# Parallel Barrier Effects for Distant Receivers

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**16. Abstract**
The research described in this report determined the effects of parallel noise barriers as a contributing factor to the perception of increased noise levels by distant receivers. Data to quantify the characteristics of noise propagation was acquired at the HAM-71-11.44 and SUM-8-6.8 parallel barrier sites. Both sites had complaints of increased noise levels due to barrier construction.

An in-situ test system using a point source was devised and developed to identify the existence, location, and relative intensity of reflections between parallel noise barriers. Multiple reflections from barrier walls existed at each receiver location for all parallel barrier sites tested. The reflections increased noise levels for receivers from below 1 dB for receivers closest to the noise barriers, to increases approaching the theoretical maximum of 3 dB for receivers farther from the noise barriers. Reflection contributions to receiver sound levels increased with greater receiver distance from the highway up to 120 m from the noise barrier. A mean barrier attenuation of 2-4 dB was predicted for modeled receivers 180m to 420m from the near barrier. The propagation path height change with the barrier construction increased received levels from a test signal point source by an average of 3 to 4 dB, but as much as 14 dB for receivers 180m to 360m from the barriers. The increase in received levels was attributed to a reduction in ground attenuation caused by the increased ray path height following barrier construction. The sound-absorbing panels used to retrofit the west side noise barrier on the Summit 8 project substantially reduced the contribution of reflections for east side receivers. The reduction in reflection contributions due to the sound-absorbing panels was greater for receivers at increased distances from the highway.

The results of the investigation support the hypothesis that many of these distant receivers realized little barrier attenuation following noise barrier construction. Further, the amount of barrier attenuation realized was in many cases more than offset by the loss in ground attenuation due to the change in noise path height due to barrier construction. Finally, reflections between parallel noise barriers increased noise levels above the levels expected for single barriers.

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# PARALLEL BARRIER EFFECTS FOR DISTANT RECEIVERS

## FINAL REPORT

Prepared in Cooperation with the

OHIO DEPARTMENT OF TRANSPORTATION and
U.S. DEPARTMENT OF TRANSPORTATION,
FEDERAL HIGHWAY ADMINISTRATION


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July 2002

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## NOTATIONS

**A-weighting network**: An electronic filter in a sound level meter which approximates under defined conditions the frequency response of the human ear. The A-weighting network is most commonly used.

**Absorption coefficient**: Ratio of sound absorbing effectiveness, at a specific frequency. The ratio is an indication of the amount of acoustic energy absorbed by a material relative to the amount of acoustic energy incident on the material.

**AFTER measurements**: Sound measurements made after the construction of a noise barrier.

**Ambient noise**: All-encompassing sound that is associated with a given environment, excluding the analysis system's electrical noise and the sound source of interest.

**Background noise**: All-encompassing sounds of a given environment that includes ambient, as well as analysis system noise, excluding the sound source of interest.

**BEFORE measurements**: Sound measurements made before the construction of a noise barrier.

**Calibration**: Adjustment of a sound measurement system so that it agrees with a reference sound source.

**Correlogram**: The value of the cross-correlation function plotted versus time.

**Cross-correlation**: The correlation of two equal length arrays.

**Decibels (dB)**: A unit of logarithmic measure based on ratios of power-related quantities, thereby compressing a wide range of amplitude values into a small set of numbers.

**Diffraction**: The deflection of a sound wave caused by an obstruction or by non-homogeneity in a medium or between media.

**Fast time weighting**: The response speed of the detector in sound measurement system using a time constant is 1/8 second (125 ms) to detect changes in sound level more rapidly.

**First order reflection**: A reflection that has only struck one of the barriers before reaching the receiver.

**Frequency**: The number of cyclical variations (periods) unit of time. Expressed in cycles per second (cps) also denoted as Hertz (Hz).

**Free field**: A sound field whose boundaries exert a negligible influence on the sound waves. In a free-field environment, sound spreads spherically from a source and decreases in level at a rate of 6 dB per doubling of distance from a point source, and at a rate of 3 dB per doubling distance from a line source.

**Hard ground**: Any highly reflective surface in which the phase of the sound energy is essentially preserved upon reflection; examples include water, asphalt, and concrete.

**Hertz (Hz)**: The unit of frequency measurement, representing cycles per second.

**Intensity**: The magnitude of the pressure increases and decreases of an object.

**LAeq**: Equivalent continuous sound pressure level. The steady A-weighted sound level which would produce the same A-weighted sound energy over a stated period of time as a specified time-varying sound. LAeq(h) is the LAeq for a one hour period.

**Maximum sound level (LAFMX)**: The maximum, A-weighted sound level associated with a given event.

**Octave**: Two frequencies are an octave apart if the ratio of the higher frequency to the lower frequency is two.

**Octave (frequency) bands**: Frequency ranges in which the upper limit of each band is twice the lower limit.

**Parallel Barrier Degradation**: The reduction in barrier effectiveness for noise barriers constructed on both sides of a highway, and parallel to each other, compared to the effectiveness of a single barrier. The presence of reflections between the parallel barriers can reduce the amount of noise attenuation provided by the barriers (ie. increase the sound level for receivers).

**Propagation**: The transmission of acoustic energy through air from a noise source to a receiver.

**REMEL**: Reference Energy Mean Emission Level. The statistical mean of acoustic energy emitted by a vehicle class as measured at a reference distance perpendicular to the centerline of the vehicle path.

**Receiver**: One or more observation points at which sound is measured or evaluated. The effect of sound on an individual receiver is usually evaluated by measurements near the ear or close to the body.

**Second order reflection**: A reflection that has struck both barriers before reaching the receiver.

**Soft ground**: Any highly absorptive surface in which the phase of the sound energy is changed upon reflection; examples include terrain covered with dense vegetation or freshly fallen snow.

**Sound pressure level**: The ratio, expressed in decibels, of mean-square sound pressure to a reference mean-square pressure which by convention has been selected to be equal to the assumed threshold of hearing.

**Source**: An object (ex. traffic) which radiates sound energy.

**Spectral, spectrum**: Description, for a function of time, of the resolution of a signal into components, each of different frequency and usually different amplitude and phase.

**Wavelength**: For a periodic wave in an isotropic medium, the perpendicular distance between two wave-fronts in which the displacements have a difference in phase of one complete period.

# 1.0 INTRODUCTION

In 1988, the Ohio Department of Transportation (ODOT) studied the I-71 corridor in Hamilton County, north of Cincinnati, to determine the environmental impacts of traffic lane additions for project HAM 71-11.44. This study concluded that traffic noise abatement for residents living near the I-71 corridor was warranted according to the Federal Highway Administration (FHWA) noise abatement criteria.

In 1988, ODOT decided to expedite construction of additional traffic lanes with a commitment to design and build traffic noise barriers. The 5.4-mile long traffic noise abatement project had broad variations in terrain and barrier configuration and is the largest and most complex ODOT project of its type to date. Construction of the noise barrier project began in the fall of 1993 and was completed in April 1995 at a cost of $9.4 million. The project's completion brought mixed responses from the public; some residents claimed traffic noise levels were reduced, while others contended that noise levels had increased. In 1995 ODOT decided to investigate the abatement project to determine what, if anything had gone wrong.

To determine the nature and extent of any problems with the noise barrier construction, a preliminary assessment project was initiated. The assessment indicated that the perception of increased traffic noise levels due to noise barrier construction was the most pervasive complaint and was cited most often by residents living approximately 180m to 540m from I-71. Additionally, residents protected by parallel barrier configurations were more likely to perceive increased levels than those protected by single barriers [Herman et. al., 1997]

Direct sound level measurements to determine whether or not noise levels had increased could not be made, since sound level measurements for comparison were not made prior to noise barrier construction. Therefore, the preliminary assessment suggested a potential cause of the increased noise levels. Generally, noise barriers are most effective for residents located in the first or second row of houses from the highway. Distant receivers, those living in the third row of houses and beyond, tend to neither require nor realize significant noise attenuation from barriers. However, the presence of barriers can reduce the ground attenuation that contributes to the lower noise levels experienced by distant receivers prior to noise barrier construction. While trade offs between ground attenuation and barrier attenuation could result in little or no net effect for distant receivers, reflections from parallel barriers could increase noise levels beyond comparable levels for single barrier configurations. Reflections from parallel barriers may have caused the overall increase in noise levels perceived by the distant receivers.

The preliminary assessment report recommended that the validity of the parallel barrier reflection hypothesis be tested using acoustical measurements and computer modeling. That recommendation resulted in the investigation described in this report.

## 2.0 RESEARCH OBJECTIVE

The goal of this study was to determine if parallel noise barriers were a contributing factor to the perception of increased noise levels by residents located approximately 180m to 540m from I-71. To accomplish this goal the following objectives were stated in the project proposal:

1. Verifying both the existence and significance of multiple reflections for parallel barrier configurations through field measurements.
2. Ascertaining the range in ground attenuation forfeited by noise barrier construction by applying the noise propagation theory and computer modeling to representative sites.
3. Performing computer modeling to determine both the potential for noise level increases from multiple reflections between parallel barriers, and the potential for noise level reduction by using sound absorptive barriers.
4. Identifying modeling procedures to be used on future projects that can avoid existing problems and indicate when absorptive materials should be employed.
5. Developing a field measurement database to evaluate future modifications to existing noise barriers to and correct problems in the project area.

As the study progressed new opportunities and insights led to modifications of the objectives outlined above. An experimental method, which is preferable to computer modeling, was developed to achieve Objective 2 and the potential for noise level reduction outlined in Objective 3. The inherent assumptions and limitations of models can compromise their reliability for investigating complex propagation paths, such as those involved in this project. The FHWA Traffic Noise Model (TNM), which had not been released when the proposal for this research project was written, was planned as the primary modeling tool. TMN is a very sophisticated model with extensive improvements over the previous model STAMINA 2.0. Unfortunately, the TNM validation process is still ongoing, and therefore required more time than the research for this project. Therefore, experimental methods were employed to achieve the portions of Objectives 2 and 3 which required modeling.

A sound absorbing noise barrier retrofit project for State Route 8 in Summit County, Ohio was initiated after this research project began. This retrofit project allowed Objective 3 to be completed using experimental methods and to strengthen the basis of findings and recommendations. Consequently, Objective 3 was expanded to include two sub-objectives which investigated the performance of the Summit 8 sound absorbing panels:

3a. Characterize and quantify the reverberant qualities of the single and parallel barrier systems by identifying the number of significant reflections and their relative intensities for both the east and west barriers.

3b. Evaluate the effectiveness of the sound absorbing material in reducing the number and intensity of the identified reflections.

Computer modeling using TNM was completed for Objective 3, as originally planned, to determine the potential increase in noise levels due to multiple reflections, as a supplement to the experimental results.

# 3.0 GENERAL DESCRIPTION OF RESEARCH

The major challenge for this project was to devise field experiments that would either support or undermine the hypothesis given in the preliminary assessment report. Three considerations were factored into the development of new experimental methods to achieve the outlined objectives. First, traffic noise level measurements were not made at residential receivers prior to noise barrier construction. Therefore, no comparison could be made with measurements made after noise barrier construction. (Even if noise level measurements had been made prior to noise barrier construction, based on typical practice, they most likely would have been made for first row receivers and not distant receivers.)

Second, the investigation of specific noise attenuation mechanisms was needed to achieve the objectives for this study. However, conventional sound level measurements can only provide the overall result of combined attenuation mechanisms. For example, suppose that the noise level for a traffic noise source at a standard reference distance of 15m was measured as 80 dB. Suppose also that the noise level at a receiver some distance into the community and shielded by a noise barrier was found to be 53 dB. The value of 53 dB indicates that after all attenuations mechanisms influenced noise propagation from the source to the receiver, the final result is an attenuation of 27 dB. While the total attenuation is known, the precise makeup of that attenuation is not known. That is, the amount of attenuation influenced by the barrier, the ground, atmospheric effects, building shielding, reflections, etc, is not known.

Third, as stated in Section 2, experimental methods were preferred for this study. Developing experimental methods to investigate sound propagation characteristics in lieu of an investigation based on modeling took on increased importance as the project progressed.

## 3.1 REFLECTION MEASUREMENTS

When traffic noise barriers are constructed on both sides of the roadway, as they are for a significant portion of the I-71 project, the noise normally propagated away from a receiver may be reflected toward the receiver by the barrier located on the opposite side of the roadway, causing increased noise levels at the receiver. Therefore, the addition of the second barrier, constructed parallel to the first barrier, degrades the performance of the first barrier. This reduction in insertion loss is referred to as parallel barrier degradation. Both the existence and significance of reflected noise between parallel traffic noise barriers has been the subject of many studies since the 1960s [W. Bowlby et. al., 1987].

Typically, experimental parallel barrier system investigations have been based on a comparison of before and after measurements. Measurements are made before barrier construction, and then repeat measurements are made with one barrier constructed, followed by measurements made after construction of the second barrier. If the measured insertion loss for the parallel barrier system is less than the insertion loss for the single barrier system, it is concluded that the insertion loss degradation is caused by reflections. That is, one infers the existence of reflections based on the change in noise levels. This inference is justified if there is source, terrain, and atmospheric equivalence, which have proved challenging to establish in most studies.

The typical method of experimental investigation was not appropriate for this study for two reasons. First, no "before" measurements were available for comparison. Second, the first objective of this study was to verify the existence and significance of any reflections. The achievement of this objective could not be based upon inference. A method to both detect the location and measure the relative intensity of any reflections was needed. A major part of this project involved the conception and development of this method, which is described below.

*Measurement System Concept*

The reflection analysis measurement method uses signal processing techniques to generate and subsequently analyze test signals after their transmittal from an artificial source and received at locations of interest. The test signal is noise designed to exhibit specific, recognizable characteristics, which can be distinguished from ambient noise generated from other sources, including traffic noise. The measurement method can be employed to detect the existence of noise reflections. Since a reflected test signal has the same "signature" as the original test signal, it too, can be identified from the composite noise received from all sources at a given location. Further, the relative reflection intensity can be determined from test data analysis. The test system used on this project was designed to investigate only reflections from sound waves with rays that travel along a line perpendicular to the traffic noise barriers, the reflective surfaces of interest. While it may be desirable to investigate reflections from other angles, this particular study focuses on the reflections corresponding to those created from vehicle sources at the point of peak noise level for the vehicle pass-by, which occurs when the vehicle is perpendicular to a given receiver. The test signal source approximates a point source; therefore, the results must be carefully interpreted before they can be applied to traffic noise sources.

*System Design*

The sound source equipment consists of four major components: two loudspeakers, an amplifier, a power supply, and an output device. The loudspeakers, constructed for outdoor use, each contain a 12-inch woofer and a high-frequency horn to provide a maximum rated output of 500 watts and 131 dB at 1 meter, according to manufacturer specifications. When wired in a mono configuration, the amplifier supplies 1000 watts of continuous power, through its internal crossover at several different speaker impedance loads. A liquid-gel-cell battery provides the portable power supply for the amplifier. The sound source output device consists of a DAT that contained a prerecorded series of test signals, which is input into the amplifier.

Several components comprise the acoustical instrumentation used. The first of these components, the sound level meter (SLM), consisting of a pre-amp, microphone, and windscreen, receives the sound transmitted by the sound source. After the SLM receives the signal, it is inputted into a second component, the DAT. The recorded signal is then stored on digital audio tapes in binary format. Next, the recorded signal data stored on the DAT is imported via a digital I/O adapter to the computer used to process the signal. Then using a specially developed C program this recorded 48,000 Hz, 16-bit, mono noise signal is cross-correlated with the original computer-generated signal. The cross-correlation result generated by this program, which uses a Fast Fourier Transform, is output to another file. Finally, the cross-correlation is plotted and printed to display the number and relative reflection magnitude.

### 3.1.1 HAM 71 Measurements

#### 3.1.1.1 Field Procedures

*Procedure for the Placement of the Source Equipment*

Locating sites and assembling the two loudspeakers on tripods were the first tasks completed during the field measurements. To ensure accuracy and repeatability of the test system, the A-weighted sound levels produced from a previously created digital tape of white noise were measured using a calibrated sound level meter at a distance of one meter from the center of the woofer. To ensure constant source levels, the levels were noted so that any changes in loudspeaker performance from site to site, and for the AFTER measurements.

The speakers and tripods were then assembled at specified locations, either on the median or the shoulder of the roadway. The tripod heights were adjusted to 1.5 m from the ground to the woofer center. In some cases the height was increased to ensure the speakers were above the concrete Jersey barrier medians. Both loudspeakers were oriented with their direction of sound propagation perpendicular to the noise barriers and highway, which have a north and south orientation. The loudspeakers produce two equal but oppositely directed signals. This configuration approximates a point source where only propagation along the perpendicular line to the barriers is of interest.

Loudspeaker #1 was always positioned south of loudspeaker #2, and directed to the west. Loudspeaker #2 was directed to the east. After the loudspeakers were set up, distances from the noise barriers to the loudspeakers were measured using a laser-based instrument. The van containing the equipment to generate and amplify the test signals was approximately 30 m (100 ft) from the loudspeakers, minimizing potential sound reflections from the van.

A complete set of signals, consisting of ten pseudo-random signals and ten frequency sweeps (also referred to as chirps), was broadcast in succession for two minutes.

*Procedure for the Location, Placement, and Set up of Receivers*

Each receiver consisted of a sound level meter (SLM) connected to a digital audio tape recorder (DAT). The times on each DAT were synchronized to the nearest second so specific tests stored on the DAT tapes could be identified. Calibration tones were recorded on each DAT and the DATs adjusted so the calibration tones were the maximum level that could be recorded without distortion. The calibration tones were 94 dB at 1000 Hz, which provided a dynamic range suitable for microphone positions shielded by the noise barrier. However, DATs #1 and #5 received a calibration tone of 114 dB at 1000 Hz. These microphones were positioned above the noise barriers and often exposed to levels above 94 dB. The higher level tone kept these DATs from overloading during testing.

Each DAT and SLM was systematically numbered for consistency in the BEFORE and AFTER measurements. The microphones on the east side started at #1, while the microphones on the west side started at #5. Therefore, microphones with higher numbers were placed farther from the highway than microphones with lower numbers.

The barrier microphones were positioned at least one meter above the barrier on both sides of the highway. The other microphones were linearly stationed at incremental distances (30m, 60m, and 120m) perpendicular from the barrier. Each microphone was positioned at a height of 1.5 m on tripods and oriented at 70° from the horizontal. No microphones were placed near large reflective objects such as houses or large signs. Dimensioned drawings and videos were made during the BEFORE measurements to document the receiver locations so the same locations could be used for AFTER measurements.

Upon completion of the setup and documentation, the source equipment operator initiated the test. Records were made of interference that occurred during the recording. At the end of the recording, all DATs were checked to see that they were still recording correctly. Tests were repeated for DATs that had stopped recording.

#### 3.1.1.2 Data Reduction and Analysis

*Frequency-Modulated Chirp*

The reflection detection system uses a recorded computer-generated signal to produce the test signal, the frequency-modulated (FM) chirp, which builds linearly from 60 Hz to 15,000 Hz over one second and is followed by two seconds of silence. This sequence is repeated twenty times. Each chirp is transmitted from the loudspeaker source in the median and recorded at the different community microphone positions. The recordings are transferred to a computer to compute an averaged signal. The averaged chirp signal is then cross-correlated with the test signal, and a correlogram of the result is plotted.

Traffic noise is similar to band-limited white noise, which contains randomly distributed positive and negative components. If a sample of white noise or traffic noise in this case, is averaged with any number of other white noise samples, the result is zero. Time averaging the received signal eliminates most of the traffic noise and leaves the chirp since the signal contains both traffic noise and the non-random chirp test signal.

Cross-correlating and time averaging are significant signal processing components of the reflection detection system. The system does not need to overpower the ambient noise since time averaging and cross-correlating remove the ambient noise from the result. Other evaluation methods, including the standard method described in the introduction, cannot be performed in areas with high ambient noise levels. However, the digital signal processing method used in this study provides results with microphones positioned in residential areas with high ambient noise levels.

*Pseudo-Random Binary Sequences*

The analysis procedure changes slightly for pseudo-random binary sequences (PRBS). Pseudo-random means that noise appears to be random noise, but its precise pattern is known. Twenty different PRBSs, each one second long with a two-second separation period, were computer generated. The same field procedures were used to transmit and receive signals at test sites. With twenty different signals that are random in nature, averaging cannot be performed before the cross-correlation, since this would give a result of zero. Cross-correlations are performed on each of the 3-second intervals containing 48,000 samples per second, or 144,000 samples, and then the cross-correlation results are averaged.

#### 3.1.1.3 Results

In the results discussion, references are made to acoustic phenomena, traffic noise, and noise barrier characteristics. Therefore, the next section provides background information regarding these topics.

*Background*

Noise levels are affected by several physical phenomena as they travel from the source to the receiver. Three of these phenomena, atmospheric absorption, geometric spreading, and diffraction, which are attenuation mechanisms, are described in the following paragraphs.

Atmospheric absorption characterizes the noise energy lost through the interaction of sound waves with air molecules and attenuates noise as a function of frequency and distance. However, the magnitude of the attenuation is small compared to other phenomena.

Just as a rock thrown into a calm pond of water produces ripples that spread in ever-widening circles, the sound waves in the air expand over larger areas as the distance from the source increases. This spreading effect distributes the energy over increasingly greater areas. Sound levels are reduced as the energy per unit area diminishes with increased distance from the source. Noise barriers break the line-of-sight between the noise source and the noise receiver.

The amount of noise reduced by a barrier depends upon the site geometry. The relative distances between the source, barrier, and receiver, and the differences in elevation of the source, receiver, and the top edge of the barrier influence the overall reduction. Figure 3.1 shows a schematic of a noise source, barrier, and receiver. The amount of noise diffracted at the top edge of the barrier is proportional to the difference in sound path lengths represented in the figure. The direct path, as if the barrier was not present, is compared to the path over the top of the barrier. The greater the difference between the two path lengths, the more diffraction the wave experiences and results in greater noise attenuation. The figure indicates that this path length difference can be increased by moving either the source or receiver closer to the barrier, or by increasing the height of the barrier. Barrier attenuation can also be reduced by raising the source height, which decreases the angle between the ray path and the vertical barrier surface to diminish the path length difference.

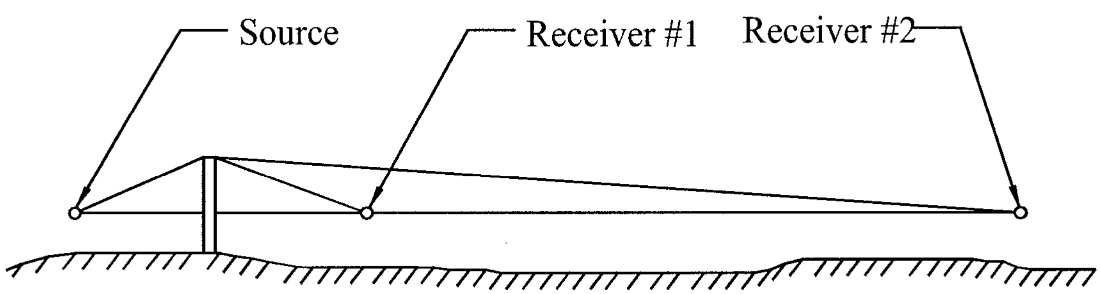


**Figure 3.1** Schematic of noise source, barrier, and receiver

*System Tests and Verification*

Initial system tests evaluated the reflection detection system. Cross-correlations of the test signal, which is the transmitted signal, with the signals received at two microphone locations are plotted as examples in Figure 3.2 and Figure 3.3. Figure 3.2 is a correlogram for a configuration with no barriers. As expected, there is only one point of correlation for the test signal and the received signal. This point appears as a vertical spike in the correlogram. Figure 3.3 is a correlogram for a configuration with parallel barriers with the source located in the highway median. A match with the test signal was found at several points in the received signal, which indicate the presence of reflections.

