EVALUATION OF FREEWAY NOISE BARRIERS

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Of the various noise control methods, the construction of freeway noise barriers is often the only noise protective measure that can be directly implemented along existing freeways by a transportation department. This paper describes five different noise barriers, including their materials, type of support, and costs, constructed in metropolitan Toronto and provides data on their effectiveness. The results indicated that barriers 10 to 12 ft high, located midway between the houses and the pavement or at the highway shoulder, 60 to 140 ft from the nearest houses, provided only a 2- to 6-dBA reduction at the first row of houses, 4 ft above ground. Immediately behind the barriers, where the reductions are of little real benefit, reductions of 8 to 14 dBA were achieved. In addition to the overall decrease of sound levels, the sound level fluctuation, defined as the standard deviation of the recorded signal, was decreased at the first row of houses by 0.4 to 1.0 dBA. Measured sound levels and measured reductions due to the barriers were compared with calculated sound levels. In general, calculated reductions due to a barrier were overestimated rather than underestimated. A variety of other results and conclusions related to the influence of barrier height, the vertical distribution of sound levels, and the effects of cut and fill sections were quantified and are described.

•IN recent years, complaints about freeway noise have increased significantly. A solution commonly preferred by residents living adjacent to freeways is construction of a noise barrier (1). Although there are several approaches that must be combined to achieve effective freeway noise control (2), construction of noise barriers is often the only noise protective measure that can be directly implemented along existing freeways by a highway agency.

Data on the field performance of noise barriers are scarce. Field testing of noise barriers in Germany (3) showed that barriers, in addition to reducing overall sound levels, reduce the fluctuation of sound levels. Rapin (4) carried out extensive laboratory measurements of sound level reductions resulting from the use of barriers and other highway design features. His results, obtained on small models, were in good agreement with theory (5). Full-scale noise barrier testing conducted in the United Kingdom using a point source (6) showed that, due to ground attenuation effects, measured sound level reductions (based on measured levels without barriers) were considerably smaller (2 to 10 dBA) than the reductions calculated by a theoretical method developed by Maekawa (7).

In response to complaints of local residents and in view of an apparent lack of data on full-scale field performance of noise barriers adjacent to freeways, the Ontario Ministry of Transportation and Communications constructed an experimental noise barrier in a location where it would also provide useful noise protection. The resulting 1.2-mile long barrier constructed by the Ministry in metropolitan Toronto in the summer of 1971 will be referred to as the Highway 401 barrier. At about the same time, in response to similar complaints, the Metropolitan Toronto Roads and Traffic Depart-

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ment constructed four relatively short barriers of different types along the Don Valley Parkway. The acoustical evaluation of all barriers was conducted by the Ministry.

The principal objectives of the paper are (a) to review briefly the types of noise abatement walls constructed in the metropolitan Toronto area, (b) to report results on the effectiveness of barriers in attenuating highway traffic noise, (c) to compare sound levels calculated by means of an existing highway noise estimation procedure (8, 9) with the sound levels measured in the field, and (d) to provide data on measured sound level reductions resulting from cut and fill sections and intervening houses.

METHOD OF ANALYSIS

Effect of Barrier

A nonporous wall of sufficient mass (minimum of about 4 lb/ft^2) interposed between source and receiver can produce a significant noise reduction because sound waves can reach the receiver only by diffraction around the barrier edges. The expected sound level reduction due to the wall is governed by the following formula (10):

$$\text{Sound level reduction} = f\ (SWR,\ D,\ \lambda) \qquad (1)$$

where (according to Fig. 1)

SWR = distance traveled by the diffracted sound waves (source, top of wall, receiver),
D = distance between the source and the receiver, and
λ = wave length of the sound.

The attenuation of sound due to barriers is highly dependent on the frequency spectrum of the sound. Low-frequency sound, having sound waves several feet long, diffracts over the top of a barrier considerably more than high-frequency sound, which is effectively reflected and absorbed by the barrier. Figure 2 shows sound spectra measured behind a 12-ft wall, constructed along a 6-lane freeway, at various distances from the wall and heights above the ground. Figure 2 shows that the reductions due to the barrier tend to decrease with increasing distance from the barrier because sound waves, diffracted over the top of the barrier, can reach the points farther from the barrier more easily.

Barrier Design Criteria

Equation 1 suggests that, given adequate barrier density and fixed barrier location relative to source and receiver location, the design problem becomes one of defining the height of barrier required to reduce sound levels to a desired value. Preliminary studies obtained L_{10} sound levels (levels exceeded 10 percent of the time) of 70 to 80 dBA at the first row of houses at the proposed Highway 401 barrier location. Slightly lower values were obtained at the locations of the Don Valley Parkway barriers. The Bolt, Baranek and Newman (BBN) noise estimation procedure (9) was used to estimate the height of the barrier required to reduce the sound levels to "acceptable" values. Although it was thought desirable to achieve L_{10} levels of about 60 dBA at the first row of houses [comparable to a design criterion of a 70-dBA peak applied in California with apparent success (11)], barrier heights greater than about 10 to 12 ft were considered unacceptable because of cost, aesthetics, and possible snow-drifting. For the most part, the 10- to 12-ft height criterion governed the design.

