after-barrier condition at a microphone height of 5 ft and noise levels around 61 dB(A). Other variables showed similar trends as for the before-barrier conclusion. The net result is about 1 dB(A) more insertion loss after barrier construction if the model can be field-validated before barrier construction.

Responses to questionnaires indicated general satisfaction with barriers. Residents in the second and third row of houses next to the freeways were generally not affected by traffic noise. Some individuals did not want walls or were not satisfied for various reasons. The overall feeling of the residents appeared to be governed by the amount of noise reduction provided by the barrier. Many individual comments were received by persons concerned about things such as view, aesthetics, and cost.

Total cost of barriers per house per dB(A) ranged up to $3115; explicit barrier costs were up to $2085. The maximum cost per linear foot was $227.

ACKNOWLEDGMENT

This study was performed in cooperation with FHWA. The contents of this report reflect our views and we are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of FHWA or Caltrans and do not constitute a standard specification or regulation. A copy of the detailed report for this study is available from Caltrans.

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Transparent Noise Barriers Along I-95 in Baltimore City, Maryland

ROBERT D. DOUGLASS AND JEFFREY K. DRINKWATER

The Archbishop Keough Noise Barrier Project is classified as a category 2 experimental project by the Federal Highway Administration because of the barrier material (Lexan) used in the project. Lexan, a clear plastic panel system, has never been used as a noise-abatement measure in this area and its inclusion in this project provides cost and performance information for future project comparisons. Lexan was chosen for this project because of its effectiveness in attenuating highway noise levels while at the same time not interfering with the natural, scenic vista from a highway. It was incorporated into the system of noise barriers along Interstate 95 and protects Archbishop Keough High School from elevated noise levels due to the highway. The Keough noise barrier consists of 58 transparent panels, each 10 ft high by 0.25 in thick, supported at a 7.5-ft on-center width. The panels are held in place by steel posts that are attached to a concrete footing that runs the entire 435-ft length of the project. The project was built at a cost of $151 770. The cost of the barrier itself was $87 000. Delays in the delivery of materials and our underestimation in the number of working days were not totally unexpected due to the experimental nature of the project.

In 1968 a multidisciplinary concept team was assembled in Baltimore City, Maryland, to study its future transportation needs and problems and to recommend solutions. Environmental and aesthetic concerns were carefully evaluated by the teams of architects, engineers, and urban planners. Early in the process the need for transparent noise barriers on elevated highway sections was identified. Two benefits were attributed to transparent barriers over their opaque counterparts. The first, and most obvious, reason is that the motorists' vista and sunlight penetration to the roadway and ground are not blocked. The second benefit is that the highway and barrier would look much less imposing with a transparent barrier when viewed from the ground. On one preliminary expressway plan prepared for Interstate 83, a transparent noise barrier was shown in the area of the Canton and Fells Point communities. Even though this roadway alternative was rejected, the benefits and desire for transparent barriers remained.

As plans for I-95 progressed, the requests for transparent noise barriers on elevated expressways continued. The Interstate division staff made repeated inquiries for information on transparent barriers but were unable to find similar projects. Transparent barriers were not considered for I-95 due to unanswered questions such as,

1. Are the transparent materials available suitable for noise barriers?
2. How can they be supported?
3. How much will they cost?
4. Are there maintenance problems?
5. How will the material hold up in urban environments?
6. Will they increase reflections of sun and headlights?
7. Will they work from an acoustical standpoint?

Since our inquiries did not produce any similar projects, but we felt that the concept of transparent noise barriers was valid, we decided to look for a test project site.

THE PROJECT

The Archbishop Keough High School was identified as a potential noise-mitigation site because of elevated noise levels due to increasing traffic on I-95. Concerned school officials prompted a noise study by the Interstate division for Baltimore City. The study did, indeed, identify a noise problem once I-95 was fully opened. It was decided that, because of the pleasing vista of the school property from the highway and the limited length of barrier needed to protect the school, this project provided an ideal situation in which to implement a transparent barrier.

The Maryland Division of the Federal Highway Administration (FHWA) agreed and approved the project as a type 2 experimental project. FHWA funding participation on this project totaled 90 percent; Baltimore City contributed the local share of 10 percent.