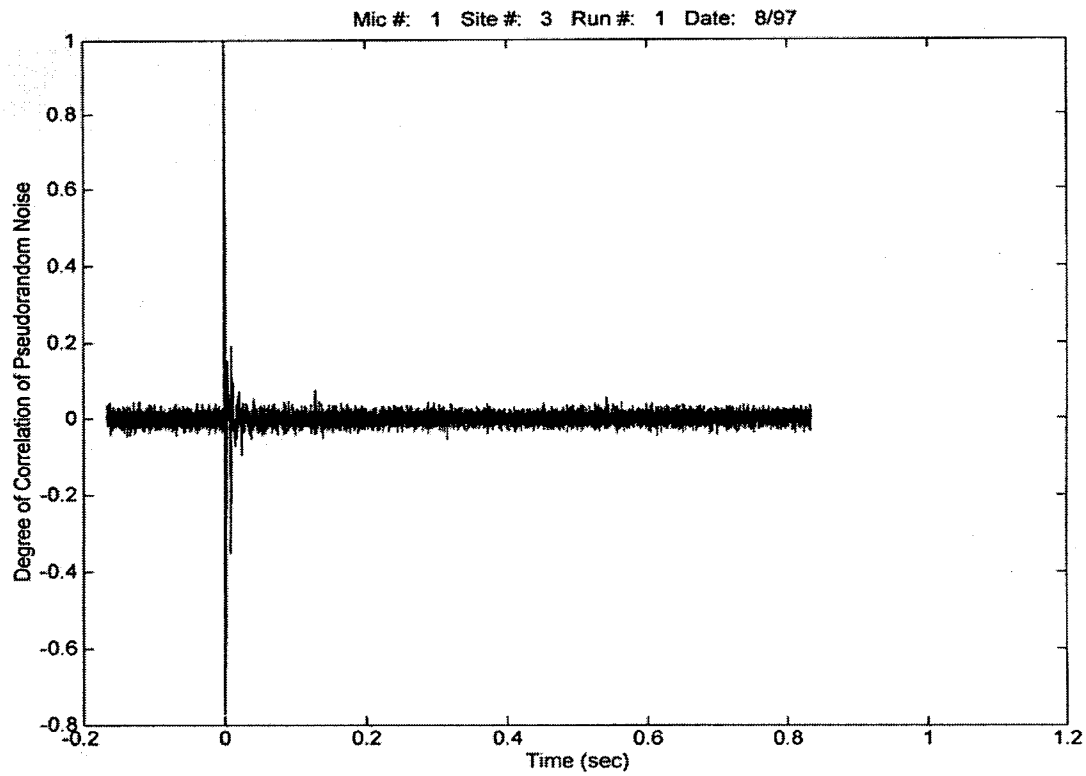


**Figure 3.2** Correlogram of a configuration without barriers.

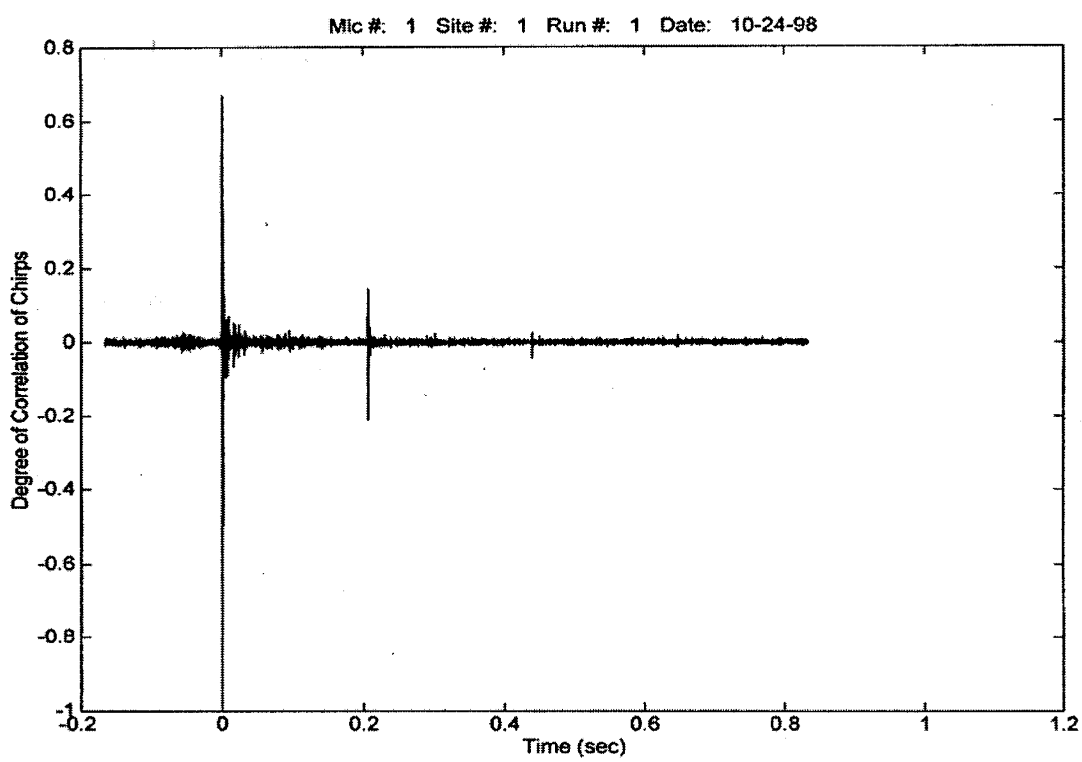


**Figure 3.3** A typical correlogram of a measurement with barriers

The first vertical line, or spike, at the left of the plot represents the direct ray, meaning the ray that arrives at the microphone directly from the source. Normally, only a direct ray reaches a resident living near a typical highway without noise barriers or where a barrier is between the source and receiver. However, for single barrier configurations, where a barrier is located on the opposite side of the highway from a resident, a ray directed from the source toward the barrier will be reflected back across the highway to the resident. The same principle applies to parallel barrier configurations. However, the reflected ray may undergo any number of reflections between the parallel barriers before reaching the resident. For both barrier configurations, the reflected rays contribute to the noise levels experienced by residents.

While the correlogram in Figure 3.3 shows several very small spikes, which will be addressed later, the larger spikes spaced at specific times are of particular interest. Their significance can be explained by considering the geometry of the test site. The diagram depicted in Figure 3.4 gives a representation of the equipment set-up used in this study with the source located in the median and the receiver located above one of the barriers.

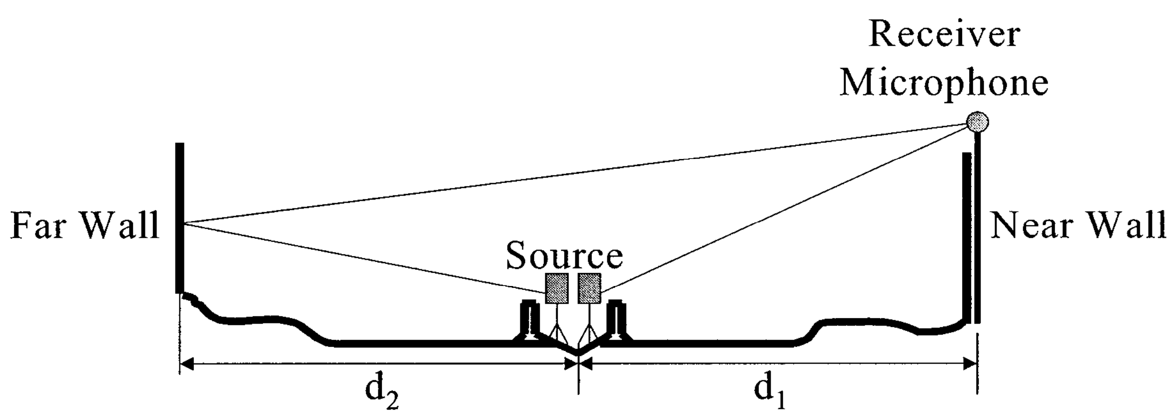


**Figure 3.4** A typical parallel barrier cross-section of the HAM 71 project

Distances d1 and d2 describe the distances between the source and the near wall and the source and the far wall, were measured and recorded at each test site. Assuming that the distance the sound traveled is equal to the horizontal distance (an assumption that can be made because of the small angles involved), the second spike in the Figure 3.3 correlogram should be the result of the first reflection at the far wall. The distance that the sound wave travels before it reaches the microphone is equal to d2 + d2 + d1, whereas the distance the direct signal has traveled is d1. The net distance that the reflected wave traveled is equal to d2 + d2, or 2d2. Therefore, the time difference between the direct signal spike and reflected signal spike equals the time the wave travels the distance 2d2, which is equal to 2d2 divided by the speed of sound 342.9 m/sec (1125 fps).

The time difference of 0.326 seconds between the direct signal and the predicted time the reflected signal should reach the receiver microphone was calculated using only the geometry of the site and is given for configuration #1 in Table 3.1. Table 3.1 also shows the recorded times, which are the time differences between spikes on the correlograms.

**Table 3.1** Calculated and recorded time differences between the direct and first reflected signal, and the first and second reflected signals

| Configuration | Reflection | Recorded Time Difference | Time Difference From Geometry |
|---|---|---|---|
| 1 | 1st | 0.328 | 0.326 |
| | 2nd | 0.080 | 0.080 |
| 2 | 1st | 0.104 | 0.103 |
| | 2nd | 0.304 | 0.304 |
| 3 | 1st | 0.213 | 0.214 |
| | 2nd | 0.192 | 0.195 |
| 4 | 1st | 0.143 | 0.142 |
| | 2nd | 0.233 | 0.232 |
| 5 | 1st | 0.083 | 0.083 |
| | 2nd | 0.241 | 0.243 |
| 6 | 1st | 0.202 | 0.208 |
| | 2nd | 0.117 | 0.119 |
| 7 | 1st | 0.208 | 0.207 |
| | 2nd | 0.233 | 0.233 |
| 8 | 1st | 0.204 | 0.201 |
| | 2nd | 0.242 | 0.242 |
| 9 | 1st | 0.137 | 0.136 |
| | 2nd | 0.120 | 0.120 |

The largest error between the distances calculated from the site geometry and the distances corresponding to the time differences measured with the test system is only 0.67 m (2 feet). Human error in the measuring process could easily account for this discrepancy, since the distance measurements were made with a hand-held infrared laser while the operator was standing beside the source speakers.

The results shown in Table 3.1 confirm that the spikes must represent reflections at the noise barriers. The system's precision precludes the possibility that the very small spikes could come from barrier reflections; rather, they are from some other reflective surface, such as buildings, houses, garages, the Jersey safety barriers in the median, or from the highway pavement.

The second reflection can also be analyzed. The path of the second reflection would have spanned from the near wall, shown in Figure 3.4, back across the corridor to the far wall, and then returned across the corridor to the receiver located above the near wall. The total distance traveled for the second reflection signal is d1 + d1+ d2 + d2 + d1. When the first reflection's distance (d2 + d2 + d1) is subtracted from that of the second, the result is 2d1, a distance that corresponds with the time differences between the first and second reflections. These time differences are also illustrated in Table 3.1.

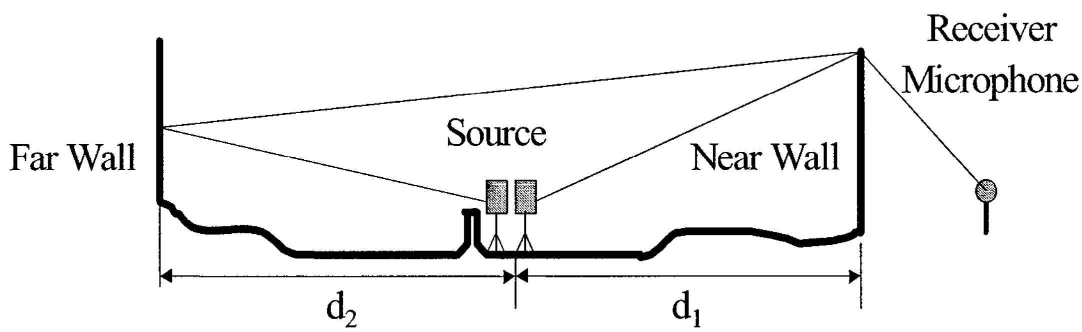


**Figure 3.5** Cross-section showing change in diffraction for reflected rays

The receiver microphone in Figure 3.4 is located above the barrier so that neither the direct nor the reflected rays undergo attenuation by diffraction. Therefore, attenuation due to geometric spreading and atmospheric absorption caused the time differences for the distance traveled by each ray. By contrast, the direct ray depicted in Figure 3.5 is diffracted by the top edge of the barrier, thus attenuating the signal before it reaches the receiver behind the barrier. The reflected ray travels in the opposite direction and is reflected from the far barrier before traveling back across the highway. While the reflected ray undergoes greater attenuation due to geometric spreading over the longer distance, the angle at which the ray reaches the top edge of the barrier is less than the angle for the direct ray. Therefore, the diffraction experienced by the reflected ray is less than for the direct ray, resulting in less attenuation. Attenuation from diffraction compared to attenuation by geometric spreading results in less of a noise level difference between the direct and reflected rays at the receiver microphone behind the barrier, than if the microphone was at the barrier top.

The geometry depicted in Figure 3.5 indicates that receivers located behind the barriers and farther into the community should have smaller differences between direct and reflected rays than those receivers located closer to the highway. As receiver distance from the barrier increases, the relative difference in path lengths between direct and reflected rays diminishes. When compared to the direct ray path, the angle the reflected ray path makes with the barrier tends to reduce barrier attenuation for the reflected ray. The combination of these factors could cause similar intensity between the reflected ray and the direct ray. This effect was modeled mathematically and is shown in Figure 3.6, where the intensity difference between direct ray and a reflected ray diminishes as receiver distance behind the barrier increases. The varying differences between direct and reflected rays with distance is shown in Figure 3.7 as the contribution that the first reflected ray makes to the overall sound level. Note that the contribution of the first reflection approaches 3 dB, the value expected if the rays were of equal intensity. The noise level at a given receiver, as a function of distance, is shown in Figure 3.8 as a combination of decreasing levels, due to geometric spreading, and increasing contributions from reflections.

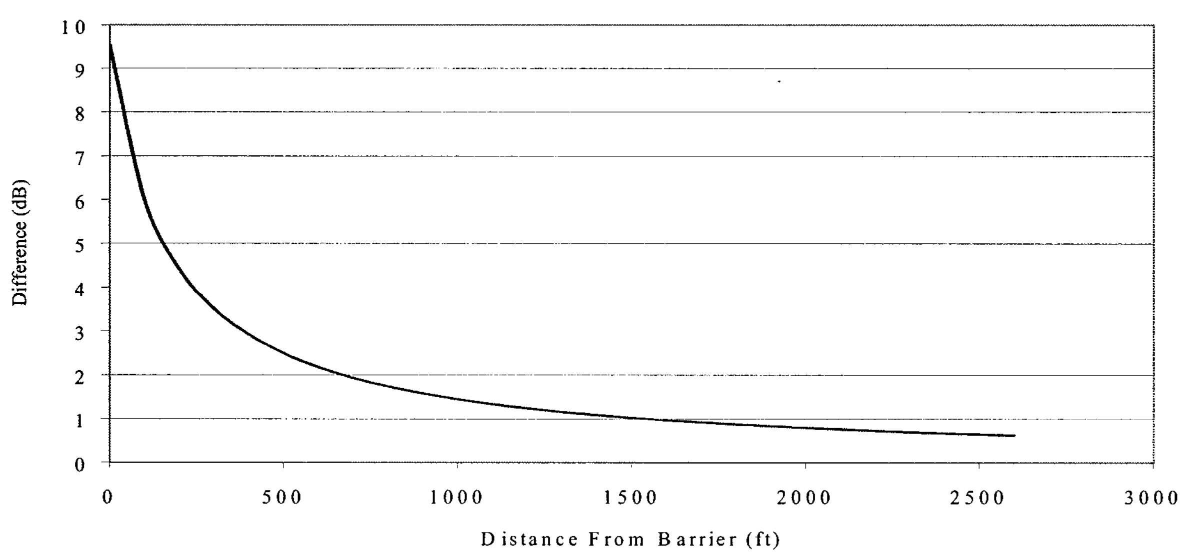


**Figure 3.6** Calculated difference between the direct signal and the first reflection from geometric spreading

This same principle increases the importance of reflections for rays that are not perpendicular from the barrier to receiver, as shown in Figure 3.9. The path length difference decreases for the increasing receiver distances, and the reflected ray experiences less attenuation due to diffraction by the top edge of the near barrier. While contributions from reflections increase for distant receivers, the overall level (as shown in Figure 3.8) will always be less than the level for receivers located closer to the barrier. Note that these cases assume the source is located near the mid-position between the barriers. For a source position near the far barrier, the case with an outside traffic lane, the effect would be more pronounced since the path length difference would be even less.

The trends presented in Figures 3.6, 3.7, 3.8, and 3.9 are calculated based on the principle of geometric spreading, which is the dominant mechanism involved. The equivalent continuous level for traffic noise is reduced at a rate of 3 decibels per distance doubling (dB/DD) due to geometric spreading for a vehicle pass-by, and the peak pass-by level for individual vehicles is reduced by 6 dB/DD, the latter being the same as for point sources. The effects of barrier absorption coefficients, atmospheric absorption, and ground attenuation are not included.

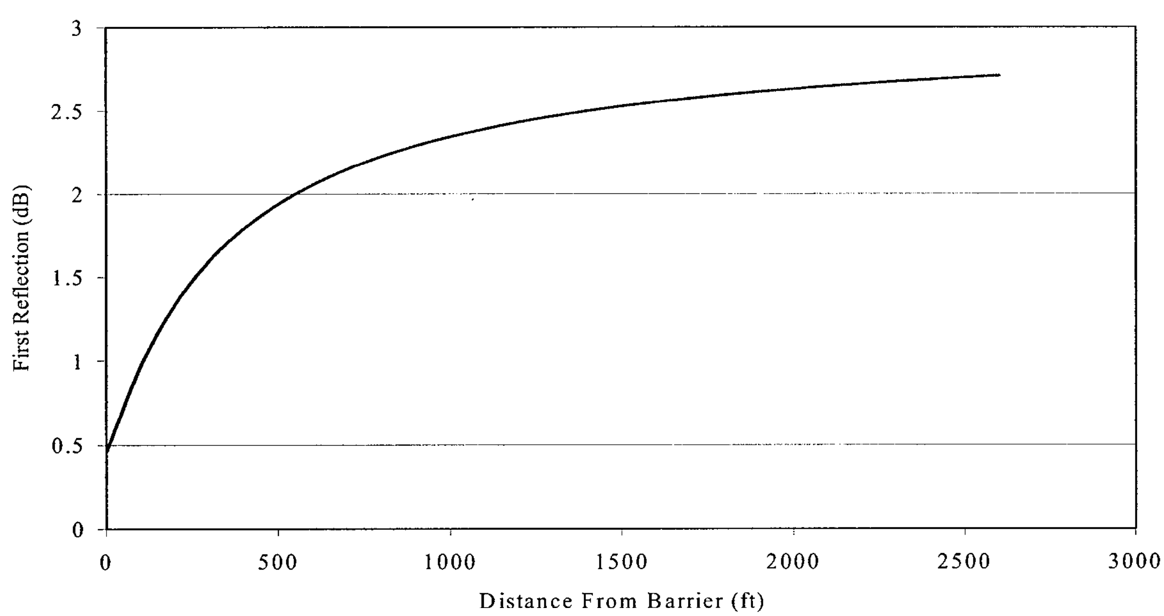


**Figure 3.7** Calculated increase in overall level due to the contribution of the first reflection with increasing distance

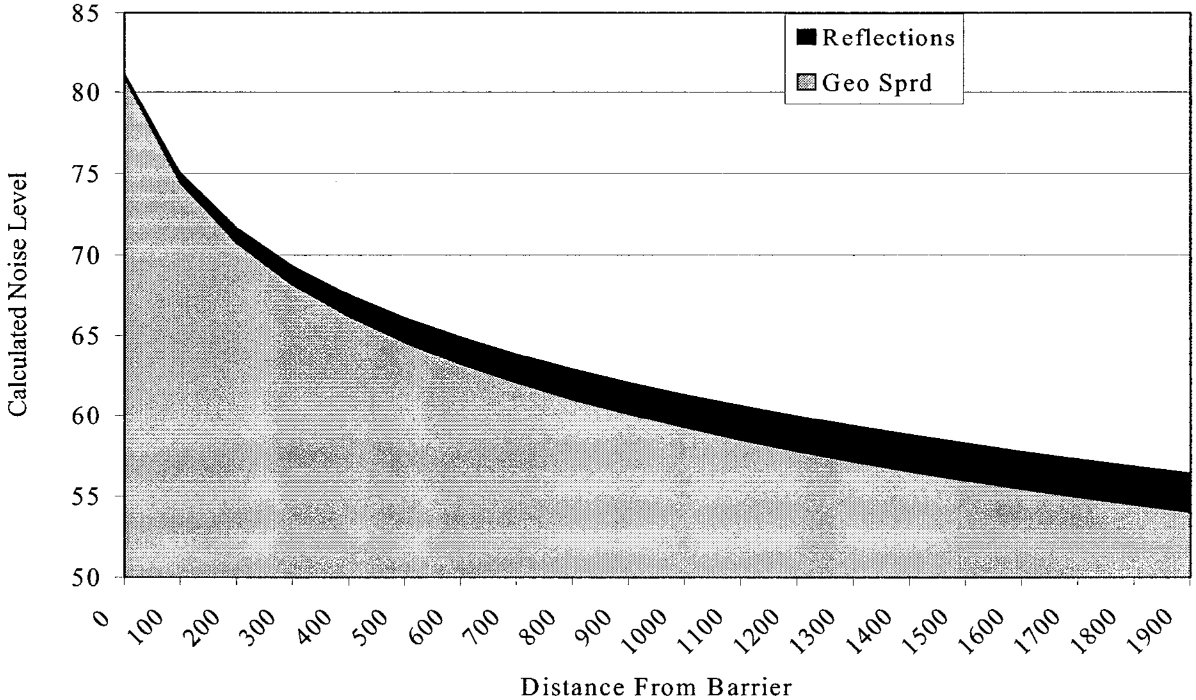


**Figure 3.8** Change in noise level as a function of distance due to geometric spreading and the contribution from the first reflection

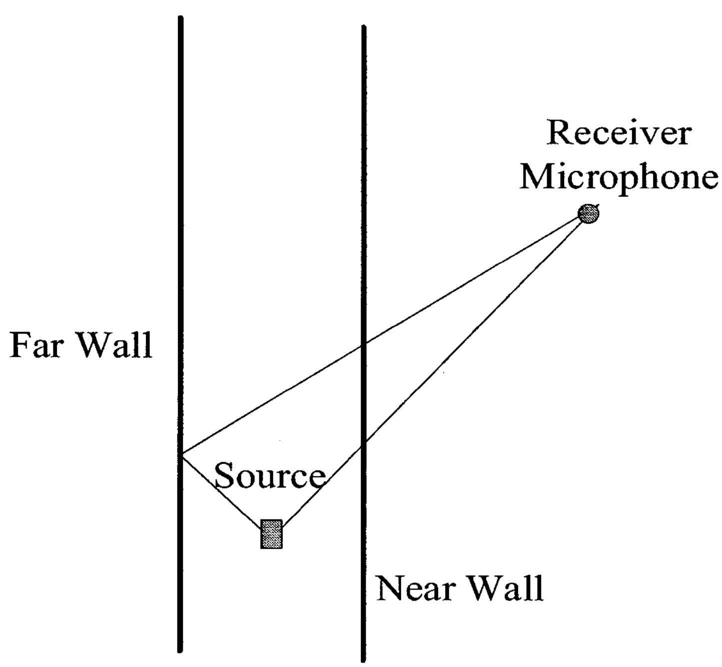


**Figure 3.9** Change in path length and diffraction for angled incidence

*Site Measurements*

The following section describes the results of the measurements made for the HAM 71 project. The reflection detection system identified both the location and contribution of reflections at the various parallel barrier cross sections shown in Figure 3.10. Each reflected ray increases the noise level from the level that would be measured if there were no reflections. To establish a trend for each cross section, the increase at various microphone positions is shown in the figures for the first reflection measured. Multiple tests were conducted at each cross section. Tests at each section were conducted using both psuedo-random binary sequence and frequency modulated sweep (chirp) test signals. Since the results are similar, only the cross correlation of the chirp tests are shown in the figures below. The sound source for some tests was located in the median and for other tests was located on either the west or east shoulders. A configuration number was assigned to uniquely identify each test. The microphone positions are identified with a letter, which indicates its location on the east (E) or west (W) side of the highway, and a number, as described in the Procedure for the Location, Placement, and Set Up of Receivers section. Microphones with higher numbers were placed farther from the highway than microphones with lower numbers.