The barriers were designed to resist severe weather and salt spray and to withstand wind forces up to 80 mph. Damaged portions of the barriers may be easily replaced if necessary. Also, in some cases, wall heights and lengths could be increased if required.

Barrier Description

A detailed description of the noise barriers was given in an earlier report (12). Briefly, the Highway 401 barrier, constructed along the 10-lane expressway, is

6,170 ft long and incorporates 5 different barrier types. The setting of the barrier, highway, and adjacent houses is shown in Figure 3. Data on barrier materials, type of support, prices, and so forth are given in Table 1.

Four relatively short barriers were constructed along the 6-lane Don Valley Parkway: a plywood barrier, an aluminum panel wall, a gabion wall, and a precast lightweight cellular concrete panel wall. Figures 4 through 7 show the general settings of the highway, the barriers, adjacent houses, and sound measurement observation points and data. Additional data are given in Table 1. The appearance of two of the barriers is shown in Figures 8 and 9.

Sound Measurement Program

Short sound recording tests, generally 10 to 15 min in duration, were carried out before and after the construction of the barriers to investigate barrier effectiveness. Measurements were taken about 4 ft above ground level on the locations shown in Figures 3 through 7. Uncontrollable variations were minimized by duplicating the weekday and starting time of the measurements for both before and after measurements. Continuous 16-hour tests investigating the variation of sound levels from about 6:00 p. m. to midnight were also carried out simultaneously with traffic classification surveys and speed measurements. These tests indicated little variation in sound levels throughout the day, about 5 to 9 dBA during this period.

Sound was monitored by a 1-in. wind-shielded microphone connected to a B&K 2204 precision sound level meter and was recorded by a tape recorder. During the measurements, wind speed and direction, temperature, and atmospheric pressure were also recorded. No measurements were made at wind speeds exceeding 10 mph. Details on the equipment used to record sound in the field and to analyze recorded sound in the laboratory are given elsewhere (13) Factors influencing sound propagation outdoors have been discussed elsewhere (10).

EVALUATION OF HIGHWAY 401 NOISE BARRIERS

Sound Levels Before Construction of Barrier

Sound recording tests were conducted on 66 observation points (Fig. 3) during several discrete 2- to 3-hour daily time periods. The sequence of measurements on the observation points and the time interval in which the sound was recorded during a certain period were randomized. Statistical analyses were conducted on the "before" sound measurement results to determine whether sound levels differed significantly during various time periods. Because no statistically significant difference was found between sound levels measured during two time periods (1:00 to 4:15 p. m. and 4:15 to 6:30 p. m.) (13), sound levels for these periods were averaged for each observation point. The average values were then used for construction of measured isodecibel lines shown in Figure 10 to illustrate measured sound levels simply and graphically. As such they are not "true" isodecibel lines, which would exhibit large variations due to individual houses. In Figure 10, the dashed lines indicate calculated isodecibel lines.

Sound Level Reductions Due to Barrier

After construction of the barrier, a series of "after" measurements was conducted on all observation points used for the before survey, during the two time periods. Averaged after values for each observation point were subtracted from the values obtained before the construction of the barrier. The sound level reductions are shown in the form of isodecibel lines (Fig. 11). The reductions are relatively small, the maximum reductions at the first row of houses being on the order of 6 dBA. Immediately behind the barrier, where the benefit of reductions is limited, reductions of 8 to 14 dBA were achieved. The small reductions measured near the constructed earth barrier (HEPC open field) probably result from the existence of an earth mound, deposited along the highway right-of-way prior to the performance of the before study for use in the future earth barrier. Unfortunately, the smallest first-row reductions (3 dBA) were obtained in an area with several two-story houses. Consequently, upper bedroom stories received no protection.

Figure 1. Effective height of barrier.

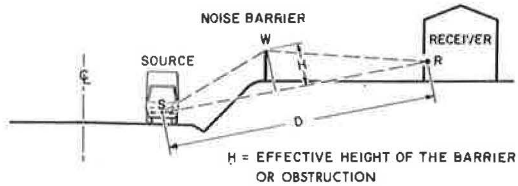


Figure 2. Sound spectrums measured behind 12-ft high wall.

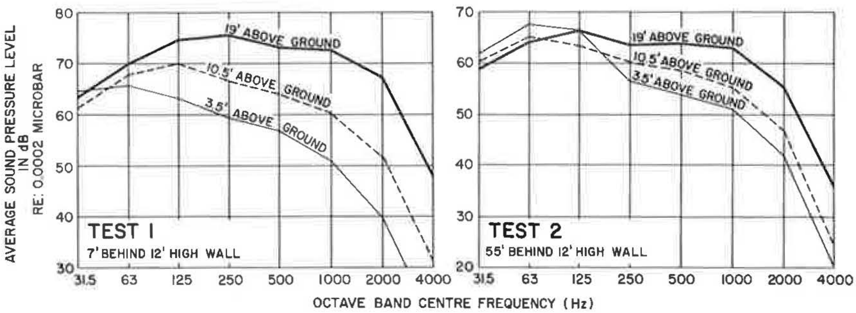


Figure 3. Highway 401 noise barrier, general setting.

