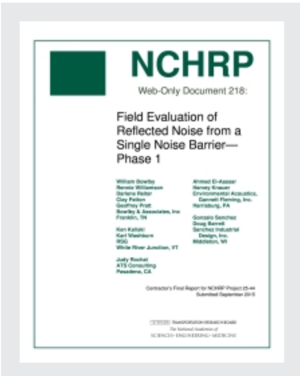

Field Evaluation of Reflected Noise from a Single Noise Barrier—Phase 1

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Field Evaluation of Reflected Noise from a Single Noise Barrier—Phase 1

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Contractor's Final Report for NCHRP Project 25-44
Submitted September 2015

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William Bowlby, Ph.D., P.E., of Bowlby & Associates (B&A) served as the Technical Lead for the project and Kenneth Kaliski, P.E., INCE Bd. Cert. of RSG served as overall project manager under RSG.

The lead authors of this Final Report are Dr. Bowlby of B&A, Mr. Kaliski of RSG, Judy Rochat, Ph. D., of ATS Consulting, Karl Washburn, INCE Bd. Cert. of RSG, and Rennie Williamson of B&A.

Dr. Bowlby was the lead author of the Task 1 Amplified Work Plan.

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The noise measurements in Task 5 were performed by the following:

- I-90, Illinois: Staff of SID, including Mr. Sanchez, Mr. Barrett, Paul Schick, Ryan Cranfill, and Lisa Sanchez
- SR-71, California; Dr. Rochat, Shannon McKenna and Tony Evans of ATS Consulting, Mr. Sanchez of SID, and Mr. Patton of B&A
- MD-5, Maryland: Adam Alexander, Sonnie Peterson, Anjoli Martin, Dr. John MacDonald of Environmental Acoustics (EA), Mr. Sanchez of SID, and Mr. Patton of B&A

Data reduction, processing, analysis, and quality control were performed by: Mr. Sanchez, and Paul Schick of SID; Dr. Bowlby, Mr. Williamson, Mr. Pratt, and Mr. Patton of B&A; Dr. Rochat, Dr. Hugh Saurenman, Chris Ono, Jack Meighan, and Jackie Chavez of ATS; Mr. Kaliski, Mr. Washburn, and Isaac Old of RSG; and Dr. El-Aassar, Harvey Knauer, P.E., Mr. Alexander, Ms. Peterson, Ms. Martin, and Dr. MacDonald of EA.

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ABSTRACT

This research studied the change in sound levels and characteristics caused by sound reflections off a reflective (non-absorptive) noise barrier on the opposite side of a highway. The analysis was done using measurements at five Barrier sites and adjacent sites without a barrier under equivalent site, source, and meteorological conditions. Changes in broadband and 1/3 octave band equivalent sound levels (L_{eq}) were studied, along with statistical descriptors, particularly the L_{90} and L_{99} metrics. Evidence is seen of increased L_{eq} both across the road from the barrier and at positions between the road and the barrier. In some cases, even greater increases in L_{90} and L_{99} suggest a sustaining of the received sound due to the reflections. Spectrograms, visualizations of the spectral time history, reveal that the presence of the barrier causes sound levels to increase over a broad range of frequencies and causes higher sound levels to be sustained for a longer period of time. Psychoacoustic metrics were calculated and combined into three measures of annoyance. Annoyance metrics opposite the barrier tended to increase relative to the No Barrier site in lighter traffic where individual vehicle passbys are distinct.

EXECUTIVE SUMMARY

This research studied, through field measurements and audio recordings, the possible change in sound levels and sound characteristics caused by sound reflections off a reflective (non-absorptive) noise barrier on the opposite side of a highway.

The analysis was done using:

- a modification to a method in a Federal Highway Administration (FHWA) noise measurement manual in which simultaneous measurements were made at the Barrier site and at an equivalent adjacent site without a barrier under equivalent source and meteorological conditions ("FHWA Method");
- acoustical spectrograms, which show the frequency content of sound as a function of time; and
- psychoacoustic measures of Loudness, Sharpness, Roughness, and Fluctuation Strength combined into metrics of Annoyance.

Additionally, changes in the statistical exceedance (L_n) descriptors were also addressed. Broadband unweighted sound pressure levels and A-weighted sound levels were studied as well as 1/3 octave band sound pressure levels.

Five locations were selected for data collection and analysis in this study:

- I-24, Murfreesboro, TN
- Briley Parkway, Nashville, TN
- I-90, Rockford, IL
- SR-71, Chino Hills, CA
- MD-5, Hughesville, MD

With one exception, six sound level analyzers were deployed at each location: three at the Barrier site and three at the adjacent No Barrier site. Each site had a reference microphone on the barrier side of the road and two pairs of "community" microphones on the opposite side of the road from the barrier. These microphones were positioned in terms of their distance from the road and height above the road such that the results from each pair were directly comparable. The I-24 and SR-71 locations also afforded the opportunity to place the Barrier reference microphone between the barrier and the road so that it could be compared to the No Barrier reference microphone as a primary point that might be affected by reflected noise. Evening measurements at the Briley Parkway and MD-5 locations were scheduled to capture isolated, single-vehicle passby events. A meteorological station collected simultaneous wind speed and direction, and a video camera and laser speed gun were used to collect traffic volume and classification data and travel speeds.

Four hours of data were collected at each location, logged at one-second intervals, and processed in one-minute periods. The one-minute data blocks were examined to see if there was contamination from intrusive noise sources and eliminated these as necessary. They were then grouped into five-minute periods for comparability, For highway traffic, this amount of time averages the short-term vehicle passby and intervening lulls and allows for the same vehicles to be captured at both Barrier to No Barrier microphones, with only slight differences at the beginning and ending of the block.

Broadband A-weighted sound levels and unweighted sound pressure levels were examined for the five-minute periods without consideration of the source and meteorological equivalence of the periods to each other. This analysis reveals evidence of sound level increases at the Barrier microphones, both for those positions in front of the barrier as well as across the road.

The five-minute periods were tested for source equivalence—in terms of the reference sound level data and speed data—and for meteorological equivalence. The meteorological classes consist of a combination of wind direction (Upwind, Calm and Downwind) and temperature gradient (Lapse, Neutral and

Inversion). When three or more equivalent periods were identified based on source and meteorological class, they were grouped together and their broadband and 1/3 octave band sound level differences, in terms of the five-minute equivalent sound level, L_{eq}(5min), were examined.

Additionally, the one-second data were processed to determine statistical exceedance descriptors ranging from L_1 to L_{99}, both for the broadband levels and the 1/3 octave band levels.

From the above data, the following findings were developed:

1. Measured broadband unweighted sound pressure levels and A-weighted sound levels are generally higher at the Barrier microphones than at the No Barrier microphones.
2. The differences in Barrier and No Barrier levels are frequency-specific and vary by location and site. There are clear examples of enhanced levels opposite the barrier compared to the corresponding No Barrier position.
3. Sound levels are higher and spectral content changes at a position between the barrier and the road, compared to the No Barrier site, as evidenced at I-24 and SR-71.
4. The background sound pressure level is elevated in the presence of the noise barrier at the microphone position between the barrier and the road.
5. Even at the reference microphone position atop the barrier the level can be slightly higher than at the equivalent No Barrier position, as evidenced at I-90. However, little difference was seen at MD-5.
6. Near the edge of the road for the lower-height microphones, the Barrier levels are roughly the same as the No Barrier, being slightly higher in the very low frequency bands, as evidenced at SR-71.
7. Near the edge of the road for the lower-height microphones, there is some evidence of an increase in the background A-weighted sound level on the order of 1 dB to 1.5 dB at BarCom03, as seen at SR-71.
8. Farther back from the road, but still within 100 ft, the Barrier levels are higher than No Barrier levels by 0.5 to 1.5 dB and the spectrum is changed by even more in some of the frequency bands between 250 Hz and 630 Hz and in some of the bands at and above 1 kHz, as evidenced at I-24, I-90, and MD-5.
9. Farther back from the road, but still within 100 ft, the background level increases in the bands from 630 Hz up through 3.15 kHz, as evidenced at I-90 and MD-5, but not I-24.
10. Back at 400 ft from the road, the Barrier levels are typically 1 dB to 4 dB higher than at the No Barrier site, as evidenced at SR-71.
11. Back at 400 ft from the road, all of the L_n descriptors were higher at the Barrier site, not just the background levels, as evidenced at SR-71.
12. The increase in levels due to reflections decreased by 1 dB to 2 dB going from a lower-height microphone to a higher microphone, as evidenced at I-24, I-90, and MD-5.
13. No effect on sound level differences was seen as a function of traffic volume, as evidenced at all microphone pairs at all locations.
14. There are slight differences in the sound level differences for different meteorological classes, however there are no clear trends, as evidenced at I-90, I-24, and MD-5. Data collected at greater distances from the road might tell more.

Spectrograms were generated for individual and groups of vehicle passby events, as well as samples of highway traffic for each of the measurement sites. The spectrograms compare data collected at the Barrier site and at an equivalent position at the No Barrier site. This comparison allows for a visual examination of the effect of barrier-reflected noise.

The spectrogram data reveal that the presence of a reflective noise barrier causes sound levels to increase over a broad range of frequencies and causes higher sound levels to be sustained for a longer period of time. The increased sound levels include frequencies that dominate highway traffic noise. These observations apply to vehicles traveling on either side of the road, for a range of distances from the road and heights above the road, and for the vehicle types examined (autos, heavy trucks, and motorcycles).

An additional observation is that there is evidence that the barrier effect is more pronounced at farther distances from the road. It is assumed that the path length difference between direct and reflected sound is one of the variables controlling the strength of the effect seen from barrier reflections (smaller difference = greater effect).

At each site, the signal from each sound level meter's microphone was digitally recorded. These audio recordings were filtered and post-processed to extract basic psychoacoustic metrics as a function of time. In turn, these were combined into three different measures of psychoacoustic annoyance: Unbiased Annoyance, Psychoacoustic Annoyance, and Category Scale of Annoyance. Descriptive statistics for the annoyance metrics were compiled for each site. The statistics were investigated as indicators of whether the received sound from Barrier sites would be significantly different from those at No Barrier sites. Our findings of the psychoacoustic assessment were that:

1. Unbiased Annoyance and Psychoacoustic Annoyance yield similar results, while Category Scale of Annoyance does not yield useful indications.
2. Annoyance metrics show differences between Barrier and No Barrier sites at moderate distances, but the results are contra-indicative.
3. Annoyance metrics are less effective in heavy, constant traffic, but show differences in lighter traffic with separated passbys.

The research team found several applications of this research. The most immediate application is for traffic noise analysis and abatement practitioners: traffic sound levels and sound characteristics for receptors across from a proposed single reflective noise barrier can change after the installation of the barrier. This understanding can lead to the appropriate specification of sound-absorbing surfaces on these single barriers, especially for highway widenings where the roadway already exists. In addition, the study found spectrograms to be very useful in identifying the change in sound characteristics due to barrier reflections in both the time and frequency scales. Spectrograms could help policy makers provide guidance on when it may be effective to use sound-absorbing barriers and help in showing the public what an absorptive barrier could provide. It was also found that psychoacoustic metrics of annoyance are not effective for looking at subtle changes in constant traffic, but are helpful to provide insights into increased annoyance at lower traffic levels.

Finally, the research team made several recommendations and considerations for future research. In summary, these included:

1. Creating a screening tool to determine when sound absorption may be appropriate.
2. Conducting before/after studies to assess the effect of the barrier in situ, using techniques developed in this project and others, as needed.
3. Developing a layman's guide to improve understanding of barrier reflections.
4. Incorporating some of these findings into various courses on highway traffic noise.
5. Studying sound reflections off of sound-absorbing barriers.
6. Evaluating Time-Based and Time-Above metrics to help understand other drivers of adverse community perception.
7. Using TNM to further investigate why the barrier reflection effects are greater closer to the ground by studying the frequency ranges being affected by shielding from median barriers and highway vehicles and also ground effects, which may show that sound-reducing propagation effects help to "expose" barrier-reflected noise.
8. Conducting listening trials to directly assess human reaction to reflected noise.

CHAPTER 1

Introduction

The Problem

By the end of 2010, over 180 million square feet of highway noise barriers had been constructed in the United States, of which only 2% were sound-absorbing (Ref. 1). For barriers on a single side of a highway, absorptive treatment can generally reduce the overall reflected sound level at a receptor opposite the barrier by one to two decibels. While this amount is generally considered too small to be readily perceived, state highway agencies (SHAs) have received complaints from residents on the reflective side of hard barriers after construction (see Appendix A). This research aims to quantify the sound reflected off of in-situ highway barriers compared to the sound received at similar locations without barriers by assessing the level, spectral, and sound quality differences between the two. The goal is to assess how diverse site conditions affect reflected sound.

For quite some time, on many occasions and in many different states, the issue of sound reflections off a highway noise barrier to receptors on the other side of the highway has arisen. The problem arises when the community on one side of the highway qualifies for a barrier but there are residents on the other side of the highway that for one reason or another do not qualify. The problem is often exacerbated by the fact that these residents may be impacted by the highway noise yet do not meet certain feasibility or reasonableness criteria for abatement. For them, experiencing a noticeable change in the sound level caused by their neighbors receiving abatement may upset them further.

There have been a number of studies, especially by the California Department of Transportation (Caltrans), to quantify the problem (Appendix A). Most of these studies have considered the change in the A-weighted sound level in the community opposite the barrier. The difficulty is that the change that these residents are experiencing may not be related to a simple increase in the overall A-weighted sound level. Assuming unobstructed propagation paths for the direct and reflected sound paths, physics says that the increase in the total sound level due to the addition of the reflections should be less than the 3 dB attributable to the doubling of the source energy. (In this report, the unit of dB refers to a change in level, both for unweighted sound pressure levels (designated as dBZ per the International Standards Organization (ISO)) and A-weighted sound levels (dBA)).

Conventional thinking is that an increase less than 3 dB should be just barely perceptible. However, that conventional thinking only applies if the temporal aspects (i.e., time signature) and spectral content of the increased sound is similar to that of the original sound. One hypothesis is that the noticeability and annoyance caused by the reflections might be due to other factors. One example is that the spectral content of the reflected sound may be different than the spectral content of the direct sound. In particular, the higher frequencies, which are more likely to be specularly reflected (as opposed to diffusely reflected) back across the road, may now stand out more in the total received sound, hence changing the character of the sound. Although the potential spectral change is not expected to change substantially the perceived annoyance of the highway noise, the combined effect of negative feelings about the highway, particularly for neighborhoods that did not qualify for a sound wall, in combination with a noticeable change in the sound character, could be sufficient for residents to perceive that the change has substantially increased the annoyance of the traffic noise.

It is also possible that the path of the reflected sound back across the road may experience less attenuation than the direct sound perhaps because of the nature of the intervening terrain between the edge of the near lanes of travel and the receptors on the far side of the highway. This could lead to an increase in the A-weighted sound level or changes in the spectral content that could be perceived negatively.

There is also another aspect of this phenomenon that may be coming into play. It is brought to light by a comment reported by D. Barrett of the research team and C. Menge in a presentation at the 2010 summer meeting of the Transportation Research Board Committee ADC40 (Transportation-Related Noise and Vibration) (Ref. 2). The study involved a Caltrans project where sound absorption was added to a previously reflective far-side noise barrier along U.S. 101 in San Rafael, CA. A resident was quoted in the Marin Independent Journal in January 2010, “It's a significant change…The white noise that you hear is gone. What's missing is the ‘shhhhh.’”

This comment supports the concept that higher frequency spectral content is enhanced by the barrier reflections, or at least attenuated less than low frequency content. It also suggests the potential effect of the reflected sound on the overall time history or time signature of the total received sound. When a single vehicle passes by in the absence of a far-wall barrier, one hears the sound coming exactly where the vehicle is located. However, as shown in Figure 1, when a reflective far wall is introduced, not only does one hear the sound from the direct vehicle but ones hears it coming off of the far wall—and thus from a different point along the road. The relationship between the actual source and this reflected source changes as the vehicle proceeds through the area in front of the barrier. As a result, the time signature of the passby is lengthened and, in the presence of multiple vehicles, it changes the character of the normal rise and fall of the sound level of vehicle passby, and affects the one’s ability to pinpoint the direction of the sound. For curved or irregular barriers, the effect can be heightened even further due to multiple reflections.

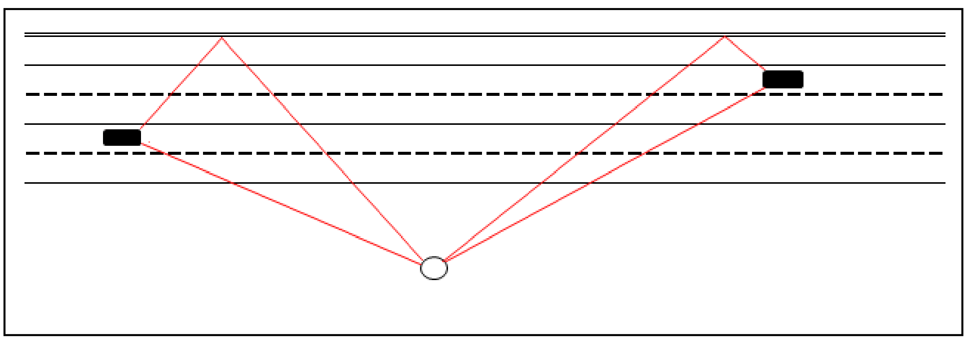

Figure 1. Plan view of the relationship between direct and reflected sound paths to a receptor across the highway from a noise barrier.

This phenomenon is exactly what was observed by this project’s principal investigator on a parallel barrier project study for Ohio DOT in the Town of Silver Lake. With parallel barriers, there are potentially many reflected paths of the multiple images created by the reflections in addition to just the direct and first far-wall reflection in the single far-wall situation. As a result, when standing behind the near wall, he could not easily point to a single vehicle's position on the roadway even if that vehicle was the only vehicle in the "canyon" between the two barriers. Instead of the traditional rise and fall of sound level during a vehicle passby, the sound level built up more quickly and dropped off more slowly when the contributions of each image were added to the noise from the actual vehicle. The effect is a sustained “shhhhh” sound behind the barrier. This and other similar observations of the sustaining of the passby noise seem quite similar to the “white noise…shhhhh” comment of the California resident. It is possible that the way in which reflections make it difficult to accurately identify the direction of the sound and raise the background level could cause humans to perceive the sound as more annoying.

Project Objectives and Approach

Given the complicated nature of reflections off of single highway noise barriers, research is needed to assess how diverse site conditions affect the nature of the reflected sound. To address this, the objectives of this research are to:

1. Determine the spectral noise level characteristics of the overall noise in the presence of a single reflective noise barrier for positions on the opposite side of a roadway through the collection of field measurements from diverse sites, and
2. Summarize and analyze the implications of the research results for purposes of understanding the actual and perceived effects of reflected noise.

To carry out these objectives, sound and other field data were collected at five locations throughout the U.S. At these locations, simultaneous measurements were made at a barrier site and at an equivalent adjacent site without a barrier under equivalent source and meteorological conditions. An analysis of this data was done by comparing:

- **A-weighted and unweighted 1/3 octave band (spectral) sound levels -** Changes in the equivalent sound level and statistical exceedance (L_n) levels under equivalent source and meteorological conditions were analyzed.
- **Acoustical spectrograms -** Both frequency (spectral) and temporal variations, with and without a noise barrier present, were examined visually using spectrograms, which are time histories of spectral data. This type of visualization can help reveal variations that may not be apparent when examining average overall A-weighted or 1/3 octave band sound levels for blocks of data. The variations found can help to focus data analysis and explain the effect of barrier-reflected noise.
- **Psychoacoustic metrics -** A fundamental question regarding residents' response to single barriers is their reported annoyance. The use of sound levels as descriptors limits the interpretation of results to energy metrics. However, other elements or complexities are incorporated into the total signal from single-barrier sites that are not present at the No Barrier sites. To the extent that these elements may be annoying residents, it is appropriate to explore and compare the received sounds using available psychoacoustic metrics. In the psychoacoustics literature, the basic metrics of Loudness, Sharpness, Roughness, and Fluctuation Strength have been combined into reliable predictors of annoyance. These metrics are straightforward to compute given a high-sample rate recording of the received sound. Therefore, it is worthwhile to examine whether these metrics can be used to identify statistically significant differences between Barrier and No Barrier sites.

Chapter 2 addresses the research approach, describing the general methodology used to satisfy the project objectives. The subsequent chapters then focus on the studied locations, results, findings, applications, conclusions, recommendations and suggested future research.

Appendix A is the literature review performed for this study. Appendix B is the Detailed Protocol and Results; it is a much more detailed presentation of the results of the analysis that led to the findings in this report. Appendix C is a complete catalog of the site photos for each microphone position, the meteorological station and traffic data collection station for each study location.

CHAPTER 2

Research Approach

As noted in Chapter 1, the objectives of this research are to:

1. Determine the spectral noise level characteristics of the overall noise in the presence of a single reflective noise barrier for positions on the opposite side of a roadway through the collection of field measurements from diverse sites, and
2. Summarize and analyze the implications of the research results for purposes of understanding the actual and perceived effects of reflected noise.

Based on its understanding of these objectives and the nature of the problem, the research team investigated the changes in the broadband A-weighted sound levels and unweighted sound pressure levels and individual 1/3 octave band sound pressure levels between No Barrier and adjacent Barrier sites. In addition, the following components were examined: (1) the spectral time signature of the signals of individual passbys with and without the far-side barrier; and (2) the difference in psychoacoustic sound quality metrics.

Research Tasks

This research consisted of six tasks. Each task is described briefly below.

Task 1. Kick-off teleconference meeting and amplified work plan development
Task 2. Completion of literature review, which is presented in Appendix A
Task 3. Development of study location selection criteria, identification of recommended study locations, and data collection, processing and analysis protocols
Task 4. Measurements and analysis for the first two study locations
Task 5. Measurements and analysis for the remaining locations and summary and analysis of implications of all research results
Task 6. Preparation and delivery of draft final and final report and PowerPoint™ presentation

Data Collection Protocol

Three types of data analysis were used in this study:

1. FHWA Method (based on the Indirect Measured procedure in Chapter 6 of FHWA's Measurement of Highway-Related Noise (Ref. 3)), where simultaneous A-weighted and 1/3 octave band measurements are made at the Barrier site and an "equivalent" No Barrier site
2. Spectrograms
3. Psychoacoustic metrics

A single data collection process yielded the data for use in all three analyses, and is discussed first. Then the data processing steps are outlined. Finally, the data analysis methodology for each type of data is discussed. In addition to the sound level data, the data collection for the FHWA Method included recording of calibrated .wav audio files at each microphone position. These files were used in this study for processing and analysis of the spectrograms and the psychoacoustic metrics.

The FHWA Method calls for equivalence of site geometry, noise sources, and meteorological parameters. As a result, the locations were chosen such that the No Barrier and Barrier sites were adjacent. Since the sound level and frequency spectrum produced by traffic are affected by the pavement and the roadway grade; these factors were considered in site selection and were required to be equivalent in the No Barrier and Barrier locations.

Two other source characteristics that can affect the sound level and frequency spectrum are the volume and speed of the traffic. Because one goal in site selection was to avoid interchanges or intersections between the Barrier and No Barrier sites and because the Barrier and No Barrier measurements were to be made simultaneously, any potential variations in traffic volume and speed between the two sites was minimized. However, traffic volumes and speeds vary over time. Likewise, experience indicates that meteorological conditions, particularly the wind speed and direction, can change even over relatively short periods of time. Therefore, time periods were grouped under equivalent source and meteorological conditions.

Measurement of Highway-Related Noise (Ref. 3) recommends a minimum of three "measurement repetitions" per site (with a preferred number of six repetitions) under equivalent source and meteorological conditions. The challenge is that it can be very difficult and time-consuming while in the field collecting data to demonstrate source equivalence and meteorological equivalence real-time. As a result, the field protocol was to:

- Collect four hours of data at each site, in one-second logging intervals, to be aggregated into one-minute periods;
- Video-record the traffic and measure speeds with a laser speed gun; and
- Collect wind speed and direction and temperature data at two heights, to be averaged in one-minute periods.

