INTRODUCTION

Federal regulations and increased public interest in reducing transportation noise have led to the construction of miles of sound walls. Most of these walls are almost perfectly non-absorptive barriers with a straight edge. There is a good reason for seeking alternatives: The performance of a sound wall is strongly dependent upon its height, but added height can be costly both in engineering and construction. If more attenuation is needed, then other solutions should be sought to increase the effectiveness of a fixed height barrier. Additionally, esthetic considerations may demand a lower barrier height while continuing to require superior performance. A number of alternate strategies have been studied in recent years, including T-top, Y-top and random edged barriers. Prior investigations by other researchers [1,2] suggest that it might be possible to improve the performance of a barrier without increasing the average height by introducing a jagged profile. This is because the jagged geometry on the edge of a sound wall alters the sound pressure level in the shadow zone by causing the region of the barrier nearest the receiver to admit multiple paths with variable phase. The direct waves from the diffracting edges of the barrier and waves subsequently reflected from the ground plane are superposed at the receiver causing constructive or destructive interference at the receiver. This is not easily amenable to analytical methods. This led to anechoic chamber testing of the various practical jagged edge treatments. The anechoic chamber located at the Transportation Noise Control Center (TNCC) facility is utilized for 1/6th scaled barrier experiments. Theoretical and experimental investigation of the effectiveness of more practical random and square wave barriers are detailed.

THEORETICAL BACKGROUND

If the sum of acoustics consisted of spherical sources radiating isotropically in a homogenous medium then very little would remain to be said about this field. The wave phenomena, particularly when diffracting, can be counterintuitive. Diffraction is a phenomena arising from the wave nature of sound. When an incident wave impinges upon the edge of a screen, the edge will diffract some of the wave into the lee, or shadow zone, of the screen, and some into the bright zone. The amount is dependant upon the geometry of the system, and the wavelength of the sound. The resultant pressure field is the superposition of all the direct rays and the rays from the diffracting edges. The mathematics of sound wall diffraction is a problem that has been thoroughly studied by Maekawa, Pierce, Anderson, Kurze and others. [3,4,5,6]
An obvious practical question when evaluating a sound wall is how much quieter (in dB) is the field behind the barrier when it is inserted. This is the change in Sound Pressure Level (SPL) at a given position when the barrier is “inserted”, given by

\[ IL = \text{SPL}_{(\text{Barrier})} - \text{SPL}_{(\text{No Barrier})} \]  

or

\[ 20 \cdot \log_{10} \left( \frac{P_{\text{Barrier}}}{P_{\text{No Barrier}}} \right) \]  

Often, insertion loss is plotted as a function of Fresnel number

\[ N_F = \frac{\text{added\_path\_length}}{\lambda/2} \]  

where added path length is an increase in total distance traveled by a wave when the screen is inserted and \( \lambda/2 \) is a half-wavelength of the sound. If the receiver is in the shadow zone (i.e. the zone in which the barrier blocks a line of sight path from the source to the receiver), the path length, and thus the Fresnel number is positive. Figure 1 illustrates a simple 2-dimensional case.

![Figure 1 Added Path Length from Source to Receiver](source.png)

Before entering into the mathematics, it is useful to imagine how the Fresnel number should effect insertion loss. A fundamental concept in the diffraction of waves is that low frequency waves diffract into the shadow of a barrier more readily than high frequency waves. Distance is also a factor. A spherically divergent wave decays proportionally to the inverse of the distance. Thus, it is reasonable to assume adding path length from source to receiver will have an effect similar to increasing the frequency. Since the frequency is inversely related to the wavelength, the Fresnel number combines the two effects.

A number of methods for predicting insertion loss of a uniform barrier have been suggested, but some of the simplest and most frequently used are Kurze’s empirical formula and Maekawa’s theoretical model based upon diffraction over a wedge.

Kurze’s formula is the simplest:

\[ IL = 20 \log_{10} \left( \frac{\sqrt{2\pi N_F}}{\tanh(\sqrt{2\pi N_F})} \right) + 5 \text{ dB} \quad \text{for} -0.2 < N_F < 12.5 \]

\[ = 24 \text{ dB} \quad \text{for} N_F > 12.5 \]  

Maekawa’s model is a bit more daunting:

\[ IL = -10 \log_{10} \left| \frac{e^{i(\pi/4)}}{\sqrt{2}} A_D(2N_F) e^{i2\pi N_F^2} \right| \]  

where

\[ A_D(2N_F) = \frac{1-i}{2} e^{i2\pi N_F^2} \left\{ 1 - (1-i) \left[ \cos(\frac{\pi^2}{2}) dt + i \int_0^\infty \sin(\frac{\pi^2}{2}) dt \right] \right\} \]  

There is no analytical solution for the Fresnel Integrals in Equation 20, but they can be evaluated from tables, or expanded into an infinite series. The advantage of Maekawa’s method is that it can be modified to include ground reflections and absorptive surfaces on the source or receiver.
sides of the barrier. Otherwise, the two methods yield almost the same result, and Kurze’s curve is much simpler to implement, Figure 2.