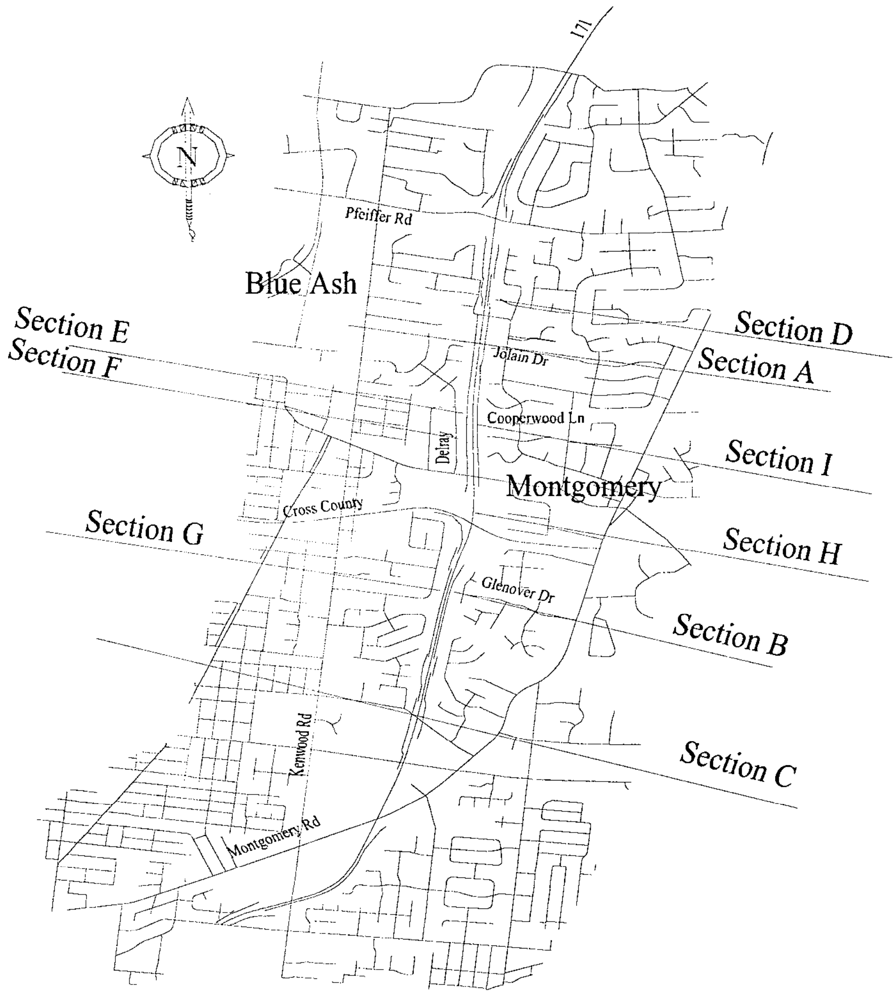


**Figure 3.10** Project Site Map

Test results from the in-situ reflection detection system reported in units of decibels must be used with caution. Assumptions that outpace the development of this new technology, such as those that equate reported level differences with the A-weighted level or the equivalent continuous level for the traffic noise sources, are not valid. Additional research needs to establish the correlation between the in-situ reflection detection system results in decibel units with typical traffic noise descriptors. The results are valid, however, for comparisons between measurements made by the system. The findings given in this report are based on such comparisons.

The contributions of reflections at the different microphone positions on the east and west sides of the highway, with the source located on the west side of the roadway, at Section A are shown Figure 3.11.

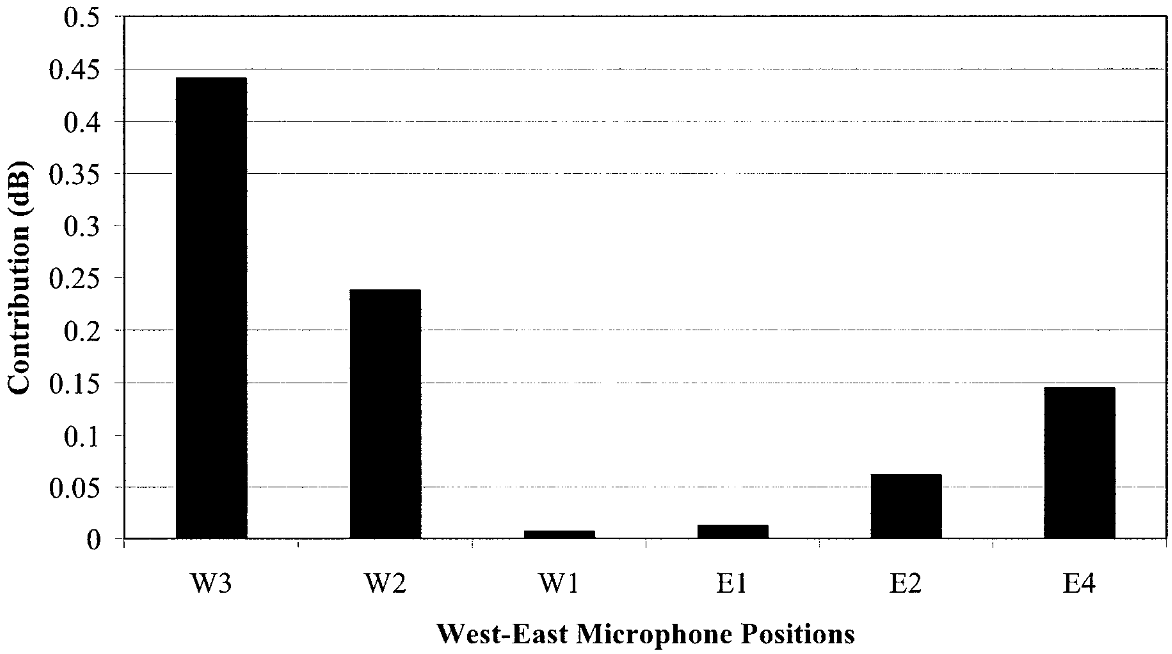


**Figure 3.11** Contribution of reflections for Section A

The figure indicates that reflections contribute more to west side receivers than to receivers on the east side of the highway. In this configuration the source was located on the east roadway shoulder. Therefore, rays reflected from the east barrier to the west receivers travel a distance only slightly greater than the direct rays, which causes them to be similar magnitudes. Conversely, a ray reflected from the west wall must travel across the highway almost two times before it reaches a receiver on the east side. A significant amount of the reflected ray's energy is lost due to geometric spreading over this distance so that a smaller amount of energy is available at the receiver to contribute to the direct ray, which has traveled a relatively short distance. The contributions of reflected rays to the direct rays increase with receiver distance from the roadway, which conforms to the predictions of the theory described in System Tests and Verification section above.

The source was located on the west roadway shoulder for configuration 2 of the same site measurements. Therefore, greater contributions are indicated for receivers on the east side of the highway, with the source on the east side of the roadway, as shown in Figure 3.12.

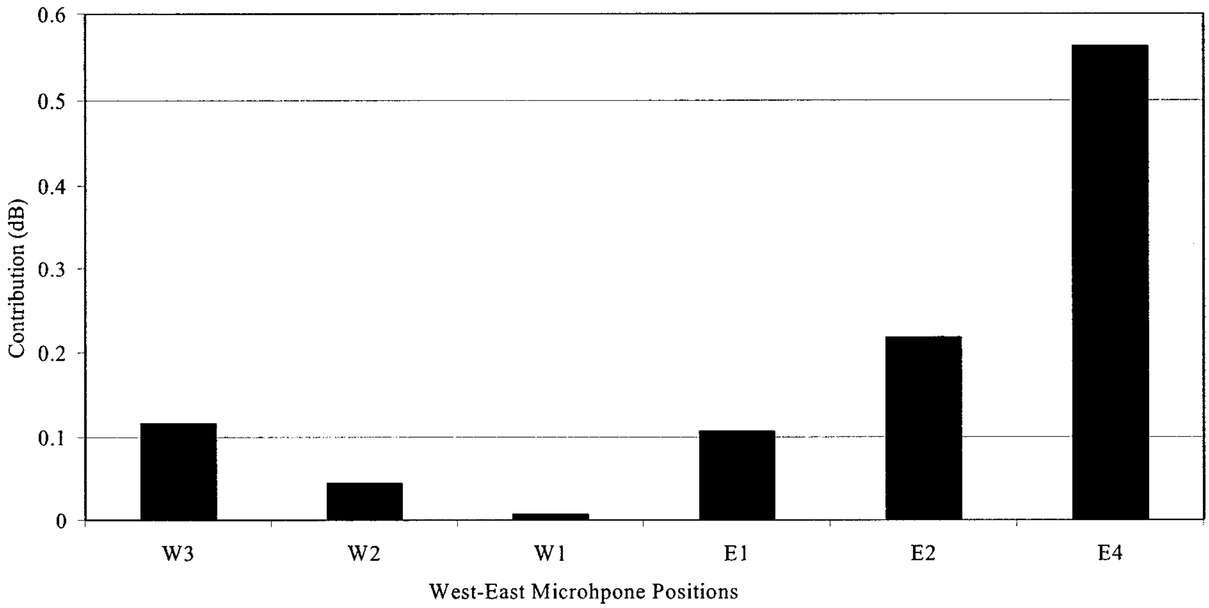


**Figure 3.12** Contribution of reflections for Section A

The results for test configuration 3 are shown in Figure 3.13 where the source was located in the highway median. The results for this configuration are more symmetrical than for configurations 1 and 2. However, the symmetry is lost somewhat with the east side receivers, especially receiver E4. The barriers at this section were not equally distant from the highway centerline. Therefore the ray path lengths and the diffraction angles at the top edges of the barriers were not equal. The reason for this drop off is not known with certainty. The most likely cause is a loss in the test signals coherence because of the receiver longer distance from the source. This loss of coherence results in low correlation values when the signals are cross correlated. This condition is a distance limitation for the test system under its current state of development.

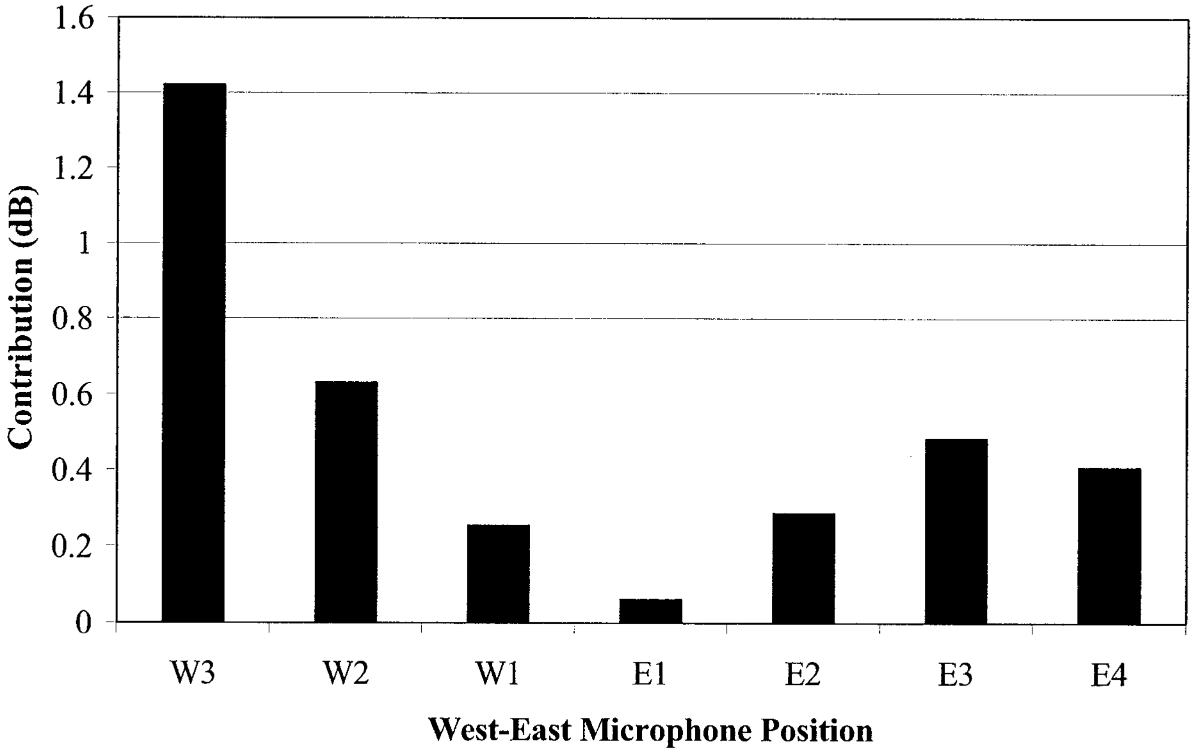


**Figure 3.13** Contributions of reflections for Section A

The results for test configuration 4, which was conducted at Section C, are shown in Figure 3.14. The source was located in the highway median; therefore, the contributions of the first reflections to the received levels tend to be similar for receivers on both sides of the highway.

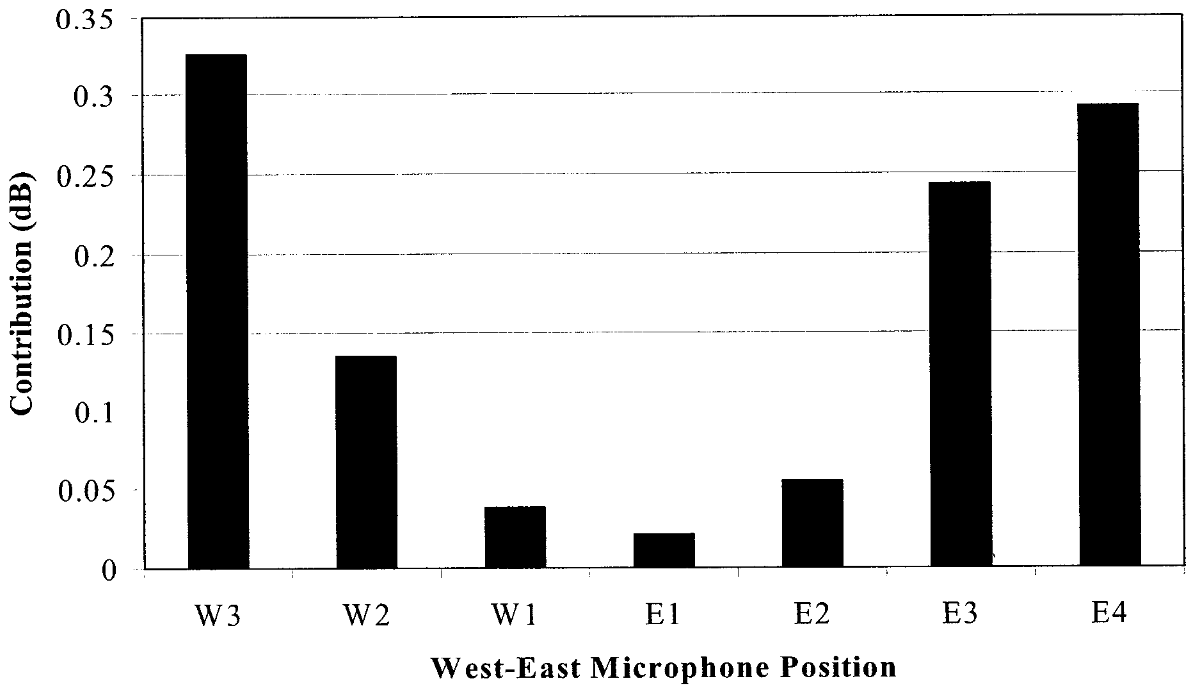


**Figure 3.14** Contributions of reflections for Section C

The location, barrier height, terrain type, and receiver positions at the Section D site were unique. Microphones were only set up on the east side of the roadway where complaints from the residents were particularly high, as reported in the preliminary assessment study. The steep terrain and dense vegetation precluded the installation of a microphone above the east noise barrier. Microphone E2 was located at the first residence from the barrier.

The contribution from the first reflection was over 5 dB for configuration 5 with the source located on the west side of the highway, as shown in Figure 3.15. The correlogram for this test configuration is shown in Figure 3.16 where the first reflection is depicted as being greater than the direct ray. This unusually high contribution resulted from the geometry for this test configuration. The source was located near the west barrier as shown in Figure 3.17. The west side barrier elevation was higher than the east side barrier elevation at this cross section so that most of the west barrier was visible from the E2 position. Therefore, reflections reaching receiver position E2 were not shielded by the near barrier. The other two microphones at this position did not have direct sight of the west barrier but their levels of contribution shown were still in excess of 1 dB.

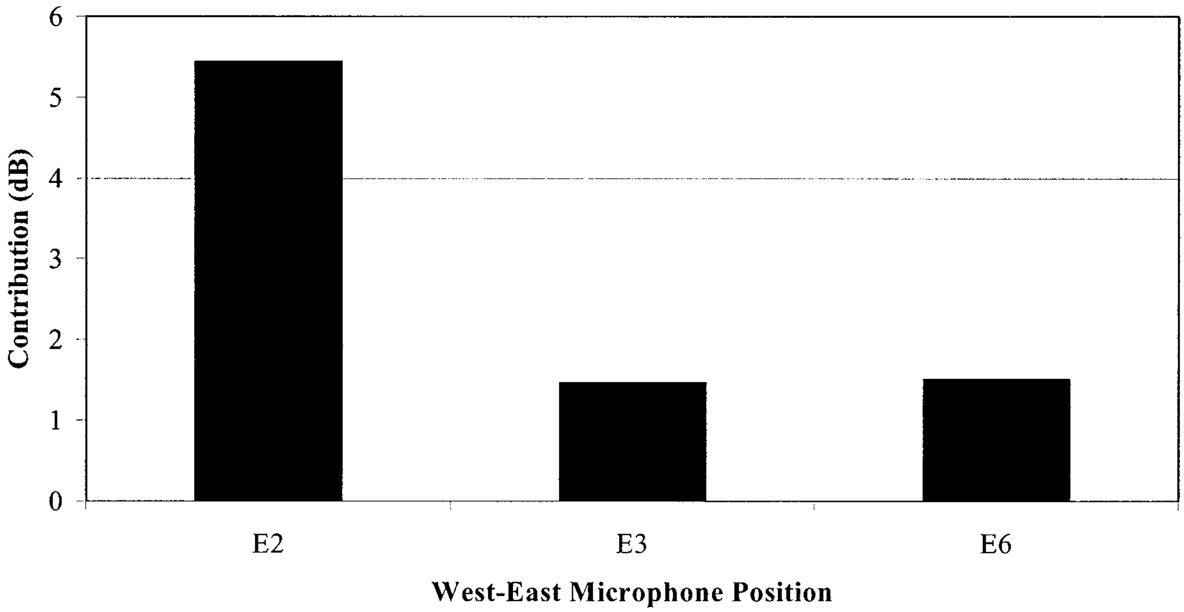


**Figure 3.15** Contribution of reflections for Section D

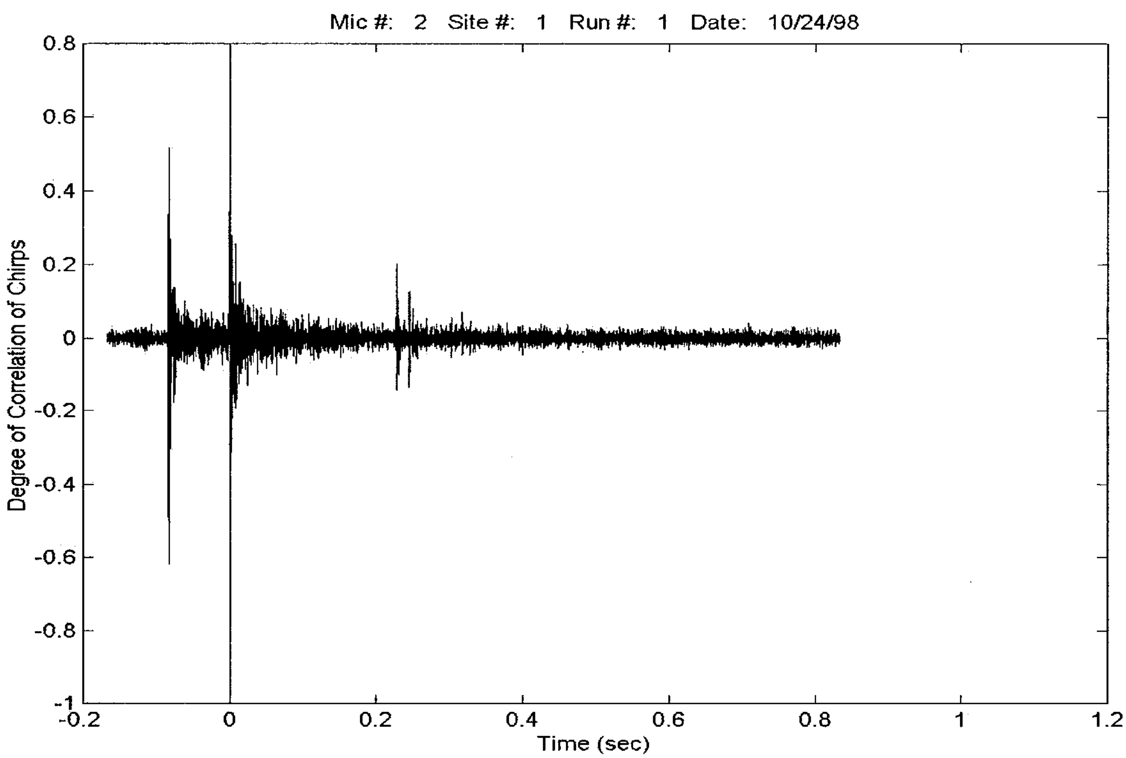


**Figure 3.16** Correlogram for configuration 5, receiver E2

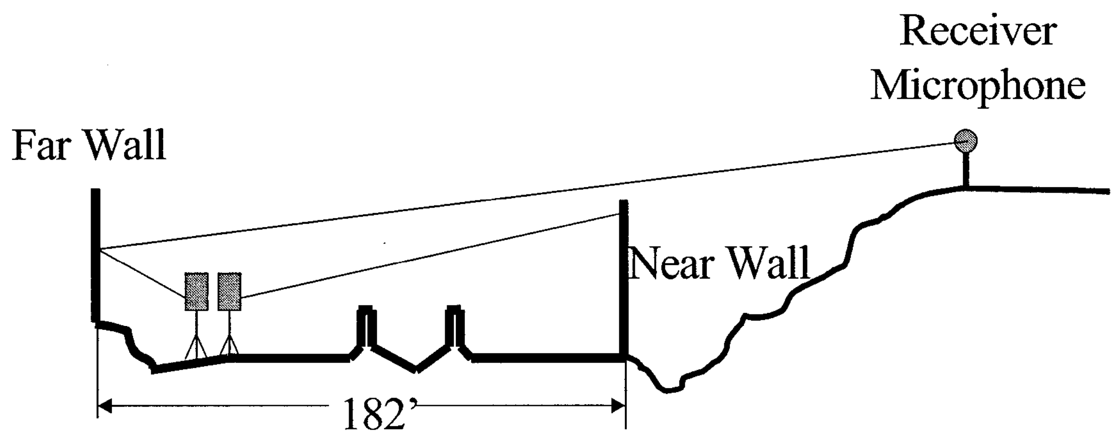


**Figure 3.17** Cross-section of test section D, configuration 5, with receiver E2

The results from test configuration 6, which was also at section D, are shown in Figure 3.18. The source was located in the median for this test configuration. The contribution of reflections is relatively high, but not as high as for configuration 5. The correlogram for receiver E2 is shown in Figure 3.19.