Then, as part of the data processing protocol, the four hours of data were divided into one-minute periods of equivalent source and meteorological conditions at the No Barrier and Barrier sites. Each period represents one "measurement repetition" for a unique combination of equivalent source and meteorological conditions.

A method of determining source equivalency between periods—based on the reference microphone sound levels and the average speeds by direction of travel—was found to work very well and was adopted for the study. Basing the source equivalence determination on the measured reference microphone data allowed the maximum tolerance between two periods to be 0.3 dB or less across all of the locations.

The wind data were processed to determine a vector wind speed (component of wind speed perpendicular to the road) and corresponding wind class (Upwind, Calm, or Downwind) for each period. The temperature data were also processed to determine the corresponding temperature gradient class (Lapse, Neutral, or Inversion) for each period. These data were merged with the source data and sorted to determine the combined equivalent source and meteorological data period repetitions.

Equipment and Sound Level Descriptors

A standardized data collection equipment package was used at all of the sites, consisting of:

- Six Type I sound level analyzers with 1/3 octave band measurement capabilities with data loggers and audio recorders;

- Meteorological data collection station with precision temperature sensors and precision quality anemometers capable of measuring wind speed in three dimensions at two heights (5 ft and 15 ft) above the ground;
- Video camera and laser speed gun; and
- Accessories including a 94-dBZ calibrator, extension cables, windscreens, microphone tripods and stands, extension poles, and guy wires.

Depending on site characteristics and goals at any of the measurement locations, the community microphones could be located at two different distances from the road or at two different heights at the same distance.

Regarding the naming of the microphones, when two microphones were at different heights at the same distance, at the Barrier site, the lower microphone was named BarCom03 and the upper one BarCom04 (Figure 2). At the No Barrier site, NoBarCom05 was the lower microphone and NoBarCom06 was the upper microphone. When the community microphones were at different distances, BarCom04 and NoBarCom06 were the distant microphones for the Barrier and No Barrier sites, respectively. The reference microphones on the barrier side of the road were named BarRef01 for the one adjacent to the Barrier and NoBarRef02 for the No Barrier site.

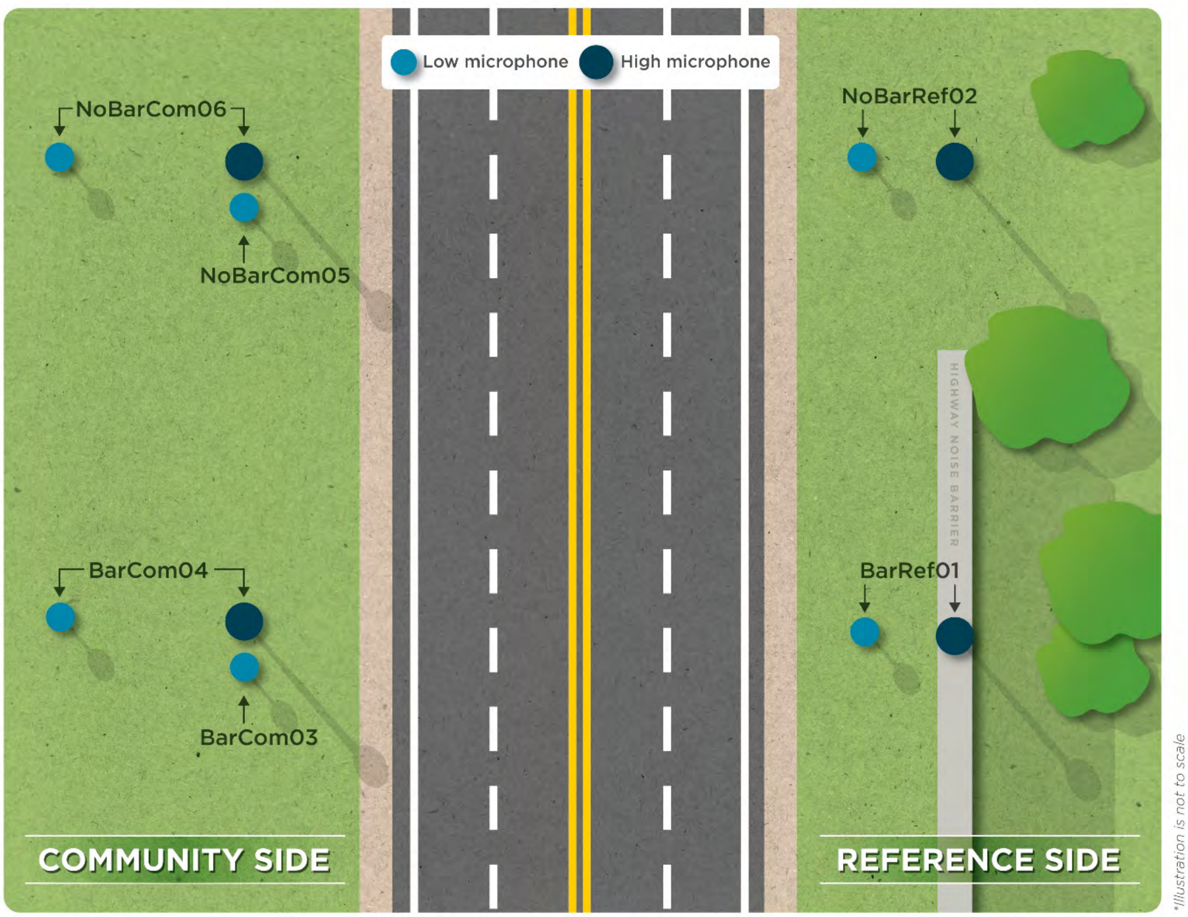

Figure 2. Typical microphone positions.

Measurements were made in terms of the equivalent sound level, L_{eq}, for the broadband (overall) A-weighted sound level and unweighted sound pressure level and individual 1/3 octave band sound pressure levels. One-second broadband A-weighted levels and unweighted sound pressure levels and 1/3-octave band unweighted sound pressure levels between 12.5 Hz and 20,000 Hz were saved, and were later processed into one-minute intervals, and the audio signal was recorded. Analysis of the initial data led to a decision to only present data in the 20 Hz to 10 kHz bands to eliminate the distraction of data irrelevant to the study and undue influence on the broadband unweighted sound pressure levels and A-weighted sound levels. These broadband levels were recomputed after the very low and high bands were deleted.

The main reason for including both the A-weighted and unweighted data was to see if there was a difference in the two, which might provide an initial indication of frequency-specific effects. For example, higher unweighted levels might point toward substantial lower frequency components of the received sound. On the other hand, if the A-weighted level was close to or higher than the unweighted levels, there could be important contributions in the 1,000 Hz to 4,000 Hz bands. Studying only the A-weighted levels could disguise lower frequency contributions. The Barrier and No Barrier spectra were studied in terms of unweighted sound pressure levels to give a true picture of the spectra and the unweighted levels were then the basis for the Barrier/No Barrier 1/3 octave band level difference comparisons described in the *FHWA Method Data Analysis Protocol* section below.

Statistical exceedance descriptors, specifically L_1, L_5, L_{10}, L_{33}, L_{50}, L_{90} and L_{99}, were computed for the five-minute periods based on the one-second data. These “L_n” descriptors were used in determining the sound level range in a sample period and in diagnosing data on individual passbys and the possible sustaining of the background level due to sound reflections off the barrier.

Meteorological Data

At each location, the meteorological station was set up in an open area near the No Barrier site. The wind data were used to determine a vector wind speed in the direction from the roadway to the microphones in order to be able to determine the appropriate wind class for the measurements. Temperature data at 5 ft and 15 ft above ground level were used to determine the appropriate gradient class for the measurements.

Measurement Procedures

Prior to going into the field, the measurements were planned in detail using a field review report as a guide. On the measurement day, the team set up and calibrated the sound level analyzers and deployed the microphones via extension cables on tripods or guyed towers. In addition to calibration, the electronic noise floor of the entire acoustic instrumentation system was established.

Approximately four hours of simultaneous data were then collected at all of the microphones. The meteorological data were saved as one-second wind speed and direction and temperature for later processing into one-minute averages, time-synched to the sound level data.

Each noise measurement person kept field logs of events, with the time of occurrence of vehicles of interest (typically heavy trucks) and any unrepresentative sounds or events that might affect the one-minute measurements. These latter events were studied for possible elimination of the one-minute data intervals from the analysis.

Samples of vehicles speeds were stored in a file in the laser gun and were also recorded manually on data sheets to identify the vehicle type. Speeds varied by lane, as expected. For consistency, for roads with more than two lanes in each direction, the majority of speeds were measured in the second lane from the outside. Additional samples of speeds were made in the other lanes to the extent possible.

At the end of the measurements, the calibration was checked for sound level analyzers, with the audio of the calibration tone recorded. All of the data were then downloaded onto personal computers, with a common file-naming convention for all of the files.

Vehicle classification counts (automobiles, medium trucks, heavy trucks, buses and motorcycles) were made from the video in one-minute intervals that matched the sound level measurement intervals. The speed data were entered into the speed spreadsheet by ID number and vehicle type. The speeds were adjusted to account for the angle of speed shooting off of head-on. As needed, the speed samples were time-adjusted forward or backward to represent the time of passage from the shooting point to a point midway between the Barrier and No Barrier sites.

FHWA Method Data Processing

Data processing for the FHWA Method involved three major steps: creation of data spreadsheets, elimination of time periods with unrepresentative events that affected the measured sound levels, and identification of equivalent time periods in terms of meteorological class and traffic parameters.

First, the sound level and meteorological data were processed into a single standardized spreadsheet format for both the “raw” one-second data and one-minute interval (or “period”) data averaged from the one-second data. The sound level data included the A-weighted sound level and unweighted sound pressure level plus the 1/3 octave band sound pressure levels.

The meteorological data included the average wind speed, wind direction, temperature, and relative humidity at each sensor (high and low heights of 15 ft and 5 ft). The vector component of the average wind velocity in a perpendicular line from the highway to the reference microphone was computed for each period, as well as the temperature gradient. Each period was classified by wind class based on Table 1 (which is Table 3 from *Measurement of Highway-Related Noise*). Winds outside these conditions (for vector components over ± 11 mph) were put into a class called *Invalid-wind*.

Table 1. Classes of wind conditions.

Wind Class	Vector Component of Wind Velocity
Upwind	-2.2 to -11 mph
Calm	-2.2 to +2.2 mph
Downwind	+2.2 to +11 mph

Each period was also classified by temperature gradient class, per Table 2. These classes are based on data collected by ATS from the Arizona Transportation Research Project (Ref. 4) several years ago. The Neutral conditions are based on the graphs presented in that report.

Then, based on the wind class and temperature gradient class, each one-minute period of sound level data was put into one of ten meteorological classes (Upwind Lapse, Calm Lapse, Downwind Lapse, Upwind Neutral, Calm Neutral, Downwind Neutral, Upwind Inversion, Calm Inversion, Downwind Inversion, and *Invalid-wind*).

Table 2. Classes of temperature gradients.

Temperature Gradient Class	Gradient: (Temp_upper – Temp_lower) Divided by Vertical Distance between Sensors
Inversion	positive > 0.1
Neutral	-0.1 to 0.1
Lapse	negative < -0.1

Based on the field notes, the data were screened for any potentially bad or unrepresentative events at each microphone position (e.g., loud non-traffic noises, periods of stopped traffic flow, etc.). As needed, the one-second data and one-minute averaged data were reviewed to see if the events affected the levels.

The next step was to determine five-minute periods that were equivalent to each other for inclusion in a measurement repetition “group.” First, five-minute running averages of the vector wind component were computed for each minute of the four-hour block (excluding those five-minute periods that had one or more bad one-minute periods). “Five-minute running averages” means that each consecutive minute is the starting minute of a five-minute period including its data and the data in the next four minutes. For example, 12:01 to 12:06, 12:02 to 12:07, and 12:03 to 12:08 would be three consecutive running five-minute periods. The use of five-minute running averages gives more flexibility when trying to determine periods that have equivalent sources and meteorological conditions.

Each five-minute period was assigned to a meteorological class, based on a requirement that at least three of the five minutes be in the same class. All of the five-minute periods in the same meteorological class that were not overlapping in time with each other were then tested for traffic equivalence. An example of overlapping periods would be 13:45 to 13:50 and 13:47 to 13:52, whereas 13:45 to 13:50 and 13:50 to 13:55 would be non-overlapping.

Finally, traffic equivalence was determined.

FHWA Method Data Analysis Protocol

After the equivalent five-minute periods were determined for the different meteorological classes and traffic conditions, each grouping of non-overlapping equivalent periods was used to compute the sound level increases between the Barrier and No Barrier microphones.

The data analysis procedure in *Measurement of Highway-Related Noise* (Ref. 3) was used, with some adjustment. The first step was to determine any needed calibration adjustments prior to data analysis. The procedure in Section 6.6.3 of *Measurement of Highway-Related Noise* was adapted for levels measured opposite the noise barrier rather than behind the barrier, and for analysis in 1/3 octave bands. Details are in Appendix B.

The sound level changes between No Barrier and Barrier sites were determined for the different groups of equivalent five-minute periods. The mean broadband A-weighted and unweighted level changes and individual 1/3 octave band sound pressure level changes were computed for each group by arithmetically averaging the differences from the individual five-minute periods. A standard deviation was computed for each sound level increase and the results were plotted.

The average differences by frequency band were then computed for all equivalent five-minute periods that were analyzed within a meteorological class occurring at each location. Differences of these averages differences were also computed to allow study of the possible effect of meteorological class on the results. After study of the average differences for each equivalent group for each meteorological class, it was decided that the average differences by meteorological class represented the individual groupings' difference quite well. Thus, these latter average differences by meteorological class are presented in this report. All of the graphs and tables of the average differences by the groups of equivalent five-minute periods are in the spreadsheets in the project record.

Finally, the differences of the L_n values for each five-minute period were computed and analyzed.

Spectrogram Data Processing and Analysis Protocol

A spectrogram analysis allows an examination of spectral (frequency) content over time, whether it is a specified time block (e.g., 5 minutes) or a vehicle passby event.

As noted above, the research team screened the master raw data spreadsheet files from the measured sound level data files and identified bad or invalid data periods. Clean data blocks were identified for the spectrogram analysis; the length of these data blocks varies among the sites, based on how often the intrusive noise events occurred and also whether or not it was desirable to examine the same five-minute data blocks as were examined with the standard analysis. Example data blocks for each site are shown in this report.

In addition, vehicle passby events were identified for investigation. The vehicle passby events were first identified using the site logs, where potential isolated events were noted. Multiple events were examined for each site and only ones that could be clearly identified at both the Barrier and No Barrier sites were retained. Example vehicle passby events for each site are shown in this report.

The audio .wav files were processed and examined in 1/3 octave bands in 1/8-second intervals. The data were then displayed using spectrogram-type graphs. In-house MATLAB code allows for the spectrogram processing and the flexibility to compare selected time blocks of data among different microphones at each site.

For the data blocks and vehicle passby events, pairs of microphones were compared, where each pair consisted of one microphone at the Barrier site and an equivalent microphone at the No Barrier site. For all sites, spectrogram data were examined for the community microphone pair BarCom03/NoBarCom05 and the community microphone pair BarCom04/NoBarCom06. The spectrograms for these two pairs show the effect of the barrier noise reflected back across the highway to communities opposite a noise barrier. At some of the sites, the reference microphones were strategically placed between the road and the barrier to capture barrier reflections on the barrier side of the highway. In these cases, microphones BarRef01 and NoBarRef02 were compared to show the effect of the barrier-reflected noise close to the reflecting surface.

Upon examination of the spectrograms, spectral shapes and values were compared for the equivalent microphone pairs, and trends were noted. Where results were similar between microphone pairs, only one pair is presented.

Psychoacoustics Processing and Analysis Protocol

The audio recordings made by the measurement team for each location were calibrated, post-processed and analyzed for the psychoacoustic parameters of interest. In some cases, audio filters were applied, especially at higher frequencies, to remove electronic artifacts prior to post-processing.

The Psychoacoustics Processing and Analysis Protocol in Appendix A outlines the background and details behind the psychoacoustic processing selected for this study. Summarizing the key points of that discussion:

1. The processing is based on a subset of industry-accepted psychoacoustic metrics.
2. Those metrics are combined parametrically to estimate potential annoyance based on three algorithms from extant sound quality literature.
3. The metrics are computed as functions of time, in one-minute intervals, for each recorded microphone signal.
4. Descriptive statistics are derived from each metric's time series to examine trends and differences between locations.

The psychoacoustic metrics applied to the audio recordings include:

- Loudness in sones;
- Sharpness in acums;
- Roughness in aspers;
- Fluctuation strength in vacils;

Not all of the psychoacoustic metrics have an internationally standardized algorithm. Therefore, among the commercially available software offerings, there is not a fixed calculation associated with each metric. As a result, all of the psychoacoustic analyses were completed using a software package developed specifically for this project by Nelson Acoustical Engineering, Inc. The algorithms encoded into the software comply with those International Standards currently available; they make use of widely accepted expressions for those metrics that are not standardized. The formulae applied in the psychoacoustic analysis software are detailed in Appendix B.

It is also important to take into account the time-varying Loudness created by traffic noise, since a barrier will create additional temporally varying sounds due to reflections. The time-varying Loudness created by traffic noise in these cases can cause interaural time differences (ITDs), interaural intensity differences (IIDs), and spectral changes that can create localization errors among other issues. To help account for the addition of the temporally varying sounds statistical values of Loudness have been calculated.

While these individual psychoacoustic metrics are useful for comparing sounds of widely different natures, they do not necessarily indicate whether an individual might be annoyed by a given sound, nor to what extent. Several annoyance scales have been suggested in the literature; each is based on regressions over listener preference trials, making use weighted combinations of the psychoacoustic parameters. The metrics demonstrated in the current work are detailed in the Psychoacoustics Processing and Analysis Protocol in Appendix B. They include:

- Unbiased Annoyance (UBA), using Loudness exceeded 10 percent of the time (N_{10}), Mean Sharpness (S_m), and Mean Fluctuation Strength (F_m)
- Psychoacoustic Annoyance (PA), using Loudness exceeded 5 percent of the time (N_5), Mean Sharpness (S_m), and Mean Fluctuation Strength (F_m), and Mean Roughness (R_m)
- Category Scale of Annoyance (CSA), using Loudness exceeded 5 percent of the time (N_5), Sharpness exceeded 50 percent of the time (S_{50}), and Mean Roughness (R_m)

For each site, for the corresponding community microphone locations in the presence and absence of the barrier, respectively, the annoyance metrics computed as a function of time are paired for comparison. Time intervals are the same as those used in the spectral analysis (one minute); this time interval is sufficiently long that short-term events, such as truck passbys, are captured at both monitoring locations.

Because the annoyance metrics UBA and PA are sensitive to Sharpness, the high-frequency content in the recordings is crucial. Some of the digital audio recordings used in this work had some high-frequency contamination due to electronic noise. Audio filtering was applied to the contaminated recordings to reduce this effect. Therefore, the annoyance metrics became sensitive to the applied filters. As a result, the Briley Parkway data were not analyzed, and the annoyance metrics computed for I-24 may be slightly biased by their filtering. The I-90 and SR-71 recordings had some contamination, but it was at lower magnitude: filtering was mild in this case, and the annoyance metrics are likely internally consistent for those sites. The recordings from MD-5 were free from contamination. However, the presence of biologics (tree frogs) in the night recordings required additional filtering. In this case, however, the same filter was applied to all of the recordings, so the resulting metrics are still comparable.

CHAPTER 3

Study Locations

Study Location Selection Criteria and Process

Location selection criteria were developed primarily to judge if a Barrier site and its potentially "equivalent" No Barrier site are indeed equivalent. The criteria were incorporated in a Preliminary Site Evaluation Form prepared by the researchers. These forms were then used by each team member in a desktop identification of potential study locations. Twenty-one potential locations were identified.

These potential locations were reviewed by the researchers, and a list of ten preliminary study locations was developed, considering these variables:

- **Comparable Barrier and No Barrier locations**: Sections of road with a consistent pavement type, either a reflective or absorptive barrier on one side, and a nearby section with no barrier; similar geometry and topography so that monitors could be placed at the same distances and heights relative to the barrier; paired simultaneous measurements could then be conducted under the same traffic and meteorological conditions with no normalization of data needed for varying traffic conditions
- **Noise sources**: Sites without other significant noise sources
- **Roadway type/classification**: Types of roadway and number of lanes
- **Road cross-section**: At-grade, elevated (on fill), or depressed (in cut)
- **Pavement type**: Asphalt or concrete
- **Traffic mix**: Traffic volumes and vehicle mix (i.e., percent trucks)
- **Noise barrier type**: Absorptive and/or reflective
- **Noise barrier height**: Different barrier heights between locations, to the extent feasible
- **Noise barrier location**: Locations at the shoulder (near the source) or at the right-of-way (near the receiver)

Field reviews were then conducted at the most promising locations. A final set of eight acceptable candidate locations was identified.

Summary of Acceptable Candidate Locations

The identified locations are listed below:

1. BA-1, I-24, Murfreesboro, TN
2. BA-3, Briley Parkway (SR 155), Nashville, TN
3. ATS-3, SR-71, Chino Hills, CA
4. BA-4, I-240, Memphis, TN
5. EA-4, Hampstead Bypass, Hampstead, MD
6. EA-5, MD Route 5, Hughesville, MD
7. RSG-3, US 3/FE Everett Turnpike, Nashua, NH
8. SID-1, I-90, north of Spring Creek Rd Rockford, IL

The originally selected California location was ATS-2, SR-99 in Bakersfield, CA. Before the measurements could be conducted, a roadway construction project was started at the ATS-2 location. An alternative location that had also been studied in Task 3, ATS-3 on SR-71 in Chino Hills, CA, was selected to replace ATS-2.

Table 3 summarizes the characteristics of the eight acceptable candidate locations. The first two locations were studied as part of Task 4. The others were identified for potential study in Task 5. At the Interim Meeting, the decision to continue with the spectrogram and psychoacoustics analyses meant that the BA-4 and RSG-3 locations would not be studied.

Then, during final inspection, it was determined that the EA-4 barrier was sound-absorbing and, being a depressed highway, this road was not the best location to include as a sound-absorbing barrier site. Instead, the decision was made to conduct extended monitoring at the EA-5 location with the goal of nighttime or off-peak sampling that would allow individual vehicle passbys to be studied.

Thus, in Task 5, three locations were studied: SID-1 (I-90), ATS-2 (SR 71) and EA-5 (MD Route 5), for a total of five locations.

Final Selected Locations

The five final selected locations were:

I-24: This 8-lane freeway in Murfreesboro, TN has a reflective 19 foot high post-and panel concrete wall, in the right-of-way. It has a relatively high volume of traffic at 78,000 vpd with a relatively high percentage of trucks at 14%.

Briley Parkway: This is a six-lane freeway in Nashville TN. It has a reflective 12- to 13-foot concrete noise barrier that is set closer to the road, along the shoulder. It carries about a third of the traffic as I-24, at 45,820 vpd and moderate truck traffic at 8% of the total volume.

I90: This six-lane freeway in Rockford, IL has a 15-foot concrete noise barrier, situated just beyond the shoulder. It carries 53,500 vpd at 9.7% trucks.

SR-71: This six-lane freeway in Chino Hills CA provides the only location with concrete pavement. It also allows for community microphones as far as 400 feet from the center of the near travel lane. The noise barrier is 13 feet high, which includes a 7 feet high concrete barrier atop a 6 feet high earthen berm. It carries 60,000 vpd with 7% trucks.

MD 5: This site in Hughesville, MD is the only arterial selected. The relatively lower volume (34,200 vpd) and monitoring extending into the night allowed the research team to observe individual vehicle passby as well as continuous traffic flow. The truck volume is moderate at 8%.