**Figure 2** Kurze’s Empirical formula for Insertion Loss from a Uniform Rigid Barrier.

Excess attenuation (EA) is conceptually similar to insertion loss. It is the difference in sound pressure level due to some arbitrary change in the system.

\[
EA = \text{SPL}_{\text{new system}} - \text{SPL}_{\text{original system}}
\]  

(21)

It could be, for example, the addition of absorptive surfaces or added barrier height. In this case, it is the addition of a novel edge treatment to a barrier. Theoretically, it may be possible to determine EA from the difference in insertion loss between the two systems, but practically, it is more complicated and a step removed from the desired result.

As mentioned previously, sound can occur as plane waves. Plane waves can hit an obstruction and travel on in a very different pattern. If the distance between a spherical source and a barrier is large enough, the waves that reach the barrier are nearly plane waves. Making this assumption simplifies the analysis of barrier diffraction problems because it is assumes that the wave hits the wall with uniform phase all along its length.

Consider a coherent plane wave normally incident on a semi-infinite, rigid screen with a flat, “knife edge” profile. The geometry is depicted graphically in Figure 3. Morse and Ingard took advantage if the plane wave approximation to arrive at a solution for this problem. [7]

\[
p(r, \phi) = Ae^{ikr \cos \phi} E\left[ \sqrt{2kr \cos \left( \frac{\phi}{2} \right)} \right] + Ae^{ikr \cos(3\pi - \phi)} E\left[ \sqrt{2kr \cos \left( \frac{3\pi - \phi}{2} \right)} \right]
\]  

(22)

where

\[
E(z) = \frac{1}{2} + \frac{1}{\sqrt{i\pi}} \int e^{i\frac{z^2}{2}} dt
\]  

(23)
Unfortunately, the integral, \( E(z) \) has no analytic solution and generally must be computed numerically. This has been carried out successfully by Dietz. [8] Figures 4-6 show how the relative intensity of the plane wave varies as the receiver is moved relative to the screen.

Figure 4  Plane Wave Diffraction Pattern for a Semi-Infinite Screen  (100 Hz)

Figure 5  Plane Wave Diffraction Pattern for a Semi-Infinite Screen  (1000 Hz)

Figure 6  Plane Wave Diffraction Pattern for a Semi-Infinite Screen  (5000 Hz)
A thorough understanding of Figures 4-6 can be gained through the Huygens principle. Assume that each point on a wavefront is a source of secondary wavelets. No waves penetrate through the barrier, but the edge acts as a line source, radiating into the bright and shadow zones. The Huygens wavelets will arrive at the observer with amplitudes proportional to the wavefront element areas and with phase retarded in accordance with their travel distance, \( r \), to the observer.

When \( y/l \) is negative, the observer is in the shadow zone, and the intensity is purely from the diffracting edge. It monotonically increases until it breaks the line of sight with the wavefront and enters the bright zone. In this region the total pressure is from both the direct and diffracted paths. These two components have traveled different distances and so will naturally have different phases. As \( y/l \) increases, the diffracted component alternately adds and subtracts from the direct component, all the while decreasing in amplitude and increasing in frequency.

This can be seen qualitatively in the spherical solution of the wave equation.

\[
p(r, t) = \frac{A}{r} e^{i(\omega t - kr)} \quad (24)
\]

Here \( r \) is the distance from an infinitesimal area on the edge of the screen to the observer, and time can be set to zero such that the diffracted wave becomes

\[
p_{\text{diffracted}} = \frac{A}{\sqrt{y^2 + l^2}} \cos(k\sqrt{y^2 + l^2}) \quad (25)
\]

\[
p_{\text{diffracted}} = \frac{A}{\sqrt{(y/l)^2 + 1}} \cos(kl\sqrt{(y/l)^2 + 1}) \quad (26)
\]

Just as in Figures 4-6, the amplitude of the diffracted component decreases as the observer moves farther into the bright zone. It is also obvious that the frequency of the cosine wave should be increasing with \( y/l \). It is interesting to consider the regions in the bright zone (positive \( y/l \)), where the presence of the barrier attenuates the direct wave. It may be possible, then, if the line source emanating from the top of the barrier was incoherent (varying phase), for the diffracted waves to destructively interfere with one another in the shadow zone.