Once the site was selected, the Interstate division for Baltimore City proceeded to search for a suitable transparent material that was applicable to a barrier situation. After considerable research, Lexan, a polycarbonate material supplied by the Fanwall Corporation, was selected. Considerations that entered into the selection of Lexan were cost, shatterability, wearing characteristics, aesthetics, and maintenance. Lexan compared favorably in all these areas with its glass and plastic counterparts.

The acoustic properties needed for the Lexan barrier were evolved for the Fanwall Corporation as a panel mass law study by the acoustic engineers, Bolt, Beranek, and Newman (1). This study determined the minimum thickness of material necessary to achieve the desired transmission loss of a 10dB minimum. Because of the relatively high cost of plastic materials as compared with typical construction material, (for example, plastic-concrete cost ratio = 100/1) it was imperative to avoid costly over-design. Bolt, Beranek, and Newman concluded that 0.25-in thickness of Lexan material would achieve the desired transmission loss.

Additional product testing included wind loading and shatterability. In shatterability testing, samples of the polycarbon sheets were subjected to pellet guns, 0.22 longs, and 0.38 police missiles. There was no shattering in any of the tests and only 0.22 longs penetrated and left tiny holes of inconsequential acoustic concern. Simulated wind load testing was performed by Arnold Greene Testing Laboratories, Inc. Tests showed that the panels withstood a loading of 170 lb/ft^2 with no failure or pull out from the posts. A loading of 170 lb/ft^2 is roughly equivalent to a wind velocity of 258 mph.

Design on the Archbishop Keough Transparent Acoustical Barrier Project was carried out by the Interstate division for Baltimore City. The final plans consist of 58 Lexan panels, each 10 ft high and 7.5 ft wide. Width of each panel was dictated by the maximum panel width available, which was 8 ft. The thickness of each panel as called for in the plans is the recommended 0.25 in. The panels are held in place by 6 W 16 steel posts and 3/16-in bent plate zee bar panel retainers (see Figure 1). The panel ends are curved to partly wrap around a 1-in diameter closed cell urethane rod. The zee bar is attached to the steel post by a 3/8-in bolt and nut (see Figure 1).

Each post has a baseplate that is attached to a 20x20-in concrete pedestal by four 3/4-in anchor bolts. Each pedestal is attached to a concrete footing that runs the 435-ft length of the project. Fifty-one railroad ties were used for cribbing on the rear slope of the project. Select backfill was used around each pedestal between the existing Jersey barrier and the cribbing (see Figure 2). Crusher run (CR-6) was then used over the backfill as a base for the top layer of asphalt (see Figure 2).

Approximately 2 in of asphalt was placed over the CR-6 and the 2:1 slope was maintained. Due to the low melting point of the Lexan panels (275° F), the hot asphalt could not be allowed to contact the panels directly. This resulted in a 0.5- to 2-in gap between the panel and the asphalt. At this time, several highway joint sealers are being tested to fill this gap.

In early 1980 a local contractor, Highways Incorporated, was awarded the contract for the Keough transparent barrier for the low bid of $151 770.40. This bid included (a) all excavation to construct footings and pedestal for acoustical barrier, (b) furnishing and placing all concrete required for constructing the footings and pedestal, (c) fabrication and erection of the barrier, and (d) final grading. The Fanwall Corporation, the material supplier for Highways Incorporated, was responsible for producing the transparent barrier.

EVALUATION

The Archbishop Keough Noise Barrier Project is classed as a category 2 experimental project by FHWA because of the barrier material (Lexan) used in the project. Since Lexan had never been used as a noise-abatement measure in this area, its inclusion in this project provided cost and performance information for future project comparisons.

FHWA funding participation on this project totaled 90 percent; the Interstate division for Baltimore City picked up the remaining 10 percent. To date the cost of the Archbishop Keough Transparent Barrier Project is $173 193.48. The cost of the barrier was $87 000, or $20/ft^2. The latter cost included the panel, posts, all hardware, and panel erection. The cost of the concrete work was $20 800, including footings and pedestals. Approximately 104 yd^3 of concrete was used for this project. An additional $2500 will be necessary to place a silicone-based joint sealer in the gap between the Lexan and the asphalt.