The final selected locations, indicated in bold with an asterisk in Table 3, provided good opportunities to study the noise barrier reflections issue. They offered a wide variety of characteristics:

- Daily traffic volumes range from 18,000 to 80,000 vehicles per day
- The cross-sections range from a total of four lanes to eight lanes
- Four locations are on freeways and one is on an arterial
- Four of the sites are essentially at-grade with surrounding terrain and one is on retaining wall
- Truck percentages range from 7% up to 14%
- Four of the pavements are dense-graded asphalt and one is concrete
- Barrier offset distances from the edge of the near travel lane range from 9 feet to 96 feet
- All barriers are sound reflective: three are precast concrete post-and-panel designs, one is cast-in-place concrete, and one is concrete block atop an earthen berm
- Barrier heights range from approximately 12 feet to 19 feet

Most of the measurement points were within the highway right-of way, meaning that most of the distances to the community microphones were within approximately 100 ft of the center of the near travel lane. The exception was the SR-71 site where the more distant microphones were able to be set up approximately 400 ft from the center of the near travel lane. It would have been desirable to measure farther back at other locations, but site conditions—mainly developed land uses and terrain—eliminated the ability to have distant Barrier and No Barrier sites that were equivalent in terms of the intervening terrain. The exception was made for SR-71 where simplified modeling with the FHWA Traffic Noise Model version 2.5 (TNM) demonstrated site equivalence for frequencies of interest.

Details of each location, including aerial and cross-sectional views, are found below.

Table 3. Acceptable candidate locations.

Location	Roadway	City, State	Road Class	Lanes	Pavement Type	Geometry Relative to Adjacent Land Uses	AADT (veh/day)	Percent Trucks	Barrier Location	Barrier Material	Barrier Height at Study Site
ATS-3*	SR-71, south of Soquel Canyon/Central, north of Pine Ave.	Chino Hills, CA	Freeway	6	Concrete (Longitudinal grooving)	At-Grade	60,000	7%	ROW	Concrete Block atop Berm	13 feet (7-ft wall atop 6-ft berm)
BA-1*	I-24, between Old Fort Pkwy/ New Salem Rd.	Murfreesboro, TN	Freeway	8	Asphalt (DGAC)	At-Grade	78,140	14%	ROW	Precast Concrete	16-19 feet
BA-3*	Briley Pkwy (SR 155), between Brick Church Pike and Dickerson Pike	Nashville, TN	Freeway	6	Asphalt (DGAC)	Fill (Retaining Wall)	45,820	8%	Shoulder	Cast-in-Place Concrete	12-13 feet
BA-4	I-240, between Getwell and Perkins Roads	Memphis, TN	Freeway	10	Asphalt (DGAC)	Slight Fill	151,700	11%	ROW	Precast Concrete	18 feet
EA-4	Hampstead Bypass (MD Rt 30), at N. Houcksville Rd.	Hampstead, MD	Arterial	2	Asphalt (DGAC)	Cut	18,000	9.4%	ROW	Precast Concrete	5-12 feet
EA-5*	MD Route 5, at Carrico Mill Rd and Alex St.	Hughesville, MD	Arterial	4	Asphalt (DGAC)	At-Grade	34,160	8%	Shoulder	Precast Concrete	16 feet
RSG-3	US 3 / FE Everett Turnpike, west of Dunstable interchange	Nashua, NH	Freeway	8-9	Asphalt (Not determined)	At-Grade	100,000	2.8%	ROW	Wood	15 feet
SID-1*	I-90, Illinois Tollway, north of Spring Creek Rd.	Rockford, IL	Freeway	6	Asphalt (Not determined)	At-Grade	53,470	9.7%	Shoulder	Precast Concrete	15 feet

***Final selected locations.**

I-24, Murfreesboro, TN (Location BA-1)

I-24 is an 8-lane freeway with dense-graded asphalt pavement that carries 78,000 vehicles per day with 14% trucks. The barrier is a reflective post-and-panel concrete wall located approximately 96 ft from the center of the near travel lane, and is 19 ft tall (see Figure 3).

Figure 3. No Barrier (left) and Barrier (right) views at BA-1, I-24. (Source: research team members.)

Six sound level analyzers were deployed at the BA-1 I-24 location, three each at the Barrier and No Barrier sites:

- A reference microphone located midway between the barrier and the edge of the roadway (BarRef01), and at a similar offset and height at the No Barrier location (NoBarRef02). The initial plan was to locate the reference microphones five feet above the top of the noise barrier at the Barrier site and at the same distance and height above the roadway at the No Barrier site. However, because of the noise barrier set-back, this first location gave a good opportunity, to study a point that clearly ought to be influenced by reflected noise with less masking by the direct traffic noise than the microphones across the road.
- Two "community" microphones on the opposite side of the road from the barrier at the Barrier site (BarCom03 and BarCom04) and the No Barrier site (NoBarCom05 and NoBarCom06).

Figure 4 shows the microphone positions at the I-24 location. The microphone positions were as shown in Table 4 as follows:

Table 4. I-24 microphone positions.

Mic Name	Side of Road	Distance from Center of Near Travel Lane (ft)	Height above Roadway Plane (ft)
BarRef01	EB	51*	10 (16 ft above ground, near midpoint of barrier)
NoBarRef02	EB	51*	10 (16 ft above ground)
BarCom03	WB	84	5 (9 ft above ground)
BarCom04	WB	84	15 (19 ft above ground)
NoBarCom05	WB	84	5 (9 ft above ground)
NoBarCom06	WB	84	15 (19 ft above ground)

*78 feet to barrier

Figure 5 shows cross-sections at the Barrier and No Barrier sites. Figure 6 shows photographs of each site.

A concrete median barrier at both the Barrier and No Barrier sites shielded the view of the vehicle tires and automobile engines and exhausts at the 5-ft high BarCom03 and NoBarCom05 microphones. It could have also shielded the BarCom03 microphone from some of the reflected noise.

The I-24 measurements were conducted from 13:13 to 17:20 on August 13, 2014 (all times are reported on a 24-hour clock). The weather was partly cloudy, with alternating periods of direct sun and clouds. Temperatures were in the upper-70° F range. Winds were calm to moderate, generally coming from the northeast through the northwest. The road runs in a northwest-to-southeast direction with the Com microphones on the northeast side of the road. Thus, most of the one-minute measurement periods were in an Upwind or Calm wind class.

Figure 4. I-24 microphone positions. (Source: Google Earth.)

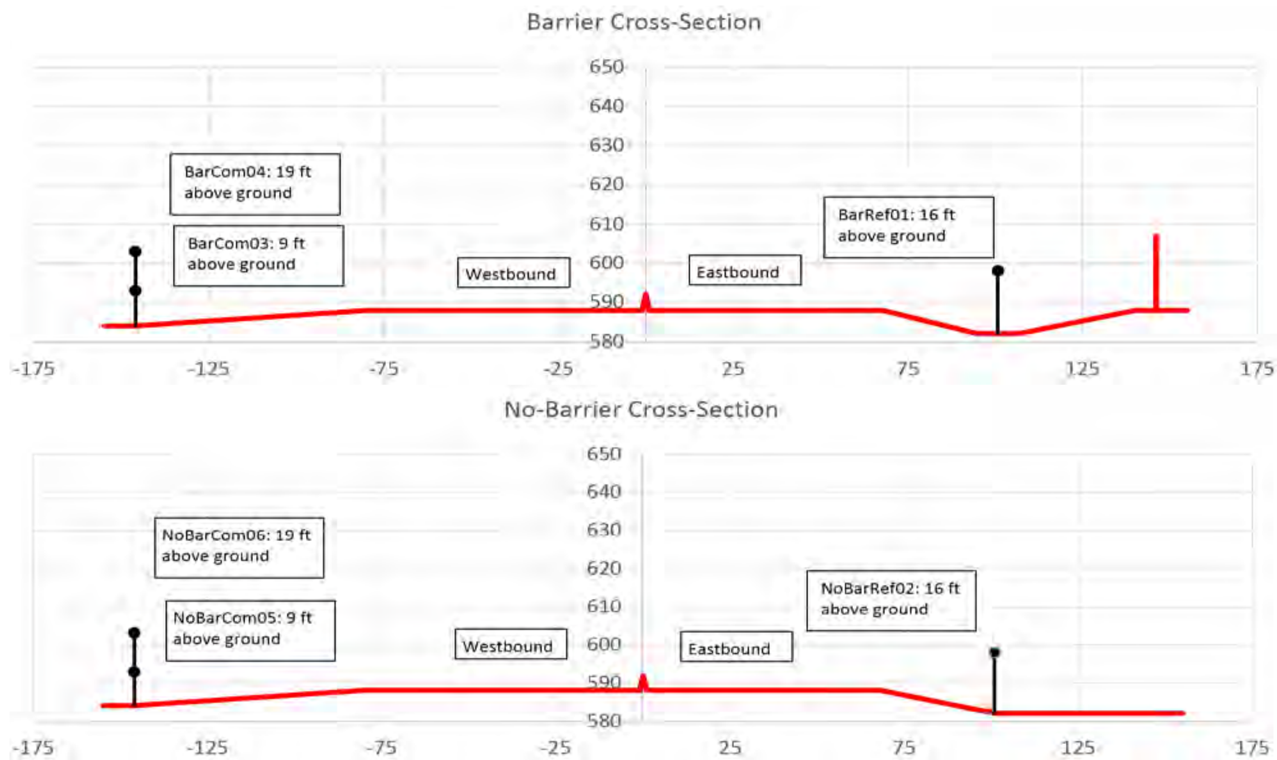

Figure 5. Cross-sections at the I-24 Barrier (top) and No Barrier (bottom) sites.

Figure 6. I-24 BarRef01 (top left), NoBarRef02 (top right), BarCom03 and BarCom04 (middle left), NoBarCom05 and NoBarCom06 (middle right), traffic video and speed (bottom left), meteorological station (bottom right). (Source: research team members.)

Briley Parkway (SR-155), Nashville, TN (Location BA-3)

Briley Parkway is a six-lane freeway located in Nashville, TN. It is has an asphalt (DGAC) roadway on fill (a retaining wall) and carries approximately 45,820 vehicles per day (Figure 7). The barrier here is 12 to 13 feet high and is cast-in-place concrete with no absorptive treatment. The barrier is relatively close to the road, located on the edge of the shoulder.

Figure 7. No Barrier (left) and Barrier BarRef01 (right) views at BA-3, Briley Parkway. (Source: research team members.)

Only five sound level analyzers were deployed at the Briley location. The No Barrier reference microphone (NoBarRef02) was not deployed because the road was on a retaining wall that was too tall to locate a microphone safely at the needed height above the roadway, and a microphone could not be placed safely on the road side of the barrier.

Because the Barrier and No Barrier sites were close together at the Briley location, it was felt that the No Barrier reference microphone was not essential for demonstrating source equivalence with the Barrier site. Also, within the FHWA Method, one use of the No Barrier reference microphone is to adjust the No Barrier community microphone levels by the difference between the Barrier and No Barrier reference sound levels. At the Briley location, the noise barrier is at the edge of a 10-ft wide shoulder. There was concern that any differences in the Barrier and No Barrier reference sound levels might be caused by sound reflections between truck trailer bodies and the noise barrier, not by differences in the noise sources themselves.

Figure 8 shows the microphone positions at the Briley location. The microphone positions were as shown in Table 5 as follows:

Table 5. Briley Parkway microphone positions.

Mic Name	Side of Road	Distance from Center of Near Travel Lane (ft)	Height Above Roadway Plane (ft)
BarRef01	EB	16	+18 (5 ft above top of barrier)
NoBarRef02	n/a	n/a	n/a
BarCom03	WB	91*	-14 (5 ft above ground)
BarCom04	WB	91*	+11 (12 ft above ground)
NoBarCom05	WB	91*	-14 (30 ft above ground)
NoBarCom06	WB	91*	+11 (37 ft above ground)

*To retaining wall, which was topped by a safety-shaped parapet at the edge of shoulder

Figure 9 shows cross-sections at the Barrier and No Barrier sites. Figure 10 shows photographs of each site. More photographs documenting each site are in Appendix C.

The Briley Parkway ("Briley") noise measurements and traffic speed measurements began at 17:04 on August 14 and ended at 21:04. Operator error caused no video to be recorded. The weather was mostly calm and warm, with afternoon temperatures in the low-80 degree range, dropping into the low-70 degree range after dark. Winds were calm throughout the measurement period.

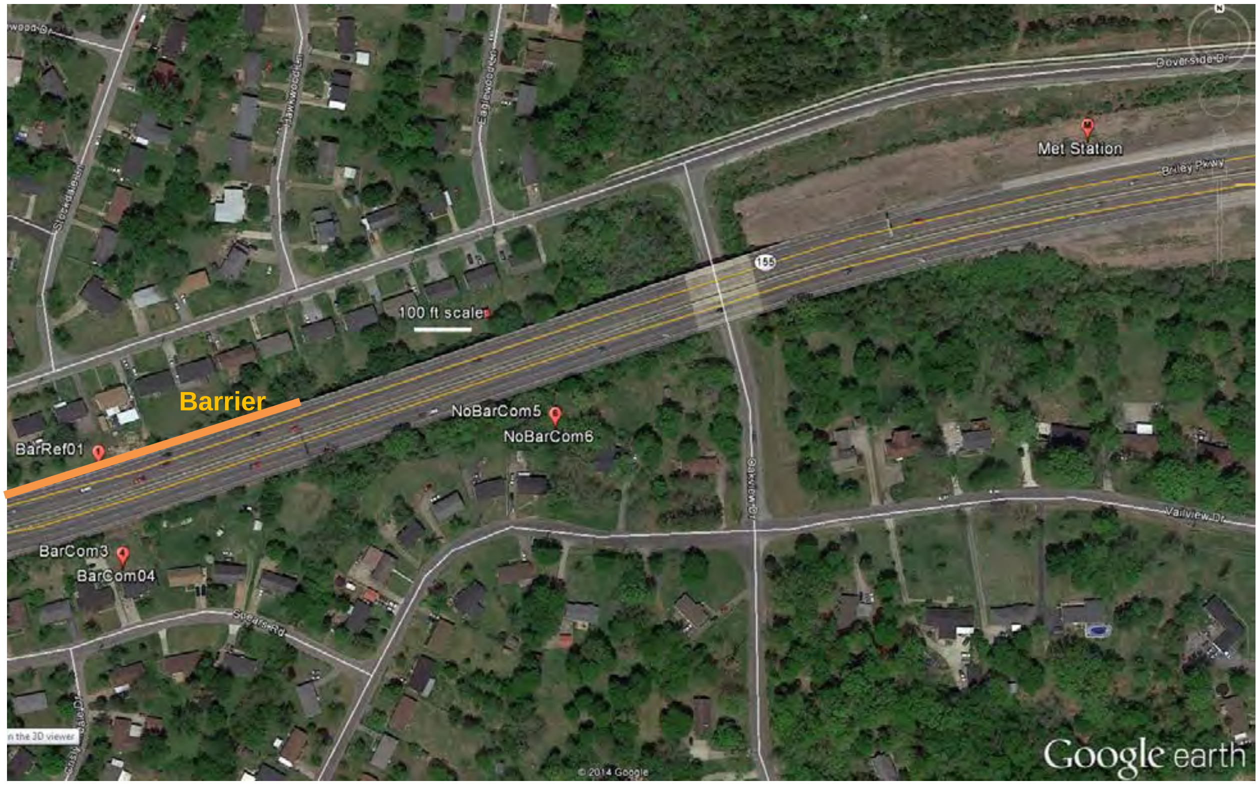

Figure 8. Briley microphone positions. (Source: Google Earth.)

The Briley Parkway location had a great deal of insect and tree frog noise as the late afternoon proceeded into the evening. The sound level data showed unusual results. The Briley Parkway data and results are discussed in detail in Appendix B, but were not used in developing the findings presented in this main report.

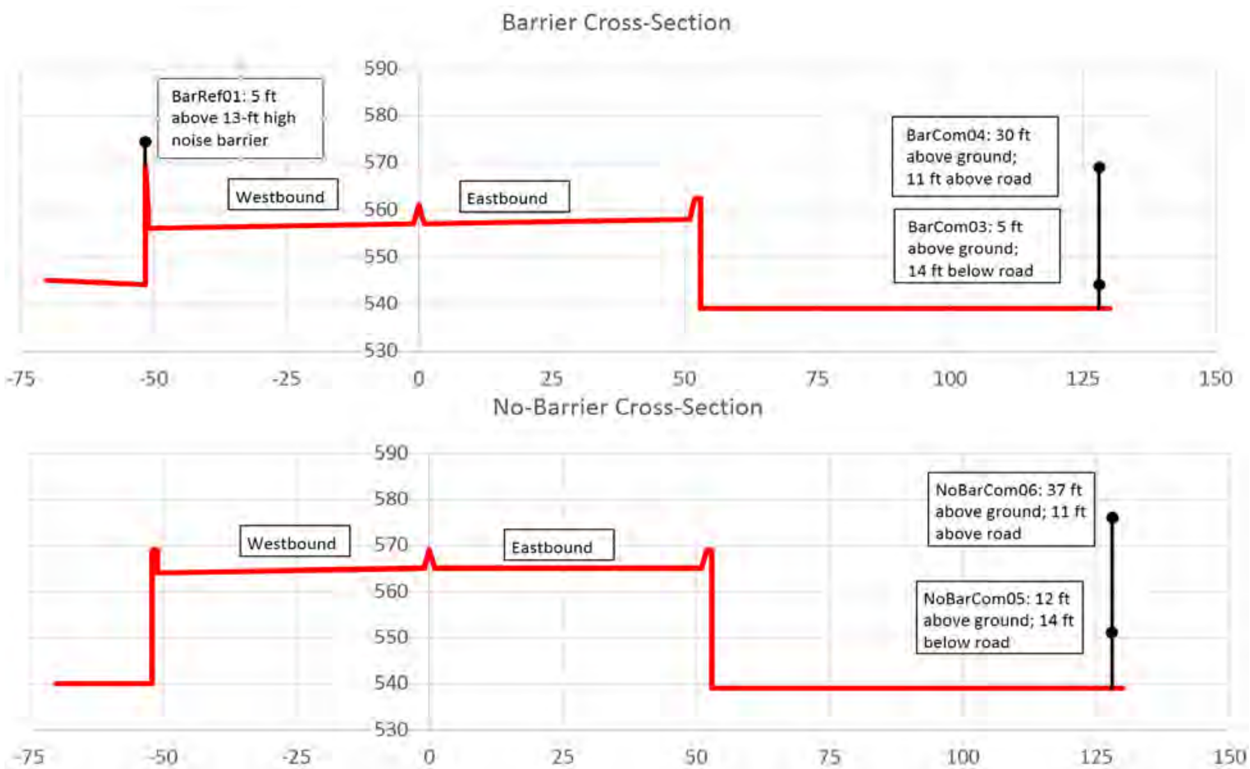

Figure 9. Cross-sections at the Briley Parkway Barrier (top) and No Barrier (bottom) sites.

Figure 10. Briley BarRef01 (top left and right), BarCom03 and BarCom04 (middle left), NoBarCom05 and NoBarCom06 (middle right), traffic video and speed (bottom left), meteorological station (bottom right). (Source: research team members.)

I-90, Rockford, IL (Location SID-1)

I-90 is part of the Illinois Tollway system and is a six-lane freeway with dense-graded asphalt pavement. It carries 53,500 vehicles per day with 9.7% trucks. The barrier is a reflective post-and precast concrete wall, located 20 ft from the center of the near travel lane. It is 15 ft tall. See Figure 11 for a roadside view of the barrier.

Figure 11. No Barrier (left) and Barrier (right) views at SID-1, I-90. (Source: research team members.)

The I-90 location in Rockford, IL and microphone positions are shown in Figure 12. The microphone positions are described in Table 6. The video camera and radar gun were located on the overpass located between the Barrier and No Barrier sites.

Table 6. I-90 microphone positions.

Mic Name	Side of Road	Distance from Center of Near Travel Lane (ft)	Height Above Roadway Plane (ft)
BarRef01	SB	20	20 (5 ft above barrier)
NoBarRef02	SB	20	20 (21 ft above ground)
BarCom03	NB	69	10.4 (6 ft 11 in above ground)
BarCom04	NB	93	17 (15.5 ft above ground)
NoBarCom05	NB	69	10.4 (5 ft above ground)
NoBarCom06	NB	93	17 (23.5 ft above ground)

Figure 13 shows cross-sections at the Barrier and No Barrier sites. Figure 14 shows photographs of each site. More photographs documenting each site are in Appendix C.

The I-90 measurements took place on Dec. 26, 2014. Setup started at 7:00 am and data collection was done from 13:00 to 17:30.

Figure 12. I-90 microphone positions. (Source: Google Earth.)

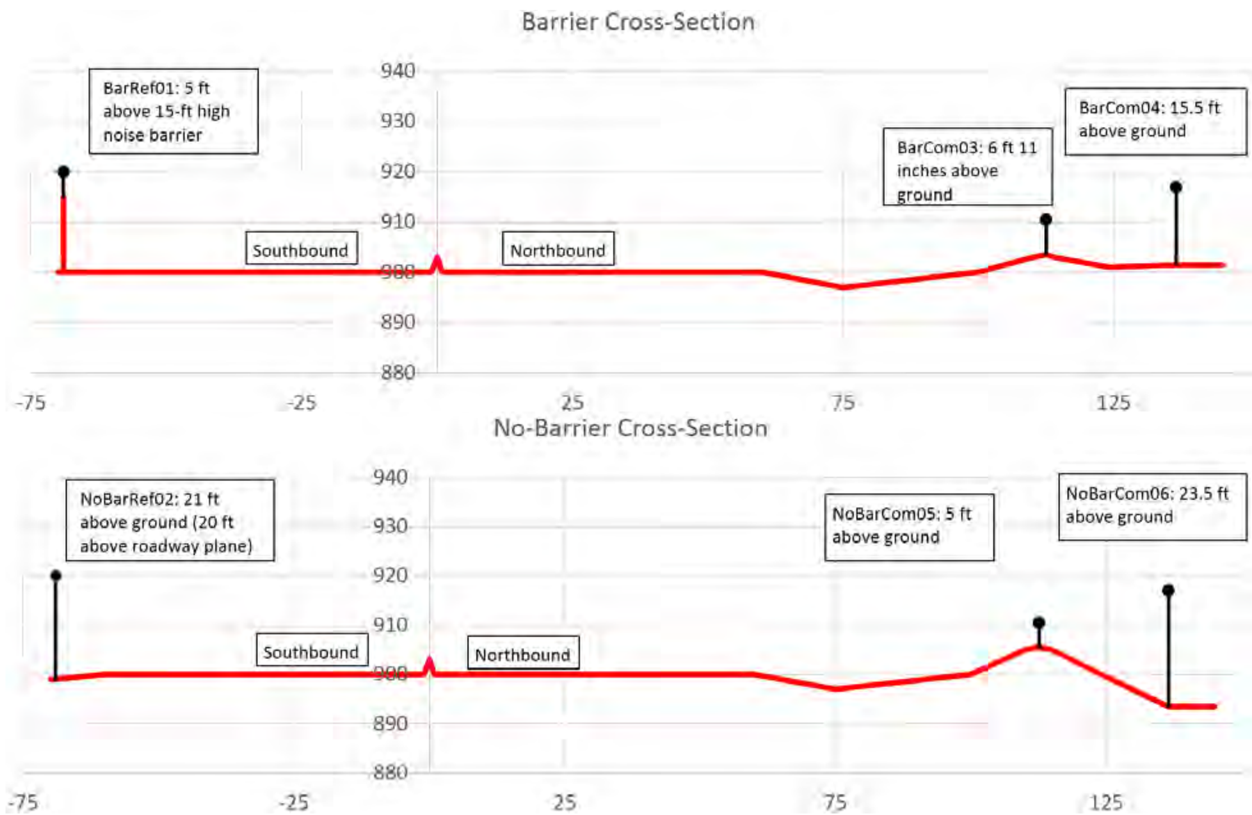

Figure 13. Cross-sections at the I-90 Barrier (top) and No Barrier (bottom) sites.