Sound can also occur as spherical waves, which is analogous to the circular waves expanding from where a pebble is dropped in water. A point source of sound produces spherical waves. After these waves pass by an obstruction, they will produce a diffraction pattern at the screen or wall where they arrive. In general, the distance between the source and barrier than in the case of plane wave diffraction. This is a more complex type of diffraction to study, because both the positions of the source and receiver are relevant. The phase of the wave along the barrier is no longer considered a constant, but varies with distance from the source. Directly in front of the source, the phase on the wall might remain fairly invariant (depending upon the frequency), but moving to either side, the rate of change accelerates to some limit that is a function of source position and wavelength. These infinitesimal pieces of the diffracting edge, by the Huygens principle, act as directional spherical sources that radiate into the shadow and bright zones. Even with the simplification of a semi-infinite, uniform barrier with no ground reflections, the analysis becomes complex. Obviously, geometry like a jagged-edge treatment makes it much more difficult.

**EXPERIMENTAL INVESTIGATION**

The idea behind a jagged edge barrier is that varying the geometry of the diffracting edge will cause the Huygens wavelets on that edge to have incoherent phase. Hopefully, the geometry is
chosen such that the sum of the contributions from the Huygens wavelets is less than for the uniform barrier of the same average height. While it may be reasonable to expect this to happen, there are a number of conceptual problems to be overcome.

First of all, it is assumed that the waves hitting the wall are coherent to begin with. This works well for a plane wave, and if a spherical wave emanates from a source directly opposite the receiver, the phase varies slowly along the portions of the barrier directly between the two. However, highway noise is not a coherent line source or a spherical source. Multiple moving vehicles are generating noise in different frequency bands, and with complex directivities. A superior edge treatment would need to either perform very well for a broad range of frequencies, or perform well at certain frequencies with no penalty at other critical frequencies.

There is also a problem at higher frequencies when comparing jagged and uniform barriers of equal average height. If the wavelength is much smaller than the characteristic lengths on the barrier, then the waves may be able to simply “shine” through the gaps where material has been removed; effectively lowering the shadow zone. This being said, it is also possible that tight spacing in a jagged edge barrier could not only break up a coherent low frequency wave, but also provide some viscous damping as well.

Finally, the amplitude of the pressure in the shadow zone may not be just the complex sum of the diffracted wavelets. There may also be a component that diffracts from the barrier and then reflects off the ground plane before arriving at the receiver. Its phase and amplitude are functions of path length, but also of the acoustic impedance of the ground. This component may be small for small Fresnel numbers, but it can dominate as the receiver moves farther into the shadow zone. For a highway sound wall the highly variable nature of acoustic impedance with location means that an edge treatment customized for one location may be less effective at another.

\[ N_f = 0 \]

Figure 7 Experimental Testing Geometry
A random edged barrier and two periodic square wave barriers as well as a baseline uniform barrier were tested in an anechoic chamber. All were designed such that the mean height was 20.25 inches. A loudspeaker was placed on one side of the chamber, projecting toward a microphone behind the barrier. Figure 7 shows the geometry of the source and receiver positions.

The floor was reflective (particleboard) on the source side of the barrier and no reflective surface was placed on the microphone side. Ideally, the floor of the anechoic chamber should absorb sound, but it is strongly suspected from data in this experiment that the tread-ways on the floor cause it to reflect some frequencies. Figure 8 shows the effect of adding absorptive and reflective surfaces to the receiver side of the barrier at 2kHz

In the absence of reflections, the sound pressure level should monotonically decrease with increasing Fresnel number. Data taken with the reflective floor is characteristic of an interference pattern. Some of the diffracted wave is reflecting from the floor and is adding to the direct-diffracted wave from the edge of the barrier. This effect is small at lower Fresnel numbers, but as the microphone approaches the ground plane the path lengths of the direct-diffracted and reflected waves are about the same, and the reflected component begins to be noticeable in the measurements. A similar interference pattern (to a much lesser extent) can be seen in the data taken with the bare anechoic chamber floor, and adding additional absorptive material nearly eliminates the pattern.

A perfectly absorptive floor is not necessary for this experiment, but interpreting the data requires that these minor reflections be recognized.