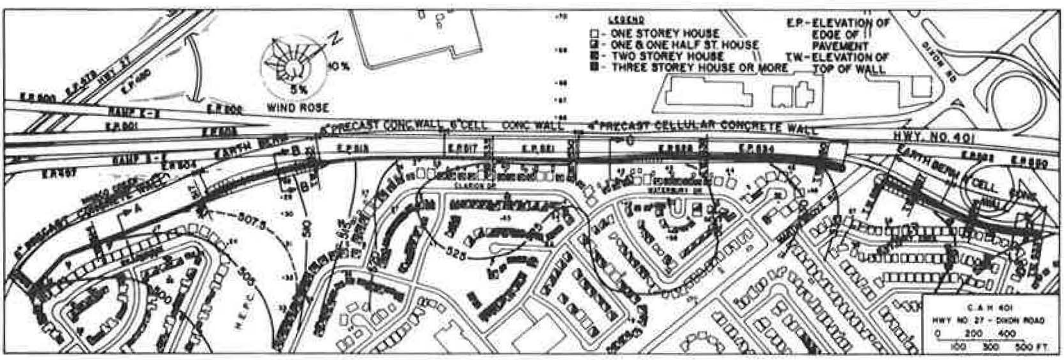


Figure 4. Sound levels before and after construction of aluminum wall (1:00 p.m. to 4:15 p.m.).

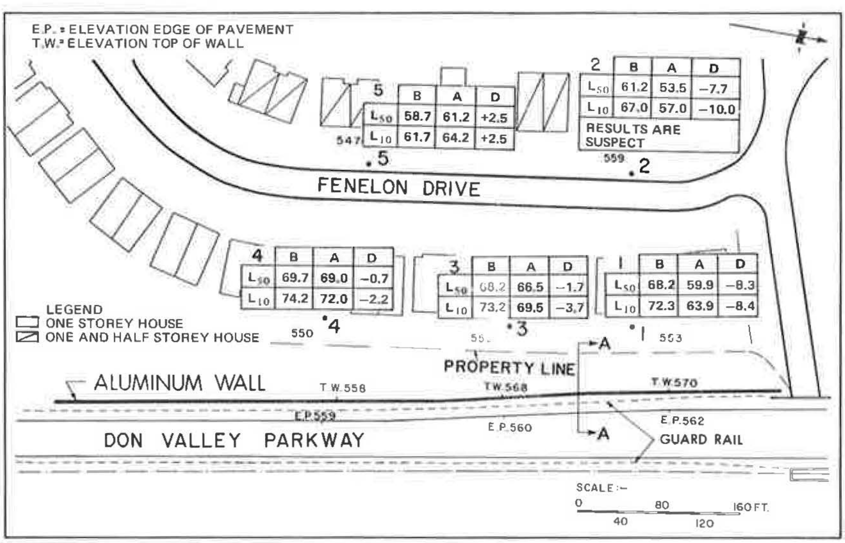


Table 1. Description of noise barriers.

Type Number	Barrier Description	Location	Thickness (in.)	Height (ft)	Total Length (ft)	Type of Support	Barrier Material	Actual Costs per Linear Foot[a] (in dollars)	Approximate Costs per Linear Foot of 10-Ft High Barrier[a] (in dollars)
1	Precast concrete wall	Highway 401, Willowridge Road, Clarion Road	6	8½ to 11	2,021	Concrete "H" columns 25 ft apart	Reinforced concrete, 4,000 psi at 28 days	48	42
2	Earth berm	Highway 401, HEPC Field, Arkley Crescent	60 (on top)	9 to 10	1,010	–	Earth fill, topsoil, sodding	25	25
3	Precast cellular concrete wall	Highway 401, Clarion Road	6	8½	800	Steel columns 8I23 20 ft apart	Reinforced concrete, 600 psi at 28 days, density 35 lb/ft³	44	55
4	Precast cellular concrete wall on top of earth berm 5 to 8 ft high	Highway 401, Waterbury Drive	4	3½ to 7½	1,650	Steel columns 6I12.5 10 ft apart	Reinforced concrete, 600 psi at 28 days, density 35 lb/ft³	36[b]	36
5	Precast cellular concrete wall	Highway 401, Arkley Crescent	4	9	690	Steel columns 6I12.5 10 ft apart	Reinforced concrete, 600 psi at 28 days, density 35 lb/ft³	41	45
6	Aluminum wall	DVP, Fenelon Drive	3	8[c]	720	Aluminum "H" columns 18 ft apart	⅛-in. aluminum plate	40	40
7	Wooden wall	DVP, Larabee Crescent	¾	9	400	Structure attached to fence	Treated fir plywood panels	12	15
8	Gabion wall	DVP, Groveland Crescent	36	8[c]	810	–	Coarse gravel	80 to 90	60
9	Porex concrete wall	DVP, Cassandra Boulevard	4	12	1,400	Steel columns 10 ft apart	Reinforced low density concrete, 40 lb/ft³	35	30

[a]Excludes costs of engineering and relocation of sewers. [b]5-ft high wall and 5-ft high earth berm. [c]Above edge of pavement.

Figure 5. Sound levels before and after construction of wooden wall (10:00 p.m. to 11:00 p.m.).