Figure 14. I-90 BarRef01 (top left), NoBarRef02 (top right), BarCom03 and BarCom04 (middle left), NoBarCom05 and NoBarCom06 (middle right), traffic video and speed (bottom left), meteorological station (bottom right) (Source: research team members)

SR-71, Chino Hills, CA (Location ATS-3)

SR-71 is a six-lane freeway in Chino Hills, CA, with longitudinally grooved concrete pavement. It carries 60,000 vehicles per day with 7% trucks. The barrier is 13 ft high, consisting of a 7-ft high reflective concrete block atop a 6-ft high earthen berm wall near the right-of-way line at distance of approximately 50 ft from the center of the near travel lane (see Figure 15).

Figure 15. No Barrier NoBarCom05 (left) and Barrier BarRef01 (right) views at ATS-3, SR-71. (Source: research team members.)

The microphone layout at the SR-71 location is shown in Figure 16. The SR-71 location consisted of six microphone positions, described in Table 7.

Table 7. SR-71 microphone positions.

Mic Name	Side of Road	Distance from Center of Near Travel Lane (ft)	Height Above Roadway Plane (ft)
BarRef01	NB	25	10 (10 ft above ground)
NoBarRef02	NB	25	10 (10 ft above ground)
BarCom03	SB	25	10 (10 ft above ground)
BarCom04	SB	400	~17 (10 ft above ground)
NoBarCom05	SB	25	10 (10 ft above ground)
NoBarCom06	SB	400	At least 5 ft (32 ft above ground)

The exact height of NoBarCom06 above the roadway plane is estimated, since elevation data for the ground could not be obtained. By observation in the field looking from the road, the microphone was at least 5 ft above the roadway plane. While having identical heights above the road would be ideal, simplified TNM modeling described in the spectrogram section gave an indication that any effect of the height difference would be minimal in the main frequencies of interest for traffic noise.

It should be noted that the far microphone at the Barrier site (BarCom04) was offset from the near-roadway microphone line. Both the near-roadway microphones and far microphone were strategically placed for the most meaningful comparisons to the No Barrier data. The parameters considered in the placement were: region of barrier influence (consideration of the end of the barrier for the far microphone position) and intervening ground (e.g., if the close microphones were placed in line with the far microphone, the ground between the highway noise source and BarCom03 would have included more pavement than for NoBarCom05 due to a merge lane; the close microphones were shifted south of where the merge lane ends).

Figure 17 shows cross-sections at the Barrier and No Barrier sites. Figure 18 and Figure 19 shows photographs of each site. Figure 19 shows traffic speed data collection, traffic count video, and the meteorological station for this site. More photographs are in Appendix C.

On January 28, 2015, data were successfully collected at the SR-71 location from about 9:00 to 13:30, with a 15 to 20 minute break in the middle for battery changes. There were calm winds in the morning and some stronger winds toward the end.

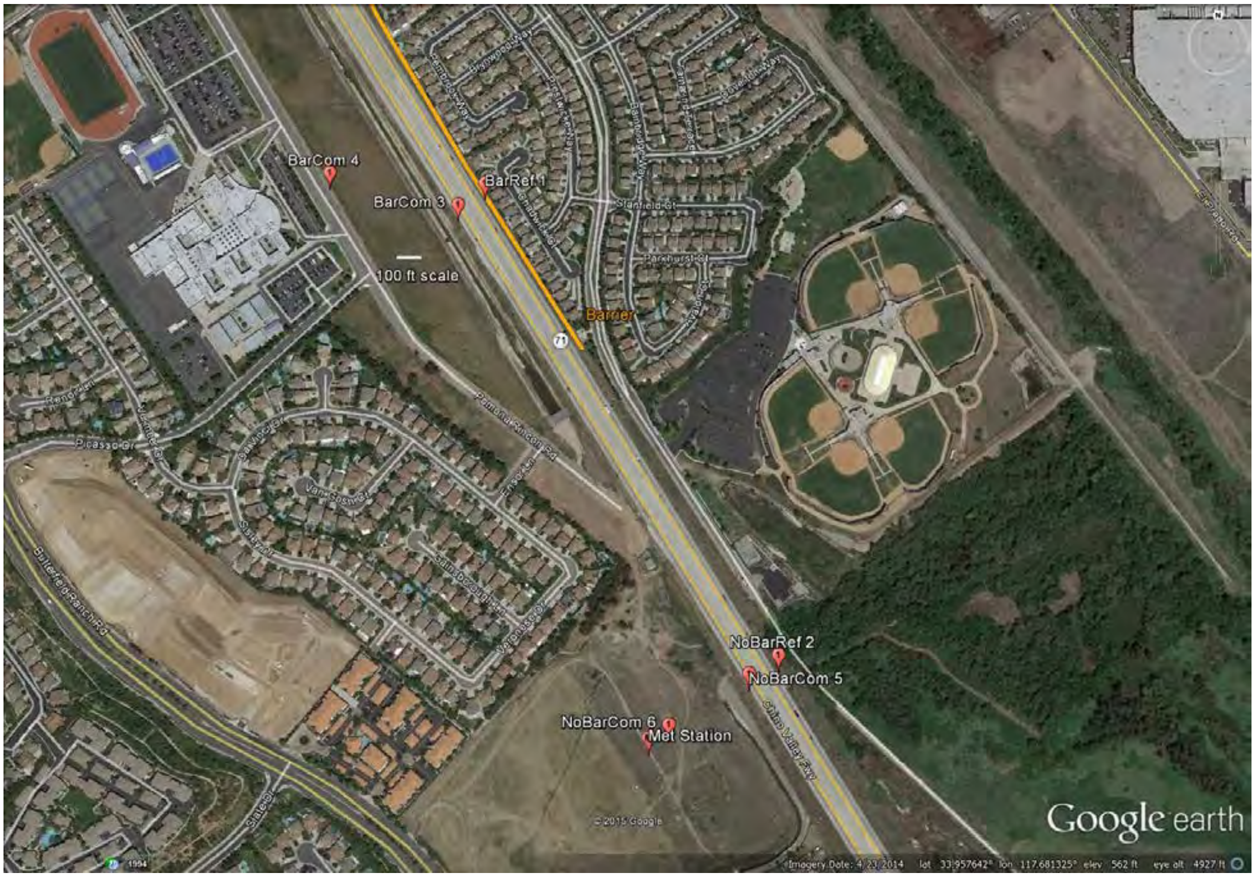

Figure 16. SR-71 microphone positions. (Source: Google Earth.)

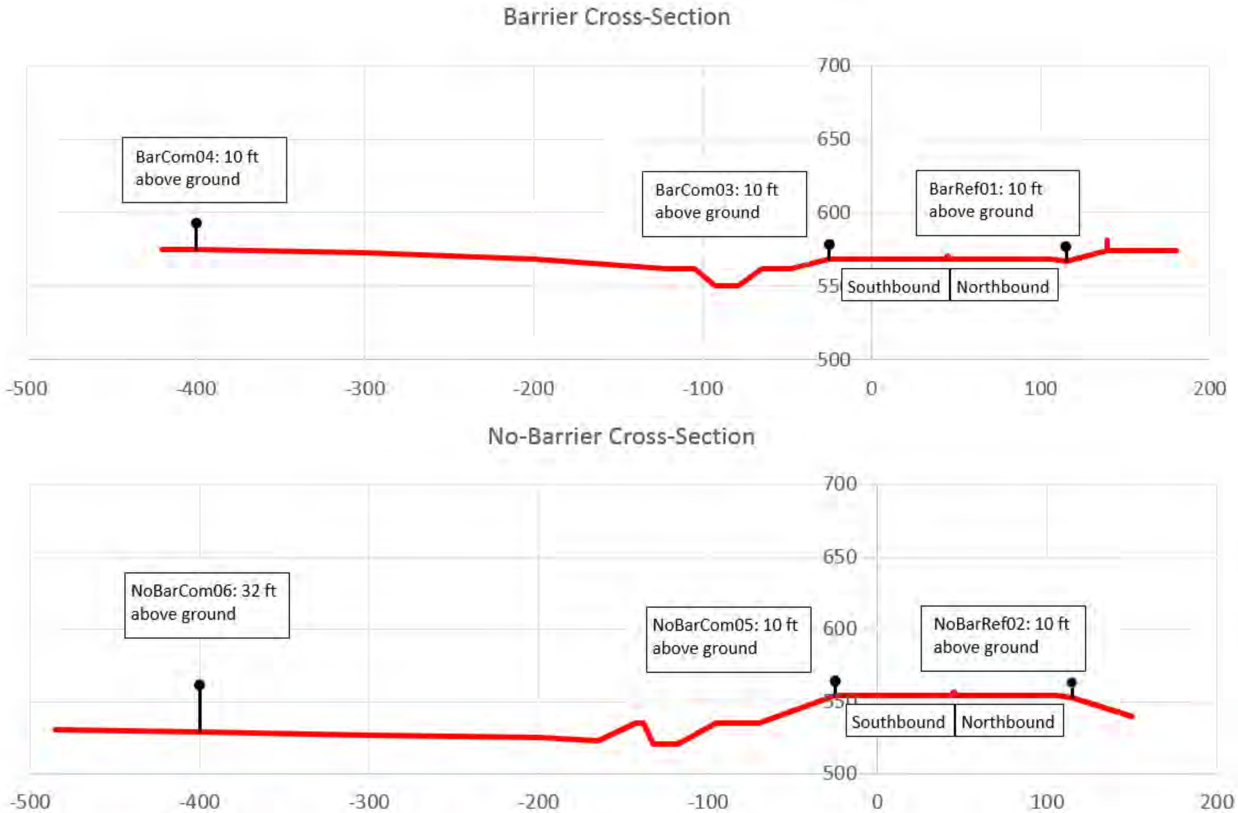

Figure 17. Cross-sections at the SR-71 Barrier (top) and No Barrier (bottom) sites.

Figure 18. SR-71 BarRef01 (top left), NoBarRef02 (top right), BarCom03 (middle left), BarCom04 (middle right), NoBarCom05 (bottom left), and NoBarCom06 (bottom right). (Source: research team members.)

Figure 19. SR-71 BarRef01 Traffic speed (top left), traffic count video (top right), meteorological station (bottom left). (Source: research team members.)

MD-5, Hughesville, MD (Location EA-5)

MD Route 5 (MD-5) is a four-lane arterial freeway with dense-graded asphalt pavement. It carries 34,200 vehicles per day with 8% trucks. The 16 ft tall barrier is a reflective post-and-panel precast place concrete wall, located approximately 9 ft from the edge of the near travel lane (see Figure 20). This road carries relatively light traffic in the nighttime hours and was studied in the evening as well as the daytime in an attempt to measure individual vehicle passages.

Figure 20. No Barrier NoBarCom05 and NoBarCom06 (left) and Barrier from meteorological station (right) views at EA-5, MD Route 5. (Source: research team members.)

At the MD-5 location, the project team set up six microphone positions, as shown in Figure 21 and detailed in Table 8. In addition to the microphones, a 15 ft meteorological tower was set up, vehicle speed was measured by laser, and traffic was video recorded.

Table 8. MD-5 microphone positions.

Mic Name	Side of Road	Distance from Center of Near Travel Lane (ft)	Height Above Roadway Plane (ft)
BarRef01	SB	15	17.5 (5 ft above barrier)
NoBarRef02	SB	18	17.5 (18 ft above ground)
BarCom03	NB	80	5 (9 ft 3 in above ground)
BarCom04	NB	80	15 (19 ft 3 in above ground)
NoBarCom05	NB	69	7 (5 ft above ground)
NoBarCom06	NB	69	17 (15 ft above ground)

Figure 22 shows cross-sections at the Barrier and No Barrier sites. Figure 23 shows photographs of each site. More photographs documenting each site are in Appendix C.

The measurements at were conducted on June 9, 2015. Two periods were measured. The first, between 12:00 and 16:10 allowed for higher volume commuting traffic. The second, between 19:40 and 23:50 allowed for lower traffic volumes and greater sensitivity to individual vehicle passbys.

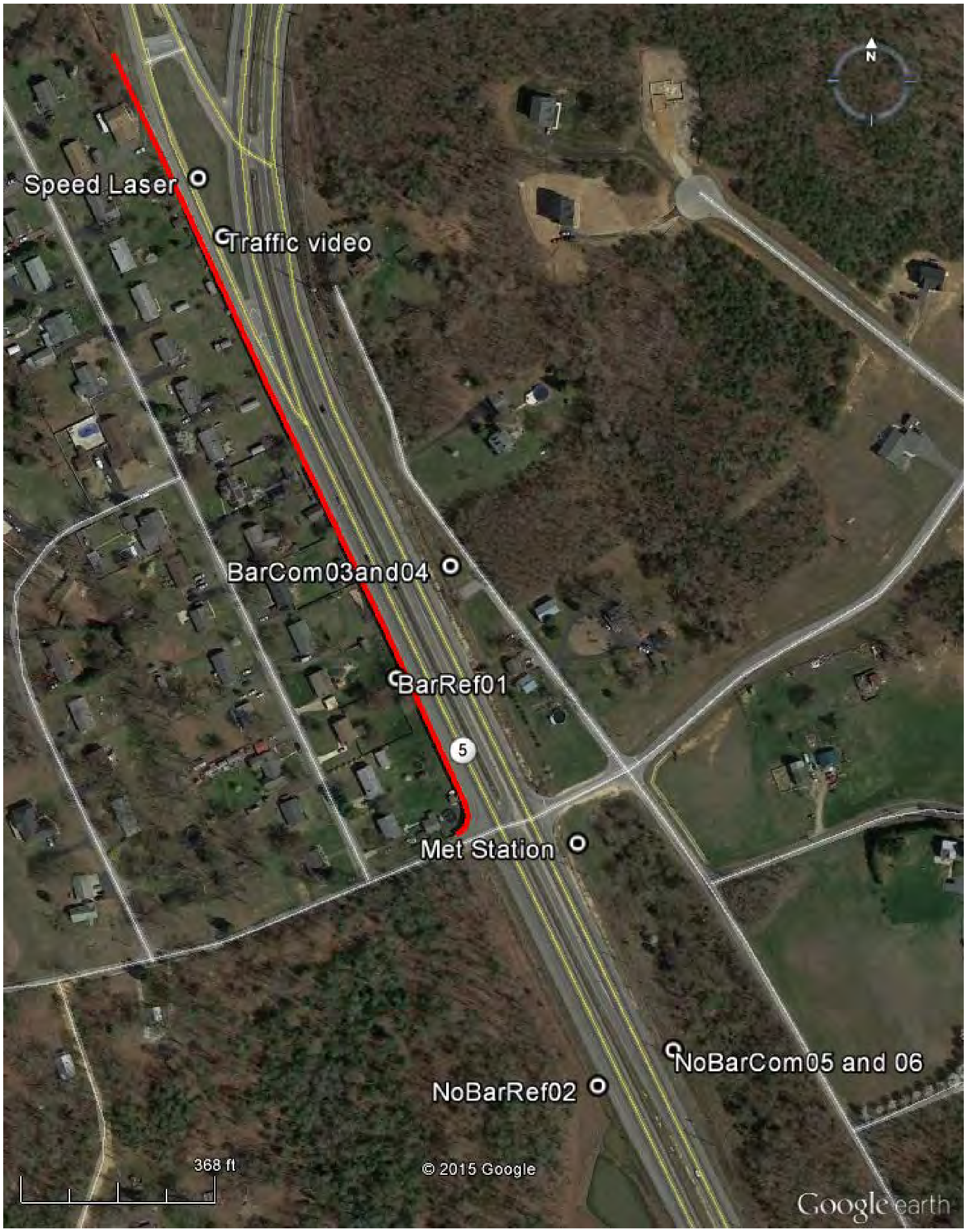

Figure 21. MD-5 microphone positions. (Source: Google Earth.)

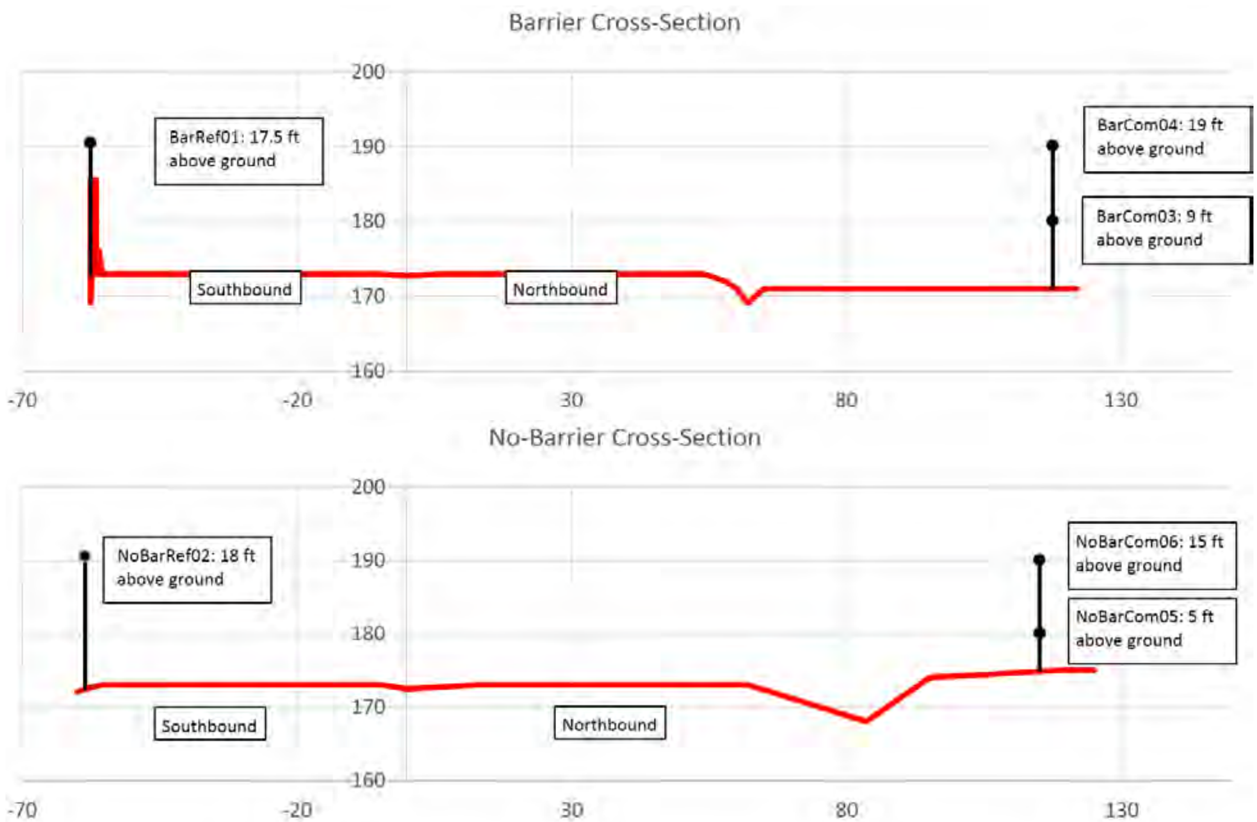

Figure 22. Cross-sections at the MD-5 Barrier (top) and No Barrier (bottom) sites.

Figure 23. MD-5 BarRef01 (top left), NoBarRef02 (top right), BarCom03 and BarCom04 (middle left), NoBarCom05 and NoBarCom06 (middle right), traffic speed (bottom left), traffic video (bottom middle), meteorological station (bottom right) (Source: research team members).

Summary of Microphone Positions

For reference, Table 9 summarizes the microphone heights and distances from the road at each location.

Table 9. Distance (ft) from microphone to Center of Near Travel Lane and barrier.

Microphone name	Distance (ft)									
	I-24		Briley		I-90		SR-71		MD-5	
	Travel Lane	Bar	Travel Lane	Bar	Travel Lane	Bar	Travel Lane	Bar	Travel Lane	Bar
BarRef01	33	45	0	0	4	0	9	19	2	0
NoBarRef02	33	45	n/a	n/a	4	0	9	19	3	0
BarCom03	66	285	75	180	53	180	9	165	64	175
BarCom04	66	285	75	180	77	205	384	540	64	175
NoBarCom05	66	285	75	180	53	180	9	165	53	175
NoBarCom06	66	285	75	180	77	205	384	540	53	175

Table 10. Microphone heights (ft) from ground (GND) and roadway (RD).

Microphone name	Distance (ft)									
	I-24		Briley		I-90		SR-71		MD-5	
	GND	RD	GND	RD	GND	RD	GND	RD	GND	RD
BarRef01	16	10	23	18	20	20	10	10	17.5	17.5
NoBarRef02	16	10	n/a	n/a	21	21	10	10	18	17.5
BarCom03	9	5	5	-14	6.9	10.4	10	10	9.3	5
BarCom04	19	15	12	11	15.5	17	10	17	19.3	15
NoBarCom05	9	5	30	-14	5	10.4	10	10	5	7
NoBarCom06	19	15	37	11	23.5	17	32	5	15	17

CHAPTER 4

Findings and Applications

FHWA Method Findings

Data were collected under a fair range of meteorological classes, as shown in Table 11, with the number of equivalent five-minute period groupings by site by meteorological class. A grouping represents three or more five-minute periods with equivalent source data (based on the reference microphone level and the average speed by direction of travel) and meteorological class. Reference will be made to the meteorological class as appropriate in the discussion of the findings.

Table 11. Number of equivalent groupings by location by meteorological class.

Meteorological Class	Number of equivalent groups				
	I-24	Briley	I-90	SR-71	MD-5
Upwind Lapse	31				
Calm Lapse	13	4			
Calm Neutral	4	4	4		10
Calm Inversion		31			15
Downwind Lapse			12		15
Downwind Neutral				6	7
Total	**48**	**39**	**16**	**6**	**47**

Based on the data collected and analyses procedures described above, the findings are outlined individually below.

Finding 1: Measured broadband unweighted sound pressure levels and A-weighted sound levels are generally higher at the Barrier microphones than at the No Barrier microphones.

As a first step in analyzing the data, the running L_{eq}(5min) for each microphone pair at Barrier and No Barrier sites were graphed and level difference plots developed. These graphs and analysis give an overall picture of the measured levels, both in terms of unweighted and A-weighted sound levels. These graphs are prior to any grouping of the five-minute periods by source and meteorological class equivalence.

As an example, the BarRef01 and NoBarRef02 levels at I-24 are shown in Figure 24 (unweighted). Then, Figure 25 shows the differences in both the unweighted and A-weighted levels for this microphone pair. A positive value means the Barrier level was higher than the No Barrier level. Similar graphs for all microphone pairs at all locations are in Appendix B.

Table 12 presents the approximate range of differences in the Barrier and No Barrier running L_{eq}(5min) for all of these pairs. These ranges are termed "approximate" because the data are prior to any attempt to group the five-minute periods into equivalent periods based on source and meteorological class. Since the MD-5 data were collected in two separate periods, ranges for both daytime and nighttime are shown for MD-5. Level differences are shown for both unweighted and A-weighted data. In general, the ranges in the differences were generally greater for the unweighted levels than for the A-weighted levels. The reason is probably due to the sampling including 1/3 octave bands ranging from 20 Hz to 10 kHz. There tends to be more variation in levels in the very low and high bands—from sources ranging from heavy trucks on to insects—which would affect a broadband unweighted level but get filtered out of broadband A-weighted level calculation. Each location is discussed below.