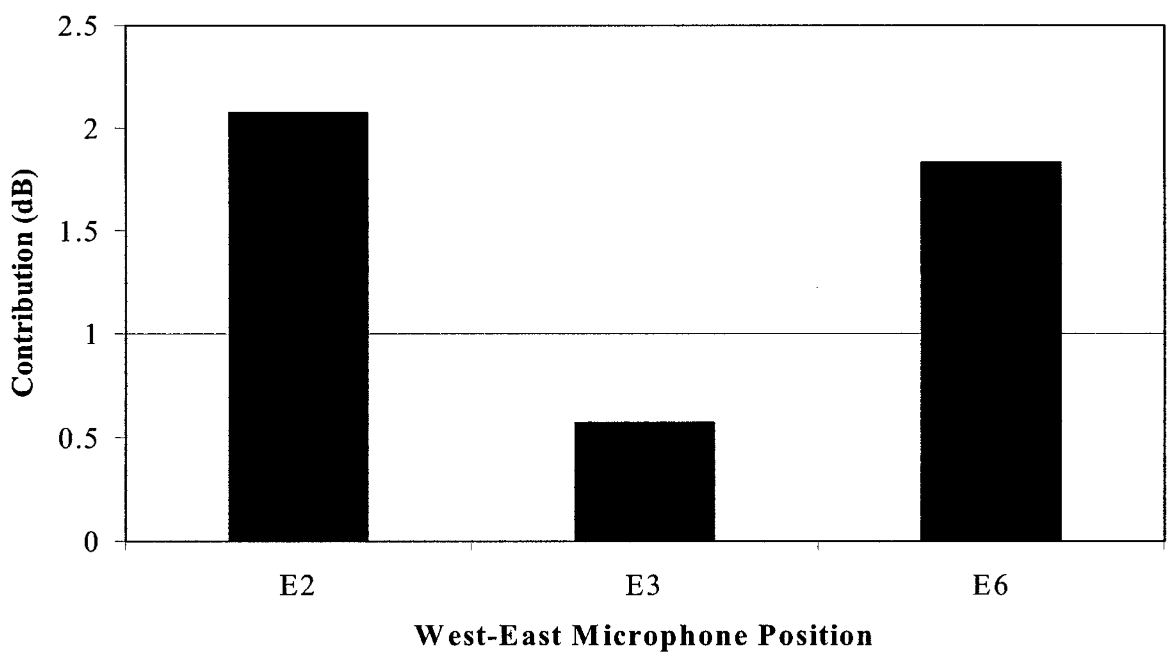


**Figure 3.18** Contributions of reflections for Section D

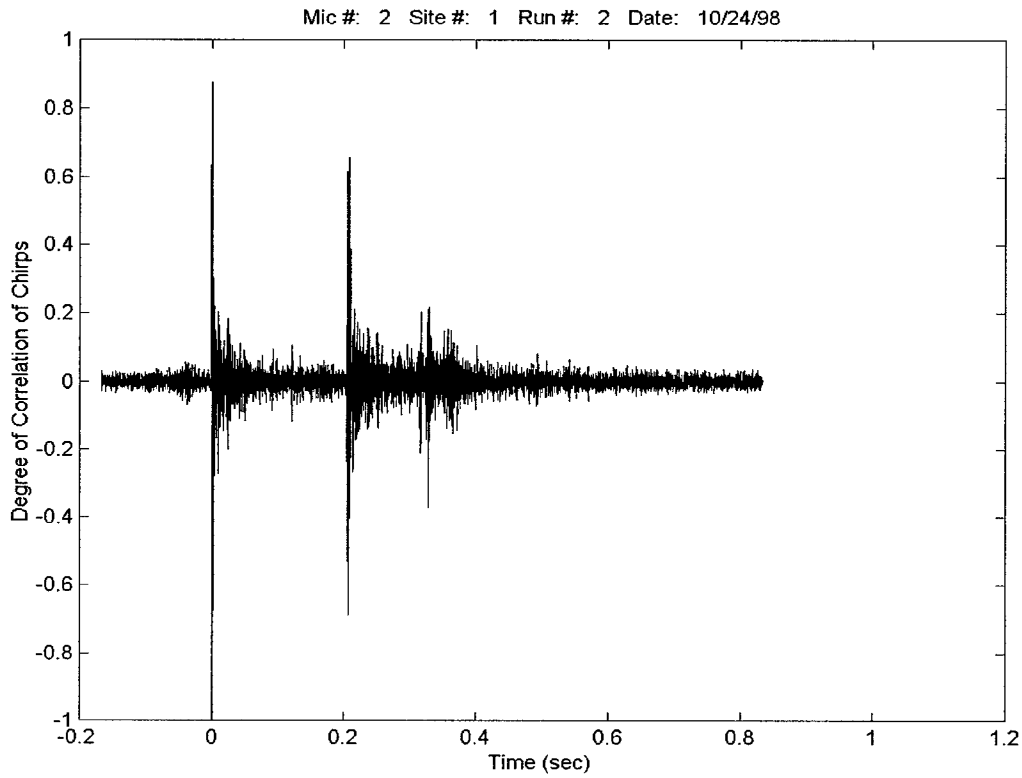


**Figure 3.19** Correlogram for configuration 6, receiver E2

Test section E was located on the west side of highway. The results for Configuration 7, in which the source was located in median, are shown in Figure 3.20.

The contributions increase progressively, according to the pattern observed in other sites, for receivers W1, W2, and W3. However, the contribution drops off for receiver W4 and is most likely caused by a loss in test signal coherence because of the receiver longer distance from the source.

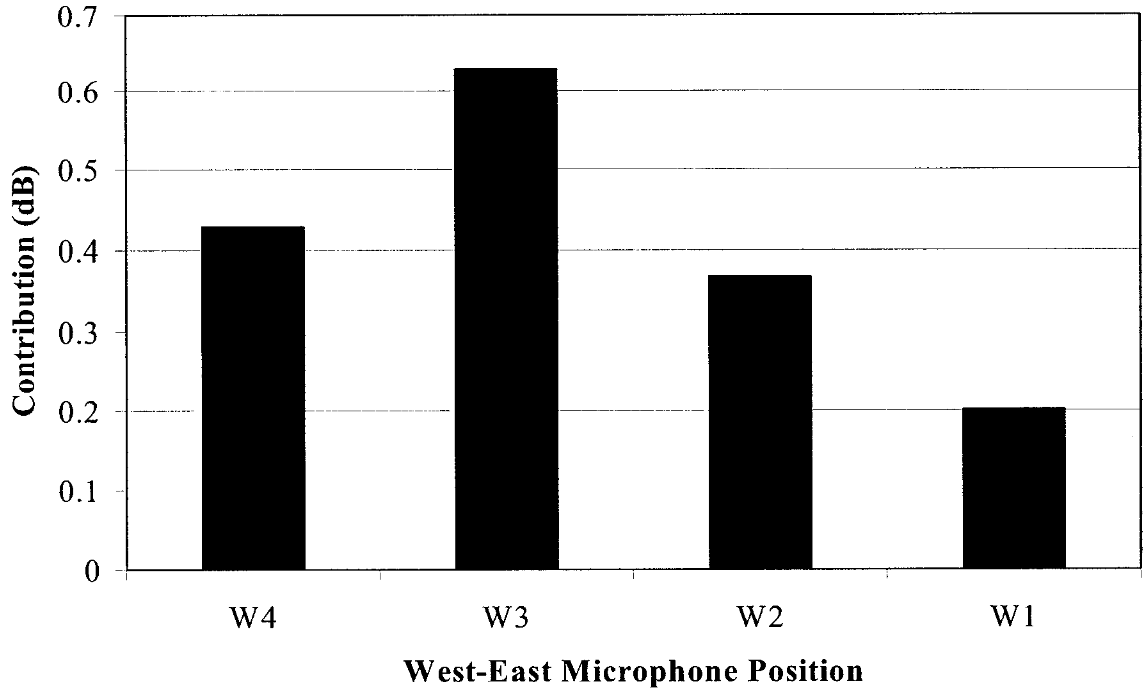


**Figure 3.20** Contribution of reflections for Section E

Test section F was also located on the west side of highway. The results for Configuration 8, in which the source was located in median, are shown in Figure 3.21. The highest contribution of the first reflection occurred for receiver W2, which was the first microphone behind the noise barrier.

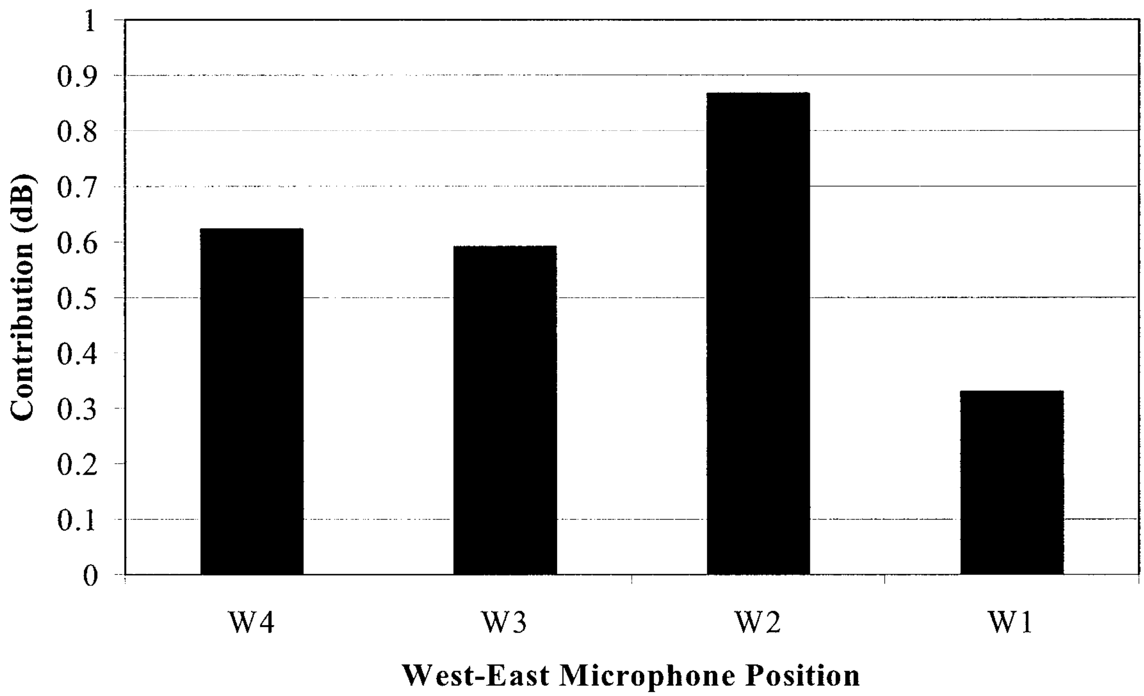


**Figure 3.21** Contribution of reflections for Section F

Test section G was also located on the west side of highway. The results for Configuration 9, in which the source was located in median, are shown in Figure 3.22.

Similar to test section F, the highest contribution from the first reflection occurred for receiver W2. The contribution was 2 dB, which resulted from a relatively intense first reflection at this site. As with test section F, the pattern of progressively increasing contributions with distance was not present for test section G.

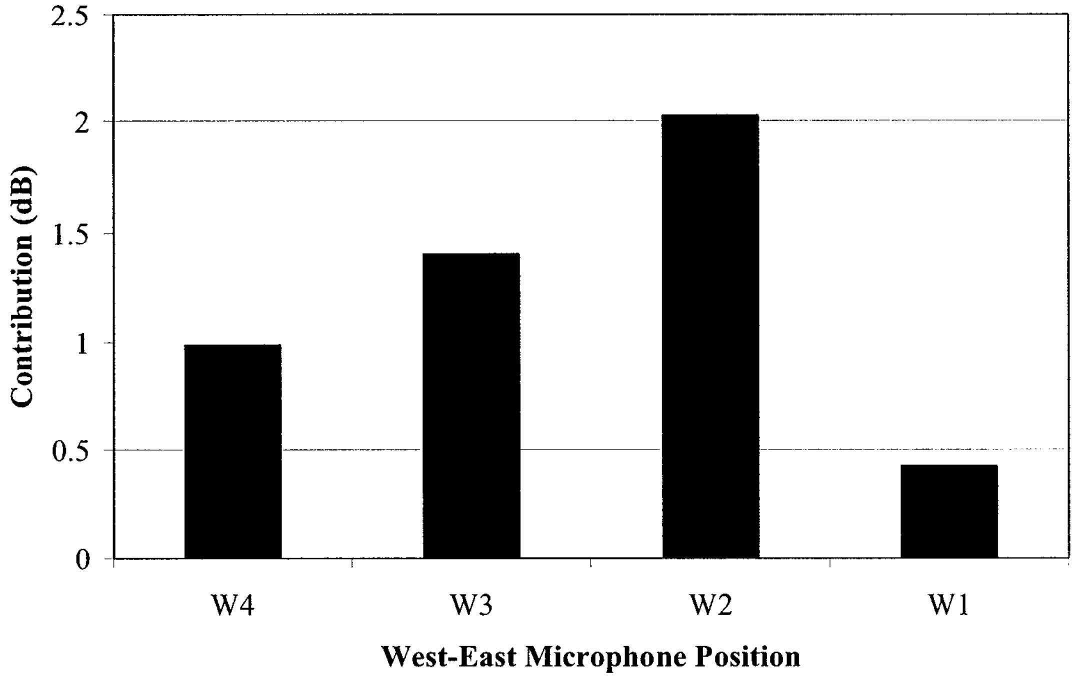


**Figure 3.22** Contribution of reflections for Section G

### 3.1.2 SUM 8 Measurements

Background

In 1994, construction of pre-cast concrete barriers to abate traffic noise began for the communities of Cuyahoga Falls and Silver Lake along Ohio's SR 8, a north-south oriented four-lane divided highway. The Silver Lake barrier, which is on the east side of the highway, was constructed first. Following construction of the west side or Cuyahoga Falls barrier, ODOT received complaints from Silver Lake residents of increased noise levels.

In 1996, Bowlby and Associates, under contract to ODOT, conducted an investigation, which resulted in the recommendation to retrofit the highway sides of both the east and west barriers with sound-absorbing panels in order to control traffic noise reflections that could be contributing to increased sound levels for residents. After considering many factors, a decision was made to retrofit the west barrier, the barrier surface that was most likely to affect Silver Lake residents due to the noise reflections from passing vehicles.

ODOT requested an evaluation of the retrofit project effectiveness. The standard evaluation procedure requires precise sound level measurements made at selected residential sites, both before and after the installation of the sound-absorbing panels. Bowlby and Associates had made such measurements during their initial investigation before the sound-absorbing panels were in place and repeat measurements made at the same locations once the sound-absorbing panels were installed to complete collection of the required data. This evaluation method captures the overall effect of the noise received at a given microphone location and any change due to the noise barrier system. However, many factors, including wind, temperature, traffic, and vegetation, affect sound waves as they are propagated from the source to the receiver. Therefore, one goal of the standard procedure is to control the many sound propagation variables sufficiently so differences between the BEFORE and AFTER sound levels can be attributed to the sound-absorbing panels.

While the standard procedure of comparing BEFORE and AFTER noise levels addresses the overall effect characteristics of the noise reflections, such as their origin, relative strength, and the amount of energy absorbed by the material for each reflection, are not addressed by this simple comparison.

The results of the system developed in the first year of this research project to meet the first objective were very encouraging. The success of this new technique in identifying the location and relative strength of reflections for the Cincinnati barriers suggested that the same approach might provide insight into the reflection characteristics and the effectiveness of sound-absorbing panels on the Summit-8-6.8 project. Therefore, this research project was expanded to include the new system in an in-situ evaluation of the effectiveness of sound absorbing materials to control reflections between parallel noise barriers. The measurement procedure was designed to acquire experimental data relevant to Objective 3 and support any recommendations concerning sound absorbing materials for use with parallel barrier systems.

## Procedures

Preliminary plans included selecting three in-situ reflection detection sites, one site for the single barrier section and two sites in the parallel section, within the project area. However, during the actual field operations, two additional sites were selected in the parallel barrier section to increase the size of the acquired database. The test site locations are shown in Figure 3.23.

The installation of sound absorbing materials on the roadway side of the west noise barrier was intended to benefit residents living on the Silver Lake (East) side of the highway. Therefore, preliminary plans did not include receiver microphones on the highway's west side. However, during the actual field operations, additional receiver stations were available during some of the tests and utilized to characterize reflections on the highway's west side.

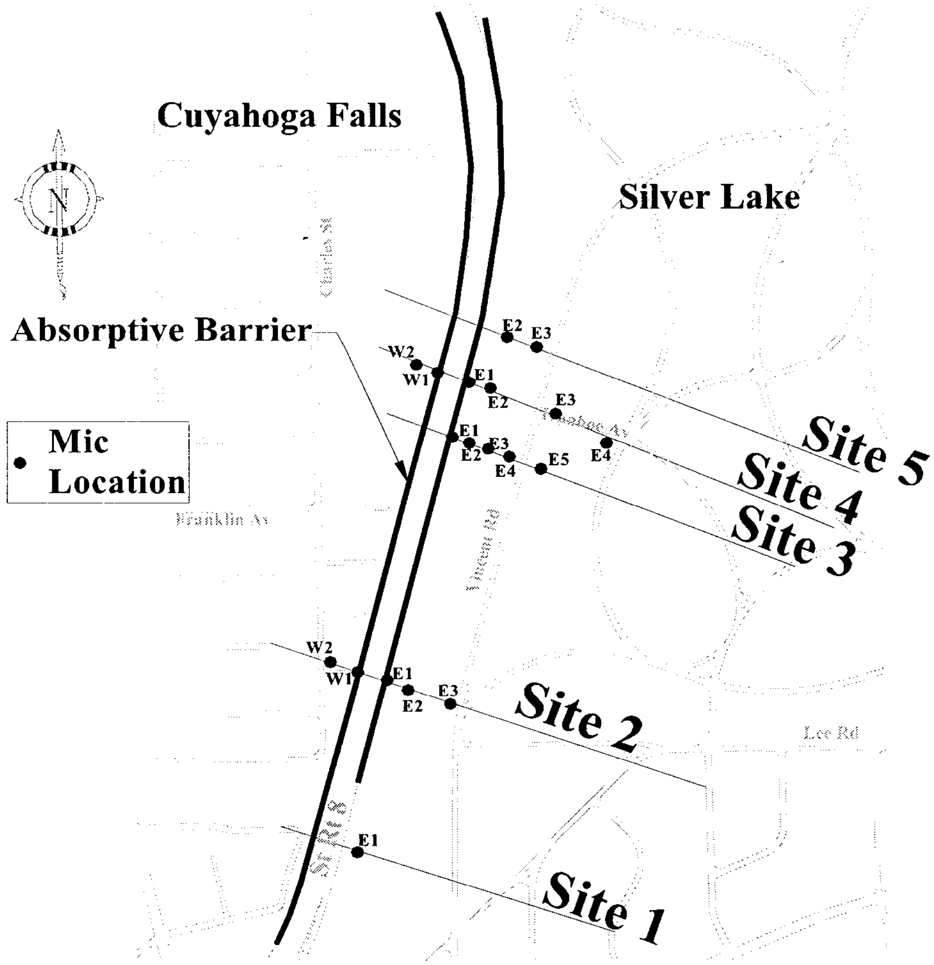


**Figure 3.23** Map of test sites on the SUM 8-6.2 project

<u>Results</u>

*"Before" Measurement Results*

The BEFORE measurement results were analyzed by test site to characterize reflections prior to the addition of sound absorbing materials to the noise barriers. Data acquisition problems occurred for the receivers at site 5; therefore, no results are given for this site.

The level of the first reflection at each site is compared to the level of the direct signal in Figure 3.24. The site number is the upper label entry for each bar shown on the horizontal axis. The lower label designates the receiver microphone position. The letter "W" (west) and "E" (east) indicate on which side of the highway the receiver microphone was located. The microphone position with respect to distance from the roadway is indicated by the number associated with the letter (distances found in Appendix A). Microphones located at the barrier are designated as "1". The number designations increase with increasing distance from the barrier. The position of each vertical bar in the figure was dictated by the microphone's distance from the roadway. This data interpretation method was selected to display trends that may be dependent on source-to-receiver distance. The largest difference between the direct ray and the first reflection occurred at site 1, a single barrier configuration located at the southern portion of the project area, as shown in Figure 3.23.

The source, located on the highway's east shoulder, at site 1 was closer to the receiver than any of the other sites. The site 1 receiver was located just beyond the highway's east right-of-way line, making the ratio of the direct path length to the reflected path length smaller for this site than for other sites. Therefore, the reflected ray for site 1 would be attenuated more, due to geometric spreading, over its relatively long path compared to the reflected rays at other sites, causing the larger difference between the direct and reflected rays.

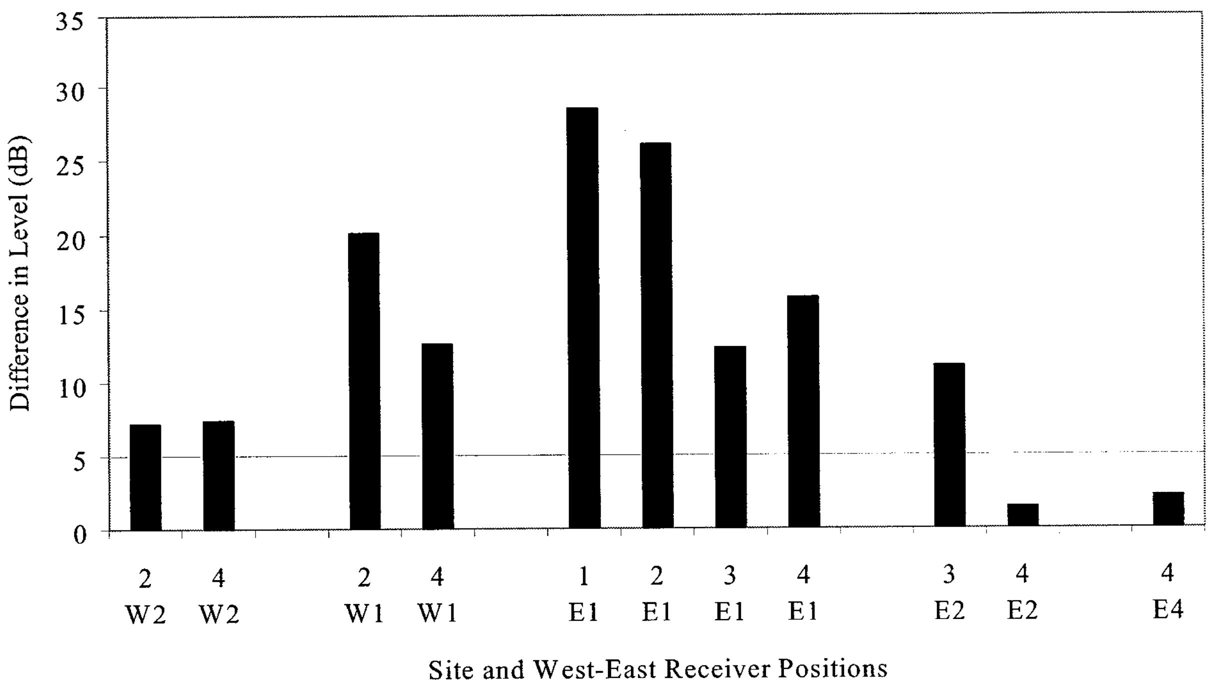


**Figure 3.24** Difference in level between the direct and first reflected for the BEFORE measurement

The site 2 results at the microphone positions above the noise barriers (E1 and W1) indicate a difference between the direct and reflected levels of 20 dB for the west side and 26 dB for the east side. The site 2 source position was the median area; however, the locations of the east and west barriers are not equi-distant from the median. The reflected wave must travel a longer distance on the west side compared to the east side, and therefore, experiences more attenuation due to geometric spreading. Since there is more attenuation, the difference between the direct ray and the reflected ray is greater. The difference in ray path lengths at site 4 also accounts for the similar pattern shown in Figure 3.24 for the barrier microphones, E1 and W1.