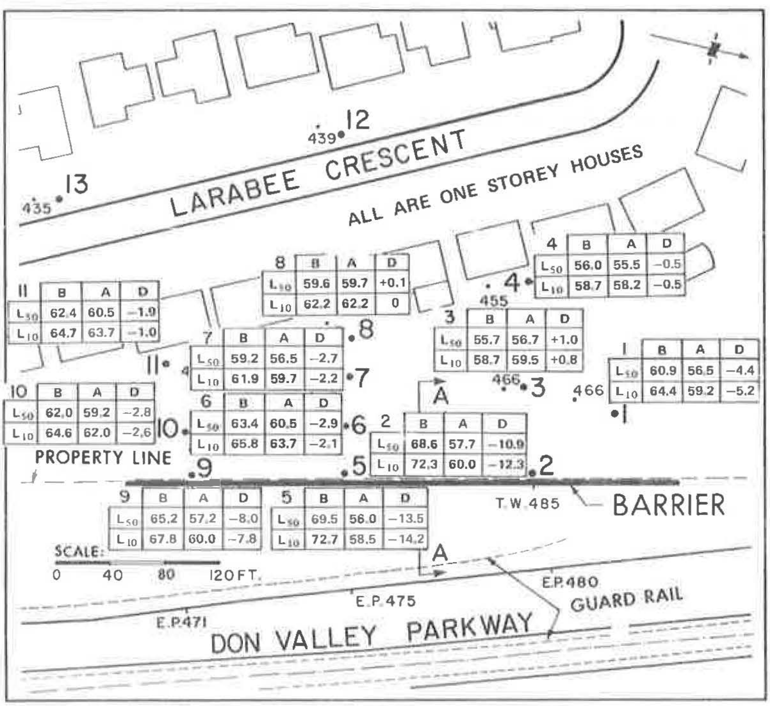


Figure 6. Sound levels before and after construction of gabion wall (9:00 a.m. to noon).

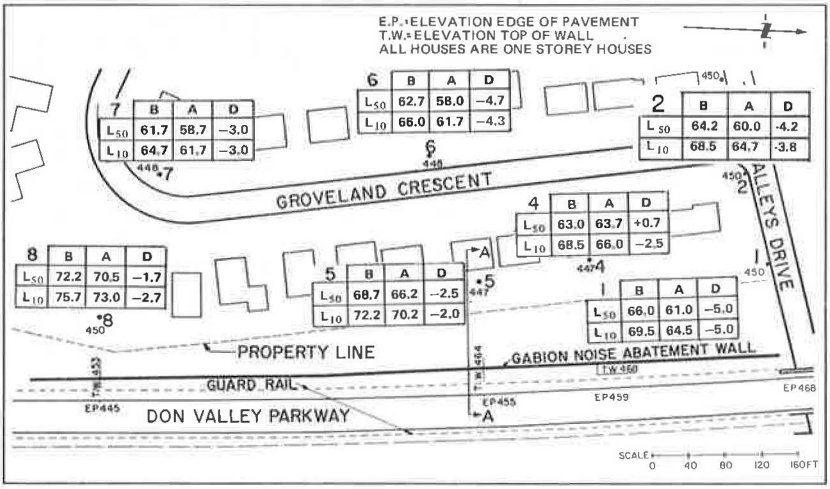


Figure 7. Sound levels before and after construction of cellular concrete wall (4:15 p.m. to 6:30 p.m.).

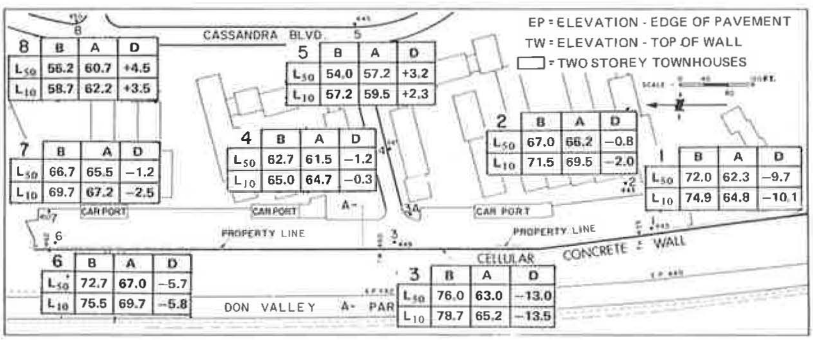


Figure 8. Highway 401 noise barrier.

Figure 9. Gabion wall, Don Valley Parkway.

Reduction of Sound Level Fluctuation

Sound level fluctuation, that is, the variation in sound level within a measurement interval, e.g., 15 min in duration, was characterized by the standard deviation of the recorded sound divided into 0.3-sec intervals. The standard deviations were calculated for sound samples recorded at observation points located behind the central part of the Highway 401 barrier during the two time intervals (1:00 to 4:15 p.m. and 4:15 to 6:30 p.m.) for both before and after conditions. These standard deviations were statistically analyzed to determine if there were significant differences in standard deviations due to various factors (barrier, distance, and time of day) and their interactions. The selected factorial design, given in Table 2 together with average values of the standard deviations, was repeated 7 times. The details on the statistical analyses are given elsewhere (13). In general, the results show that the barrier significantly reduces sound level fluctuation during both time periods but only for locations close to the expressway.