The Archbishop Keough Noise Barrier Project was started in March 1980 and completed in April 1981. The project took longer than the proposed 92 calendar days by 336. This lengthy overrun was chiefly attributed to delays in the delivery of materials and also to an underestimation in the number of working days required. Delay in the delivery of materials was caused by problems encountered in forming the curved ends of the Lexan. This can be expected in an experimental project where unforeseen problems often arise in the manufacture of materials and their assembly.

In October 1981 FHWA performed an insertion loss test on the Keough barrier as part of their barrier analysis program. This test measures noise levels in the same location, before and after the insertion of the barrier. The Lexan barrier was found to give a 10 dB insertion loss.

Noise level readings taken at five sites approximately 1-500 ft behind the barrier registered well below the FHWA guideline of 67 dB L_{eq}. The highest reading of 62.6 dB L_{eq} was registered directly behind the barrier. All readings were taken by FHWA personnel and are the product of four 15-min periods averaged into one hourly level. It is expected that traffic volumes and, consequently, noise levels on I-95, will be higher when the Fort McHenry Tunnel is opened.

Maintenance, durability, retention of transparency, and related problems can only be addressed if and when they occur. Concern for Lexan's durability was raised in a report by the California Business and Transportation Agency (2). In this study, four materials were submitted for testing. Three of the materials were plastics and one was tempered glass. Under accelerated and natural weathering conditions, the tempered glass was favored because of its ability to better withstand abrasion and discoloring. In the same tests it was found that polycarbonate materials were more susceptible to abrasion and loss of transparency than were acrylics. However, at this time (approximately 6 months since the erection of the barrier), we have found no evidence of these potential problems.

Figure 1. Detail of post attachment.

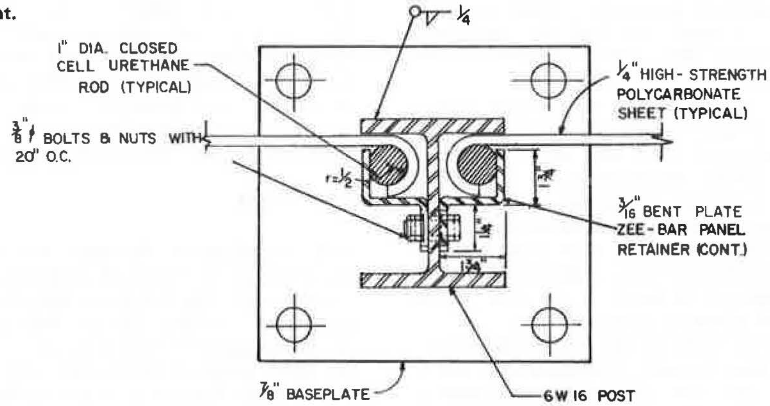
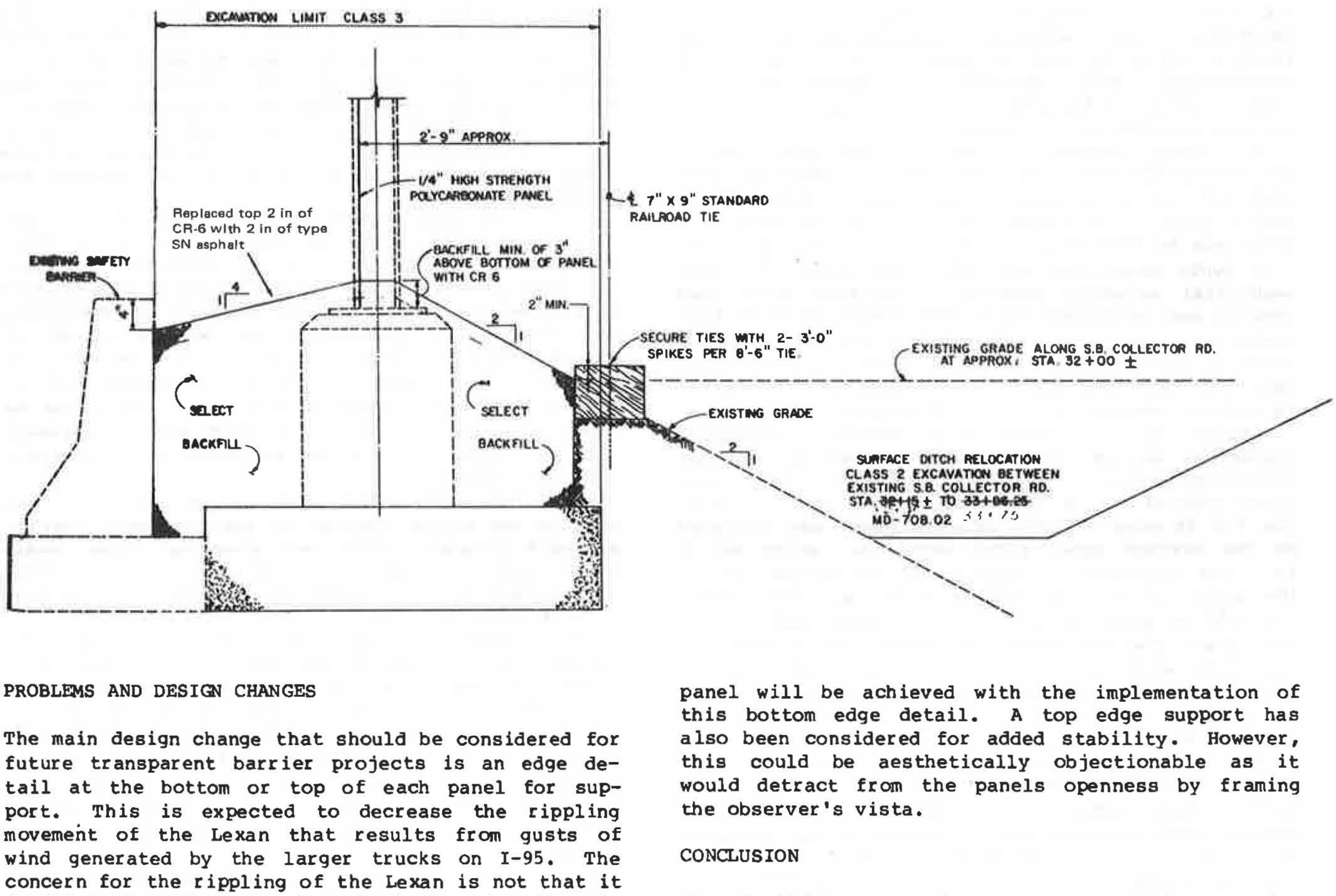