For comparisons involving receivers shielded by barriers, the difference between the direct ray and the reflected ray is also affected by barrier attenuation, in addition to geometric spreading. For example, E1 microphones at east side sites 2, 3, and 4, were located above the barrier, whereas the E2 and E4 microphones were shielded by the barrier. The difference in level between the direct and reflected rays for the E2 receivers is less than the E1 receivers. This same trend is found on the west side where the W2 microphone for sites 2 and 4 indicates less of a level difference than the W1 position at the barrier microphones for the same sites. The reason for this trend is given in the discussion of the diagrams shown in Figures 3.4 and 3.5 of the System Tests and Verification portion of Section 3.1.

Test results for microphones E1 compared with E2 and E4 for Site 4 follow these trends. However, the difference for E4 is somewhat greater than the differences for E2. This anomaly could easily be caused by variations in the atmosphere, terrain, vegetation, and obstacles located within the community, creating slight differences or reversals, as in this case.

*Results of "After" Tests*

The level difference between the direct and first reflected ray for the AFTER measurement taken following installation of after sound-absorbing panels on the west barrier is shown in Figure 3.25.

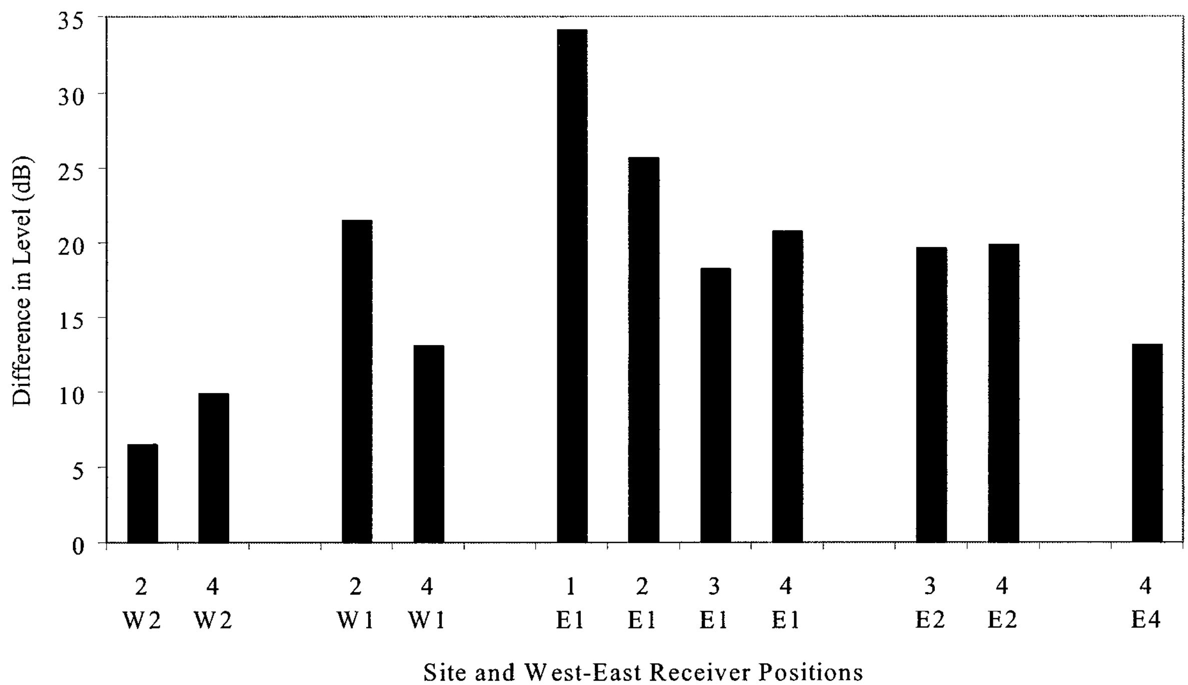


**Figure 3.25** Difference in level between the direct and first reflection for the AFTER measurement

Note that site 1 exhibits a greater drop in level for the AFTER case shown in Figure 3.25 than the BEFORE case shown in Figure 3.24. This result is directly attributed to the attenuation caused by the presence of the sound absorbing panels. The E1 receiver for site 2, however, appears to have realized little benefit from the sound absorbing panels. This result could be expected, since reflections seemed to have little effect on the receiver at this location, as indicated by the large difference in level shown in Figure 3.24. The trend described earlier for Site 4, microphones E1, E2, and E4, in Figure 3.24, in which the more distant receivers on the east side experienced less difference than those closer to the barrier, is also seen in Figure 3.25 (though not as pronounced). Overall, the drop in level between the direct and first reflected ray has increased with the installation of the sound-absorbing panels for receivers on the east side of the highway. This is shown more clearly in Figure 3.26, where the differences between BEFORE and AFTER levels of the first reflections are compared.

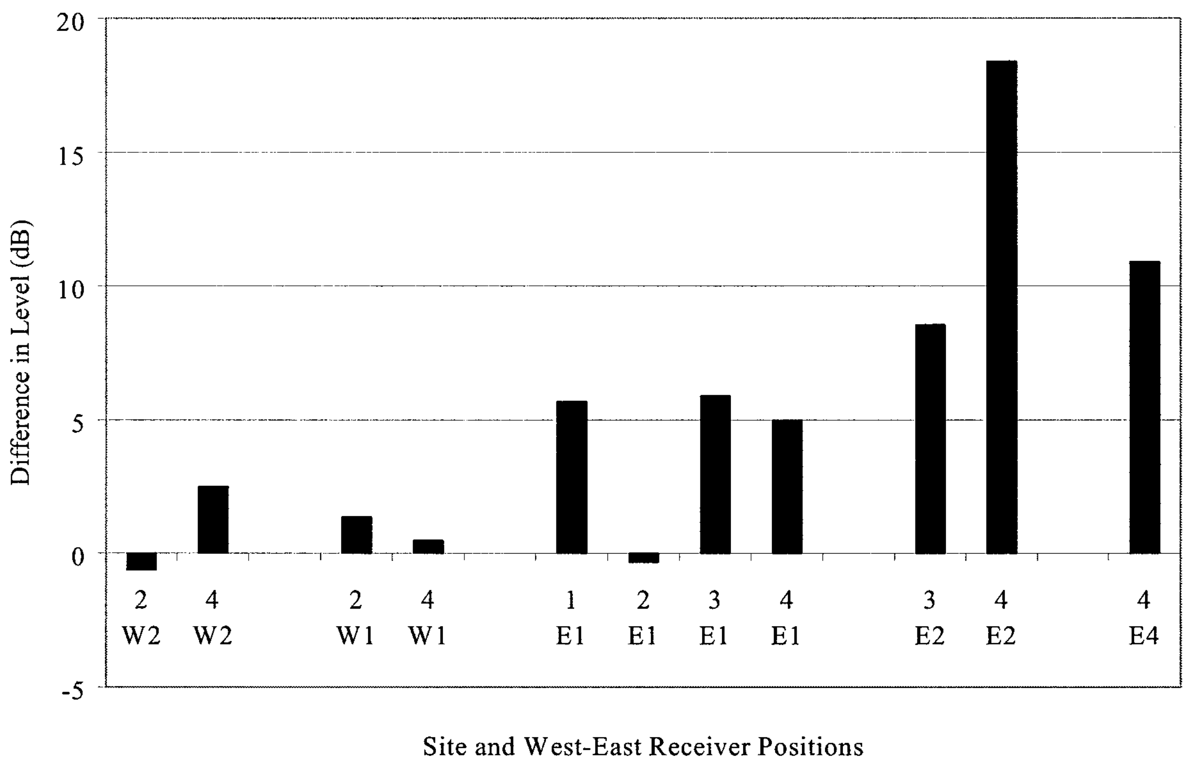


**Figure 3.26** Difference between before and after levels of the first reflections

Note that there is little difference between the BEFORE and AFTER levels on the highway's west side. The small differences are attributed to weather conditions and measurement errors. This result would be expected, since the first reflection for receivers on the west side comes from the east barrier, which has no sound-absorbing panels in either the BEFORE or the AFTER case. By contrast, the difference between BEFORE and AFTER levels is significantly greater for receivers on the east side of the highway, as shown in Figure 3.26.

The Site 3 results indicate that the further distant receiver E2 experienced increased benefits from the sound absorbing panels than E1. Likewise for Site 4, receiver E2 benefited more than receiver E1. This trend is consistent with the observations made for the BEFORE case results. Since reflections were observed to be more significant for distant receivers in the BEFORE case, the benefit of the sound-absorbing panels is greater in the AFTER case for the further distant receivers.

A portion of sound wave energy is lost when the wave is reflected from a sound absorbing surface. This loss of energy appears in the correlograms for the AFTER tests. The spikes height for reflections at the noise barrier fitted with sound absorbing material (west barrier) were found to be lower, compared to the direct signal, than the corresponding spikes for the BEFORE case. This difference between the BEFORE and AFTER levels for the reflections can be quantified by the following equation:

$$\text{Difference in level} = 20\log\left(\frac{S_d}{S_r}\right)$$

In this equation, $S_d$ and $S_r$ represent the size of the direct spike and the size of the reflected spike from its positive most value to its negative most value, respectively. The difference in the second order reflection (a reflection that has struck both barriers before reaching the receiver) levels can also be calculated. If there is a direct signal of certain strength, and additional signals (the first and second order reflections) of other strengths, the combined effect of these reflections can be calculated using logarithmic addition to show the contributions of the reflections to the overall noise level.

The differences between noise levels at each site were computed using the $S_d/S_r$ equation from above, which utilized the spike's size as measured in the correlograms that depict the reflections from the frequency-modulated chirps and the pseudo-random-binary sequences. Using the difference in noise levels, the amount contributed by the reflections to the overall noise levels is shown in Figure 3.27.

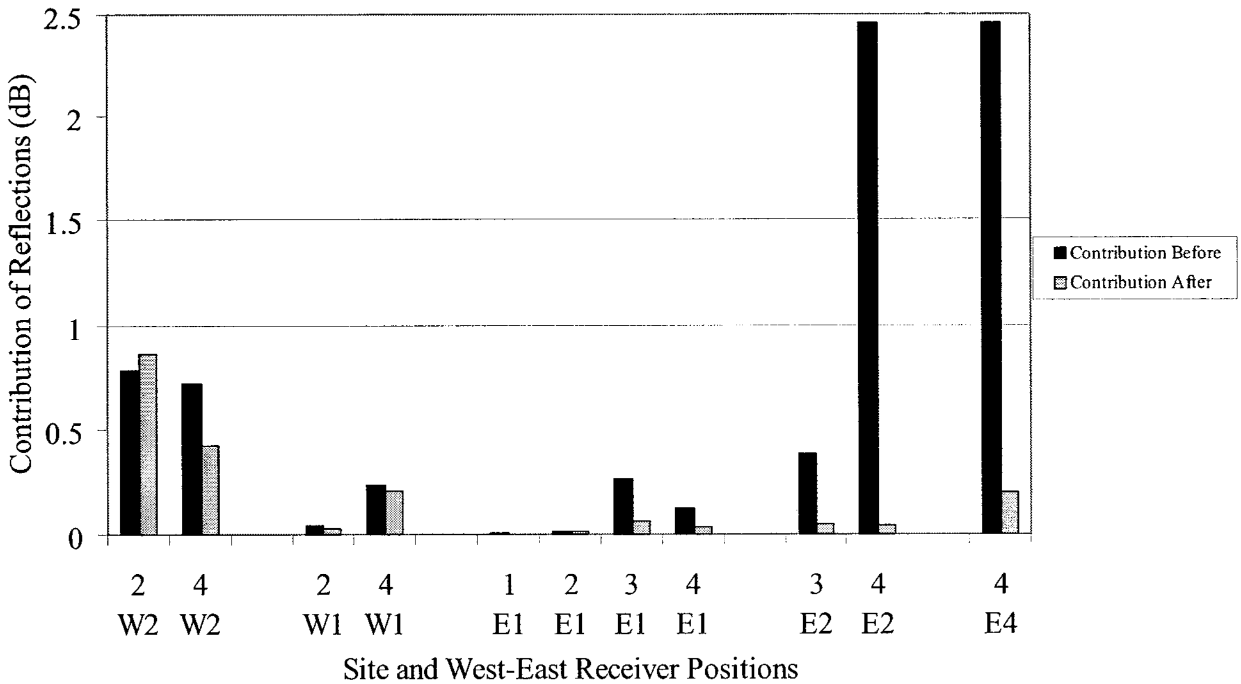


**Figure 3.27** Contributions of both 1st and 2nd order reflections

As indicated in Figure 3.27, the benefit of the sound-absorbing panels to the further distant receivers on the east side is apparent. In other words, the reflections contributed significantly to the levels for the BEFORE case. The contribution was reduced considerably for the AFTER case. By contrast, the contribution of the reflections remained nearly the same for BEFORE and AFTER cases on the west side of the highway; however, Site 4 receiver E4 did not follow this trend. Receiver E4 was the most distant receiver in the project area, as shown in Figure 3.24 for site 4. The distance from the highway to this receiver was close to exceeding the limits of the test system, which depends on having a coherent received signal to cross-correlate with the original test signal. In summary, Figure 3.27 indicates that all receivers on the east side of the highway benefited from the installation of the sound-absorbing panels.

The effect of the sound-absorbing panels on the second order reflections is illustrated in Figure 3.28.

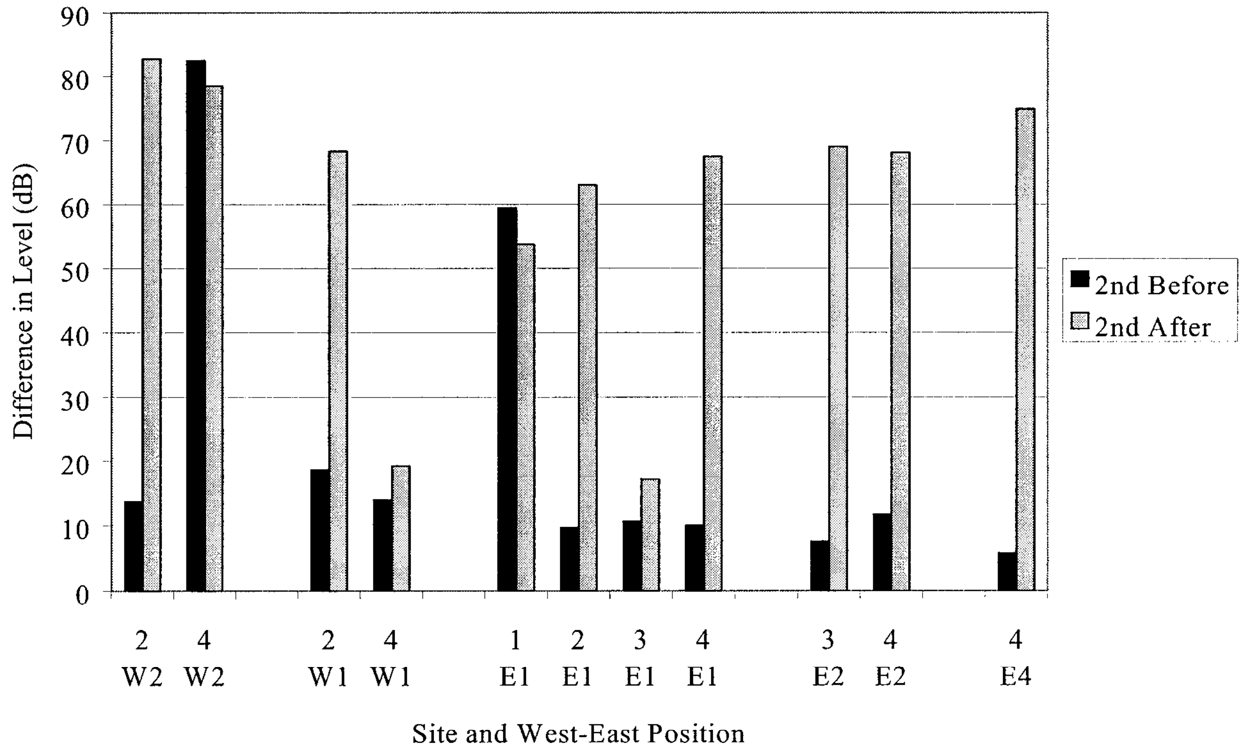


**Figure 3.28** Comparison of BEFORE and AFTER 2nd order reflections

The level difference between the second reflection and the direct signal is significantly greater for the AFTER case for receivers located on both the east and west side of the barrier. While no change was expected for the first order reflection received at the west side receivers, the second order reflection strikes the west wall first before being reflected to the east wall and then reflected again to return over the west wall. The first reflection on the west wall was reduced in intensity by the sound-absorbing panels for the AFTER case. Note that for Site 4, receiver W2, there seems to be an anomaly to the trend just described. However, the source of this anomaly stems from the procedure measuring the difference in reflection peaks on the correlogram. Since some of the second order reflections were so small, it was difficult to identify the reflection. This small value was essentially "0", which could not be entered in the equation as a logarithmic value. Therefore, the number "1" was the default value for the case of extremely small reflection peaks. However, the number "1" did not give the true value and therefore caused the anomaly shown. In other words, the second order reflection was negligible and could have been omitted.

In summary, the test results confirm that the installation of sound absorbing materials on the west noise barrier were effective in reducing the first order reflections for Silver Lake receivers and the second order reflections for both Silver Lake and Cuyahoga Falls receivers.

### 3.2 Ground Attenuation Measurements

As sound waves propagate in the air above ground surfaces, attenuation can occur if the ground surface is porous. Ground covered with vegetation, as opposed to hard surfaces, will produce substantial attenuation depending on the frequency (high or low pitch) of the sound, characteristics of the ground itself, and the sound wave's average height as it is propagated above the ground.

The construction of noise barriers alters the noise propagation path between the noise source and the receiver. A sound ray that is propagated directly from the source to the receiver in proximity to the ground, and therefore attenuated by the ground, cannot reach the receiver once a barrier has been constructed. After barrier construction only rays that are diffracted by the top edge of the barrier can reach the receiver. Since the average path height for diffracted rays is greater than for direct rays the diffracted rays, tend to have less ground attenuation.

The I-71 noise barriers are approximately 6m (17-19 feet) in height. Objective 2 was developed to quantify the effect of noise barrier construction on ground attenuation for distant receivers. Since no instrument exists to directly measure ground attenuation, objective 2 would employ computer modeling. The FHWA Traffic Noise Model (TNM), which was supposed to be released at the time the objectives were written, was developed with a much improved ground attenuation algorithm compared to the STAMINA 2.0 model, which it replaced. Since the TNM had not been validated, it was intended that the accuracy of the ground attenuation algorithms would be inferred, based on an overall calibration of the model at the sites used on this project. However, it became apparent during the course of the project that this strategy was not appropriate. Use of the TNM was precluded by differences between received levels at the reference microphone and predicted levels, as well as larger than expected atmospheric effects for distant receivers. In lieu of the approach based on the model, an experimental approach was developed to indicate the effect of path height for each receiver. The experimental approach, which involved in-situ measurements, offered the inherent advantage of accounting for all aspects of the physical propagation path between the barrier and receiver.

To perform the experiment, a mechanism and procedure were developed to position an artificial broadband noise source at a range of heights similar to propagation heights before and after construction of the noise barriers. Since the level of the source was constant differences in received levels were attributed to differences in the path height, and by inference, differences in ground attenuation.

### 3.2.1 Acoustical Instrumentation and Data Acquisition

The sound source equipment consisted of four major components: an output device, an amplifier, a power supply, and loudspeakers. The sound source output device was a Digital Audio Tape (DAT) recorder that contained a prerecorded 3-minute sample of white noise. The test signal from the tape was input to an amplifier, which was capable of supplying up to 1000 watts of continuous power. The loudspeaker contained a 12-inch woofer and a high-frequency horn to provide a maximum rated output of 500 watts and 131 dB at 1 meter, according to manufacturer specifications. The white noise was transmitted to the receiver locations in the community.

The receiver instrumentation, which was located in the residential community, included several components. The first of these components, the sound level meter (SLM), consisted of a pre-amp, microphone, and windscreen, and was used to receive the sound transmitted by the sound source. The received signal was then input to a DAT recorder where the recorded signal was stored on digital audio tapes in binary format. The recorded white noise was later analyzed with a Real Time Analyzer (RTA) in the laboratory.

### 3.2.2 Field Procedure

The ability to step receivers back through the community was the most important consideration in the site selection for ground attenuation test sites. An effort was made to locate microphone receivers at distances up to 480m from the noise barrier and still have a relatively unobstructed path to the receiver. However, all sites contained compromises to this ideal.

A tower was erected near the traffic noise barrier at different locations throughout the project. The source was raised to a height equal to the top elevation of the barriers in the area. First the white noise from the elevated source was transmitted to the receivers, then the source was lowered to within 0.5m of the ground surface, and the same signal was again transmitted to the receivers. The end of the high and the beginning of the low transmissions occurred within 1 minute of each other. This short time interval provided adequate time separation to distinguish between recorded signals on the tape while allowing the high and low tests to be conducted in close time proximity to minimize variations in atmospheric conditions for the two tests. Further, wind speed was monitored intermittently throughout the data acquisition. If the wind speed was in excess of 5 mph at any time the data was rejected and the test was repeated. Before and after each test the output from the loudspeaker was checked to ensure that the test noise level remained unchanged.

The times on the DAT recorders for each of the receivers were synchronized to the nearest second so that specific tests stored on the DAT throughout a day of measurements could be identified. Calibration tones were then recorded on each DAT. The DAT recorders were adjusted to make the level of this calibration tone the maximum the DAT could record without distortion. The calibration device produced tones that were 94 dB at 1000 Hz, which provided a dynamic range suitable for microphone positions located in the community.

As many as 7 microphone/DAT recorders were positioned at a height of 1.5m in the residential areas approximately in a straight line perpendicular to the noise barrier at distances of 180, 200, 250, 300, 360, 420, and 480 meters (600, 700, 800, 1000, 1200, 1400, and 1600 feet) from the source. However, the 420m and 480m positions could not be occupied at each site due to obstructions or other site features. The white noise test signal was then transmitted through the loudspeaker for three minutes on the elevated speaker and then three minutes on the lowered speaker while being recorded at the receivers. The ambient noise levels were also monitored at each receiver. In many cases the ambient noise levels were high enough to obscure or partially obscure the measurements of the artificial source noise levels.

### 3.2.3 Data Reduction and Analysis

The field tapes were analyzed using an RTA. The RTA provided results in both 1/3 octave levels and broadband equivalent continuous (time averaged) levels, A-frequency weighted. The broadband levels, which were of most interest for this study, were tabulated for both the elevated and the lowered speaker positions for each site. Using this information graphs were created to display the received noise levels at the various distances for each site.

### 3.2.4 Results

The broadband noise levels for the high and low source positions are plotted according to receiver distance for each site in Figures 3.29 to 3.35.