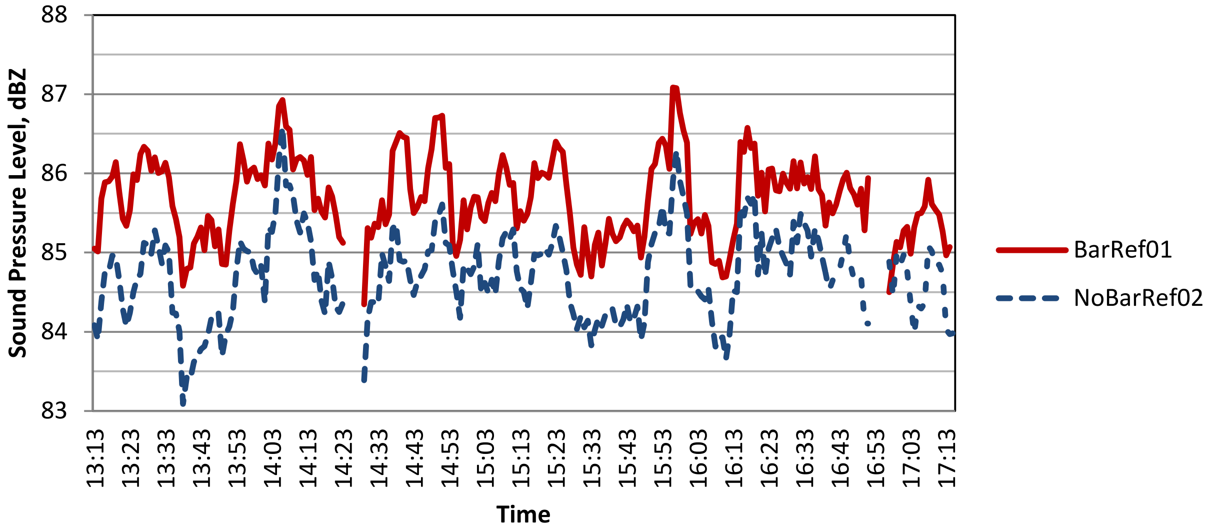

Figure 24. Running L_{eq}(5min), I-24, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

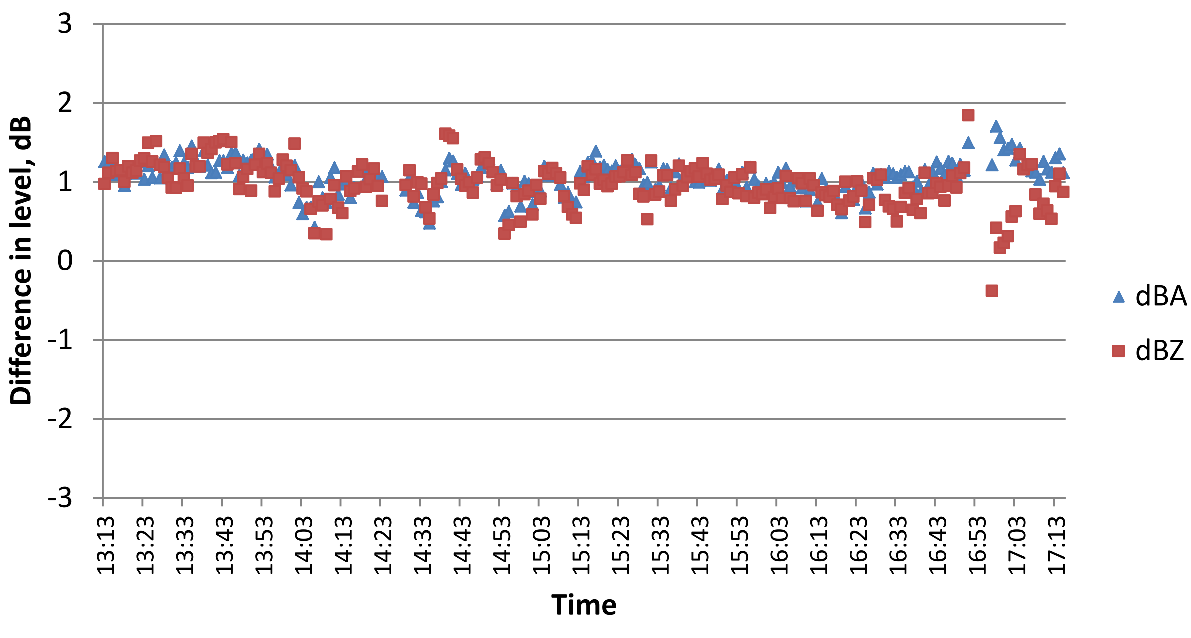

Figure 25. Differences in running L_{eq}(5min), I-24, BarRef01 minus NoBarRef02.

Table 12. Approximate range of differences in the Barrier and No Barrier running five-minute L_{eq} for all locations (Barrier minus No Barrier).

Microphone Pair	Type of Level	Approximate Range of Level Differences by Location (dB)					
		I-24	Briley	I-90	SR-71	MD-5 (day)	MD-5 (night)
BarRef01 minus NoBarRef02	Unweighted	0.5 to 1.5	n/a	0 to 1	0 to 1.8	-1 to 1.8	-2 to 2.2
	A-weighted	0.5 to 1.5	n/a	0 to 1	0 to 1	-0.5 to 0.5	-1.5 to 0.7
BarCom03 minus NoBarCom05	Unweighted	0 to 1	0 to 2	0 to 1.5	-0.9 to 1	-1 to 2	-2 to 1.5
	A-weighted	0 to 1	-3 to -1	0.4 to 1.3	-0.7 to 0.5	0.5 to 2.4	0 to 1.5
BarCom04 minus NoBarCom06	Unweighted	0 to 0.5	-1 to 1	-0.7 to 1.5	0 to 4	-0.5 to 1.8	-1 to 2
	A-weighted	-0.5 to 0.5	-1.5 to 0.5	0.2 to 1	1 to 3.9	-0.5 to 1	-0.5 to 1

I-24

For virtually all of the running L_{eq}(5min) periods, the BarRef01 levels, both unweighted and A-weighted, were higher than the NoBarRef02 levels by a range of 0.5 to 1.5 dB. These higher levels were expected because the BarRef01 microphone was located halfway between the barrier and I-24.

For a large majority of the running L_{eq}(5min) periods at the community lower microphones, the BarCom03 levels, both unweighted and A-weighted, were higher than the NoBarCom05 levels by a range of 0.0 to 1.0 dB, with some differences as much as 1.5 dB.

For most of the running L_{eq}(5min) periods at the upper microphones, the BarCom04 levels, both unweighted and A-weighted, were higher than the NoBarCom06 levels by a range of 0.0 to 0.5 dB, with some differences as much as 1.0 dB. For the other periods, the A-weighted levels at NoBarCom06 are 0 dB to 0.5 dB *higher* than the BarCom04 levels.

Briley

In general, the running L_{eq}(5min) decreased over time as the traffic decreased from the evening rush hour into the later evening. At the lower microphones, the unweighted sound pressure levels at BarCom03 were typically higher than at NoBarCom05, from a few tenths of a decibel to just over 2 dB. However, the A-weighted sound levels at BarCom03 were generally 1.5 dB to 2 dB *lower* than the NoBarCom05 levels in the first three hours of the measurement and 2 dB to 3 dB *lower* in the last hour.

The results were different for the upper microphones. The differences in the unweighted sound pressure levels at BarCom04 and NoBarCom06 varied from positive to negative over most of the measurement period and became generally negative (NoBarCom06 *higher* than BarCom04) later in the evening. The A-weighted sound levels at NoBarCom06 tend to be slightly higher than at BarCom04 in the early part of the measurement, with the difference increasing as the measurement period moved later into the evening. Insect and frog noise from trees near NoBarCom05 and NoBarCom06 became major sound contributors starting early in the evening.

I-90

For the reference microphones, both the unweighted and A-weighted running L_{eq}(5min) at BarRef01 were on the order of 0 dB to 0.5 dB above the NoBarRef02 levels for the first two hours of measurement (13:00 to 15:00). For the second half of the measurements (15:00 to 17:20), this difference increased to a range of 0.5 dB to 1.0 dB. The BarRef01 microphone was located atop the barrier and the barrier was just off the shoulder. It is speculated that the slightly higher levels at BarRef01 could be due to sound reflections off the barrier and then off the sides of the vehicles back to the microphone, especially for tractor trailer bodies.

At the lower community microphones, for all of the running L_{eq}(5min) periods, the BarCom03 unweighted sound pressure levels were on the order of 0 dB to 1.5 dB higher than the NoBarCom05 levels. For the A-weighted sound levels, the BarCom03 levels were on the order of 0.4 dB to 1.3 dB higher than the NoBarCom05 levels.

At the upper and slightly farther back microphones, for most of the running L_{eq}(5min) periods, the BarCom04 unweighted levels ranged from 0.7 dB lower than NoBarCom06 to 1.5 dB higher. The A-weighted levels ranged from 0.2 dB to 1 dB higher.

At all of the microphones, as time passed the L_{eq}(5min) dropped slowly, on the order of 1 dB to 2 dB, over the 4-hour period. In this same time period the differences in levels between the Barrier and No Barrier microphone pairs increased on the order of a half decibel.

SR-71

For the reference microphones, the unweighted running L_{eq}(5min) at BarRef01 were on the order of 0 dB to 1.8 dB higher than the NoBarRef02 levels, averaging roughly 1 dB higher. The A-weighted levels at BarRef01 were on the order of 0 dB to 1 dB higher than NoBarRef02, averaging roughly 0.5 dB. Higher levels at BarRef01 were expected because the microphone was positioned between the barrier and the road.

For the microphones just off the shoulder on the opposite side from the barrier, little evidence of reflection was seen in these broadband data. The unweighted running L_{eq}(5min) at BarCom03 ranged from 0.9 dB *lower* to 1 dB higher than those at NoBarCom05. The A-weighted running L_{eq}(5min) at BarCom03 ranged from 0.7 dB *lower* to 0.5 dB higher than those at NoBarCom05. With these microphones so close to the far lanes of traffic, relative to the distance from BarCom03 to the barrier, little increase in level due to reflections was expected.

At the distant community microphones, for virtually all of the running L_{eq}(5min) periods, the BarCom04 levels, both unweighted and A-weighted, were higher than the NoBarCom06 levels. The unweighted levels ranged mostly from 0 dB to 4 dB higher than NoBarCom06. The A-weighted levels ranged from 1 dB to nearly 4 dB higher. For both unweighted and A-weighted cases, the average difference was 2.1 dB higher at BarCom04.

MD-5

For the reference microphones, the running L_{eq}(5min) at BarRef01 and NoBarRef02 are roughly comparable. Unweighted levels at BarRef01 ranged mostly from 2 dB *below* NoBarRef02 levels to 2.2 dB above them. A-weighted levels were within ±0.5 dB of each other during the afternoon session. However, due to frog noise near NoBarRef02, its evening A-weighted levels were generally *higher* than the BarRef01 levels. Little difference in the levels was expected because the BarRef01 microphone was positioned atop the barrier, although reflections off the vehicle bodies might increase its levels, as was discussed for the I-90 location.

For the lower community microphones opposite the barrier, the daytime unweighted running L_{eq}(5min) at BarCom03 ranged from 1.0 dB *lower* to 2 dB higher than those at NoBarCom05. The daytime A-weighted levels at BarCom03 generally ranged from 0.5 dB to 2.4 dB higher than those at NoBarCom05. In the evening, the unweighted levels at the two microphones were roughly within -2 dB to 1.5 dB of each other. The BarCom03 A-weighted levels ranged mostly from 0 dB to 1.5 dB higher than the NoBarCom05 levels.

For most of the running L_{eq}(5min) periods during both the afternoon and evening, the BarCom04 levels were higher than the NoBarCom06 levels. The unweighted L_{eq}(5min) generally ranged from 0.5 dB lower to 1.5 dB higher during the day and -1 dB lower to 2 dB higher during the evening. The A-weighted levels ranged from 0.5 dB lower to 1 dB higher than NoBarCom06 during both daytime and nighttime.

Finding 2: The differences in Barrier and No Barrier levels are frequency-specific and vary by location and site. There are clear examples of enhanced levels opposite the barrier compared to the corresponding No Barrier position.

To see the differences by frequency band more clearly, graphs were developed that show the differences in L_{eq}(5min) between comparable microphones for an average of all of the equivalent five-minute periods in a particular meteorological class, with their error bars. The error bars are +/- one standard deviation for each average value.

Each graph shows the averages of the average level differences for the A-weighted sound level, the unweighted sound pressure level and the 1/3 octave band sound pressure levels from 20 Hz to 10 kHz. Similar plots for each group of equivalent five-minute periods are in spreadsheet files in the project record.

The trends across the 1/3 octave band frequencies are generally similar in these individual groups of equivalent periods, with some differences likely related to background noise and the uniqueness of vehicle noise sources in the five-minute periods in each group.

Shown in Figure 26 is a sample plot of sound pressure level spectra for the MD-5 BarCom03 and NoBarCom05 microphones. Then, shown in Figure 27 is the frequency-based average level difference graph for all of the equivalent groups in the Calm Inversion class. There are higher levels at BarCom03 in the bands from 200 Hz to 500 Hz (with the maximum at 5 dB higher at 250 Hz and 315 Hz), as well as 0.5 dB to 1 dB higher levels in the 800 Hz to 2.5 kHz bands. The 4 kHz band is 6 dB higher at NoBarCom05 than BarCom03 due to localized frog noise. The large barrier effect in the 200 Hz to 500 Hz bands in Figure 27 is evidence of a loss of some of the ground effects in these bands that is indicated by the “dip” in the No Barrier spectrum in Figure 28. More is said on this effect in Finding 8.

More examples will be shown in the findings that follow, and a complete location-by-location presentation of all of the results is in Appendix B.

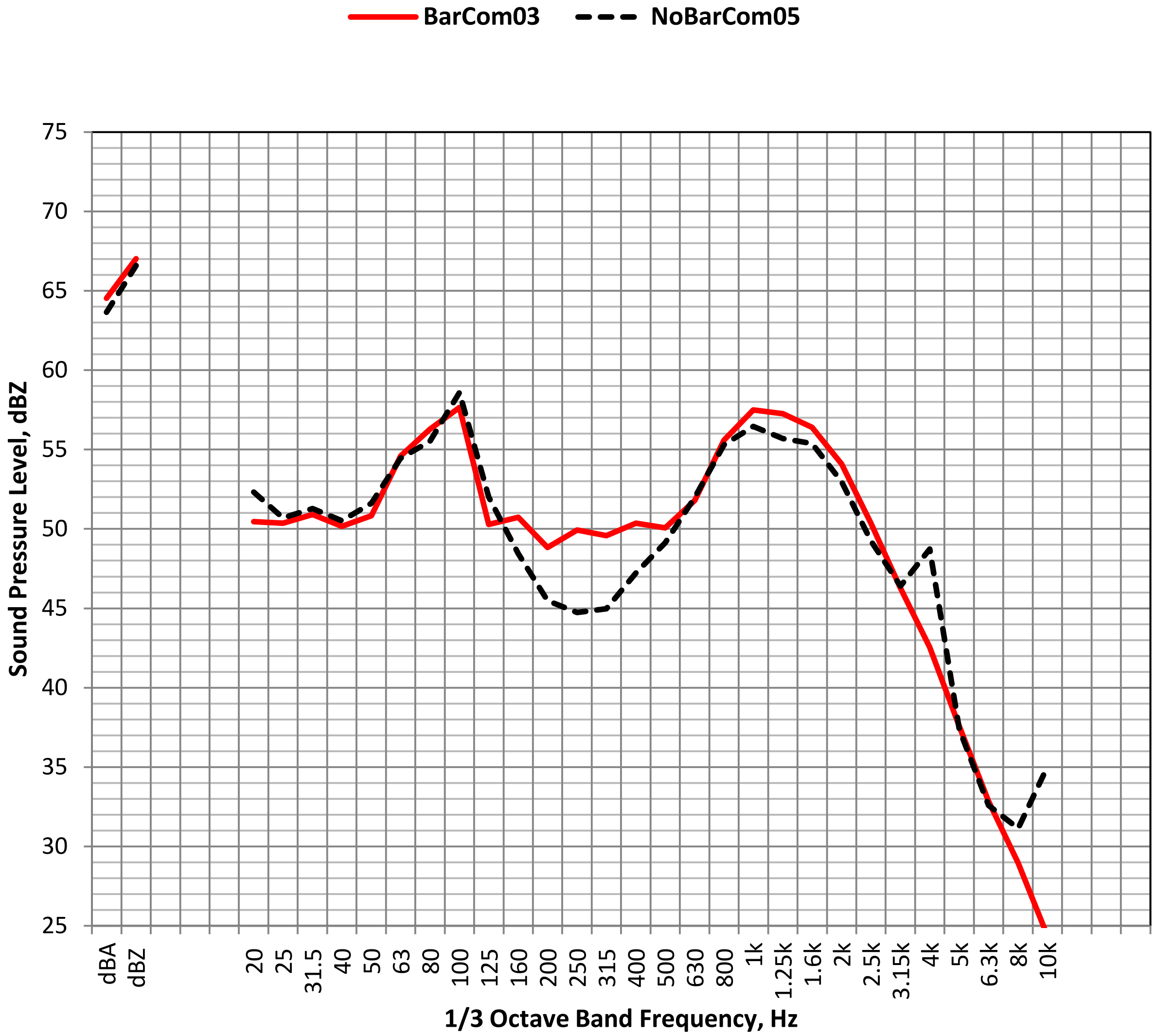

Figure 26. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Calm Inversion Group CIG-3-4, 23:15 (L_{eq}(5min), dBZ).

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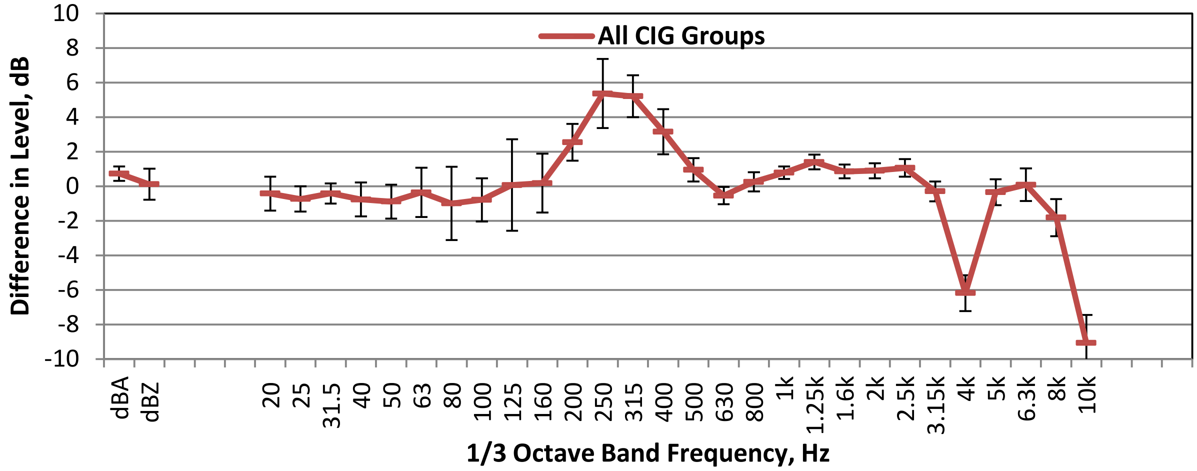


Figure 27. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Inversion groups, MD-5.

Finding 3: Sound levels are higher and spectral content changes at a position between the barrier and the road, compared to the No Barrier site, as evidenced at I-24 and SR-71.

At I-24 and SR-71, the BarRef01 microphones were set midway between the roadway and the noise barrier. As described in Section 3, the SR-71 barrier is 13 ft tall, consisting of a 7-ft concrete block wall atop a 6-ft high berm and located 50 ft from the center of the near travel lane; the BarRef01 microphone was set 25 ft from the center of the near travel lane and 10 feet above the roadway plane. At I-24, the barrier is 19 feet tall approximately 96 ft from the center of the near travel lane. The BarRef01 microphone was set 51 ft from the center of the near travel lane (33 ft from the edge of shoulder) and 45 ft in front of the barrier at a height of 10 ft above the roadway plane. At both locations, the microphones were in the paths of reflected sound.

Figure 28 shows the ungrouped running five-minute A-weighted L_{eq} data for BarRef01 and NoBarRef02 at I-24. Earlier, Figure 24 showed the unweighted L_{eq} data for the same. Figure 29 shows the differences plots for both the A-weighted and unweighted levels for the same periods. Figure 30 then shows the differences plot for the SR-71 reference microphones' running five-minute L_{eq} data. At both locations, BarRef01 A-weighted and unweighted levels are higher than at NoBarRef02 by 0.5 dB to 1.5 dB.

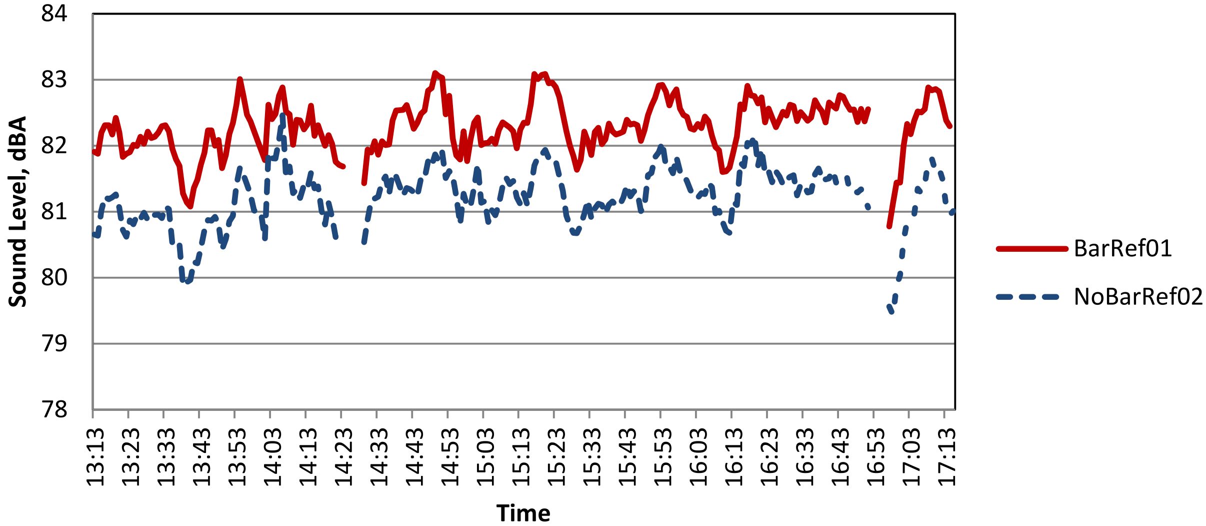


Figure 28. Running L_{eq}(5min), I-24, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

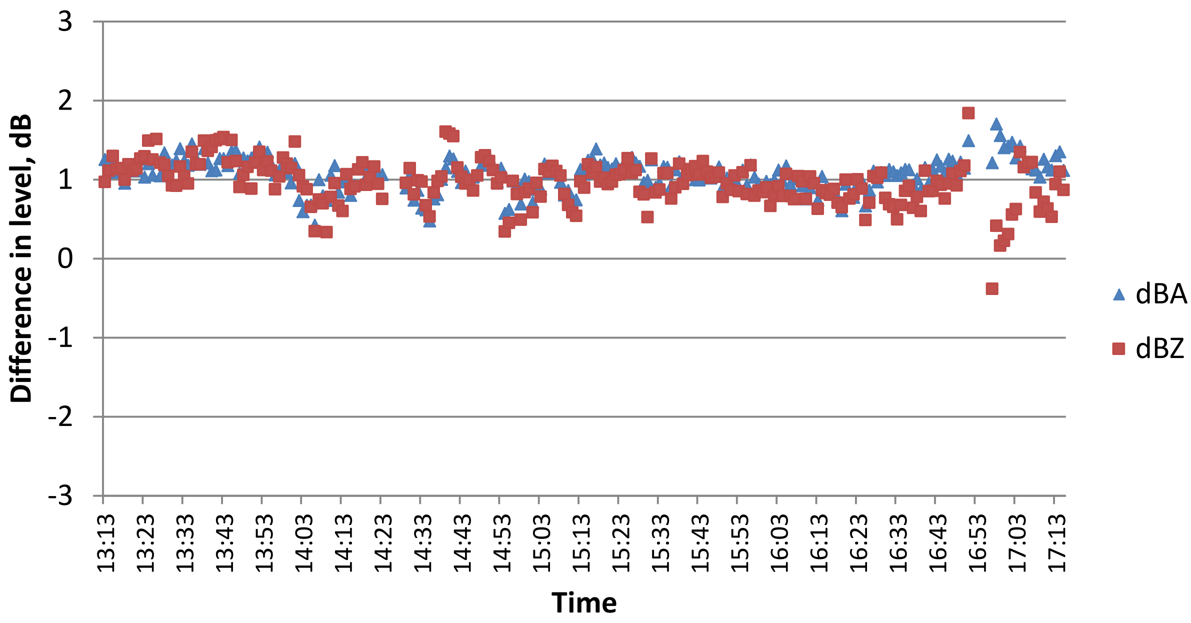


Figure 29. Differences in running L_{eq}(5min), I-24, BarRef01 minus NoBarRef02.

