NC criteria. The octave band data were determined by using the spectra of the noisiest pieces of equipment (6) and combining them logarithmically to develop a typical construction noise spectrum.

Following the determination of the exterior construction noise levels, it was necessary to determine the noise levels within the classrooms. Because of the large expanse of glass and the low-frequency content of the construction noise, it was decided that the building noise reductions specified in the Federal-Aid Highway Program Manual (1) were not valid. Based on detailed acoustic analyses, the calculated classroom noise reduction with the windows open is 7 dB and with closed windows is 15 dB. These reductions result in predicted classroom L_{eq} noise levels that range from 60 to 71 dB(A) with closed windows and from 68 to 79 dB(A) with open windows.

The sound-reduction index of the building facade was calculated by dividing the wall into elements that have similar transmission loss characteristics. The transmitted sound pressure level (SPL_T) was determined by subtracting published transmission loss values from the exterior sound-pressure level or, where published values were not available, the result of Equation 2 (3) was subtracted from the exterior sound pressure level.

$$TL = -27.3 + 15 \log (\sigma f) \quad (2)$$

where

TL = transmission loss (dB),
σ = wall element density (lb/ft²), and
f = octave band center frequency (Hz).

Equation 2 is an empirical relation that yields a lower initial value of TL and does not increase with wall element density and sound frequency as rapidly as the mass law predicts. This is because it accounts for resonance effects, induced vibrations, nonplanar wave propagation, and nonperpendicular wave incidence.

The sound pressure level transmitted to the classrooms was determined by logarithmically combining the transmitted sound pressure levels of the various wall elements by using Equation 3.

$$SPL_c = 10 \log \Sigma [S_i \times 10(SPL_{Ti}/10)] / \Sigma S_i \quad (3)$$

where

SPL_c = composite SPL transmitted into classrooms (dB),
S_i = area of each wall element (ft²), and
SPL_{Ti} = SPL transmitted through each wall element (dB).

After determination of the transmitted sound pressure level, we considered the effects of the classroom acoustics by using Equation 4 to finally determine the building noise reduction.

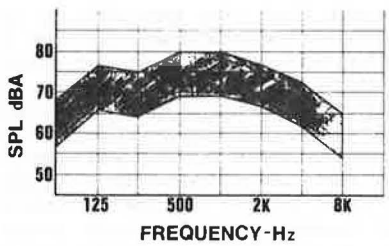
$$SPL_R = SPL_c + 10 \log (4/S\bar{\alpha}) + 10 \text{ dB} \quad (4)$$

where

SPL_R = the interior sound pressure level (dB),
SPL_c = the composite transmitted sound pressure level (dB),
S = surface area of room (ft²), and
$\bar{\alpha}$ = average absorption coefficient.

This equation is based on the Sabine formula,

Figure 3. Construction noise spectrum.



which assumes that the rate of energy removal is constant proportional to the intensity. This equation also assumes that there is no change in the area of the wavefront that enters the classrooms. The average absorption coefficient is calculated by using published frequency-dependent Sabine absorption coefficients in Equation 5.

$$\bar{\alpha} = \Sigma S_i \alpha_i / \Sigma S_i \quad (5)$$

where

$\bar{\alpha}$ = average Sabine absorption coefficient,
α_i = published Sabine absorption coefficient of individual room elements, and
S_i = area in ft^2 of individual room elements.

As part of the acoustic analysis, the reverberation time of the classrooms was found to range from 0.8 to 1.4 s. These times were calculated by using Equation 6, based on assumptions in the Sabine theory.

$$T_R = 0.049V/S\bar{\alpha} \quad (6)$$

where

T_R = room reverberation time (s),
V = room volume (ft^3),
S = room surface area (ft^2), and
$\bar{\alpha}$ = average Sabine absorption coefficient from Equation 5.

The optimum reverberation time for speech intelligibility in rooms of this size is generally acknowledged to be approximately 0.5 s (3). According to these calculations, the noise impact to students during lecture would be severe and would be aggravated by the rather poor acoustics of the classrooms. Based on this information, 13 alternative schemes were developed to mitigate the noise impact. The alternatives considered included do nothing with open windows, do nothing with closed windows, classroom relocation, source control, individual window ventilators, a large fan with exterior duct work, building ventilation modifications, air conditioning, temporary noise barriers, interior acoustical curtains, double-glazed windows, and a sealed and ventilated wall.