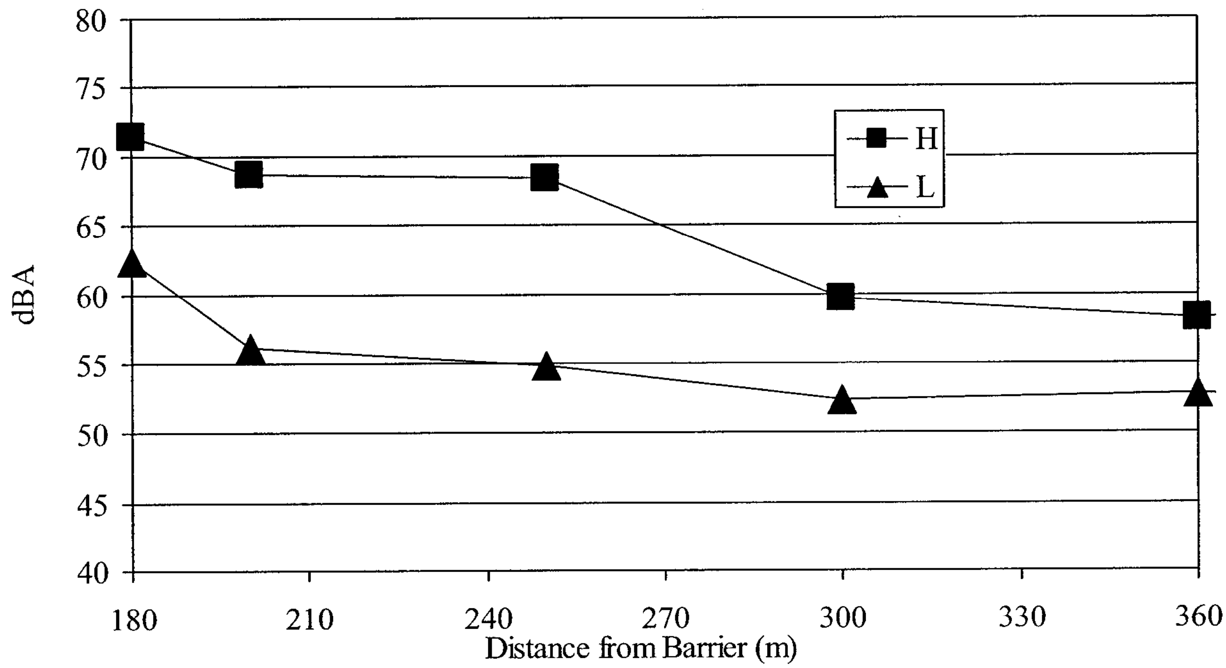


**Figure 3.29** Broad band noise levels for high and low source positions, Site 1, Cooperwood 1

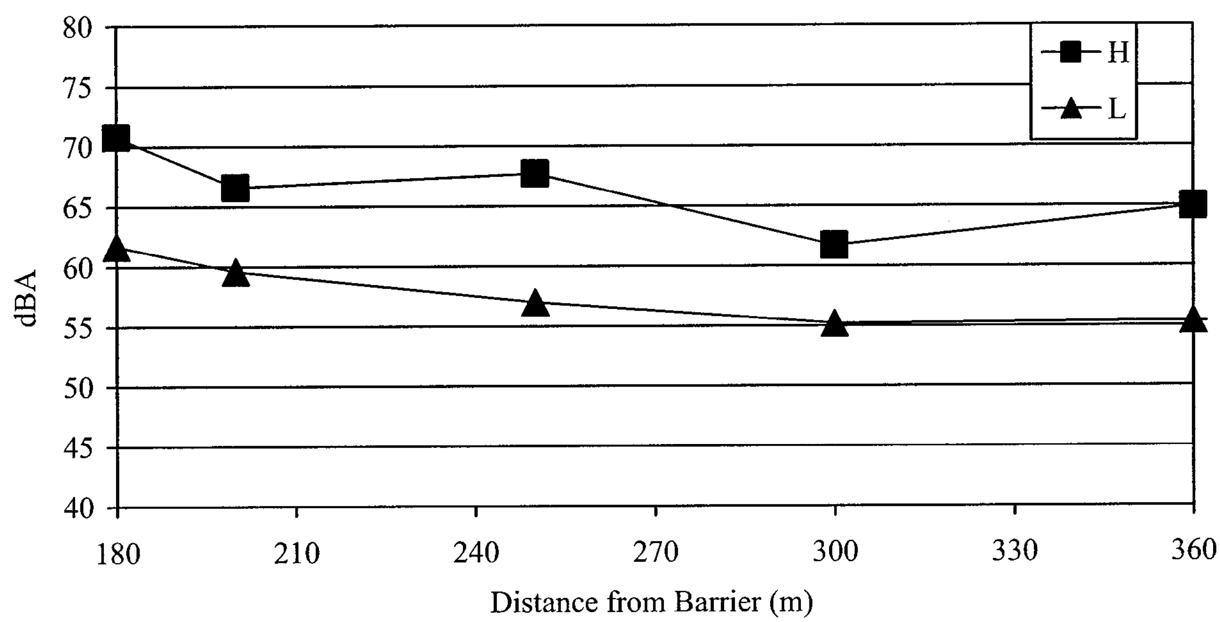


**Figure 3.30** Broad band noise levels for high and low source positions, Site 2, Cooperwood 2

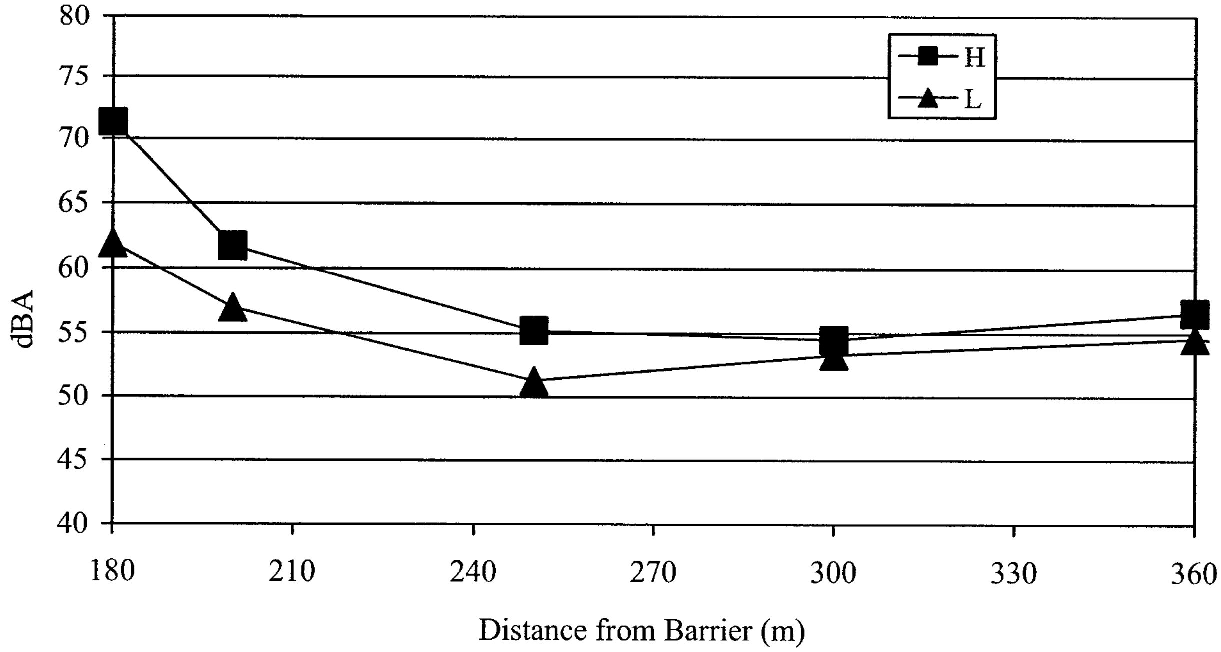


**Figure 3.31** Broad band noise levels for high and low source positions, Site 3, Delray

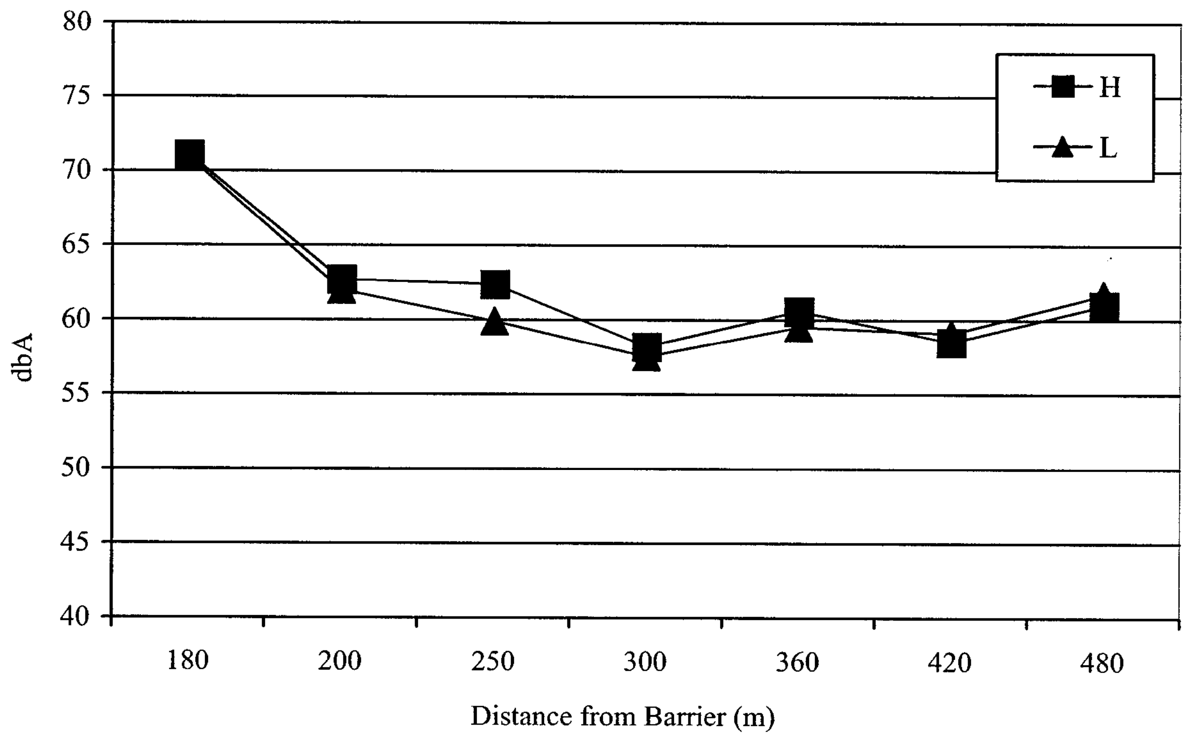


**Figure 3.32** Broad band noise levels for high and low source positions, Site 4, Glenover

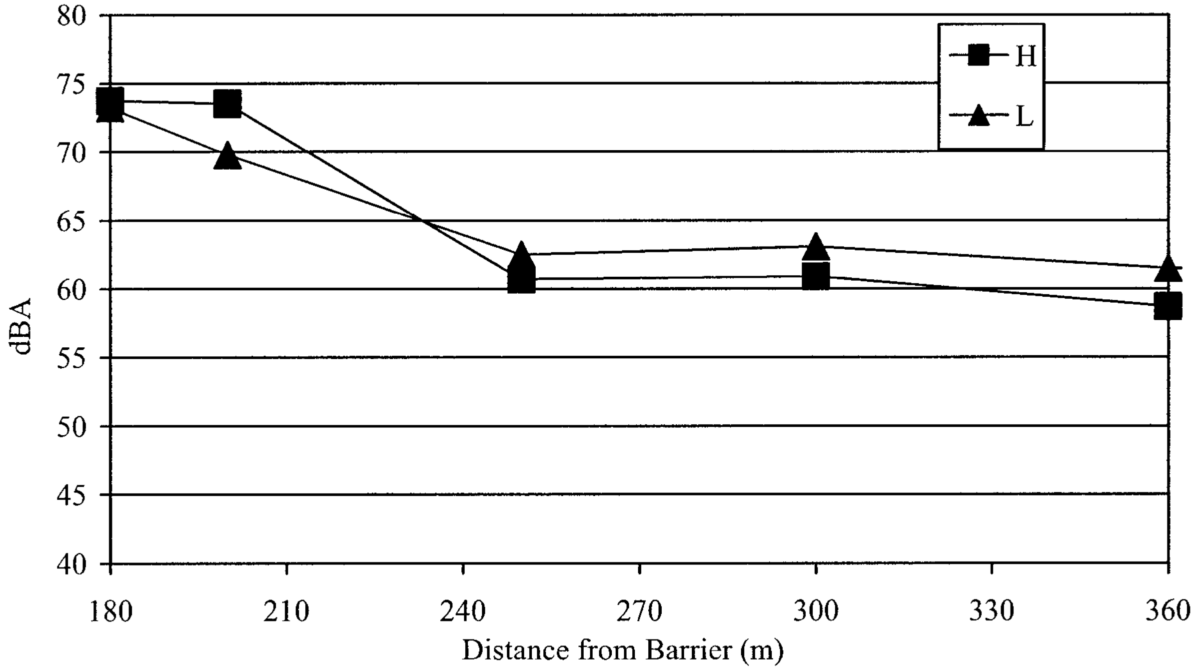


**Figure 3.33** Broad band noise levels for high and low source positions, Site 5, Jolain

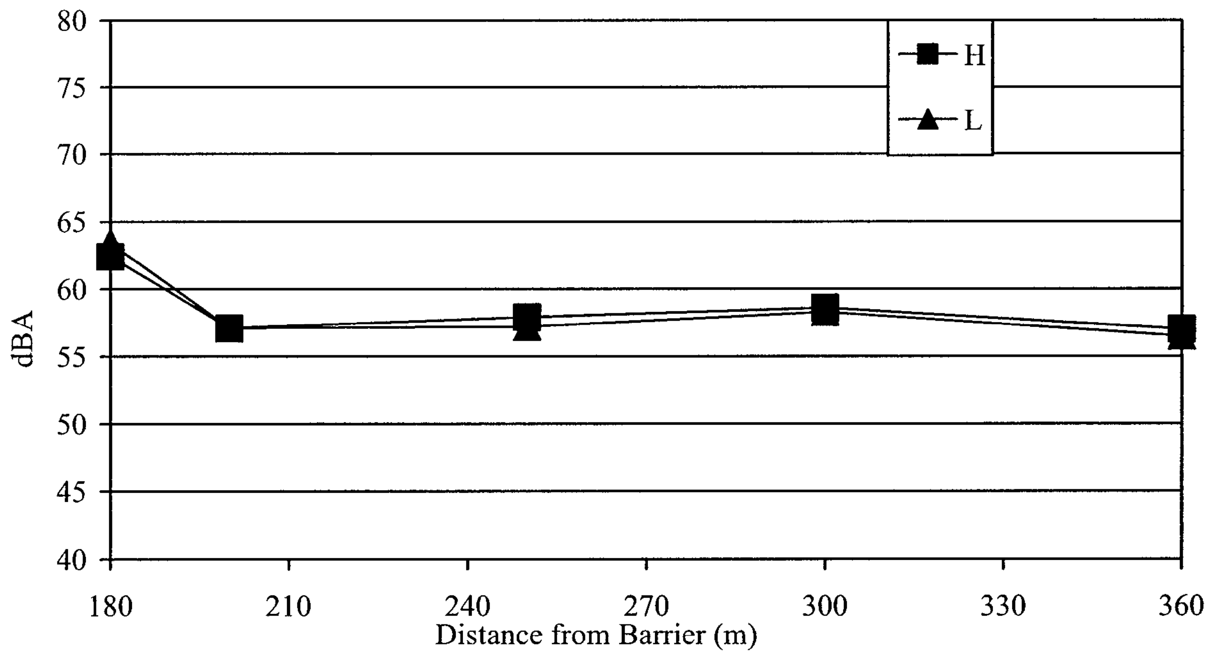


**Figure 3.34** Broad band noise levels for high and low source positions, Site 6, Cinderella

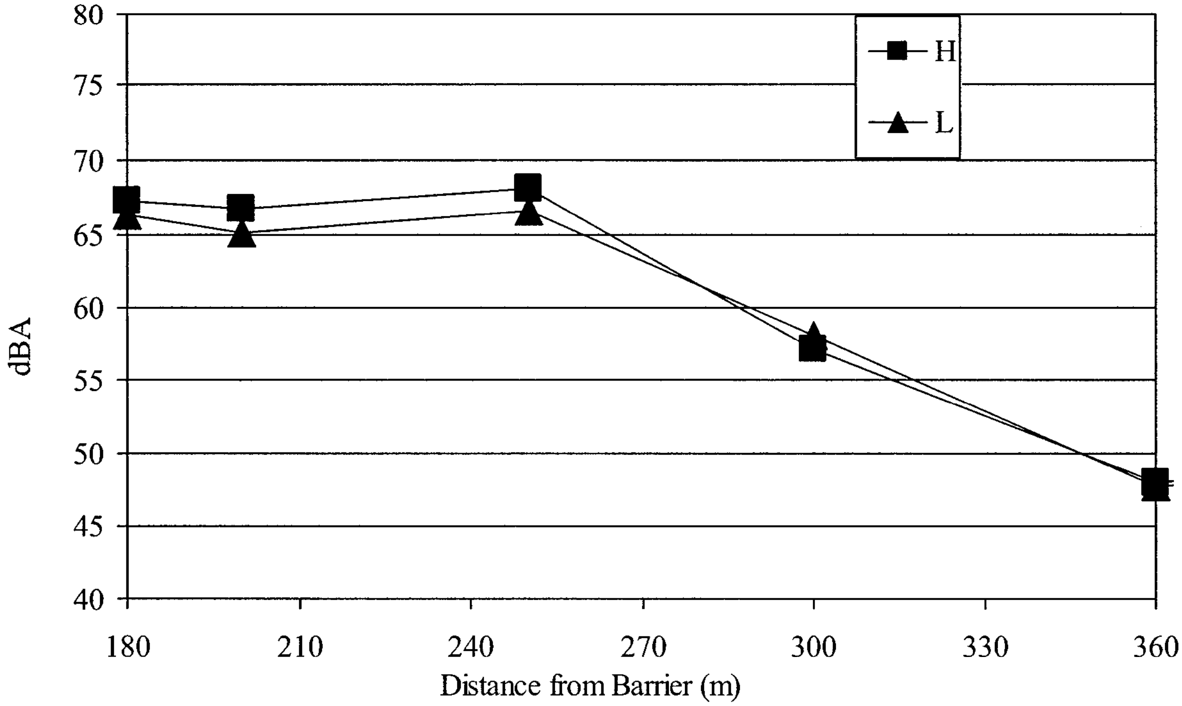


**Figure 3.35** Broad band noise levels for high and low source positions, Site 7, Kenwood Meadows

The measured levels for receiver distances in the range of 180m to 360m were plotted, since not all sites had receivers at the 420 and 480m positions. The graphs depict a large range in the results. Measurements were made at the Cooperwood site first, in which the field procedure was refined. The measurements were repeated at this site hence there are two sets of data. The difference in levels between the high and low source positions for receivers in the range of 200m to 300m was greater for the Cooperwood site then for the other sites. The reason for this difference is not apparent. One possibility is based on seasonal changes in ground attenuation. The measurements were made during the period from summer to late autumn in the order of the site numbers. It may be that ground conditions changed sufficiently to reduce ground attenuation. Measured noise levels were unexpectedly lower for the high position, compared to the low position, for some receivers at sites 5, 6, and 7. The complexities of microphone receiver positions at the sites with respect to the location of houses and hard ground surfaces, such as driveways and streets, most likely caused these reversals. As an added complication, the artificial noise source intensity was not high enough to be much louder than the ambient noise levels at the greater receiver distances for some of the measurement sites. All sites considered, the difference in measured levels between the high and low source positions ranged from –2.8 dB to +13.5 dB with the average being 3.4 dB for all receivers in the 180m to 360m distance range from the barriers. These values are based on measurements of sound propagation from a point source and do not apply directly to the time-averaged levels for vehicle pass-bys. However, they do represent the expected differences, due to ray path height changes, in the peak noise level of a vehicle pass-by.

The significance of these measurements is found in the results as a whole, not in the results for a specific receiver. The results indicate that the construction of the noise barriers can affect ground attenuation in widely varying amounts by changing the path height of sound rays as they travel from the source to the receiver.

## 3.3 COMPUTER MODELING AND ANALYSIS

### 3.3.1 Traffic Noise Model

The FHWA released TNM Version 1.0 in March 1998 to replace STAMINA 2.0/OPTIMA as the computer model approved for traffic noise predictions on federally funded projects in the U.S. Conceptually, TNM begins with an assumed noise level for the traffic noise source, which is based on empirical data and user inputs to the program. This initial level is then systematically reduced to model the following three attenuation mechanisms that affect noise propagation from the source to the receiver:

1. Geometric Spreading: the primary attenuation mechanism, which occurs as the spherical sound wave diameter increases with distance from the source thereby progressively reducing the sound intensity as energy is distributed over increasing area.
2. Atmospheric Absorption: attenuation occurs as sound energy is absorbed by air molecules displaced by the propagating wave.
3. Ground attenuation: occurs when sound waves lose energy as they are propagated over porous ground surfaces, such as vegetated areas. Further, the presence of barriers, whether natural land formations or man-made structures, attenuate noise as it propagates from its source to a given receiver through diffraction.

The complex algorithms used to model these attenuation mechanisms in TNM are based on fundamental acoustical principles and current empirical data.

The traffic noise barrier system for project HAM 71-11.44 was designed using STAMINA 2.0/OPTIMA. However, TNM was selected for the computer modeling portion of this research project, since it has the capability to model multiple reflections between highway noise barriers and predict the insertion loss degradation. While validation studies for the TNM were not complete at the time this report was written, the parallel barrier degradation results are provided to indicate trends and orders of magnitude. TNM was also used to predict the barrier attenuation for distant receivers, because an experimental method to isolate barrier attenuation was not available. Since the accuracy of the model has not been verified, trends and orders of magnitude are also the basis for interpretation of the barrier attenuation results and not the absolute values of sound levels.

### 3.3.2 Computer Modeling Procedure

**Site Selection:** Six parallel barrier sites in the project area were modeled for noise analysis using the FHWA TNM. The six sites, referenced by a street name at the site, are:

- Cooperwood
- Jolain
- Delray
- Glenover
- Baywind
- Castleford

A single barrier site (Cinderella) was also modeled to determine barrier attention and provide additional data for comparison. Both the project size and the need for a detailed site characteristics model required that each site be modeled separately. Attributes for each site were modeled using a digitized reference map of the project. This map was imported into TNM as a reference, in a separate layer from the entities, which were digitized over it. This method produced a precise model, since the background reference map could be registered in the actual project coordinates. The following model components are:

1. **Roadway Modeling:** Once the background map was registered with the project coordinates, the roadways for a particular site were modeled. A sufficient length of highway to be modeled for a given site was selected to allow subsequent modeling of all noise barriers that would affect receivers at that site. Each site was modeled with

six 4m (12 ft) wide roadways, representing the six highway lanes, which has three lanes in each direction. Each roadway was further divided into segments 76 m (250 foot) in length to produce a model that would better approximate the horizontal and vertical alignment of the roadway. The pavement material type was specified as dense-graded asphaltic concrete. Once all the roadways were modeled, typical traffic data including volume, speed, and vehicle classes (autos, medium trucks, and heavy trucks), was assigned to each roadway.

2. **Barrier Modeling:** The horizontal alignment for each traffic noise barrier was digitized from the reference map. Each top and bottom barrier elevation was obtained from the barrier design drawings for the project. Each barrier elevation was noted and entered into the model. The barrier was always digitized in the direction of the roadway adjoining it, as recommended, to avoid errors that can occur during processing by the TNM program. A Noise Reduction Coefficient (NRC) of 0.05 was assumed for all barriers on the project.
3. **Receiver Modeling:** The microphone locations used in the community noise measurements were modeled as receivers. The receiver microphones were located in a straight line perpendicular to the roadway at the following distances from the barrier: 30m, 60m, 120m, 180m, 240m, 300m, and 420m at a height of 1.5m. A reference map, which contained contours in ten-foot intervals, aided in the site topography modeling. Terrain lines were digitized along contours that represented significant ground slope changes. To model the site ground type, a ground type was selected from the TNM ground categories. An average house height of 20ft was assumed for the building shielding model components.
4. **Barrier Attenuation Prediction:** The standard output from TNM includes predicted noise levels with and without the barrier. However, barrier attenuation is not the difference in these two levels since most residential sites contain other attenuation sources such as soft ground and other houses. The predicted levels with and without the barrier will also be influenced by these attenuation sources since, unlike geometric spreading and atmospheric absorption, they are interrelated to barrier attenuation and the difference in levels cannot be attributed to barrier attenuation alone. Therefore, a procedure was needed to isolate barrier attenuation. Two

different input files were produced for this procedure. Both files had the same site and traffic data, and the ground was designated as "hard" to eliminate the ground attenuation effect. Houses were not included in the files to eliminate building shielding attenuation. The first model, designated Run 1, used the input file with no barrier. The second model, designated Run 2, used the input file containing the barrier. Barrier attenuation was obtained by running both models and finding the difference in results (Run 1 – Run 2).

5. **Parallel Barrier Degradation:** TNM contains a separate module to predict insertion loss degradation due to reflections between parallel traffic noise barriers. The analysis is performed in two dimensions. Therefore, the user must select a typical highway cross-section and parallel noise barrier alignments. The analysis assumes a frequency of 500 Hz as an approximation for the full A-weighted sound level. The analysis also includes the effect of ground attenuation by assuming an attenuation value of 1.5 decibels per distance doubling. However, the total ground attenuation amount is compared with the barrier attenuation amount. TNM retains the larger attenuation and ignores the other. The prediction results are critically dependent upon sound-source heights and the source location. Therefore, the each lane's alignment must be carefully modeled. A Noise Reduction Coefficient (the portion of sound wave energy absorbed upon reflection by a noise barrier surface) was specified as 0.05, a value typically used for reflective surfaces.