Figure 2. Detail of typical foundation.



PROBLEMS AND DESIGN CHANGES

The main design change that should be considered for future transparent barrier projects is an edge detail at the bottom or top of each panel for support. This is expected to decrease the rippling movement of the Lexan that results from gusts of wind generated by the larger trucks on I-95. The concern for the rippling of the Lexan is not that it is deleterious from a noise standpoint, but that it may have an adverse effect on wear and longevity. Other options that may effectively alleviate this problem could be either to increase the thickness of the panel itself or, if practical, to move the barrier farther away from the road. However, both of these options would require an increase of materials and, therefore, an increase of project cost.

Another problem that will require a design change is the edge detail at the bottom of the panel where the Lexan meets the asphalt. As mentioned previously, several highway joint sealants are currently being tested to fill the gap between the Lexan and the asphalt. This gap needs to be filled so that standing water could not fill the trench and, when it freezes, possibly crack the asphalt. It is hoped that some additional stabilization of the Lexan panel will be achieved with the implementation of this bottom edge detail. A top edge support has also been considered for added stability. However, this could be aesthetically objectionable as it would detract from the panels openness by framing the observer's vista.

CONCLUSION

The Archbishop Keough Transparent Noise Barrier Project not only met its objectives from acoustical and aesthetic standpoints, it also provided cost and performance information for future project comparisons. Lexan, the clear polycarbon panel material, seems to be feasible for use in a transparent barrier system.

With the addition of the edge detail, the barrier should have more stability, and the rippling should decrease appreciably or be eliminated. The inclusion of joint sealer along the bottom edge of the barrier should preclude any maintenance problems and also aid in stability. Problems encountered by the material supplier when forming the curved edges of the Lexan panel were alleviated and should not cause delays in the delivery of materials in the future.

Overall, the Keough noise barrier maintains the 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.

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

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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-