**Noise Source.** A one-inch diameter JVC tweeter sitting on foam padding was used as a sinusoidal sound source at 0.5, 1, 2, 3, 4, 5 and 10 kHz. A tweeter was chosen as a sound source because of its size. As the product of the wave number and the diameter (ka) becomes large, the loudspeaker becomes increasingly directional. [4] For small ka, (long wavelengths or small diameter) the source is nearly spherical.

The frequency response and radiation efficiency of the tweeter at different frequencies would have caused dramatic differences in sound pressure level if a constant amplitude voltage were applied to the signal generator. To normalize the measurements, a voltage setting was found at each frequency that corresponded with 43.0 dBA at $N_F = 0$ for the uniform barrier. Table 1 shows the voltage amplitudes for each frequency.
Table 1 Voltage corrections

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Voltage</th>
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<tr>
<td>500</td>
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<tr>
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</tr>
<tr>
<td>4000</td>
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<tr>
<td>5000</td>
<td>0.601</td>
</tr>
<tr>
<td>10000</td>
<td>0.87</td>
</tr>
</tbody>
</table>

**Barrier Construction.** All the barriers were built using the jig shown in Figure 9. ¾ inch by ¾ inch hardwood slats are slid into an 8-foot long particleboard pocket. All joints between boards were sealed using either modeling clay or hardening foam. On either side of the test section, a section of uniform barrier was added to eliminate flanking paths.

**Random Square Wave Barrier.** The random barrier is a modification of the barrier studied by other researchers. [1] That barrier was very thin (1/32-inch) and had a jagged profile characterized by sharp points. A more practical design was chosen for this study. Rather than allowing changes in height resembling a random triangular wave, the random barrier tested here had uniform ¾-inch block-widths and the height was allowed to vary by integer multiples of ½-inch. A random number generator with a uniform distribution was used to generate the profile. Conceivably, this type of profile could allow inexpensive manufacturing of barriers using a kit of small blocks. Figure 10 shows the difference between the jagged and periodic square wave random barriers.
**Periodic Square Wave Barriers.** The periodic square wave barriers were similar to a design tested by Wirt [2], and were built using the same jig as the random barrier. Block widths of ¾-inch and 1½-inches were used. The periodic natures of these barriers suggest that their performance might be dependent upon wavelength.

**Measurement Equipment.** The PULSE Sound System and LabShop software, developed by Bruel and Kjaer was used to record, store, and analyze the data. The PULSE Sound System includes a front-end, DSP boards, and a PC with PULSE LabShop software installed. The front-end contains all input and output terminals and is a stand-alone unit connected to the DSP cards in the PC by an interface cable.

Bruel & Kjaer free-field microphones (4155 type/½-inch diameter) were used for measurements. Free-field microphones were used because the pressure fluctuations spread freely throughout the anechoic chamber.

Accurate microphone positioning was achieved using a custom x-y table driven by two stepper motors and controlled by a dedicated processor. Measurements, analysis, and motion control were coordinated by an in-house program (TNCC MCaM) that controlled both Pulse LabShop and the motion control PC via a scripting language.

Figures 11-17 show A-weighted sound pressure levels at various Fresnel numbers for each of the 4 barrier types tested. Each figure shows the results with the source transmitting at a different frequency. Physically, the measurement stations begin at the line of sight, defined by the height of the uniform barrier which was also the average height for the random square wave and periodic square wave barriers, with the tweeter (N_f=0) and move down in a vertical line at one inch intervals. Note that although the Fresnel number of zero exactly defines the shadow zone for the uniform barrier, the other barriers extend above and below this average height. Thus the term “shadow zone” may be misleading for the random and periodic barriers.

![Figure 11 Sound Pressure Levels at 500 Hz](image-url)
Figure 12 Sound Pressure Levels at 1 kHz

Figure 13 Sound Pressure Levels at 2 kHz

Figure 14 Sound Pressure Levels at 3 kHz
500 Hertz: The SPL for each barrier at 500 Hz monotonically decreases for all of the barriers. EA (excess attenuations) are small, ranging from -.8 to .3 dBA, when comparing the random and periodic barriers with the benchmark uniform barrier. A noteworthy trend in the data is that the uniform barrier performs slightly, but consistently better than the test barriers at lower Fresnel numbers. Then, at $N_F = .1$ and higher, the barriers begin to perform essentially the same. At this measurement station, the microphone is at about the same height as the lowest diffracting edges on all of the treated barriers. The similarity in SPL for all of the barriers is likely due to the long wavelength of the 500 Hz wave. At more than 2 feet, this wavelength is significantly longer than any of the characteristic lengths on the treated barriers.
**1 Kilohertz:** The 1 kHz measurements show the effects of reflections from the floor discussed in section 4.1. Initially, the SPL drops, but then remains constant for several measurements before continuing to decline. The effect is visible in measurements for all the barriers, but does not detract significantly from the interpretation of the data. There is marked improvement for both of the periodic barriers. EA ranged from 1.6 to 3.7 dBA for the ¾- inch block-width and .6 to 3.8 dBA for the 1½-inch block-width barriers. However, the largest benefit is seen deep in the shadow zone, where interference from the ground plane has the largest impact. Performance in this region is expected to be highly dependent upon surface characteristics. There is a similar improvement for the random barrier at high Fresnel numbers.