### 3.3.3 Results

Computer modeling results of the barrier attenuation for receivers at five of the six parallel barrier study sites and the one single barrier site are shown in Table 3.2:

**Table 3.2** Computer Modeling Results of the Barrier Attenuation for Receivers

| Receiver Distance (m) | Jolain | Glenover | Cinderella | Castleford | Baywind | Delray |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | -0.1 | 5.3 | 6.5 | 4.3 | 2.5 | -0.4 |
| 60 | 0.7 | 5 | 5.6 | 3.8 | 2.6 | -0.3 |
| 120 | 1.6 | 4.3 | 3.6 | 3.5 | 3.2 | 1.8 |
| 180 | 2.2 | 3.3 | 3.1 | 3.2 | 3 | 2.2 |
| 240 | 2.5 | 2.6 | 2.7 | 3.5 | 3 | 2.2 |
| 300 | 2.7 | 2 | 2.4 | 3.6 | 5.1 | 2.3 |
| 420 | 1.9 | 2.4 | 2 | 3.6 | 4.7 | 2.2 |

The barrier attenuations generally decrease with distance from the barrier for each site. However, exceptions occur due to terrain elevation changes and the horizontal receiver locations with respect to the changing top elevations of the barriers. The mean barrier attenuation for receivers modeled in the range of 180m to 420m from the near barrier was predicted to be in the 2-4 dB range. This result is consistent with barrier attenuation theory and the concept of path length difference. The path length difference becomes progressively smaller as receiver distance from the barrier increases. Therefore, distant receivers experience less barrier attenuation than those receivers closer to the barrier.

Computer modeling of the predicted parallel barrier insertion loss degradation for receivers at each of the six parallel barrier study sites are shown in Table 3.3:

**Table 3.3** Computer Modeling of the Predicted Parallel Barrier Insertion Loss Degradation

| Receiver Distance (m) | Cooperwood | Jolain | Glenover | Castleford | Baywind | Delray |
|---|---|---|---|---|---|---|
| 0 | 1.5 | 1.9 | 0.5 | 0.3 | | 0.8 |
| 30 | 2.6 | 2.6 | 0.6 | 2.6 | 2.6 | 1.1 |
| 60 | 3.1 | 3.2 | 0.9 | 3.6 | 3.1 | 1.5 |
| 120 | 2.3 | 3.6 | 1 | 3.7 | 3.3 | 1.3 |
| 180 | 1.1 | 3.4 | 0.8 | 3.5 | 3.1 | 1.2 |
| 240 | 0 | 3.1 | 0.6 | 3.3 | 2.7 | 0.9 |
| 300 | 0 | 2.5 | 0.3 | 2.9 | 2.2 | 0.5 |
| 420 | 0 | 1.7 | 0 | 2 | 1 | 0 |

Note that no prediction was made for the Baywind site reference receiver (at 0.0m from the barrier) since the field terrain conditions precluded obtaining complete information for this receiver. The predicted parallel barrier insertion loss degradation results are also depicted graphically in Figure 3.36.

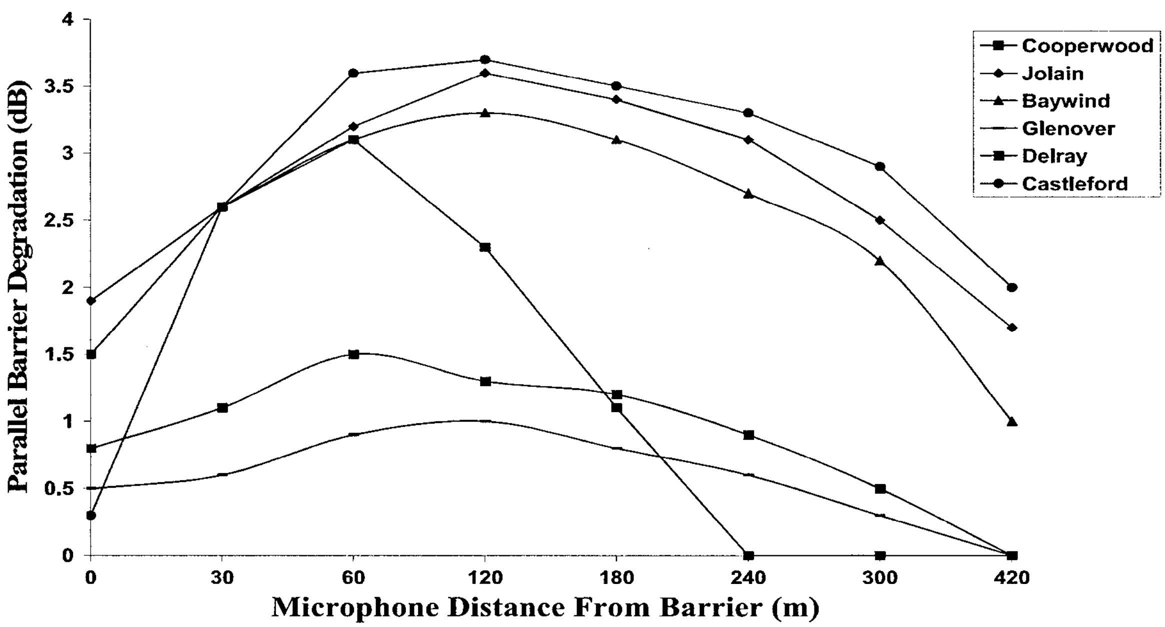


**Figure 3.36** Predicted Parallel Barrier Insertion Loss Degradation Results

The predicted insertion loss degradation results tended to have the largest magnitudes for receivers in the 60m to 180m range, with peak values ranging from 1 to over 3.5 dB. The reduced magnitudes for receivers beyond 120m seems to contradict the trends expected for reflections between barriers as discussed in Section 3.1.1.3 under *Results* and subheading System tests and verification. However, the TNM prediction results for insertion loss degradation include ground attenuation as stated above in the Parallel Barrier Degradation procedure. Therefore, the effects of reflections between parallel barriers could not be completely isolated as a single component. Never-the-less, the computer modeling results indicates multiple reflections can substantially influence sound levels for receivers in the project area.

## 3.4 COMMUNITY NOISE LEVELS AND ATMOSPHERIC EFFECTS

### 3.4.1 Introduction

Noise measurements were obtained for distant receivers affected by the traffic noise barriers in the communities adjacent to I-71. These measurements were entered into a database that will evaluate any future modifications to existing noise barriers to correct problem areas (objective 5). These evaluations will be based on comparisons of the database measurements with measurements collected after the existing noise barriers are modified. Therefore, it is imperative that terrain, source, and atmospheric equivalence be established to make valid comparisons. Changing atmospheric conditions is exacerbated for receivers located at greater distances from the roadway. Therefore, extensive atmospheric monitoring instrumentation was employed in conjunction with acoustical instrumentation to obtain meaningful data. Atmospheric monitoring instrumentation also provided the means to investigate the effect of atmospheric variations on received noise levels. Atmospheric variations were identified in the preliminary assessment as additional mechanisms that could influence the residents' perception of increased noise levels, and were recommended for additional study.

Noise propagating outdoors through the atmosphere generally decreases in level with increasing distance between the source and receiver. This attenuation involves several mechanisms, primarily geometrical spreading, atmospheric absorption, ground attenuation, attenuations due to topography (including barriers), refraction, and atmospheric turbulence. Atmospheric absorption, refraction, and atmospheric turbulence are considered atmospheric effects.

Atmospheric conditions become a significant factor that affects receiver noise levels at distances greater than 100 meters [Piercy and Daigle 1991]. Atmospheric absorption is well studied and a standard calculation method to determine the rate of atmospheric absorption was developed by the International Organization for Standard (ISO) and the American National Standard Institute (ANSI). However, current understanding of the more complex refraction and turbulence effects is less advanced and more studies to measure attenuation under various conditions and develop prediction models are needed.

Meteorological conditions such as wind and temperature and their fluctuations are the main causes of atmospheric refraction and turbulence. Vertical gradients of wind and temperature cause sound wave refraction. This bending of sound waves can be associated with increased or decreased sound levels. Also, turbulence causes sound wave scattering. That is, the distribution of acoustical energy in many different directions influences noise levels.

The atmospheric effects investigation focused on the influence of typical summertime atmospheric conditions on noise propagation. Although normal summer weather provides a relatively small variation in weather conditions compared to the wide weather variations encountered annually, residents are most likely to be outside their houses during the summer. Consequentially, residents are most likely to be impacted and annoyed by traffic noise in the summer.

Data were collected from July 15 to September 1, 1999, for seven sites with parallel barrier configurations and one site (Cinderella) with a single barrier configuration. The sites were named for prominent streets located in the vicinity of receiver microphones, as shown in Table 3.4.

**Table 3.4** Measurement Sites

| Date Measured | Main Street of Community | Site # | Side of I-71 | Average Temp. (°C) | Average RH (%) | Note |
|---|---|---|---|---|---|---|
| 7/15/99 | Cooperwood | 1 | East | 30 | 71 | |
| 7/21/99 | Glennover | 2 | East | 32 | 75 | Test #1 |
| 7/22/99 | Cinderella | 3 | East | 34 | 75 | |
| 7/27/99 | Castleford | 4 | West | 27 | 68 | |
| 8/04/99 | Jolain | 5 | East | 32 | 71 | |
| 8/17/99 | Baywind | 6 | East | 34 | 73 | |
| 8/18/99 | Delray | 7 | West | 30 | 70 | |
| 8/26/99 | Glennover | 2 | East | 23 | 64 | Test #2 |
| 9/01/99 | Bayberry | 8 | West | 28 | 69 | |

Figure 3.37 illustrates a plan view of the barriers and site locations adjacent to I-71, as listed in Table 3.4. As indicated in Table 3.4, experiments at Site 2 (Glennover) were performed twice. The noise receivers and weather stations for the second measurement (test #2) were situated in the same positions as the first measurements (test #1). This ensured an accurate comparison of the results with differing weather conditions.

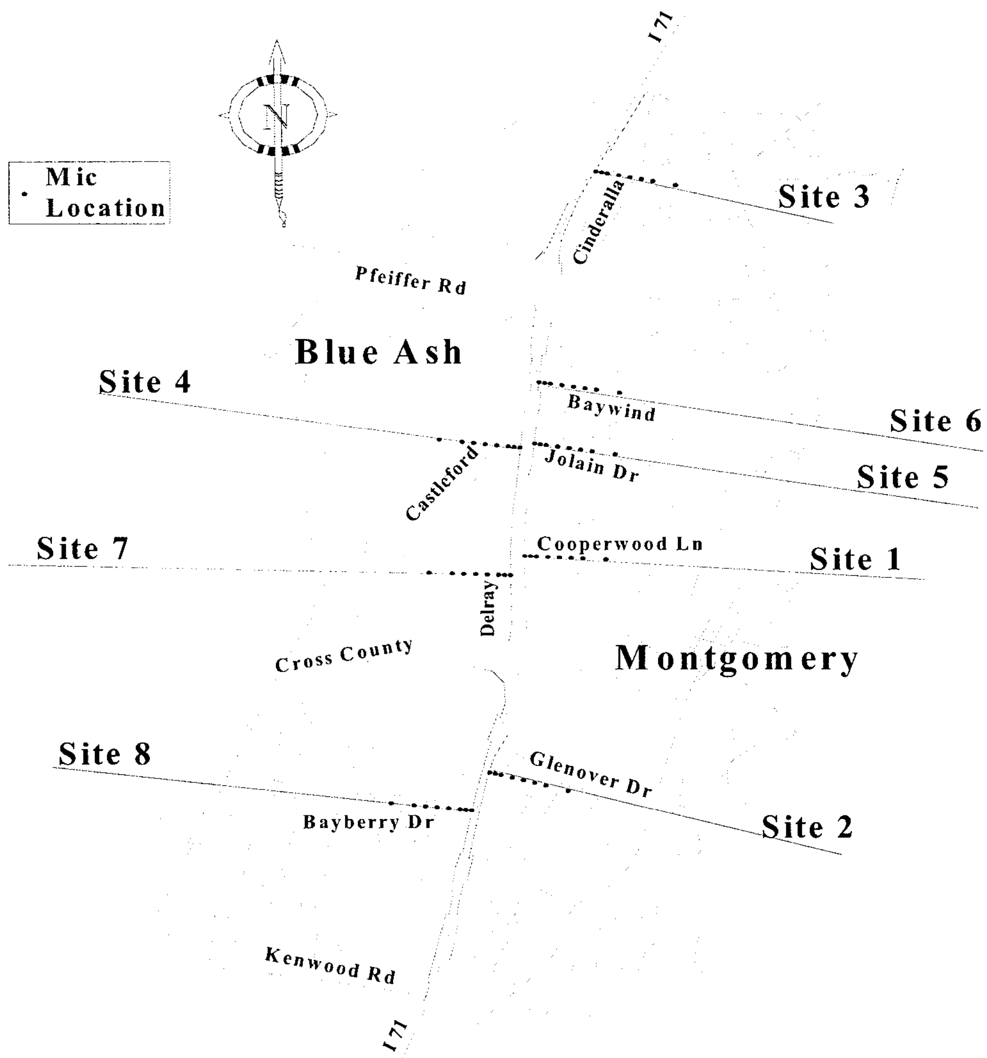


**Figure 3.37** A map of field measurement sites

### 3.4.2 Field Data collection Procedures

The following section describes the noise and meteorological data collection procedures. For the noise data recordings, all instruments were calibrated prior to placement at the site and careful calibrations were recorded on each tape to ensure data integrity and provide a base for later processing. The specific instruments and equipment used in the procedures are listed in Appendix B.

Acoustical Instrument Setup Procedure

At each site, the I-71 traffic was used as the noise source and eight microphones covering a total distance of 420 meters were perpendicular to the highway. The microphone spacings used throughout the experiments were 0, 30, 60, 120, 180, 240, 300, and 420 meters relative to the noise barrier, as shown in Figure 3.38. These microphone spacings placed the first four receivers at distances which repeatedly doubled, since noise drop-off rates are constant rates per doubling of distance.

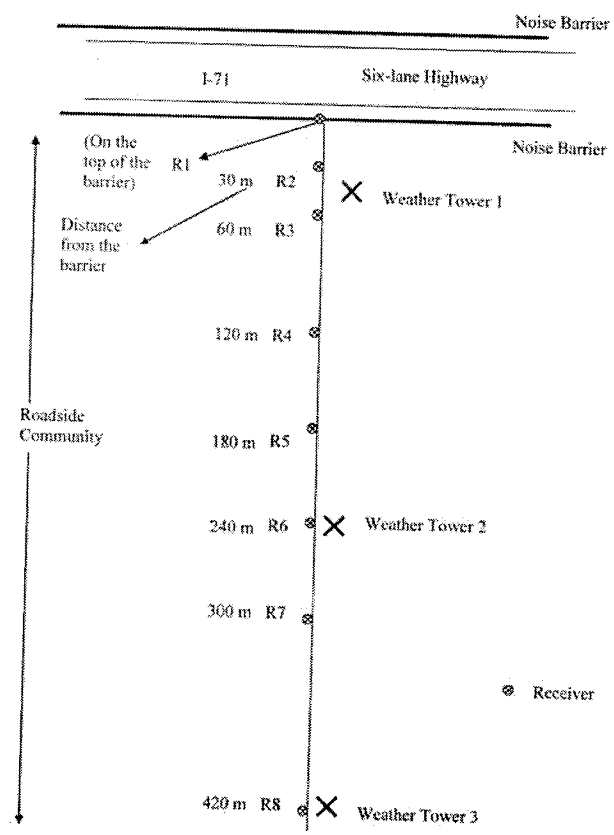


**Figure 3.38** Microphone spacing used throughout the experiment

The last four receivers were located approximately 180 to 540 m from the noise barriers since the preliminary assessment concluded the most pervasive complaints of perceived noise level increases were reported by residents living in this range from I-71 [Herman et al. 1997]. Highway noise at receivers beyond this range was often undetectable, since ambient noise frequently masked the I-71 noise source.

Reference Microphone

The reference microphone, Microphone 1, was positioned 1.5m above the top of the barrier, on a steel pole. The reference microphone was exposed directly to the source to indicate the relative noise level of the source for a given measurement interval. The microphone and preamplifier were placed in a nylon holder and then mounted on the end of the pole. The preamplifier was connected to a sound level meter (SLM) close to the ground which allowed noise recordings to be controlled from the ground.

Study Microphones

The study microphones (receivers 2 to 8) used to collect the acoustical data was shielded from direct source exposure by the noise barrier. Each microphone and measurement system was mounted on a tripod and positioned 1.5m (+/- 0.1m) above the ground. Each microphone location was inspected for possible ambient noise disturbances and any natural or structural elements that could cause interference to ensure suitability for noise measurements. Microphones were carefully situated at suitable distances from buildings and other reflective surfaces in accordance with ANSI S12.8 "Methods for Determination of Insertion Loss of Outdoor Noise Barriers." Also, measurements were not performed in locations that had dense vegetation.

Meteorological Equipment Setup Procedure

Weather towers were positioned near the beginning, middle, and end of the microphone line. At most of the sites, weather tower 1 was placed between receivers 2 and 3 since the topography between the barrier and receiver 2 (usually sloped) made tower placement difficult. Weather tower 2 was positioned near receiver 6, which was 240 m from the barrier. Weather tower 3 was placed close to the last receiver, located 420 m from the barrier.

Wind-speed measurements were recorded at the standard meteorological a height of 10 m. This height approximates the upper limit of the viscous boundary layer, the region where most wind variation occurs.

Towers 1 and 3 had identical configurations. Two polar wind monitors were installed at heights of 10 m and 1.5 m. Tower 2, which was positioned near the middle of the microphone line, contained additional weather equipment. Two UVW anemometers were installed at heights of 10 m and 1.5 m. Temperature sensors were mounted on tower 2 at 10 m, 1.5 m, and 0.1 m. In addition, a relative humidity sensor was mounted on the tripod near tower 2 at a height of 1 m. Figure 3.39 illustrates the view of the meteorological instruments used in each field measurement.

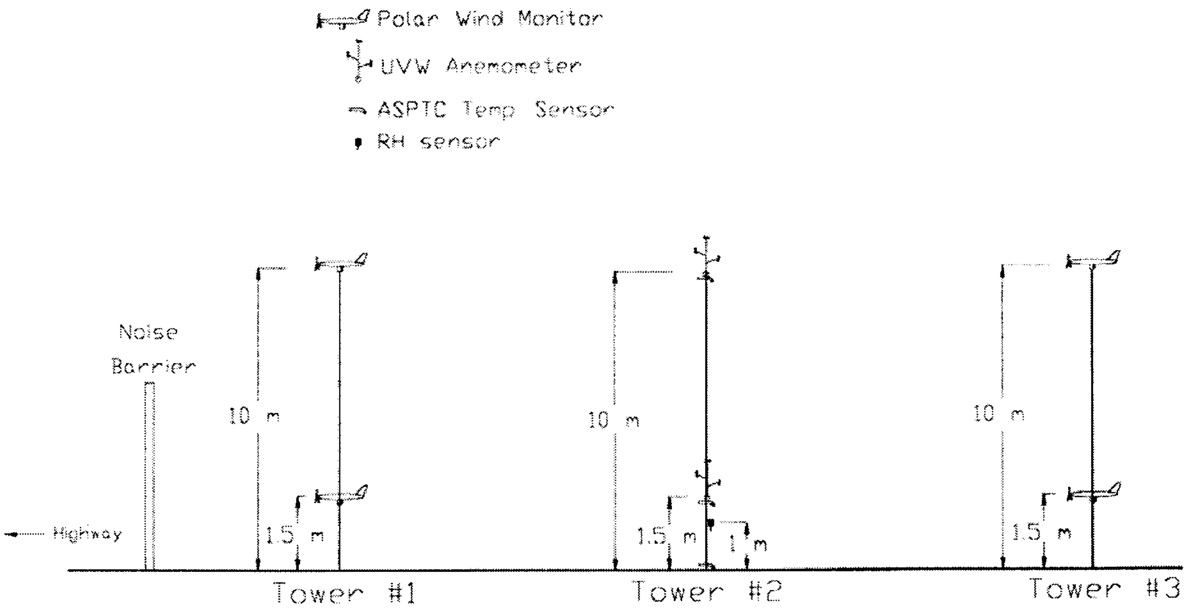


**Figure 3.39** – Location of meteorological instruments

<u>Traffic Data Collection Procedure</u>

The traffic noise source was characterized to establish source equivalence for noise level comparison measurements collected before and after noise barrier system modifications. Traffic noise levels are affected by the vehicle type, number and speed on the roadway at any particular time. Two video cameras (one for northbound and one for southbound lanes) recorded the traffic operations during the acoustical and meteorological measurements. The video tapes provided raw data for subsequent laboratory analysis.

### 3.4.3 Data Reduction

Raw data for each site included recorded DAT tapes, weather data in the dataloggers, and traffic video tapes. DAT tapes were analyzed using a real time analyzer (RTA), weather data was downloaded to a computer for further analysis, and the traffic video tapes were analyzed using a machine vision processor.

Acoustical Data Reduction

Only data categorized as "good" minutes on the field data logging sheet from each site were played back and analyzed using a Larson Davis real-time analyzer Model 2900b. The selected noise analyzer output was in one-third octave bands from 50 to 10,000 Hz. An equivalent continuous level (LEQ) spectrum type was used. The data was analyzed in the single channel standard analysis mode, and a short filter was used.

While analyzing a tape, a real time analyzer displayed the noise data in a spectrum that showed noise sound pressure levels at different frequencies. Figure 3.40 illustrates a noise analysis result from RTA 2900B. Each result includes the corresponding A-weighted sound pressure level. The A-weighted noise level for the example in Figure 3.40 is 64.7 dB, which represents the noise level recorded for that minute.

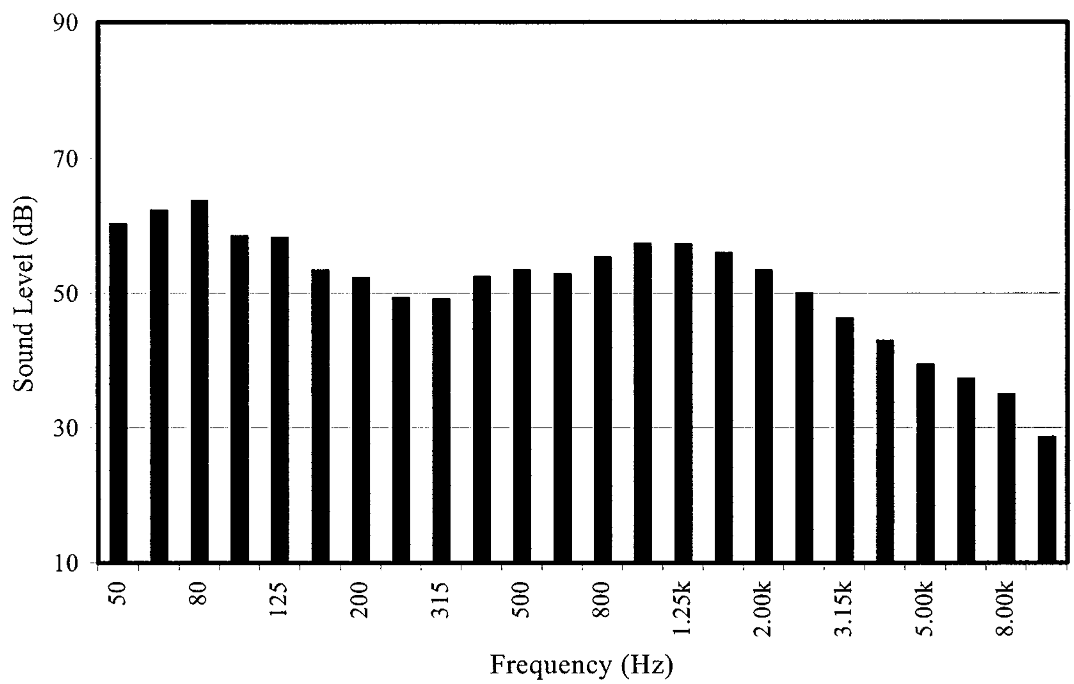


**Figure 3.40** Noise analysis output example (at Site 1, Test 1, microphone 2, 2:46 pm).

Meteorological Data Reduction

Four dataloggers were programmed to record data for every test minute interval, except for the CR10X 2b (see Table 3.2). The wind data parameters collected by the CR10X 1 datalogger included wind speed (m/s), wind direction (o), and standard deviation of direction at both high and low wind meters. CR10X 2a collected relative humidity (%) and three temperatures (C°) at heights of 0.1 m, 1.5 m, 10 m in tower 2.