Several of these alternatives were eliminated because they could not meet the noise-reduction criteria. Those that remained, including classroom relocation, interior vinyl acoustical curtains, double-glazed windows, and exterior sealed wall, were presented to the FHWA regional office and Rutgers University officials.

The criteria used by the New Jersey Department of Transportation and FHWA for review were the cost, effectiveness, and energy use of the abatement. Based on these criteria, the double-glazed window alternative was eliminated. This alternative was ruled out because of its cost, which was estimated at $600 000. The noise levels would have been acceptable if two panes of 3/16-in glass were separated by a 4-in air space. This alternative would also require extensive modifications to the buildings' existing ventilation systems, which would involve reversing the flow of each system to change it from an exhaust to a supply system. As designed, the fresh air supply for the classrooms is through the openable windows. Obviously, with windows open the noise-reduction goals could not be realized and, thus, the ventilation modifications would be necessary.

An energy use analysis (7) required by FHWA (8) indicated that the double-glazed windows would reduce the total heat requirements of each dormitory building by 4 percent. However, if the windows were sealed, the classrooms would require positive ventilation and air conditioning, which would increase the climate-control costs for each building by nearly 40 percent.

Several constraints on the designs were imposed by Rutgers University. They insisted on minimal class disruption and return of the buildings to their original condition on completion of the project. School officials were also concerned about vandalism and so required that the system be relatively vandal-resistant.

Based on these constraints, the university rejected the classroom relocation proposal because of the logistics problems of class scheduling, disruption of student busing schedules, the loss of revenue from classroom rental between semesters, and concern for an adequate learning environment.

Vinyl acoustical curtains mounted inside the existing windows with a 4-in airspace were also rejected by the school officials. This alternative provided marginally acceptable classroom noise levels and, at an estimated cost of $300 000, was moderately expensive. The officials thought that the vinyl curtains would be easily vandalized and present a constant maintenance problem.

The exterior sealed wall was acceptable to the university, although it meant the loss of several parking spaces behind each dormitory building. The modular absorptive wall system would be attached to an overhang on the building and sealed at the ends. The advantage of this system was that all construction was external to the building, which minimized classroom disruption. Once the freeway construction is completed, the wall can be removed for reuse elsewhere and the building can easily be returned to its original condition.

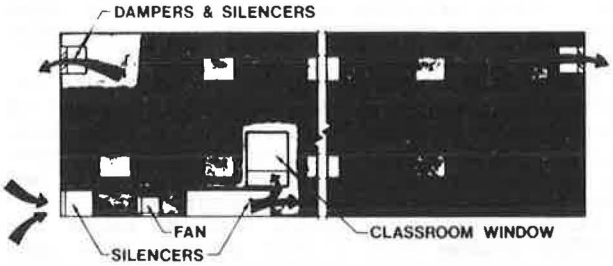
This alternative also met the acoustic design goals set at the outset of the investigation. During the noisiest phases of construction, with the fans operational and classroom windows open, the NC value for the classrooms is predicted to be 35, the SIL will be 29 dB, and the peak hourly L_{eq} will be 56 dB(A). The estimated cost for this alternative was $225 000.

The wall consists of a supporting steel framework bolted to a concrete leveling curb and to a concrete ledge that overhangs the classrooms and serves as the floor of an open-air colonnade for the dormitories. Modular, 4-in thick absorptive panels were slipped into the supports and interlocked by an integral tongue-and-groove design. The wall was sealed to completely isolate the classrooms from the construction noise. Windows were provided in several of the panels to allow for natural lighting and to minimize the feeling of claustrophobia in the classrooms caused by the wall (see Figures 4 and 5.)

A vaneaxial fan was installed in the lower part of each wall (below the first-floor windows) and its intake was located away from the building entrances. The fan was incorporated to provide positive fresh-

Figure 4. Partly constructed wall.

Figure 5. Schematic of air flow.



air ventilation through the openable windows without modification to the buildings' existing ventilation systems. The fan was isolated with intake and exhaust silencers, a 2-in absorptive cover panel, and solid steel safe-off panels, where required, to prevent short circuiting of air flow.

Barometric dampers were installed in the upper ends of the noise walls to modulate the air flow into the classrooms. A 3-ft medium-pressure drop silencer was attached to each damper to attenuate construction noise entering through the open dampers to a level sufficient to meet the acoustic design goals.