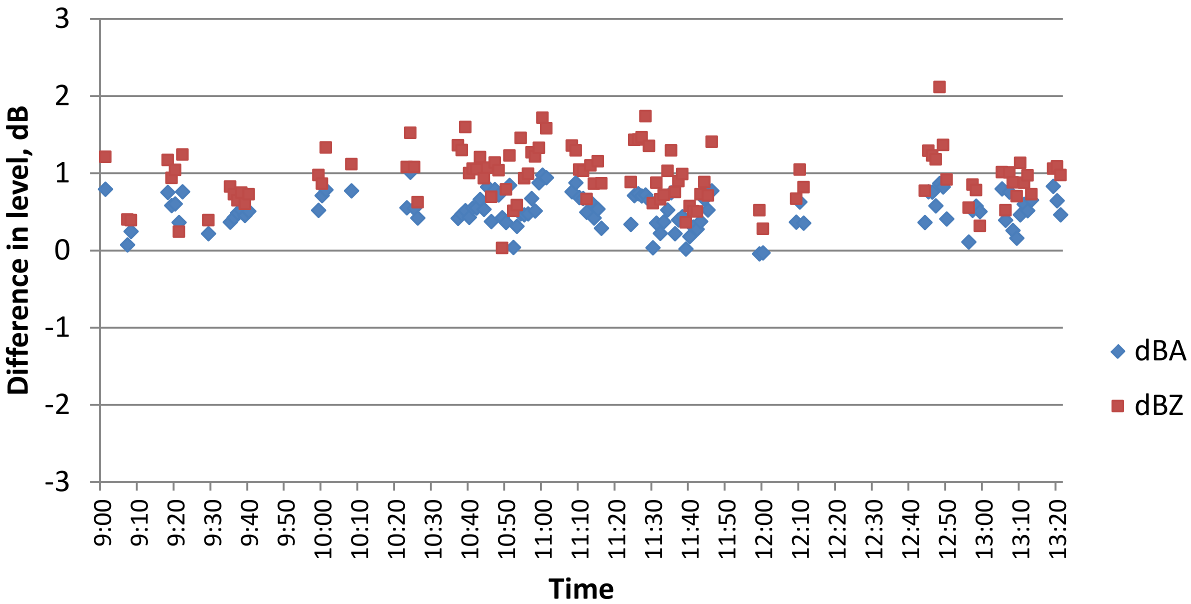


Figure 30. Differences in running L_{eq}(5min), SR-71, BarRef01 minus NoBarRef02.

Figure 31 and Figure 32 then show typical sound pressure level spectra respectively, for I-24 (an Upwind Lapse five-minute period) and SR-71 (a Downwind Neutral five-minute period). The broadband A-weighted and unweighted levels are on the left side of the graphs. Both sets of spectra show that the Barrier and No Barrier differences are frequency-specific.

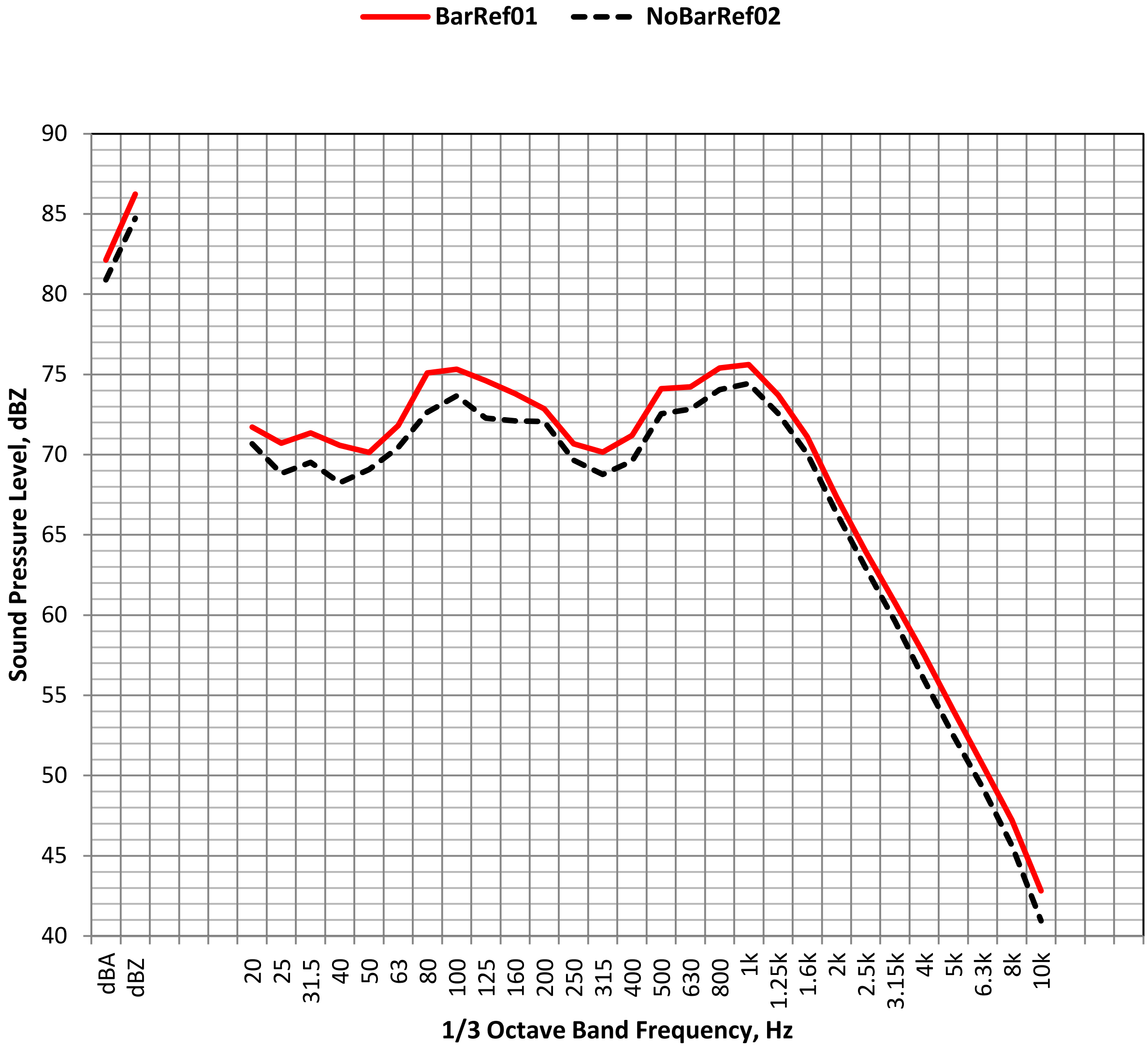


Figure 31. Sample sound pressure level spectra for BarRef01 and NoBarRef02, I-24, Upwind Lapse group ULG-3-2, 13:26-13:31 (L_{eq}(5min), dBZ).

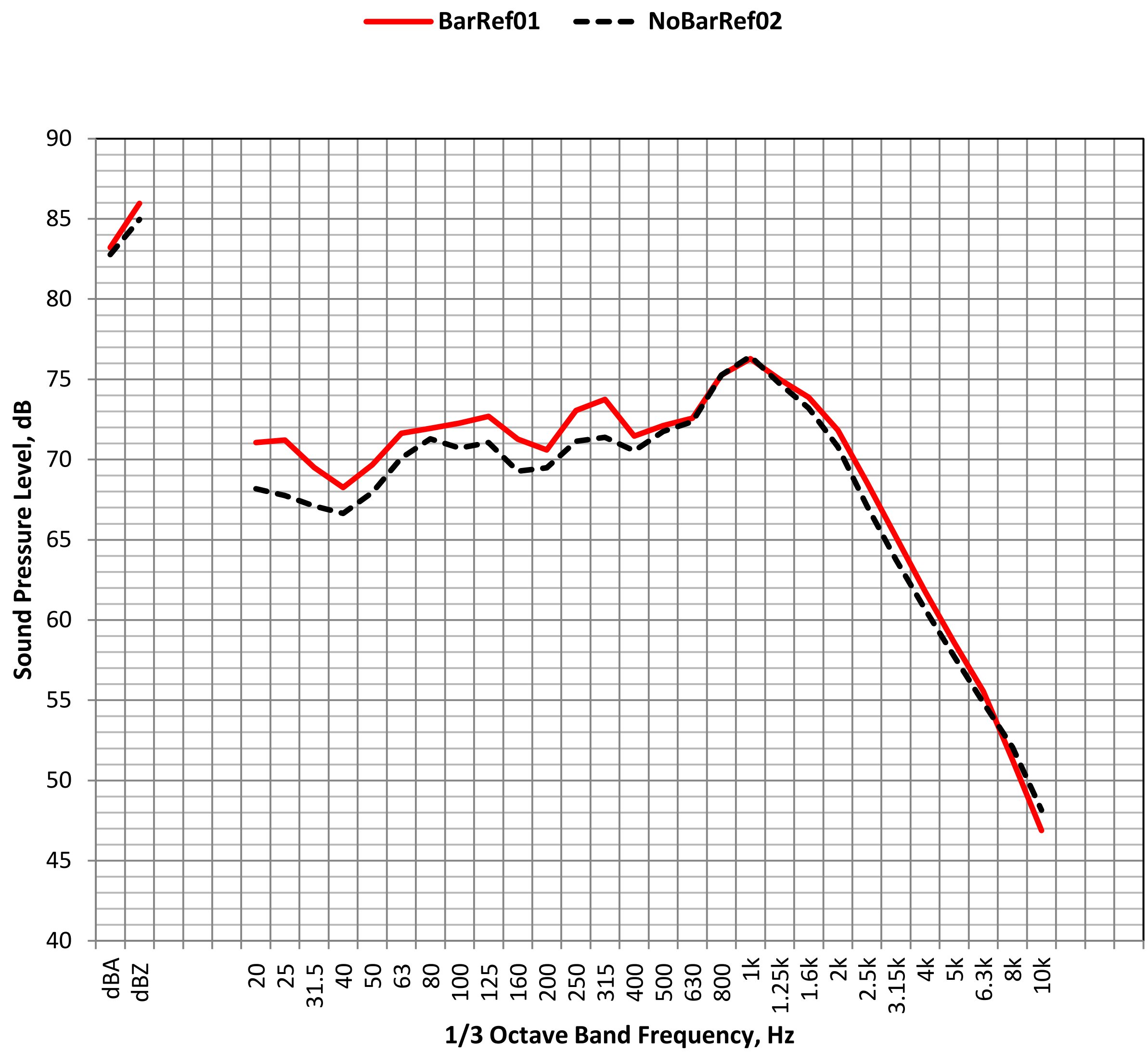


Figure 32. Sample sound pressure level spectra for BarRef01 and NoBarRef02, SR-71, Downwind Neutral group DNG-3-2, 11:38-11:43 (L_{eq}(5min), dBZ).

These spectral differences are better seen in the 1/3 octave band differences plots. For I-24, Figure 33 shows the 1/3 octave band differences of the average of all of the average differences for the Upwind Lapse meteorological class. In general, the BarRef01 levels are roughly 0.9 dB to 1.3 dB higher than the NoBarRef02 levels across the entire spectrum. At 25 Hz, the difference is 2 dB; at 200 Hz and 250 Hz, it is approximately 0.5 dB.

For SR-71, Figure 34 shows the 1/3 octave band differences plot of the average of all of the average differences for the Downwind Neutral meteorological class. The BarRef01 levels are higher than the NoBarRef02 levels across virtually the entire spectrum, with exception of 8 kHz and 10 kHz. The BarRef01 levels are higher by 3 dB at 31.5 Hz, 2.5 dB at 125 Hz and 1.5 dB at 2.5 kHz. In the range from 400 Hz to 1.25 kHz, the differences are less than 0.5 dB.

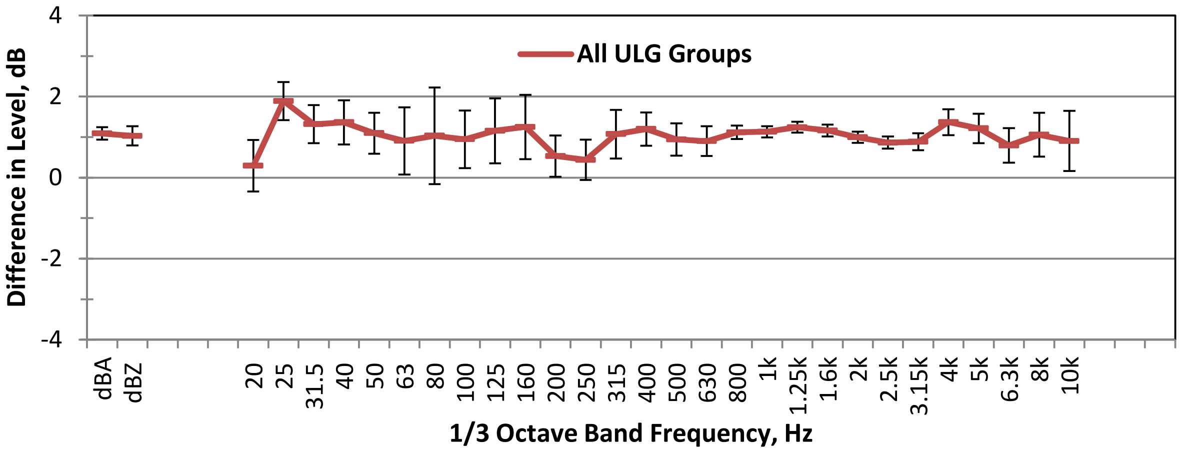


Figure 33. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarRef01 minus NoBarRef02, for all Upwind Lapse groups, I-24.

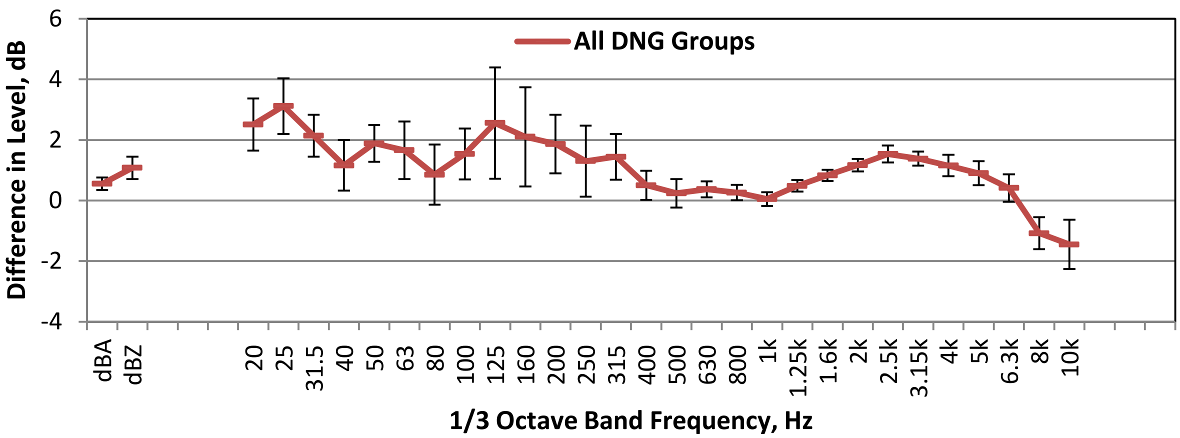


Figure 34. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Downwind Neutral groups, SR-71.

Finding 4: The background sound pressure level is elevated in the presence of the noise barrier at the microphone position between the barrier and the road.

There is evidence that background level increased at the BarRef01 position in front of the barrier for both I-24 and SR-71.

For I-24, Figure 35 presents the L_{90}(5min) and L_{99}(5min) for BarRef01 and NoBarRef02, in terms of overall A-weighted sound levels and unweighted sound pressure level. The upper graphs are L_{90} (A-weighted on the left and unweighted on the right).The lower graphs are L_{99} (A-weighted on the left and unweighted on the right).

Then, Figure 36 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min),computed as BarRef1 minus NoBarRef2 for the A-weighted sound levels.

The results show that while the L_{eq}(5min) averages about 1 dB higher at BarRef01 than at NoBarRef02, the L_{90} and L_{99} at BarRef01 are much higher than at NoBarRef02. This effect on these two descriptors is evidence of an increase in the background level in front of the barrier that could be attributed to the presence of reflected sound rays reaching the microphone in addition to the direct rays from the passing vehicles.

The results support the idea of not only a reflection component during the moment of passage, but also approach and receding components of the reflections, as illustrated earlier in Figure 1. Thus, the sound level rises sooner and recedes later for each vehicle. This sustaining of the sound for a single vehicle overlaps with the same pattern for other vehicles, elevating the background level and reducing the time during which the background level might decrease between vehicle passages. This hypothesis is supported by the spectrogram findings to be discussed later.

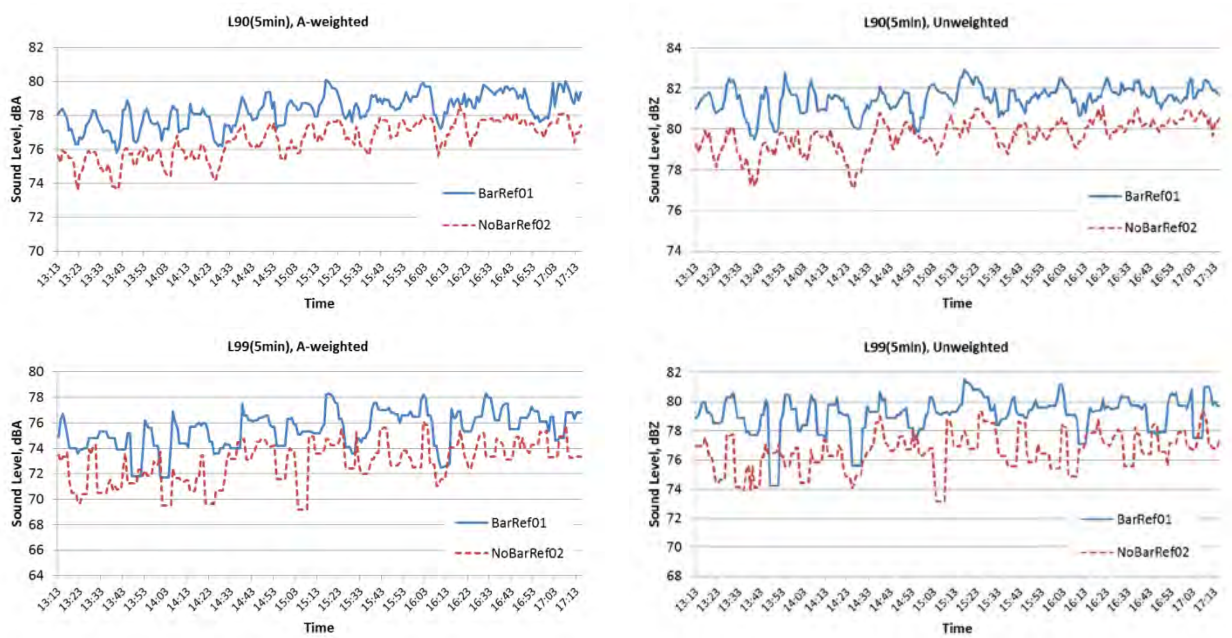


Figure 35. L_{90}(5min) and L_{99}(5min), I-24, BarRef01 and NoBarRef02 – unweighted and A-weighted sound levels.

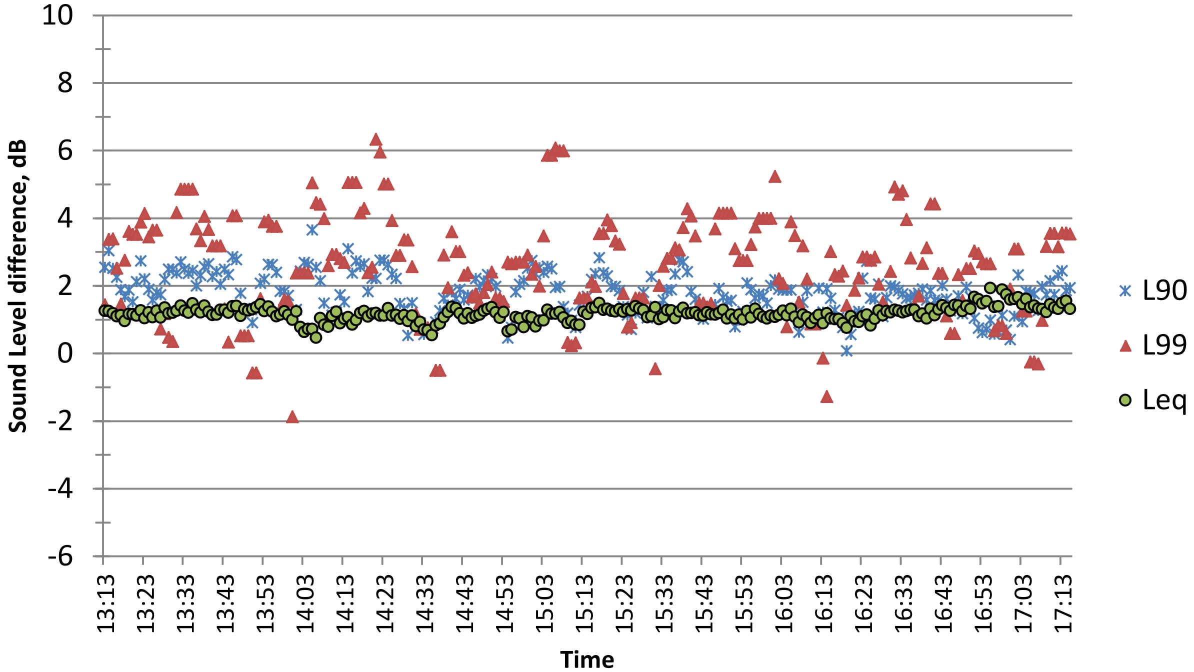


Figure 36. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-24, BarRef1 and NoBarRef2.

Figure 37 presents the SR-71 differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min), computed as BarRef1 minus NoBarRef2 for the A-weighted sound levels. Much like the I-24 data, the results show that while the L_{eq}(5min) averages about 0 dB to 1 dB higher at BarRef01 than at NoBarRef02, the L_{90}(5min) and L_{99}(5min) at BarRef01 are much higher than at NoBarRef02: L_{90} by as much as 4 dB and L_{99} by as much as 7 dB. These differences are strong evidence of an increase in the background level in front of the barrier that could be attributed to the presence of reflected sound rays from the passing vehicles reaching the microphone in addition to the direct rays, producing a sustained sound that keeps the background level from dropping off during gaps between vehicles.