CR10X 2b collected data similar to the data collected by CR10X 1. Since the data was recorded by a UVW anemometer, additional vertical wind speed data was included. The CR10X 2b was programmed to automatically incorporate U and V components into one horizontal wind speed and the corresponding direction. Thus, the only difference in the data between CR10X 1 and CR10X 2b is vertical wind speed. The CR10X 3 in tower 3 utilized the same datalogger program as the CR10X 1 in tower 1.

After the field weather data collection was completed, data stored in the dataloggers was transferred to a computer and processed into numerical data by executing Campbell Scientific software (PC208W). The numeric data was displayed in an Excel format.

Traffic Data Reduction

The video images of traffic operations were processed with a vision analyzer linked to a computer. Vehicle counting, classification, and speed detectors were calibrated to obtain vehicle volumes and speeds by vehicle classification for each highway lane in one-minute intervals. The system is less precise for vehicle classifications that it is for volumes and speeds. Therefore, the video tapes were reviewed and adjustments to correct classification errors were made manually. The FHWA classifications of automobiles, medium trucks, and heavy trucks for noise analysis were used.

### 3.4.4 Data Analysis

This section describes the methods employed to determine atmospheric absorption for broad band and A-weighted noise data for each measurement day. The methodology utilized to determine the air absorption was based on a standard developed by the International Organization for Standardization [International Organization for Standardization 1990]. In addition, correlation analyses were performed on the noise data from each site to investigate if traffic source variation was the major effect for the noise level fluctuations recorded by the study microphones. Finally, a series of multiple variable regression models correlated weather variables and noise attenuation values, as determined with the measured data.

Determination of Atmospheric Absorption

The ISO method yields atmospheric absorption for a specific frequency band at a given temperature and humidity level. However, the noise levels used in the model developed for this study were broad band levels, which included all frequencies from 50 Hz to 10,000 Hz. Therefore, a single atmospheric absorption value that represented this range of frequencies was needed.

The ISO standard method calculated the absorption for each measurement day from the average RH and temperature over the two hour data collection. The ISO standard method results in an atmospheric absorption coefficient (dB/km) for a given frequency. An extensive interpolation procedure determined an equivalent absorption coefficient for the broad frequency range for this project.

Noise Data Correlation Analysis

Acoustic theory indicates noise propagating outdoors is mainly affected by four mechanisms: geometric spreading, atmospheric absorption, the ground effect, and barrier attenuation. Assuming that atmospheric conditions are homogeneous, noise source attenuation by these four mechanisms is primarily a function of distance. Thus, attenuation should be constant if distance remains unchanged. Noise levels recorded by distant receivers should correlate with noise levels recorded near the source, in this case at the reference microphone. Accordingly, a noise level change of 1 dB at the reference microphone should also be experienced by the distant receivers. Deviations from this expected correlation can indicate the influence of changing atmospheric conditions.

Multiple Regression Analysis

Several multiple linear regression analyses were performed using the least squares method. Each regression model contained one dependent variable and potentially important independent variables. These regression analyses were done using a commercial software statistical testing package, "SPSS" [SPSS Inc. 1999].

Potential Independent Variables

The possible experimental weather variables can be divided into three categories: wind, temperature, and turbulence.

Wind variables - shown in the following table:

**Table 3.5** Wind variable information

| Wind Parameter Category | Unit | Variable Name | | | Description |
|---|---|---|---|---|---|
| | | Tower 1 | Tower 2 | Tower 3 | |
| Cross Wind Speed at 10 m | m/s | H1 | H2 | H3 | |
| Cross Wind Speed at 1.5 m | m/s | L1 | L2 | L3 | |
| Average Cross Wind at a Tower | m/s | Avg 1 | Avg 2 | Avg 3 | =(Hi+Li)/2 |
| Wind Shear at a Tower | m/s | Shear 1 | Shear 2 | Shear 3 | =Hi - Li |
| Vertical Wind Speed at 10 m | m/s | | Vert H | | |
| Vertical Wind Speed at 1.5 m | m/s | | Vert L | | |

The positive Hi, Li, and Avg values indicate a downwind condition for traffic noise propagation. Positive wind shear values occur when the H wind speed is greater than the L wind speed indicating the receiver is downwind from the source. This condition produces a refracting atmosphere in which sound rays are bent downward.

Temperature - lapse rate was the only independent temperature variable used. The lapse rate at tower 2 was calculated as:

Lapse= (Temperature at 1.5 m –Temperature at 10 m) / 8.5 m

A positive lapse rate, signified by a decrease in temperature with height, indicates a normal daytime lapse rate during the summer.

Turbulence - turbulence parameters consisted of the standard deviation for each wind vector (U, V, W) at tower 2, as shown in Table 3.6.

**Table 3.6** Turbulence variable information

| Direction of Wind Speed Component | Name of variable | | Description |
|---|---|---|---|
| | At 10 m height | At 1.5 m height | |
| U | HUSTD | LUSTD | Parallel to Highway |
| V | HVSTD | LVSTD | Perpendicular to Highway |
| W | HWSTD | LWSTD | Vertical |

### 3.4.5 Results

For this portion of the study a database of community measurement was developed and the effects of summertime atmospheric variations on highway noise diffracted by a noise barrier were investigated. The atmospheric data was analyzed with regression techniques to define the relative magnitude or importance of each atmospheric variable affecting noise attenuation. The results show that cross wind speed, wind shear, lapse rate, and turbulence all influence the attenuation between an unshielded reference microphone and study microphones located in the surrounding community.

In the field, each of these variables fluctuated almost continuously. The effect of these fluctuations on noise attenuation depended on the combination of individual variables at any one time. For example, under clam wind conditions, low turbulence, and high lapse rates, received noise levels might be reduced by 2dB at 200m from the noise barriers to as much as 3.5dB at 420 m, compared to conditions with normal lapse rates. However, in down wind conditions, low turbulence, and high lapse rates, received noise levels might be unchanged at 200m from the noise barriers but increased by 2dB at 420m compared to conditions with normal lapse rates. During conditions of low lapse rates and high turbulence for the downwind receivers, noise levels might be increased from 6dB at 200m to 13 dB at 420m, compared to low turbulence conditions.

The dominant common factor in all cases of noise changes with different receiver distances and weather changes is the influences of wind condition, turbulence and temperature lapse increase in magnitude with increasing distance from the highway.

# 4.0 DISCUSSION OF RESULTS

The goal of this research project was to determine the effects of parallel noise barriers as a contributing factor to the perception of increased noise levels by residents located 180m to 540m from I-71. This research project's objectives were to test the validity of the hypothesis given in the preliminary assessment project report (and summarized in the introduction to this report) using acoustical measurements and computer modeling. The entire propagation path from source to receiver was evaluated. The attenuation mechanisms that affect this path are geometric divergence, atmospheric absorption, barrier attenuation, building shielding, ground attenuation, reflections, and atmospheric effects. Since the perception of increased noise levels occurred after construction of the traffic noise barriers, not all mechanisms were investigated. Geometric divergence and atmospheric absorption are distance related and their effect is the same with or without barriers. Buildings were present before noise barrier construction. Therefore, any attenuation due to their presence was the same. However, the investigation of barrier attenuation, and ground attenuation was necessary. The effect of reflections as a cause of perceived noise level increases was also considered, since parallel barriers were being studied. While atmospheric effects would be present without barriers (though they may be altered in the presence of barriers); these effects were studied to determine their significance for measurements at distant receiver locations.

Devising field and modeling experiments to support or undermined this project's hypothesis was a challenge. Since sound level measurements were not collected prior to barrier construction, a comparison of measurement collected after barrier construction could not be made. Even if direct sound level measurements were made, the results would not have indicated the specific reasons for the change in levels. For example, suppose that a typical traffic noise source measured at the standard reference distance near the roadway resulted in a source level of 80 dB. Further, suppose that the noise level at a receiver some distance into the community and shielded by a noise barrier was found to be 53 dB. The difference between the two measured sound levels would lead to the conclusion that after all attenuation mechanisms influenced the noise propagation from the source to the receiver, their combined effect is an attenuation of 27 dB. While the total attenuation may be known, the effect of individual attenuation mechanisms cannot be calculated. The field and modeling experiments described in the previous sections were designed to identify the magnitudes of these individual attenuation mechanisms.

Field measurements could not isolate noise barrier attenuation from other attenuation factors. However, noise barrier attenuation was predicted using computer modeling for five parallel barrier sites and one single barrier site. At each barrier site, barrier attenuations generally decreased with distance from the barrier. This result was anticipated since noise barriers are most effective for receivers located near the barriers. Distant receivers neither receive nor require substantial amounts of barrier attenuation. The mean barrier attenuation for receivers modeled 180m to 420m from the near barrier was predicted to be in the 2-4 dB range. The predicted barrier attenuations were the values that would result if only barriers were present. However, most of the receivers experienced some shielding from other houses in the community, which would have been present prior to noise barrier construction. Receivers 180m to 540m from the noise barriers experience more attenuation from building shielding than receivers located closer to the noise barriers since more houses are located between these receivers and the highway noise source. The specific amount of attenuation would be highly variable, depending on the orientation and placement of houses and receivers with respect to the highway noise source. Estimates of building shielding attenuations would typically be 1- 3 dB. However, attenuations from barriers and building shielding are not additive. While construction of a noise barrier between the highway and community contributes attenuation beyond the building shielding attenuation present prior to barrier construction, the additional barrier attenuation would be less than the amount realized if no buildings existed. Therefore, the predicted barrier attenuations are somewhat over estimated.

Ground attenuation could not be measured directly, but the effect of changing the propagation path height with the construction of the barriers was studied. The difference in received levels for a constant level point source positioned at elevations approximating ray path heights before and after barrier construction was approximately –3 dB to +14 dB with the average being between 3 and 4 dB for all receivers 180m to 360m from the barriers. The large variations were attributed to differences in site characteristics. However, the results indicate that substantial amounts of ground attenuation were forfeited for some receivers due to noise barrier construction. The precise amount of ground attenuation forfeited could change with relatively small changes in receiver location and with ground conditions, which vary throughout the year.

The consideration of ground attenuation in this study was based solely on the difference in ray path heights. Typical barrier heights for the test sites were 5.2-5.8m (17-19 ft) which is higher than the barriers found on many noise abatement projects. Furthermore, lower barrier heights result in less difference in ray path heights and therefore, less ground attenuation is forfeited due to the barrier construction.

A reflection test system devised and developed as a part of this project investigated the location and relative intensity of reflections between parallel noise barriers. Multiple reflections existed for all parallel barrier sections tested and resulted for ray paths reflected from more than one barrier surface. A ray may be reflected a number of times between parallel noise barriers before being propagated over the top of a barrier. Only the first reflection, the most significant one, was included in the calculations to quantify the reflection contribution to the noise level at a receiver. Therefore, the reflection contributions, as presented in the results, are somewhat under-estimated.

The presence of reflections caused higher sound levels for receivers. The increase in level, or the reflection contribution varied greatly depending on the test site and receiver locations. While a number of locations, particularly those closest to the noise barriers, received contributions well below 1 dB, others received contributions approaching the theoretical maximum of 3 dB. In one particular case the contribution exceeded 5 dB, due to the unusual noise barrier geometry at that test site. Note the specific levels measured with test system, which used a point source, represent values where the source to receiver line is perpendicular to the noise barriers. The values would be different for the non-perpendicular case and for the time-averaged level contributions of a vehicle pass-by. The contribution of reflected rays to direct rays increased with receiver distance from the highway. This trend, which was prominent throughout the results, is significant for distant receivers. The effect of noise level increases due to reflections between parallel noise barriers is greater for distant receivers than for those located closer to the noise barriers.

The preliminary assessment study found that the most pervasive complaint, the perception of increased traffic noise levels due to noise barrier construction, was cited most often by residents living 180m to 540m from I-71. The receivers located 120m from the noise barriers approached or exceeded the limits of the reflection test system. The contribution of reflected rays to distant rays should continue for more distant receivers, but these contributions could not be quantified for receivers 180m to 540m from the barriers with the test system.

The STAMINA 2.0 computer model, which was used to design the noise barriers for this project, did not have the capability to model noise reflections between parallel barriers. The Federal Highway Administration's Traffic Noise Model (TNM) contains a parallel barrier module to predict the effect of reflections. The model predicts the decrease in parallel barrier performance when compared to a single barrier configuration. This decrease, or parallel barrier degradation, describes the predicted noise level increases for a receiver due to reflections between the parallel barriers.

TNM modeled multiple reflections between parallel barriers for receivers located at five sites. The model reports the parallel barrier degradation as time-averaged noise levels for the vehicle pass-bys comprising the traffic flow. The peak predicted parallel barrier degradation, which ranged from 1 dB to 3.5 dB, occurred for receivers between 60m and 180m from the noise barriers. The range of receiver distances modeled did not match the range of receiver distances in the reflection tests. Never-the-less, the computer modeling results indicate that multiple reflections definitely influence sound levels for receivers in the project area, and the results support the findings from the reflection field measurements conducted for the study.

This study strongly indicates that noise levels increased 180m to 540m from the centerline of I-71 following the barrier construction in the project area. To summarize, many distant receivers realized little barrier attenuation following noise barrier construction. The amount of barrier attenuation realized was in many cases more than offset by the loss in ground attenuation from the change in noise path height imposed by the noise barriers. Further, the construction of parallel noise barriers affected the receivers by increasing noise levels due to reflections.

The interaction of attenuation mechanisms was not uniform. Data analysis suggests that specific areas, which may be proximate, could experience noticeably different noise levels. The surrounding landscape and site features introduce variables which alter the attenuation mechanisms and affect the sound propagation path. Further, even minor atmospheric variations can cause noticeable noise level changes for distant receivers.

Most of the variables affecting sound propagation from the source to the receiver cannot be controlled. However, the results confirm that reflections between parallel barriers can be effectively controlled by designing barriers with sound absorbing surfaces. Reflection tests on state Route 8 in Summit County evaluated the performance of sound absorbing barriers and indicated the sound absorbing materials substantially reduced or eliminated the contribution of both first and second order reflections. Reduction was also greater for receivers at increased distances from the highway. Parallel noise barrier configurations have been categorized in three ranges of width-to-height ratios: less than 10:1, 10:1 to 20:1, and greater than 20:1 [Fleming and Rickley, 1992]. The parallel noise barriers constructed on this project had width-to-height ratios in the less than 10:1, and the 10:1 to 20:1 ranges. The use of sound absorbing walls is specifically recommended for parallel barrier configurations with these ratios. Reflection tests of parallel barriers with width-to-height ratios in the upper range are recommended.

These findings are based on broad band test signals, which cover most of the audible frequency range. A test system capable of determining the effectiveness of absorbing materials in specific frequency bands would yield results useful to compare alternative sound absorbing materials.

While variations in ground attenuation cannot be controlled, the sound path height can be controlled. The primary goal in abatement design is to provide acceptable noise levels for residents living close to the highway. Strategies that both meet this goal and address the loss of ground attenuation for distant receivers should be considered. Using TNM for noise barrier design will result in lower barrier heights compared to designs based on STAMINA 2.0 noise level predictions. The FHWA mandated use of TNM will therefore result in lower noise path heights as a result of lower barrier height. When space within the right-of-way is not an issue, earth berms should also be considered. In some cases, earth berm and wall combinations might be utilized.

Controlling traffic noise at its source is a comprehensive strategy. Lower traffic noise levels at the source will result in fewer and lower noise barriers. Lower noise barriers will result not only in more ground attenuation, but also in less surface area for reflections between noise barriers. In addition, all receivers, both near and distant, will benefit. Each 1 dB reduction in source levels results in a corresponding 1 dB reduction in received levels, in contrast to noise reduction by barriers where distant receivers experience a smaller reduction than near receivers. While transportation agencies cannot control the vehicle component of traffic noise, they can control the pavement component. Pavement types that result in lower levels of tire/road noise should also be considered. ODOT has previously sponsored research to rank Ohio's pavement types according to their noise producing characteristics [Herman and Ambroziak 1999].

# 5.0 CONCLUSIONS AND RECOMMENDATIONS

The goal of this study was to determine the effects of parallel noise barriers as a contributing factor to the perception of increased noise levels by residents located 180m to 540m from I-71. The results of the investigation support the hypothesis that many of these distant receivers realized little barrier attenuation following noise barrier construction. Further, the amount of barrier attenuation realized was in many cases more than offset by the loss in ground attenuation due to the change in noise path height imposed by the presence of the noise barriers. Finally, reflections between parallel noise barriers increased noise levels above the levels expected for single barriers.

## 5.1 FINDINGS

The findings of this study are detailed below:

1. An in-situ test system using a point source was devised and developed to identify the existence, location, and relative intensity of reflections between parallel noise barriers. Multiple reflections from barrier walls existed at each receiver location for all parallel barrier sites tested. The reflections increased noise levels for receivers from below 1 dB for receivers closest to the noise barriers, to increases approaching the theoretical maximum of 3 dB for receivers farther from the noise barriers. In one particular case the contribution was over 5 dB, due to the unusual geometry of the noise barriers at that test site.
2. Reflection contributions to receiver sound levels increased with greater receiver distance from the highway up to 120 m from the noise barrier.
3. A mean barrier attenuation of 2-4 dB was predicted for modeled receivers 180m to 420m from the near barrier.
4. The propagation path height change with the barrier construction increased received levels from a test signal point source by an average of 3 to 4 dB, but as much as 14 dB for receivers 180m to 360m from the barriers. The increase in received levels was attributed to a reduction in ground attenuation caused by the increased ray path height following barrier construction. The noise barrier heights for this project, however, were higher than for typical projects. Therefore the change in propagation path height would not be as great for typical projects.

5. The peak predicted parallel barrier degradation, which ranged from 1 dB to 3.5 dB, occurred for receivers located between 60m and 180m from the noise barriers. The computer modeling results indicate that multiple reflections definitely influence sound levels for receivers in the project area.
6. The sound-absorbing panels used to retrofit the West noise barrier on the Summit 8 project substantially reduced the contribution of 1st order reflections for east side receivers, but did not affect 1st order reflections for west side receivers.
7. The sound-absorbing panels substantially reduced or eliminated 2nd order reflections for both east and west receivers.
8. The reduction in reflection contributions due to the sound-absorbing panels was greater for receivers at increased distances from the highway.
9. The interaction of the attenuation mechanisms, which was responsible for the noise level increases, was not uniform. Data analysis suggests that specific areas, which may be proximate, could experience noticeably different noise levels. The surrounding landscape and site features introduce variables which alter the attenuation mechanisms and affect the sound propagation path.
10. A database of community sound level measurements and coincident atmospheric conditions was developed for the I-71 project area. The influences of wind condition, turbulence, and temperature lapse increased in magnitude with increasing distance from the highway, even under relatively mild weather conditions.

## 5.2 RECOMMENDATIONS

The following strategies and noise abatement design approaches are recommended based on the results of this study:

1. The parallel noise barriers constructed on this project had width-to-height ratios in the less than 10:1, and the 10:1 to 20:1 ranges. Therefore, the use of sound absorbing walls is specifically recommended for parallel barrier configurations with these ratios.
2. The primary goal in abatement design is to provide acceptable noise levels for residents living close to the highway. Strategies that both meet this goal and address the loss of ground attenuation for distant receivers should be considered. Using TNM for noise barrier design results in lower barrier heights compared to designs based on

STAMINA 2.0 noise level predictions. The FHWA mandated use of TNM will therefore result in lower noise path heights as a result of lower barrier heights.

3. When space within the right-of-way is not an issue, earth berms should be considered. Earth berms will provide more ground attenuation than noise walls of the same height. Where the right-of-way may be restricted an earth berm and wall combination might be utilized.
4. Controlling traffic noise at its source is a comprehensive strategy. Lower traffic noise source levels will result in fewer and lower noise barriers. Lower noise barriers will result not only in more ground attenuation, but also in less surface area for reflections between noise barriers. In addition, all receivers, both near and distant, will benefit. Each 1 dB reduction in source levels results in a corresponding 1 dB reduction in received levels, in contrast to noise reduction by barriers where distant receivers experience a smaller reduction than near receivers. While transportation agencies cannot control the vehicle component of traffic noise they can control the pavement component. Pavement types resulting in lower levels of tire/road noise should be considered.
5. The extreme reflection problem for residents in the section D test area should be addressed. Alternative design strategies, such as installing sound absorbing materials to reduce the intensity of reflections or increasing the height of the barrier closest to the affected receivers to provide shielding from reflections, should be implemented.
6. The following recommendations are made for future study:
    a. Reflection tests of parallel barriers with width-to-height ratios greater than 20:1 are recommended to assess the need for sound absorbing barrier surfaces.
    b. The test system devised for this project should be developed to measure reflected energy in specific frequency bands. This feature would be useful in the evaluation of sound absorbing materials. The system should also be developed to extend its useful range to cover distant receivers.
    c. The correlation between reflection test signal results and A-weighted vehicle pass-by levels should be determined.
    d. The reflection test system should be applied to single barriers to identify reflections for receivers on the opposite side of the highway from the noise wall.

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# APPENDIX A

**Microphone Distances from the Barriers**

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Microphone Distances from the Barriers
Appendix A
Parallel Barrier Effects for Distant Receivers
FINAL Report

| Site | Mic | Distance (m) |
|---|---|---|
| 1 | E1 | 27.5* |
| 2 | E1 | 0 |
| 2 | E2 | 15 |
| 2 | E3 | 60 |
| 2 | W1 | 0 |
| 2 | W2 | 30 |
| 3 | E1 | 0 |
| 3 | E2 | 15 |
| 3 | E3 | 30 |
| 3 | E4 | 60 |
| 3 | E5 | 90 |
| 4 | E1 | 0 |
| 4 | E2 | 45 |
| 4 | E3 | 90 |
| 4 | E4 | 150 |
| 4 | W1 | 0 |
| 4 | W2 | 15 |
| 5 | E2 | 30 |
| 5 | E3 | 67.5 |

*indicates distances from the source.

# APPENDIX B

**Instruments and Equipment**

APPENDIX B
Instruments and Equipment
Parallel Barrier Effects for Distant Receivers
FINAL Report

| Equipment | Model | Quantity | Serial Number |
|---|---|---|---|
| Larson-Davis Real Time Analyzer | 2900B | 1 | 0740 |
| Larson-Davis Preamplifier | PRM828 | 8 | 1259, 1261, 1263, 1264, 1265, 1266, 1340, 1348 |
| Larson-Davis Microphone | 2560 | 8 | 2494, 2568, 2496, 2578, 2594, 2567, 2755, 2762 |
| Larson-Davis Sound Level Meter | 812 | 8 | 0336, 0337, 0338, 0339, 0340, 0341, 0417, 0418 |
| Sony Digital Audio Tape-Corder | TCD-D8 | 8 | 548971, 558631, 548973, 548975, 276991, 565200, 548974, 561841 |
| Larson-Davis Acoustic Calibrator | CA 200 | 1 | 0423 |
| Young Polar Wind Monitor | 05701-5 | 4 | WM29681, WM29682, WM29983, WM29982 |
| Young Gill UVW Anemometer | 27005 | 2 | UV02148, UV02149 |
| Campbell Scientific Thermometer | ASPTC | 3 | 1110, 1132, 1133 |
| Campbell Scientific Relative Humidity Probe | HMP45C-L | 1 | 1026 |
| Campbell Scientific Datalogger | CR10X | 4 | 12052, 12053, 12054, 12055 |