The reductions are of interest for those noise rating methods that take into account noise fluctuation, for example, Robinson's noise pollution level, L_{NP}, defined as (14)

$$L_{NP} = L_{50} + 2.56\sigma \text{ (dBA)} \quad (2)$$

According to Eq. 2, a 1-dBA reduction of the standard deviation, σ, can have the same influence on human response as a 2.56-dBA reduction of L_{50} level (level exceeded 50 percent of the time). In this instance, however, the reductions in standard deviation due to the barrier are almost negligible because the decreases are all smaller than 1 dBA.

Effect of Increasing Height

Because the barriers were found to provide little protection, the effect of increasing the Highway 401 barrier to 20 ft was analyzed. The analysis indicated that, at best, only slight improvement would be achieved. At 4 ft above ground, where the 3-dBA reductions were measured, a further 4- to 6-dBA reduction might be achieved for a total 7- to 9-dBA reduction. At the second-story level, an additional (and total) reduction of about 3 dBA would be achieved.

EVALUATION OF DON VALLEY PARKWAY BARRIERS

The before (B) and after (A) sound level measurements and their differences (D) for the 4 Parkway barriers are shown in Figures 4 through 7. The results are very similar to those obtained for the Highway 401 barrier and show no detectable variation among the barriers. Again, sound levels immediately behind the barriers were reduced by 8 to 14 dBA, but near the houses the sound level reductions were much smaller, typically 1 to 4 dBA. It is believed that the increase in sound levels, obtained for some observation points located relatively far from the barriers, indicated by the plus sign in Figures 4 through 7, should be attributed to experimental error and should not be considered a genuine barrier effect.

RELATED STUDIES

Correlation With BBN Noise Estimation Method

During the past few years, various highway noise estimation procedures have been developed for determining sound levels without requiring direct measurement. The BBN method (8, 9) is one of the most fully developed and best known procedures. Data collected in this study were used to validate the BBN procedure. However, the full validation of all aspects of the BBN method would require much more data than it was possible to collect within the scope of this study. The calculation of sound levels has been done by a computer program based on the BBN method and its inherent approximations (9).

"Before" Isodecibel Lines at Highway 401 Test Site—Measured and calculated isodecibel lines, shown in Figure 10, show very good agreement in the central part of the test site close to the freeway. The calculated and measured isodecibel lines are close together and, for a given dBA level, generally fall between the same rows of houses. With increasing distance from the freeway, calculated values tend to be somewhat overestimated. The discrepancy between measured and calculated levels in the western part of the area is again due to earth material deposited prior to the performance of the before measurements.

Calculated Reductions—Measured sound level reduction isodecibel lines (4 ft above ground), shown in Figure 11, agree within 1 to 4 dBA with the calculated sound level reduction isodecibel lines shown in Figure 12 in the central and eastern parts of the area. Calculated reductions are usually somewhat larger than measured reductions. Comparisons in the western part of the area are again complicated because of the earth mound deposited prior to performance of the before survey.

Attenuation Due to Distance and Houses—Measured and calculated sound attenuations due to distance are shown in Figure 13. The measured values shown in Figure 13 are averages of 4 measurements taken 4 ft above ground in observation points 66 through 70 (Fig. 3) under various weather and traffic conditions. The calculated values of sound levels, estimated for the same conditions, exhibit an attenuation of 2.9 dBA per doubling of distance from edge of pavement, compared to the measured rate of 4.0 dBA.

Because the BBN method incorporates a distance attenuation of 4 dBA per doubling of distance, Figure 13, which shows a calculated attenuation of 2.9 dBA, requires some explanation. The discrepancy is caused by division of the 10-lane freeway into separate eastbound and westbound elements, as recommended by the method. This results in two parallel line sources with the shown combined sound attenuation of 2.9 dBA. This probably explains the tendency for sound levels to be overestimated with increasing distance from the freeway, as shown in Figure 10. It should be noted that the rate of attenuation due to distance was related to the edge of pavement. Slightly higher rates of attenuation with distance would result if the source of sound was assumed somewhere between the edge of pavement and the median of the 10-lane freeway.

Figure 13 also shows some experimental data pertaining to the combined effects of distance and houses. There is considerable scatter in the measured values, but, on the average, a single row, double row, and three or more rows of houses produced further attenuations of about 4 dBA, 8 dBA, and 9 dBA respectively. This agrees quite well with the BBN recommendations of 5 dBA, 10 dBA, and 10 dBA for the same conditions, considering that different results might be expected for different sized houses and distances among them.

Vertical Distribution of Sound Levels—Figure 14 shows the vertical distribution of sound levels in open field and behind the Highway 401 barrier projected on vertical planes perpendicular to the highway. On one plane are also projected the outlines of the nearest houses. Measured sound levels plotted on the figure were obtained by using simultaneously 3 or 4 microphones mounted on a 20-ft long pole. For comparison, the results of calculated noise levels using the BBN method are also plotted.