A modular absorptive barrier system with the absorptive surface facing the classrooms was specified for several reasons. The primary reason was that the speed and blade configuration of the fans were unknown when the wall proposal went out to bid. Since the fan acted as a steady source of noise with many discrete tonal components (especially at harmonics of the blade-passage frequency), there was concern that some of these components would coincide with the eigen frequencies of the plenum. This would result in resonances that cause large noise-level magnifications at specific frequencies.

A second reason for absorption was that, after the construction noise enters the plenum, the plenum becomes a noise source room to the classrooms. By using a technique often used for noise control in receiver rooms, absorptive material was used in the plenum room to lower the plenum sound level and thus to reduce the sound energy transmitted to the classrooms. Finally, a modular panel system was specified because it is relatively inexpensive, easily erected, and can be disassembled for future use after the project is completed.

The major constraint to fan selection was an adequate flow rate provided by a relatively small fan. The space allowed for the fan is 39 in wide and 43 in deep. The fan was placed inside the wall to minimize the chances of vandalism. Additional reasons for selecting the vaneaxial fan included lower installed cost, wide operating range, relatively low noise levels, and energy-saving design.

A 3-ft low pressure drop silencer was placed on the inlet side of the fan to attenuate the fan noise that reaches the dormitory rooms at night. The silencer was sized to reduce the noise to 40 dB(A) at the dormitory rooms. A 10-ft low pressure drop silencer was placed on the outlet side of the fan to meet the acoustic design goals for the classrooms. A smaller silencer could have been used that has similar attenuation characteristics; however, it would have a higher pressure drop and require more energy to operate the fan.

CONSTRUCTION

As part of the contract specifications required by FHWA, no construction activity was permitted when classes were in session for approximately the 2000 ft along the freeway that was near the dormitories until the construction-noise-abatement wall was in place and operational. A second restraint was the university's desire that erection of the wall take place during a school recess period to avoid interrupting classes.

The concrete curb for the wall was placed in January during the semester break (see Figure 6). This was a leveling curb poured on top of the existing bituminous parking lot surface and fixed by steel dowels into the pavement. Protruding from the curb were the bolts used to attach the wide flange beam-support structure.

Because of delays in the approval of the shop drawings submitted by the panel manufacturer, the erection of the support structure did not take place until the spring recess in early March. These 5-in wide flange beams, located on 12-ft centers, were bolted to the leveling curb at the bottom and welded to a steel angle bracket bolted to the 12-in concrete overhang (see Figure 7).

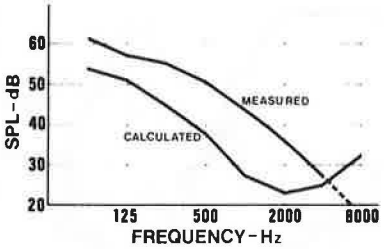
A neoprene gasket was also glued to a flange on each beam at this time. A 16-gauge steel U-channel over a neoprene gasket was ramset along the concrete curb between the vertical supports. This channel is used to provide a positive seal at the bottom of the first wall panels (see Figure 8).

The exterior skin of the panels is constructed of 18-gauge galvanized steel and the inner face is 22-gauge perforated (3/32-in holes staggered on 3/16-in centers) stainless steel. The panels are constructed with a 4-in cavity filled with 4.25-in thick fiberglass. Stainless steel is used for the inner skin to prevent corrosion in the unprotected perforations. The inner and outer panel skins are Tedlar-coated colonial red. In order to prevent unprotected holes in the Tedlar and galvanizing coatings that would be made with spot-welded assembly, the panels were assembled with stainless-steel rivets.

At the request of the university, window panels were added to the design. Two 3/16-in tempered glass panes separated by a 3.5-in air space were used. These panes were set in a neoprene gasket to provide a positive seal and excellent vibration isolation from the remainder of the panel. Each of these window areas was also framed with an 18-gauge steel channel to stiffen the assembly.