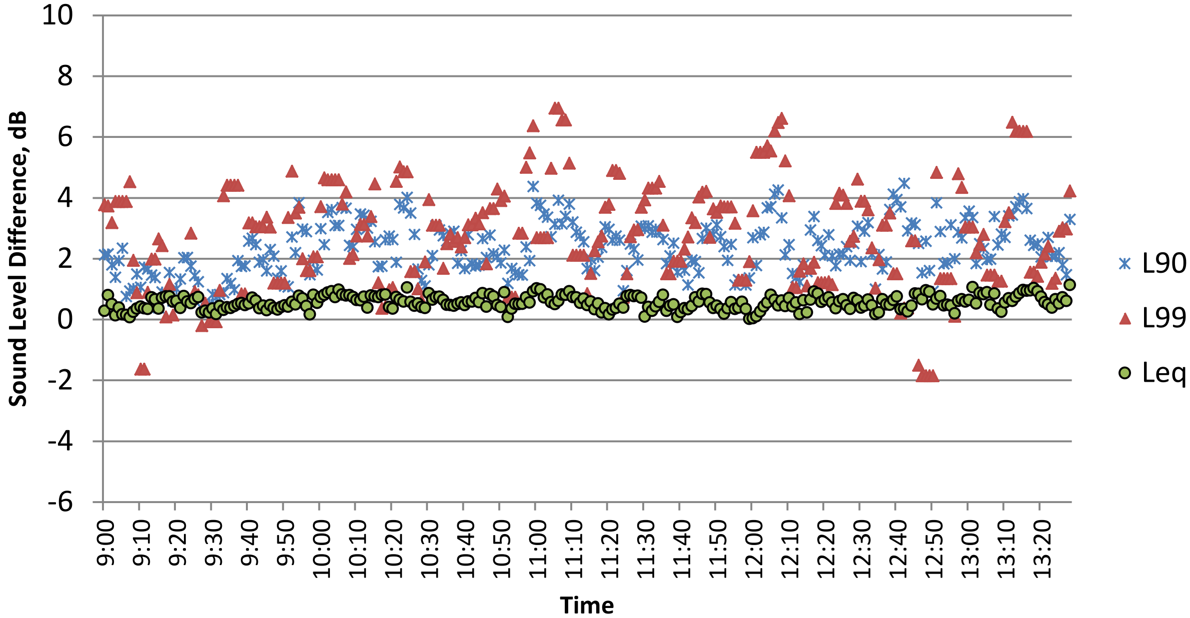


Figure 37. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, SR-71, BarRef01 and NoBarRef02.

The above graphs are for the broadband A-weighted sound levels and unweighted sound pressure levels only. Figure 38 for I-24, shown below, broadens the analysis to include the individual 1/3 octave bands through the use of color shading. The brown color means that the BarRef01 levels are higher than the NoBarRef02 levels and blue means that NoBarRef02 is higher.

In the graph, time runs from top to bottom (increasing as one moves down each figure, with each row representing the starting minute of a running five-minute period) and the total block representing approximately four hours. The 1/3 octave bands run across from left to right, with the broadband A-weighted sound levels and unweighted sound pressure levels on the far left.

Within each band's column of data are the differences for seven Ln sound pressure level L_n values (L_1, L_5, L_{10}, L_{33}, L_{50}, L_{90} and L_{99}) and L_{eq} in the order illustrated in Figure 39 for a single 1/3 octave band. Over 57,000 L_n sound pressure level differences are represented in the figure by color shading.

In Figure 38 for I-24, vertical brown streaks are on the right sides of the data columns (representing L_{90}(5min) and L_{99}(5min)) in the frequency bands from 400 Hz up through 2 kHz for most of the sample period and up through 5 kHz for the first half of the sample period. These brown streaks mean that the BarRef01 background levels are higher than the NoBarRef02 background levels, evidence of a sustaining of a vehicle's passby noise due to the creation of an image source for each vehicle as the sound reflects off the barrier. In contrast, the vertical blue streaks in the 8 kHz band are evidence of elevated background levels at the NoBarRef02, likely attributable insect noise in the vegetation behind this position.

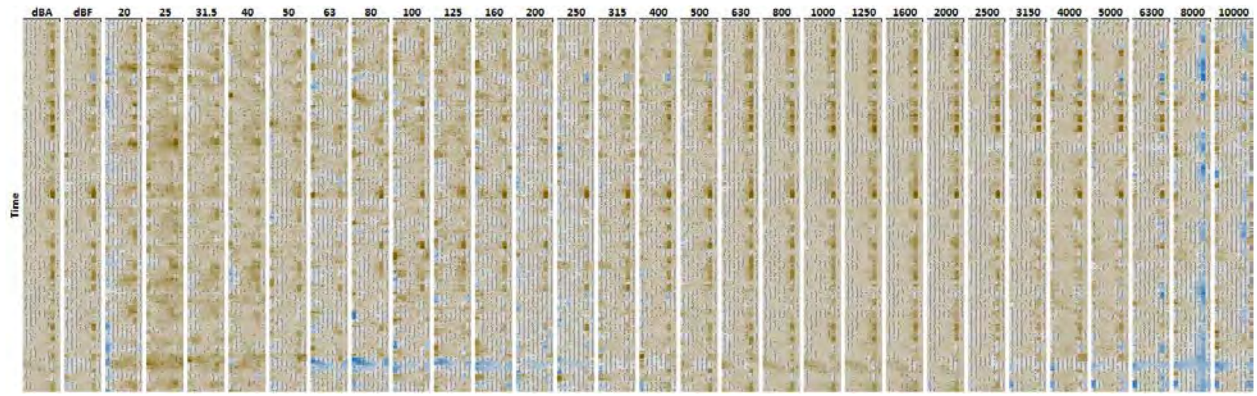


Figure 38. I-24 Differences in L_n(5min) by 1/3 octave frequency bands: BarRef01 and NoBarRef02.

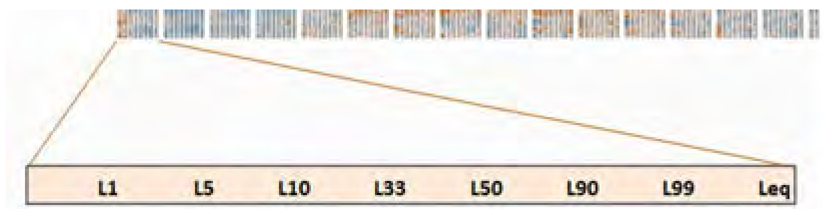


Figure 39. Order of statistical levels for a single 1/3 octave band

A similar pattern is seen in Figure 40 for SR-71 between BarRef01 and NoBarRef02. Vertical brown streaks are on the right sides of the data columns (representing L_{90}(5min) and L_{99}(5min)) in the frequency bands from 500 Hz up through 4 kHz for nearly all of the sample period, and up through 5 kHz for the first half of the sample period. These brown streaks mean that the BarRef01 background levels are higher than the NoBarRef02 background levels. The BarRef01 levels were also higher in the 20 Hz to 31.5 Hz bands across most of the descriptors for most of the measurement period. The reason for that difference in those very low frequency bands is not apparent.

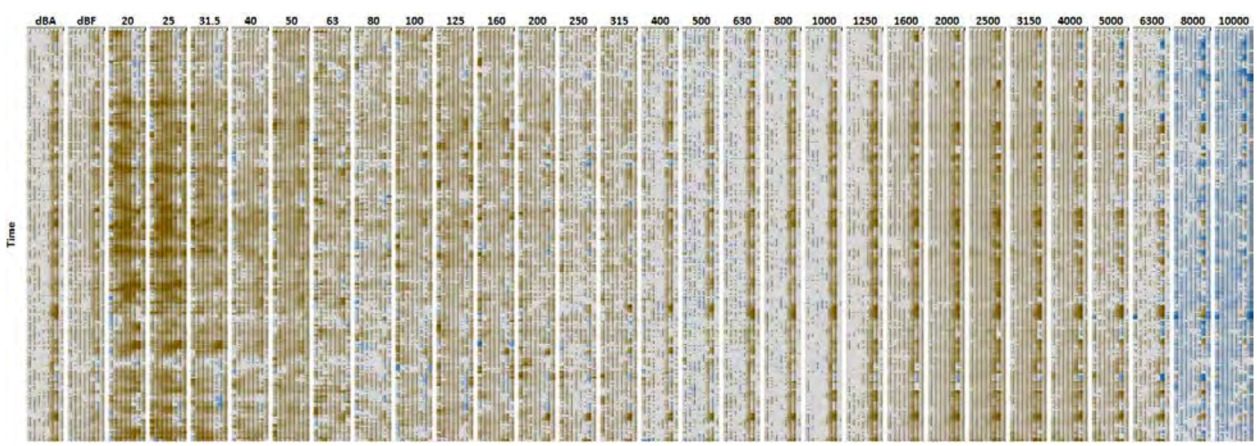


Figure 40. SR-71 Differences in L_n(5min) by 1/3 octave frequency bands: BarRef01 and NoBarRef02.

Finding 5: Even at the reference microphone position atop the barrier, the level can be slightly higher than at the equivalent No Barrier position, as evidenced at I-90. However, little difference was seen at MD-5.

The I-90 and MD-5 noise barriers are located close to the edge of shoulder of the road. The BarRef01 microphones were placed 5 feet directly above the top of the barriers.

Figure 41 shows the differences in the unweighted and A-weighted running L_{eq}(5min) between BarRef01 and NoBarRef02 at I-90. In general, both the unweighted sound pressure levels and A-weighted sound levels are higher at the Barrier microphones than at the No Barrier microphones. For the I-90 reference microphones, both the unweighted and A-weighted running L_{eq}(5min) at BarRef01 are on the order of 0 dB to 0.5 dB above the NoBarRef02 levels for the first two hours of measurement (13:00 to 15:00). For the second half of the measurements (15:00 to 17:20), this difference increased to a range of 0.5 dB to 1.0 dB. The slightly higher levels at BarRef01 could be due to sound reflections off the barrier and then off the sides of the vehicles, especially for heavy truck trailers.

There are mixed results for the MD-5 reference microphones. Figure 42 shows the running L_{eq}(5min) at BarRef01 and NoBarRef02 to be roughly equal. Unweighted levels at BarRef01 ranged mostly from 1.5 dB below NoBarRef02 levels to 2 dB above. A-weighted levels were within ±0.5 dB of each other during the afternoon session. However, due to frog noise near NoBarRef02, its evening A-weighted levels were generally about 1 dB higher than the BarRef01 levels. Little difference in the levels was expected because the BarRef01 microphone was positioned atop the barrier, although reflections off the vehicle bodies might increase its levels, as noted above for I-90.

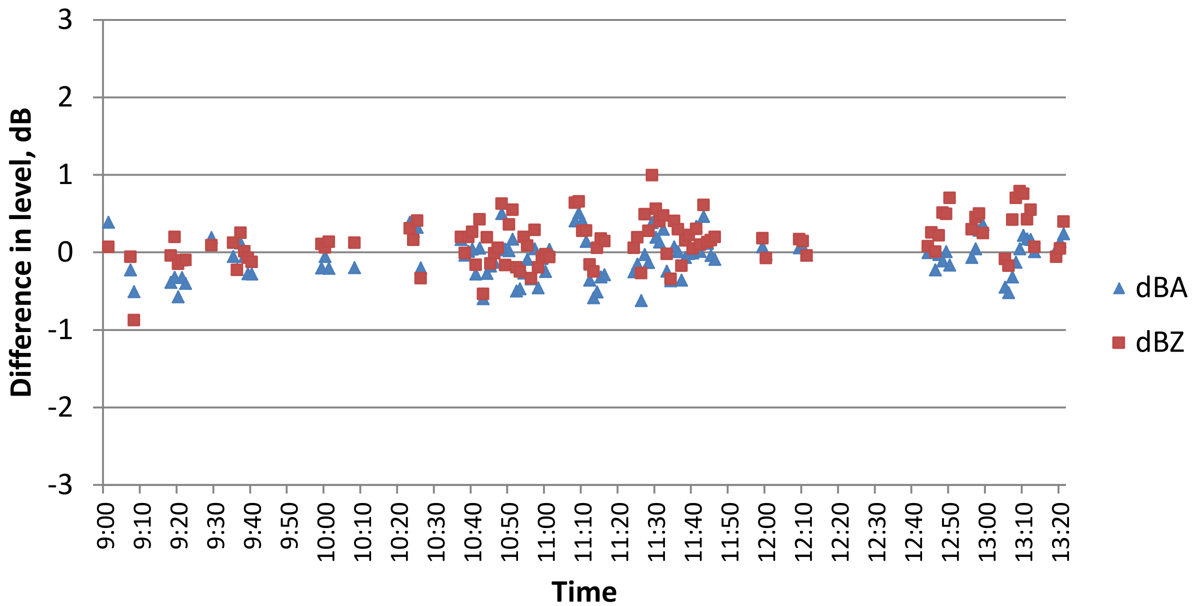


Figure 41. Differences in running L_{eq}(5min), I-90, BarRef01 minus NoBarRef02.

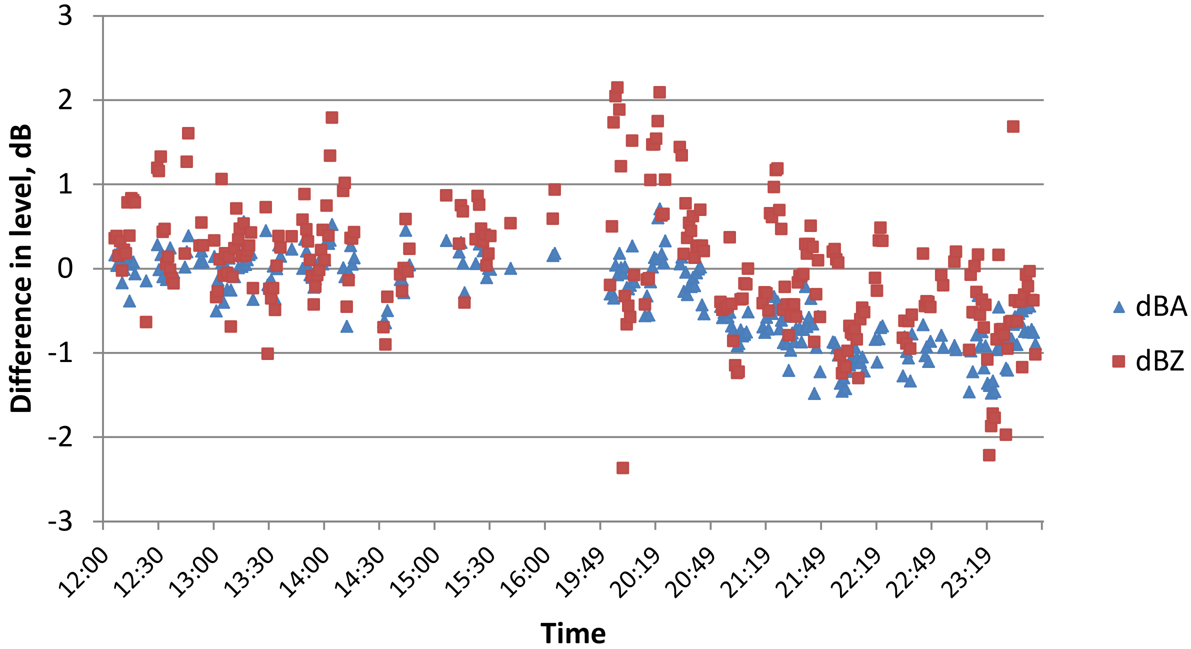


Figure 42. Differences in running L_{eq}(5min), MD-5, BarRef01 minus NoBarRef02.

The Calm Neutral meteorological class spectral difference plot for the I-90 reference microphone is shown as Figure 43. In general, the BarRef01 levels are 0 dB to 1 dB higher than the NoBarRef02 levels at 400 Hz and below. Above 400 Hz up through 3.15 kHz, these levels are 0.5 dB to 1 dB higher than the NoBarRef02 levels. Above 4 kHz, the No Barrier levels are higher, likely due to localized insect noise. These results are similar to the I-24 reference microphone results, where that microphone was placed between the barrier and the road.

The corresponding plot for the MD-5 reference microphones in Figure 44 shows the results for the Downwind Neutral class. In general, the BarRef01 levels vary little compared to NoBarRef02 from 500 Hz through 6.3 kHz. Below 500 Hz, the BarRef01 levels were generally less than a decibel above those at NoBarRef02. The Downwind Neutral time periods were in the afternoon before the high-frequency frog noise began at NoBarRef02.

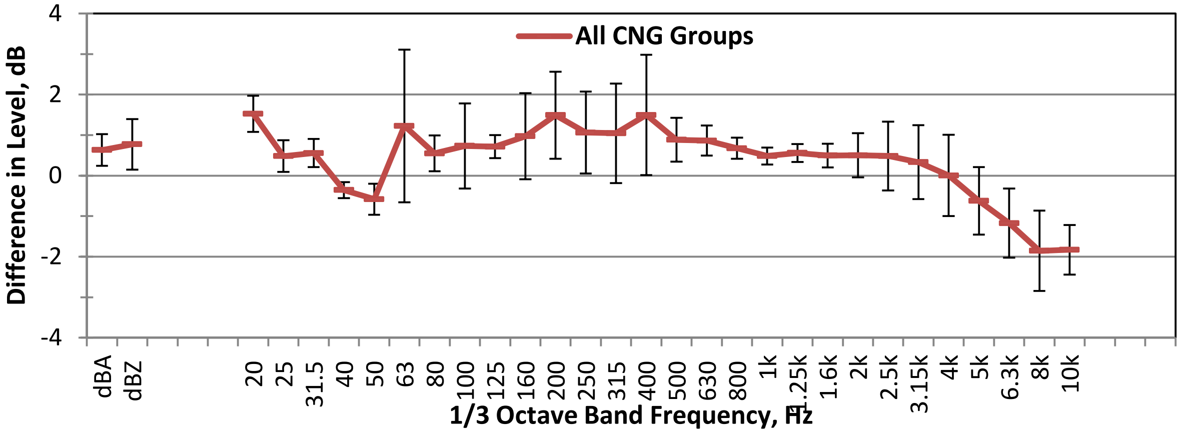


Figure 43. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarRef01 minus NoBarRef02, for all Calm Neutral groups, I-90.

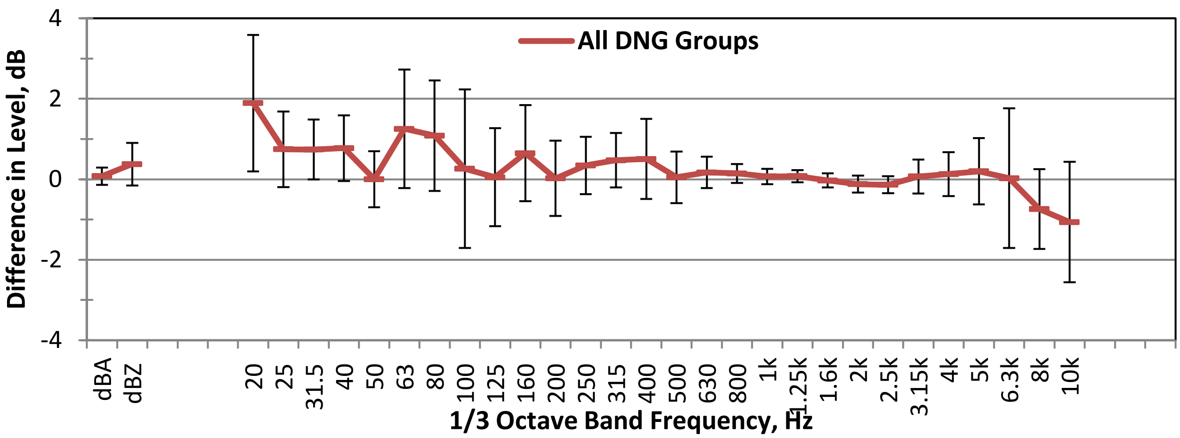


Figure 44. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Downwind Neutral groups, MD-5.

There was no evidence of the sustaining or elevating of the background level at BarRef01 for both I-90 and MD-5 based on the difference graphs for L_{90}(5min) and L_{99}(5min), both in terms of the broadband A-weighted levels and the 1/3 octave bands. The supporting figures and discussion are in Appendix B.

Finding 6: Near the edge of the road for the lower-height microphones, the BarCom03 levels are roughly the same as the NoBarCom05 levels, being slightly higher in the very low frequency bands, as evidenced at SR-71.

At the SR-71 location, the BarCom03 and NoBarCom05 microphones were located just off the shoulder of the road, 25 feet from the center of the near travel lane, at heights of 10 feet above the roadway surface. These were the closest community microphones to the road on the side opposite the barrier of all of the studied locations.

Figure 45 shows the differences in the broadband unweighted and A-weighted levels for BarCom03 and NoBarCom05 for SR-71. For these broadband measures, little evidence of reflection is seen. The unweighted levels at BarCom03 range from 0.9 dB lower to 1 dB higher than those at NoBarCom05. The A-weighted levels at BarCom03 range from 0.7 dB lower to 0.5 dB higher than those at NoBarCom05. With these microphones so close to the far lanes of traffic, relative to the distance from BarCom03 to the barrier, little increase in level due to reflections was expected.

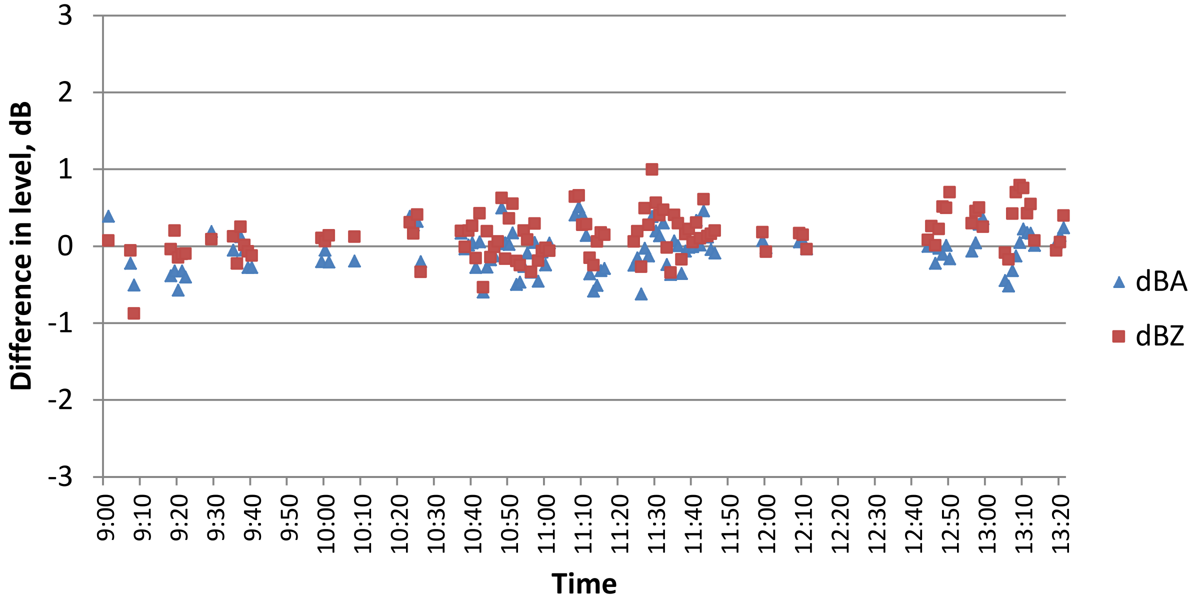


Figure 45. Differences in running L_{eq}(5min), SR-71, BarCom03 minus NoBarCom05.

Figure 46 then shows the averages of the differences in the BarCom03 and NoBarCom05 levels for all of the Downwind Neutral groups. The levels at BarCom03 are generally higher than or the same as those at NoBarCom05. The levels in the frequency bands from 20 Hz up through 125 Hz are 0.5 dB to 1.5 dB higher at BarCom03. From 160 Hz up through 1.6 kHz, the levels are different by only 0.5 dB or less. From 2 kHz through 5 kHz, the BarCom03 levels are a half decibel higher than NoBarCom05. The NoBarCom05 levels are less than 1.5 dB higher than BarCom03 at and above 6.3 kHz.

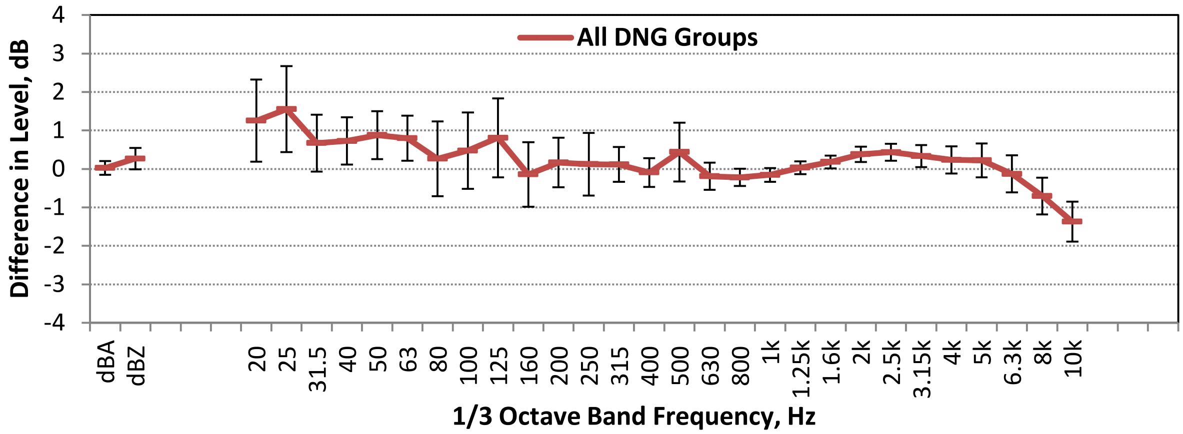


Figure 46. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarCom03 minus NoBarCom05 for all Downwind Neutral groups, SR-71.