Measured sound levels vary by as much as 10 dBA with a change of elevation of 10 to 12 ft even if there are no obstructions. This variation is not accounted for by the BBN method, which reports only one noise level for a certain distance from the highway. This effect of ground attenuation has also been noted by Scholes and Sargent (15), who cite Ingard (16) and Delany and Bazley (17) in attributing it to destructive interference between direct sound and sound that has undergone a complex reflection from the ground surface.

With a noise barrier, variation of noise levels with elevation is expected, but some differences appear when measured values are compared with calculated values. Perhaps one of the most important comparisons is at the second-story windows of houses adjacent to the highway, where measured noise levels are approximately 5 dBA higher than the values calculated. Measured and calculated reductions at the same location differ by about 5 dBA.

Attenuation Due to Cut and Fill Sections

Sound attenuation due to highway features, such as cut and fill sections, is governed by the same relation as is sound attenuation due to barriers. Figure 15 shows the

Figure 10. Measured and calculated sound levels (L_{10}) before barrier construction.

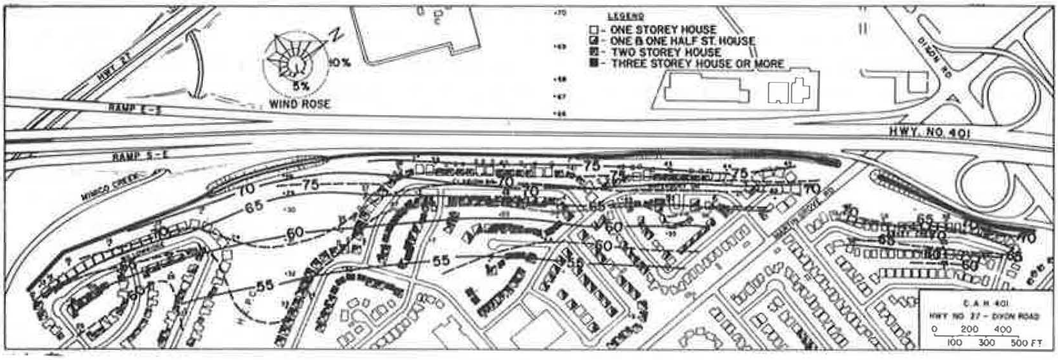


Figure 11. Measured reductions of sound levels (L_{10}) due to Highway 401 barrier.

Table 2. Sound level standard deviations.

Group Number	Sound Level Before Construction of Barrier		Sound Level After Construction of Barrier	
	1:00 to 4:15 p.m.	4:15 to 6:30 p.m.	1:00 to 4:15 p.m.	4:15 to 6:30 p.m.
1	3.351	2.576	2.399	2.185
2	2.118	2.271	1.991	1.913
3	2.325	2.471	2.533	2.102

Note: Observation points (Fig. 3) in group 1 were 38, 39, 40, 41, 43, 44, and 45; in group 2 they were 3, 4, 48, 49, 50, 51, and 52; and in group 3 they were 6, 7, 8A, 53, 54, 55, and 56.

Figure 12. Calculated reductions of sound levels (L_{10}) due to Highway 401 barrier.

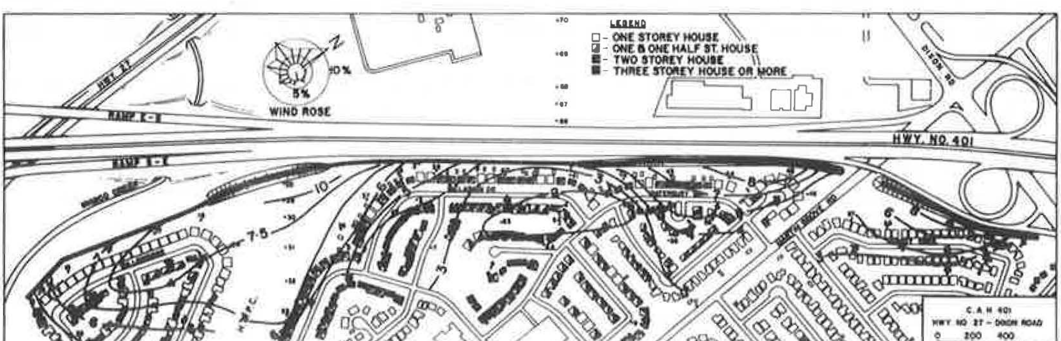


Figure 13. Attenuation of sound due to distance and houses.