**2 Kilohertz:** The random and periodic barriers perform much worse than the uniform barrier at 2 kHz. EA is as low as -5.1 dBA for the random and 1½ inch periodic barriers. The ¾-inch periodic barrier performs marginally better than the other two, but is still more than 1.0 dBA louder than the benchmark at most stations. Worst performance is consistently at low Fresnel numbers for all the treated barriers. For the uniform barrier there is a noticeable increase in SPL at low Fresnel numbers. This is due to the reflections discussed in section 4.1.

**3 Kilohertz:** Excess attenuations are highly variable for all of the treated barriers. Some of this is caused by oscillations in the benchmark measurements. However, there is clearly no trend indicating an overall improvement for the treated barriers.

**4 Kilohertz:** Except for deep in the shadow zone, the random and periodic barriers perform significantly worse than the uniform barrier. The 1½ inch periodic barrier’s performance is particularly bad—as low as –8.7 dBA. This is probably due to the large gaps in this edge treatment. At 4kHz the wavelength is about 3.4 inches, and is approaching the block-width of the 1½-inch barrier.

**5 Kilohertz:** The random barrier performs well sometimes and poorly in other cases. Over the range of Fresnel numbers there is an average EA of 1.9 dBA, but it drops as low as –3.6 dBA. The 1½-inch periodic barrier performs worse still. This is a continuation of the effect noted in the 4kHz measurements. The ¾-inch periodic barrier closely follows the trend for the uniform barrier with an average EA of less than 1 dBA.

**10 Kilohertz:** Measurements at 10 kHz were included to verify the anticipated trend. Once the wavelength becomes sufficiently small (1.4 inches in this case), the waves are largely unperturbed by the edge treatments. The low points on the barrier become the new diffracting edge, and the sound can “shine” between the taller blocks. EA is large and negative for all of the edge treatments.

**CONCLUDING REMARKS**

Theoretical and experimental studies show that jagged geometry on the edge of a sound wall will alter the sound pressure level in the shadow zone by causing the region of the barrier nearest the receiver to admit multiple paths with variable phase. The direct waves from the diffracting edges of the barrier and waves subsequently reflected from the ground plane are superposed at the receiver causing constructive or destructive interference at the receiver. Whether the interference is constructive or destructive is complex function of the boundary conditions and not easily amenable to analytical methods. This led to anechoic chamber testing of the various jagged edge-treatments.

None of the barrier edge-treatments show a consistent benefit when compared to the benchmark for all the frequencies studied. However, the ¾-inch periodic and 1½-inch periodic barriers showed consistently positive EA at 1 kHz, averaging 2.5 and 2.2 dBA respectively. The
same two barriers performed consistently worse at 2 kHz averaging –1.5 and –2.6 dBA. At all other frequencies, the EA was either consistently negative, or variable with Fresnel number.

Ground reflections near the microphone were noted, but their effect does not negatively affect the interpretation of the data. Rather, they provide useful insight about the interaction between a barrier and real-world surroundings. Particularly when deep in the shadow zone, the acoustic impedance of the ground plane is a significant factor. For locations where this can not be carefully designed, any possible benefit from an edge treatment could be overwhelmed by unanticipated secondary waves. Future research should include more deliberate control of the acoustic characteristics on the ground plane.

In all, there seems to be no overwhelming benefit to having a jagged edge-treatment. It is generally accepted that human beings can hardly notice a reduction in sound pressure level of 3 dB so overall improvements in barriers of less than this amount would not be significant. The variation of the results at different frequencies and a mandate to “do no harm” suggest resources could be better spent on additional height or some other type of barrier modifications.
References


Experimental Apparatus

**Hardware Block Diagram**

Measurements, analysis, and motion control is coordinated through three programs running simultaneously on two computers. Pulse LabShop (a B&K product) interfaces with the digital signal processor, and the real-time motion control software interfaces with the motion control circuitry. A third program (TNCC MCaM) coordinates everything according to a script written by the user.