The silencers were also delivered to the site with the wall panels. They are constructed of 26-gauge perforated galvanized steel inner surfaces and 22-gauge steel outer shell. They are also

Figure 12. Fan sound level.



possible through the dedicated efforts of the many New Jersey Department of Transportation, FHWA, and Rutgers University personnel involved. Special thanks go to Fred Bogdan and Joe Maiorino, both of Bureau of Surface Design, Area 3, for their input, guidance, and support; to Paul Wygovsky and Robert Lane of the Bureau of Quality Control, for their monitoring data; to Al Ari, resident engineer, construction, and his staff for supervising and coordinating the wall installation; to Lloyd Jacobs, FHWA Environmental Specialist, for his comments; and to Bruce Whitehead, superintendant of plant and equipment, Rutgers University, for his input and coordination with the university. Thanks are also in order to personnel in special engineering, construction practices, and structural design for their input during various phases of the project.

REFERENCES

1. Right-of-Way and Environment. Federal-Aid Highway Program Manual, Vol. 7. FHWA, 1976, Chpt. 7, Section 3.
2. A. Thuman and R.K. Miller. Secrets of Noise Control. Fairmont Press, Atlanta, 1976.
3. G. Porges. Applied Acoustics. Edward Arnold Publishers, Ltd., London, 1977.
4. Dames and Moore. Report of 1977 Symposium on Highway Construction Noise. Office of Development, FHWA, FHWA-TS-77-211, 1977.
5. C.A. Grant and J.A. Reagan. Highway Construction Noise: Measurement, Prediction, and Mitigation. Office of Environmental Policy, FHWA, March 1977. NTIS PB-272-841/8ST.
6. P.D. Schomer and B. Homans. Construction Noise: Specification, Control, Measurement and Mitigation. U.S. Army Construction Engineering Research Laboratory, Champaign, IL, Technical Rept. E-53/ADA 009668, April 1975.
7. B.A. Davy and S.R. Skale. Insulation of Buildings Against Highway Traffic Noise. Office of Development, FHWA, FHWA-TS-77-202, 1977.
8. President's Urban Noise Initiatives. FHWA Notice N6640.20, May 30, 1980.

Role of Airport Noise Allocations in a Regional Airport System

CHRIS BRITTLE

This paper describes an approach developed in the San Francisco Bay Area to manage aircraft noise at the three major air carrier facilities—San Francisco International Airport, Metropolitan Oakland International Airport, and San Jose Municipal Airport—and to implement policies to develop regional air service. Airport noise allocations, defined by the number of residential dwelling units exposed to noise levels in excess of mandated California state noise standards, represent the noise capacity of each airport. Noise allocations are established at the regional level in a two-step process. First, projected Bay Area air passenger and air cargo demand are assigned to each airport in order to make optimum use of the three regional airports and to expose a minimum of the total Bay Area population to excessive airport noise. Next, noise levels are projected at each airport, with the assumption that aircraft that do not meet federal aircraft noise certification standards are either replaced or retrofitted with quieter engines, and the number of dwelling units in the noise impact area is calculated. Regional noise allocations are designed to accommodate increased aviation demand as well as to encourage airlines to expand their services at Oakland Airport, which is convenient and has the least noise impact of any Bay Area airport. The regional noise allocation is implemented through the power of the individual airports to establish appropriate restrictions on use if annual allocations are not being achieved.

The San Francisco Bay Area is served by three major air carrier facilities: San Francisco International (SFO), Metropolitan Oakland International (OAK), and San Jose Municipal (SJC). Airport noise affects a large number of persons in the Bay Area, hence additional growth in regional aviation demand must be accompanied by a coordinated approach to areawide airport noise problems. Airport system planning studies conducted by the Association of Bay Area Governments and the Metropolitan Transportation Commission, and funded by the Federal Aviation Administration (FAA), have addressed the noise-control problem and the optimum distribution of traffic among the three air carrier airports to handle future demand.

Two major areas that will provide significant noise relief include a redistribution of airline flights among the Bay Area airports as traffic grows and a reduction in the noise levels of the aircraft. Federal law provides a phased schedule for the retirement of aircraft that do not comply with Federal Aviation Regulation (FAR), part 36, aircraft noise certification standards. Regional studies since 1972 have highlighted the need for greater use of Oakland and San Jose Airports (1,2); however, like other multiairport hubs, most service is concentrated at a single airport--San Francisco International. Since the passage of the Airline Deregulation Act of 1978, service at Oakland and San Jose Airports has declined significantly, due partly to competitive forces and partly to national economic problems.

In spite of the current economic malaise, the long-range outlook is for significant growth in air traffic, which, in turn, will produce increased pressure for effective noise control. The regional noise-allocation strategy is designed to encourage