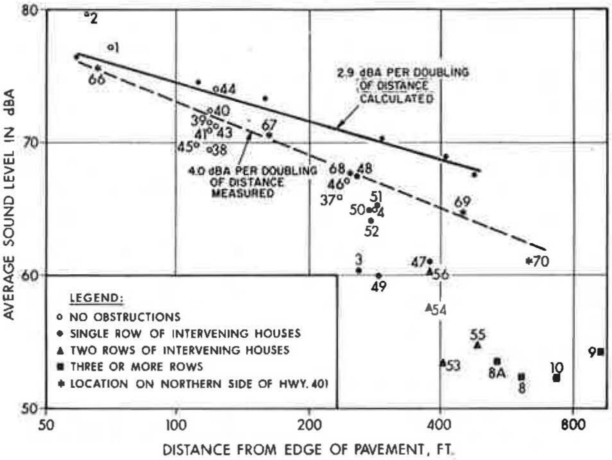
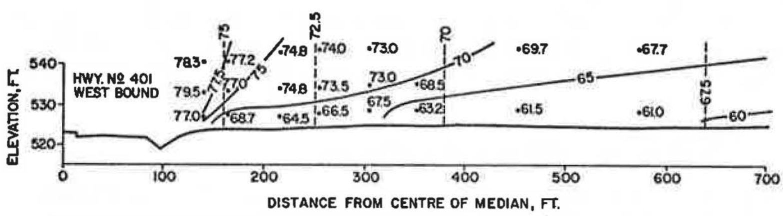
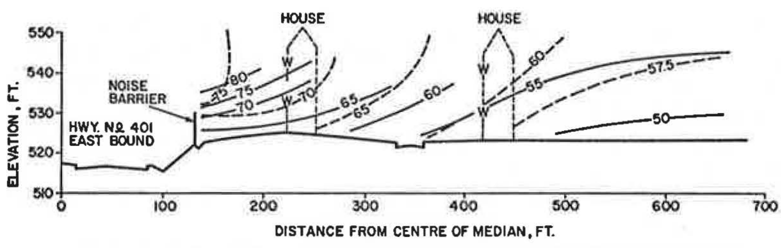


Figure 14. Vertical distribution of measured and calculated sound levels.



COMPARISON OF MEASURED AND CALCULATED LEVELS IN OPEN FIELD



COMPARISON OF MEASURED AND CALCULATED SOUND LEVELS BEHIND NOISE BARRIER

LEGEND:
- • MEASURED AVERAGE SOUND LEVEL IN dBA
- —— ISODECIBEL LINE FOR L_{50} IN dBA - MEASURED
- - - - ISODECIBEL LINE FOR L_{50} IN dBA - CALCULATED

vertical distribution of measured sound levels emitted by traffic on major expressways in the vicinity of an open field, an earth embankment (Highway 401 barrier test site), and cut and fill retaining walls. The measurements were conducted using simultaneously four sound recording sets. Three microphones, mounted at different heights on a 20-ft long pole, were placed successively at increasing distances from the expressway. One microphone monitored sound levels close to the expressway to eliminate effects of sound level variation during the successive measurements.

Sound attenuation due to different highway features and distance (Fig. 15) was compared with the sound attenuation due to distance in the open field for two heights above ground: 5 ft and 20 ft. The results, shown in Figure 16, were related to an arbitrary value of 75 dBA, 50 ft from edge of pavement in open field and 20 ft above ground.

It may be noted that the height of the retaining walls and the height of the earth berm are approximately the same: 11 to 12 ft above or below a flat terrain. Traffic flow composition and speed were similar at all four test locations, and the measurements were conducted under similar weather conditions.

Figure 16 suggests that the most effective measure, of those evaluated, is a cut section. Reductions of sound levels were obtained at both low and high positions above ground (5 ft and 20 ft), and the rate of reduction increased with distance from the expressway. Reductions of sound levels due to the fill section were obtained only at low heights above ground, and the reduction generally decreased with distance from the expressway. The effect of the earth berm was similar to the effect of the fill sections at low heights above ground. However, for positions close to the barrier, sound levels 20 ft above ground were up to 3 dBA higher than the corresponding sound levels in the open field. This phenomenon is probably attributable to the relative position of the sound source for the "shadow zone" behind the barrier, which is effectively shifted to the top of the barrier.

SUMMARY AND CONCLUSIONS

Five experimental 8- to 12-ft high noise barriers were constructed in metropolitan Toronto during 1971. Results of the field evaluation studies on these barriers are summarized as follows:

1. "Before" and "after" surveys indicated that immediately behind the barriers, where the reductions are of little real benefit, sound level reductions of 8 to 14 dBA could be achieved. At the first row of houses, 4 ft above ground level, sound level reductions were considerably smaller, typically 1 to 6 dBA.
2. The sound level reductions due to the barrier decreased with distance from the barrier and were highly frequency dependent.
3. There was no indication in the study that barrier material significantly affected barrier effectiveness. All barriers performed in a similar manner.
4. There was a small reduction in the fluctuation (standard deviation) of sound levels about the mean level due to the barrier, not exceeding 1 dB. Some researchers (14) have suggested that a reduction in the standard deviation of the sound level may be several times as effective in reducing annoyance as an equal decibel reduction in the mean sound level.
5. A brief social survey indicated that people living behind Don Valley Parkway barriers considered them beneficial in that their retention was favored. Possible side benefits of even low barriers (7 to 10 ft) may be psychological (visual) shielding and shielding against headlight glare, dust, and salt spray.
6. To be effective (sound level reductions of 8 to 10 dBA) noise barriers would have to be constructed to heights of 20 to 25 ft (on level terrain, possibly less with favorable topography) at estimated costs of at least $100 per linear foot.
7. Even 20- to 25-ft high barriers appear to be effective only for single-story houses. Second and higher stories become virtually unprotectable by noise barriers.

Related studies and studies performed to validate the BBN noise estimation procedure (9) have led to the summarized conclusions that follow. The tentative nature

Figure 15. Vertical distribution of sound levels (L_{50}).

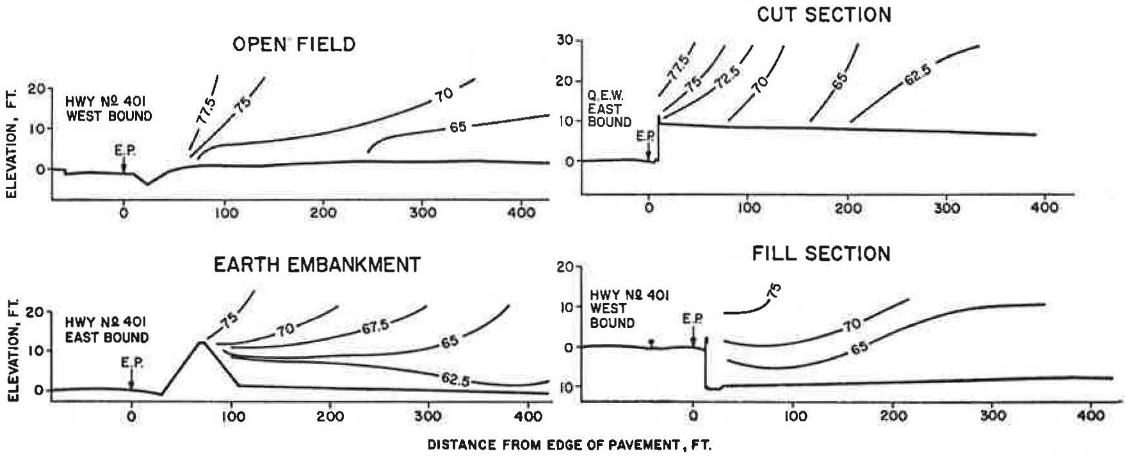
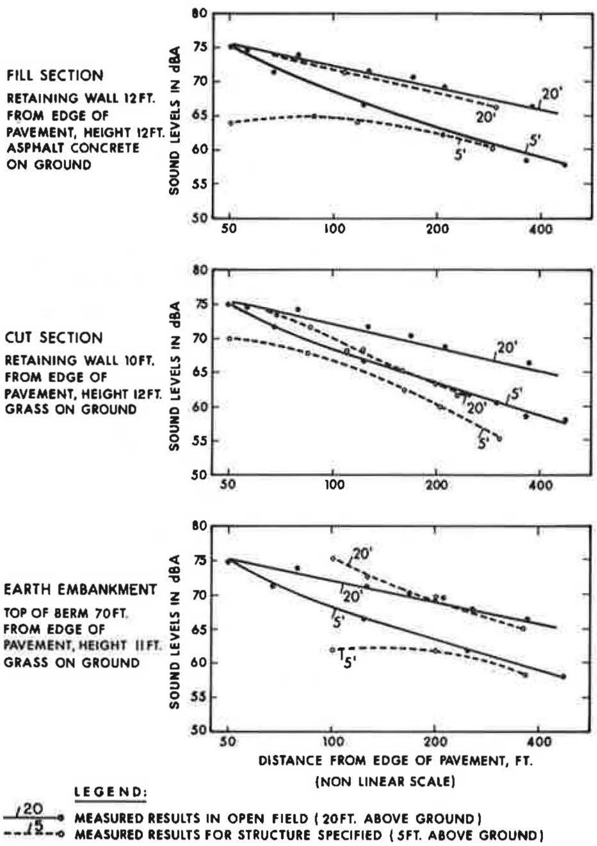


Figure 16. Effectiveness of highway structures in reducing sound levels.



of these findings should be stressed. A full validation of the BBN procedure would require considerably more data than were collected during this program. The conclusions are as follows:

1. Calculated sound levels, both without and with the barrier, for locations close to a wide expressway (60 to 120 ft from edge of pavement and about 4 ft above ground) are in good agreement with measured sound levels (generally within ±3 dBA).

2. Sound levels tend to be overestimated with increasing distance from the freeway (Fig. 13).

3. Sound level reductions due to a barrier located close to a freeway, calculated for observation points (4 ft above ground) at distances in the range of 120 to 200 ft from the barrier were overestimated by 2 to 5 dBA. In general, calculated sound reductions due to a barrier are overestimated rather than underestimated. At the second-story level, reductions were overestimated by about 5 dBA.

4. Sound level reductions provided by rows of intervening houses appear to be estimated properly.

5. Highway traffic noise levels in dBA depend on both distance from the highway and distance above ground. Figure 14 suggests that the assumption of variation of sound levels with distance from the highway only can yield errors of 5 to 10 dBA relatively close to the highway.

6. Reductions of sound levels due to fill sections are achieved only at low elevations close to the fill slope or face, as expected. Cut sections have limited effectiveness very close to the expressway, but their effectiveness increases with distance (Fig. 16). The most effective section appears to be a cut section with an earth embankment or other barrier on the crest.

In conclusion, barriers alone, because of their high cost, limited effectiveness, and other adverse effects (aesthetics, shadow, and effect on snow-drifting), do not appear to be the most cost-effective solution to highway noise. Greater attention and emphasis should be given to other noise control measures such as housing modifications, land use control, and control of vehicular noise emissions at the source.

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