Finding 7: Near the edge of the road for the lower-height microphones, there is some evidence of an increase in the background A-weighted sound level on the order of 1 dB to 1.5 dB at BarCom03, as evidenced at SR-71.

Figure 47 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the background A-weighted sound levels, computed as BarCom03 minus NoBarCom05 along SR-71. There is some evidence of the elevated background level at BarCom03 compared to NoBarCom05 even though these two microphones are very close to the edge of the shoulder for the far-lane traffic across from the barrier. While the L_{eq}(5min) averages about ± 2 dB compared to NoBarCom05, the L_{90} at BarCom03 are, on average about a decibel higher than NoBarCom05 and the L_{99} at BarCom03 average approximately 1.5 dB higher.

For both descriptors, there are also many times when the NoBarCom05 levels are higher than the BarCom03 levels. This variation in level differences is likely related to the 50-ft setback of the barrier from the center of the near lane on the opposite side of the highway and differences in traffic from one data block to the next. Regarding the barrier setback, the near-lane traffic would tend to cause the highest levels at the nearby BarCom03 and NoBarCom05 microphones, followed by the far-lane traffic and then any far-lane reflections, followed by any near-lane reflections. Regarding traffic, because there is some difference in distance between the Barrier and No Barrier sites, the exact same vehicles are not passing each mic in each 5-minute period. Also, there could be operational differences of the vehicles at the two sites, such as speed and lane changes Nonetheless, it is interesting that, on average, the trend is for the L90 and L99 to be higher at the Barrier mic. As observed when listening to the audio recordings, one senses the “presence” of the barrier at the Barrier microphone.

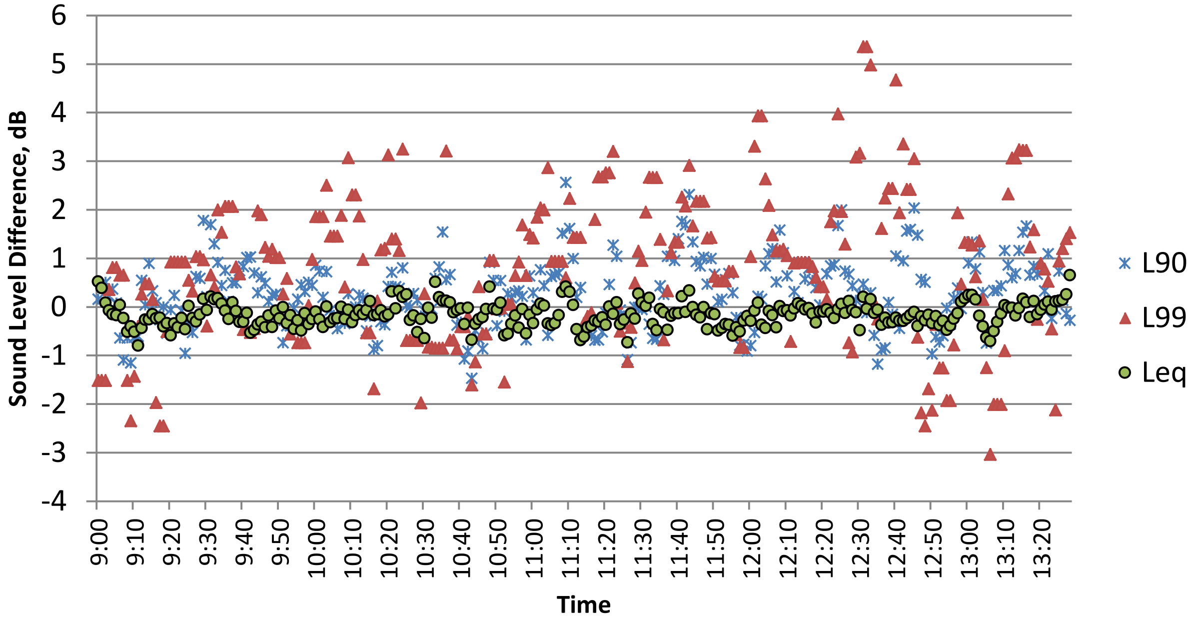


Figure 47. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, SR-71, BarCom03 minus NoBarCom05.

Figure 48 presents the spectral L_n differences for BarCom03 and NoBarCom05. Not a great deal of difference is seen between the descriptors for the two microphones, which is consistent with the A-weighted sound level graphs. However, there does appear to be a slight increase in the L_{90} and L_{99} in the bands in the 1 kHz to 3.15 kHz bands, as evidenced by the brown streaks on the right side of the data columns for those bands.

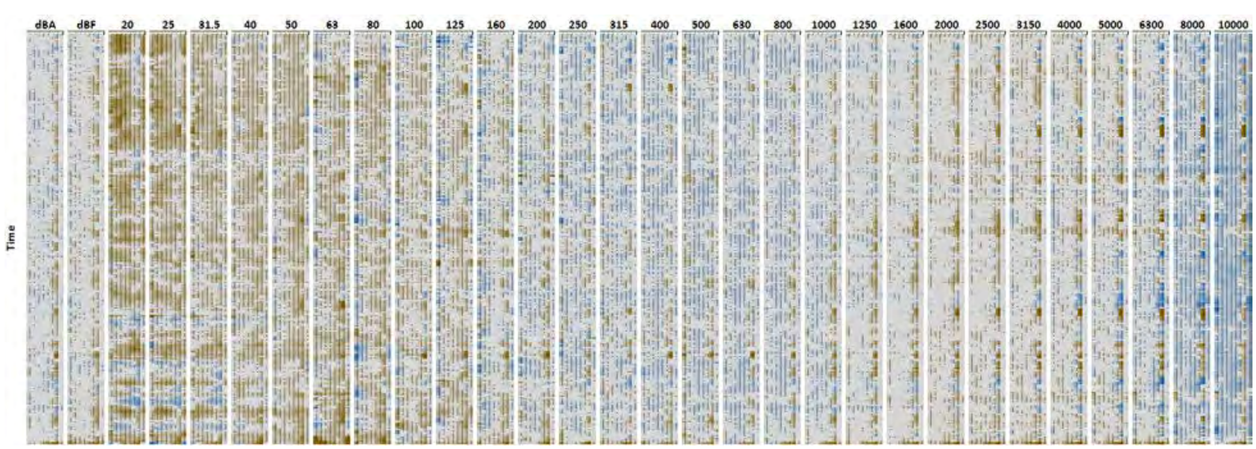


Figure 48. SR-71 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom03 minus NoBarCom05.

Finding 8: Farther back from the road, but still within 100 ft, the Barrier levels are higher than No Barrier levels by 0.5 to 1.5 dB and the spectrum is changed by even more in some of the frequency bands between 250 Hz and 630 Hz and in some of the bands above 800 Hz, as evidenced at I-24, I-90, and MD-5.

At the I-24 location, the BarCom03 and BarCom04 microphones were set back 84 ft from the center of the near travel lane and at heights of 5 ft and 15 ft above the roadway plane, with NoBarCom05 and NoBarCom06 at corresponding positions.

At the I-90 location, the BarCom03 and NoBarCom05 microphones were set back 69 ft from the center of the near travel lane and at a height of 10 ft above the roadway plane. BarCom04 and NoBarCom06 were set back 93 ft from the center of the near travel lane and at a height of 17 ft above the roadway plane.

At the MD-5 location, the BarCom03 and BarCom04 microphones were set back 80 ft from the center of the near travel lane and also at heights of 5 ft and 15 ft above the roadway plane.

Figure 49 shows the differences in the unweighted and A-weighted levels for the lower-height BarCom03 and NoBarCom05 microphones at I-24. For a large majority of the running five-minute Leq periods, the BarCom03 levels, both unweighted and A-weighted, are higher than the NoBarCom05 levels by a range of 0.0 to 1.0 dB, with some differences as much as 1.5 dB.

For I-90 at BarCom03 and NoBarCom05, Figure 50 shows the differences in the unweighted and A-weighted levels. For all of the running five-minute Leq periods, the BarCom03 unweighted sound pressure levels are on the order of 0 dB to 1.5 dB higher than the NoBarCom05 levels. For the A-weighted sound levels, the BarCom03 levels are on the order of 0.4 dB to 1.3 dB higher than the NoBarCom05 levels.

For MD-5, Figure 51 shows the differences in the unweighted and A-weighted levels for the lower-height BarCom03 and NoBarCom05 microphones opposite the barrier. The daytime unweighted levels at BarCom03 ranged from 1.0 dB lower to 2 dB higher than those at NoBarCom05. The A-weighted levels at BarCom03 range from 0.5 dB to 1.5 dB higher than those at NoBarCom05. In the evening, the unweighted levels at the two microphones were comparable. The BarCom03 A-weighted levels ranged mostly from 0 dB to 1 dB higher than the NoBarCom05 levels.

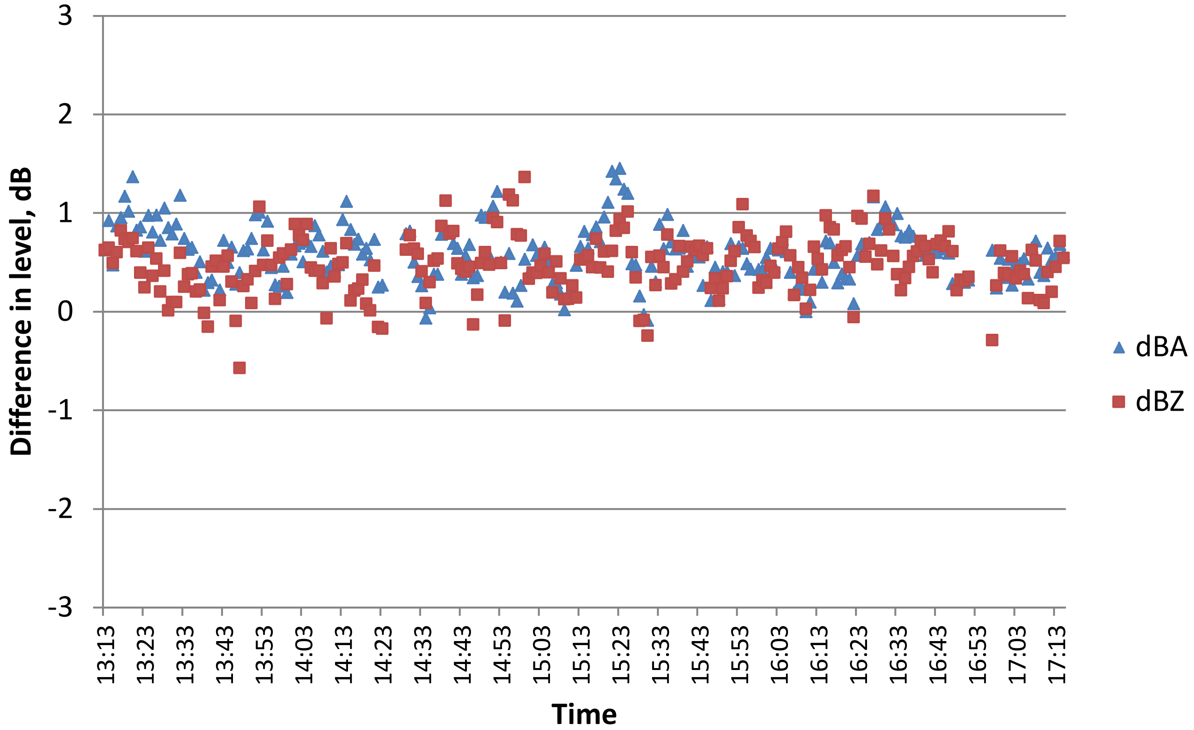


Figure 49. Differences in running L_{eq}(5min), I-24, BarCom03 minus NoBarCom05.

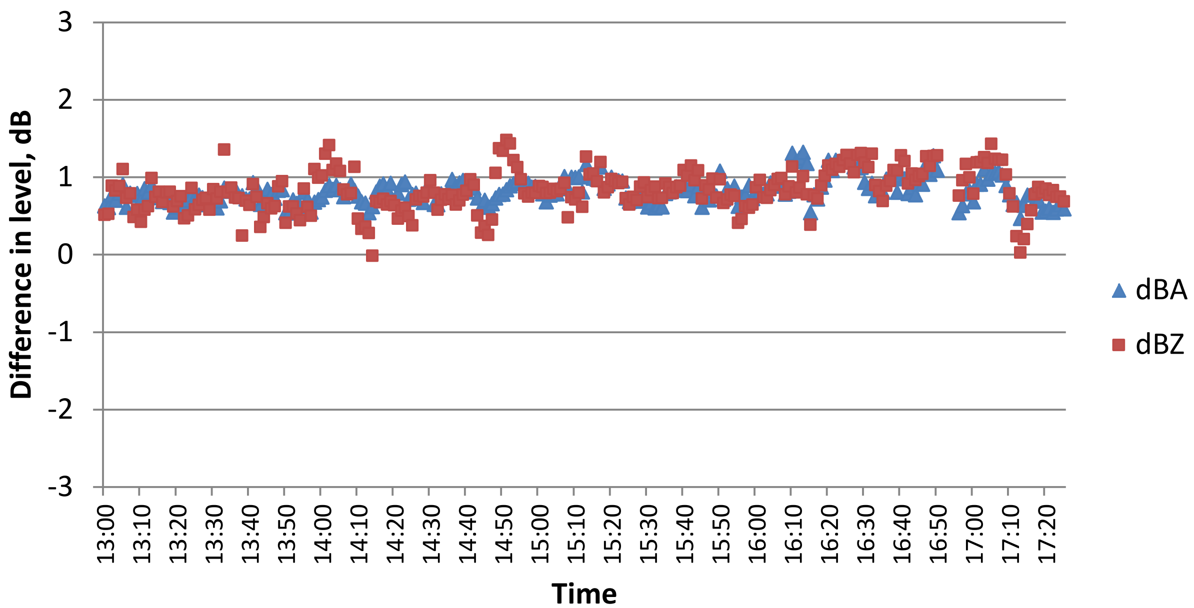


Figure 50. Differences in running L_{eq}(5min), I-90, BarCom03 minus NoBarCom05.

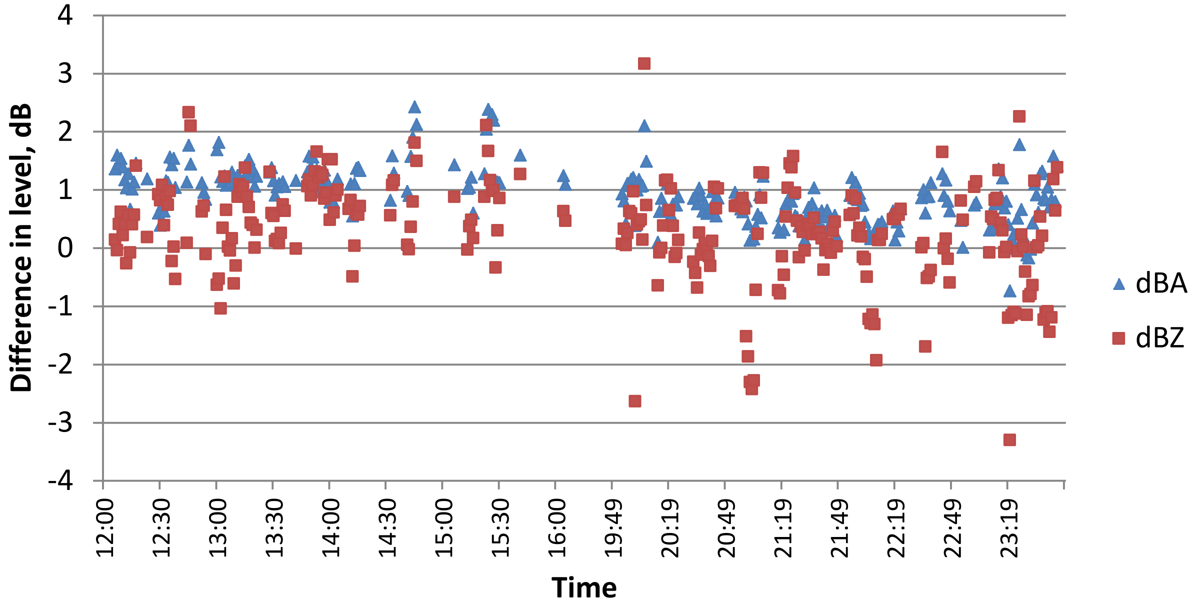


Figure 51. Differences in running L_{eq}(5min), MD-5, BarCom03 minus NoBarCom05.

Next, Figure 52 presents an example of the sound pressure level spectra for BarCom03 and NoBarCom05 (lower and closer microphones to the far side of the road) at I-90 for a Calm Neutral period. The BarCom03 levels are noticeably greater in the 250 Hz to 500 Hz 1/3 octave bands.

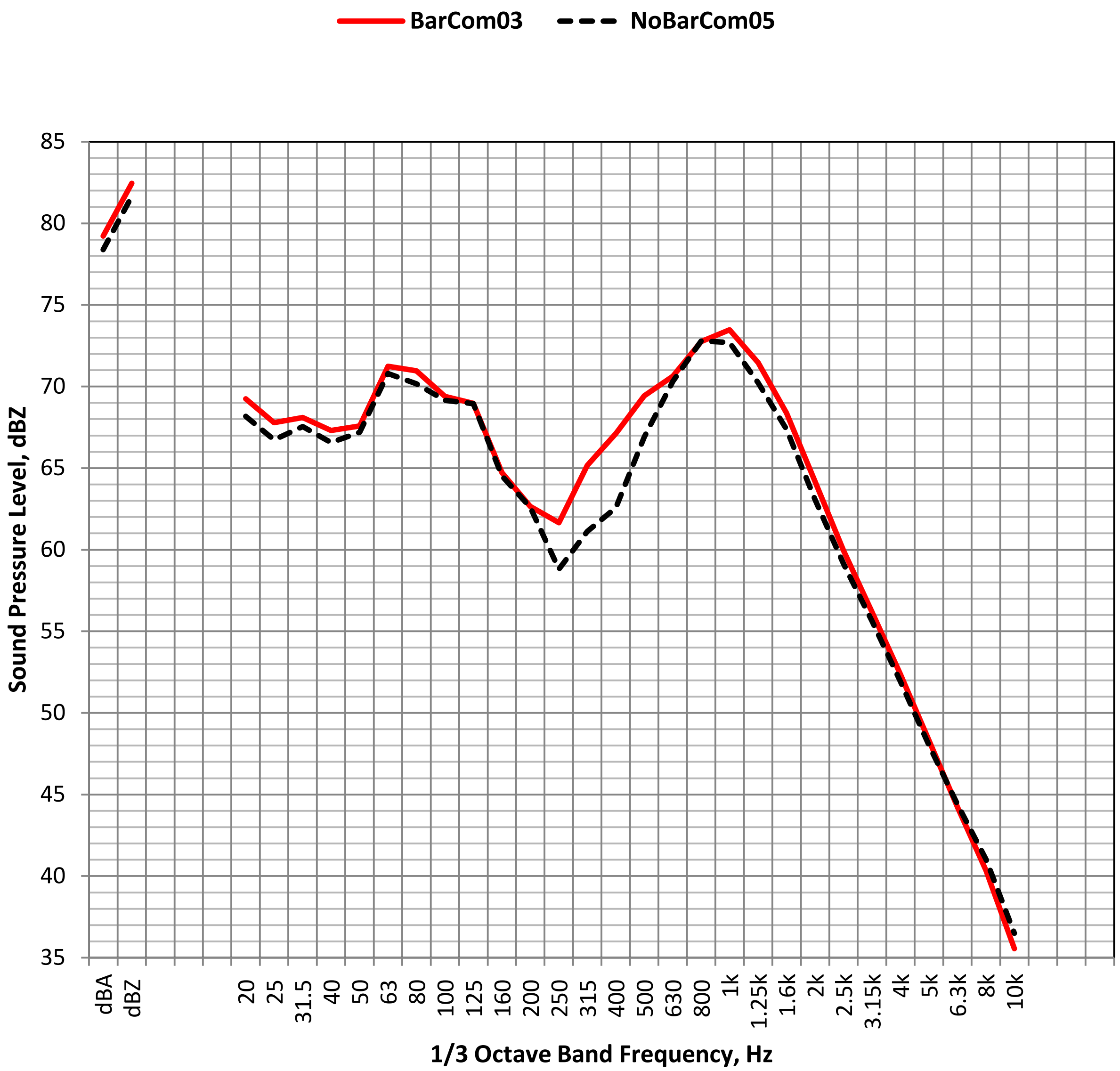


Figure 52. Sample sound pressure level spectra for BarCom03 and NoBarCom05, I-90, Calm Neutral class, CNG-1-1, Period 15:37 (L_{eq}(5min), dBZ).

The differences in the Barrier and No Barrier levels can be seen in the following figures. Figure 53 shows the differences in level between the BarCom03 and NoBarCom05 microphones at I-24 for an average of all of the Upwind Lapse groups. Both of these microphones were five feet above the roadway plane. In general, the BarCom03 levels are equal to or slightly greater than the NoBarCom05 levels over most of the frequency range up through 4 kHz. The increase is less than 1 dB from 31.5 Hz to 250 Hz, and on the order of 1 dB to 2 dB in the bands from 315 Hz to 1 kHz. Above 4 kHz, the levels at NoBarCom05 are higher than the levels at BarCom03. That high-frequency difference was caused by insects in the vegetation behind the NoBarCom05 microphone that were not present near the BarCom03 site.

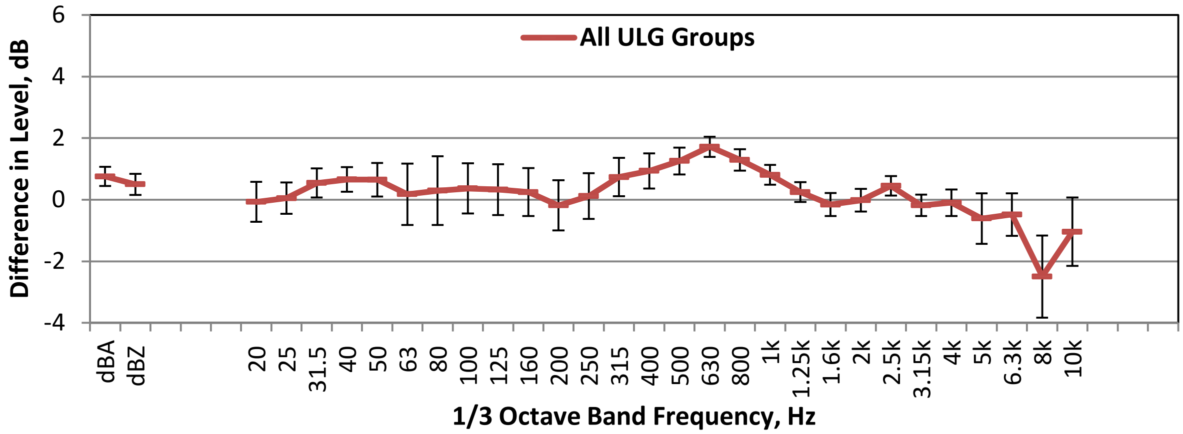


Figure 53. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarCom03 minus NoBarCom05, for all Upwind Lapse groups, I-24.

Figure 54 shows the averages of the averages of the differences in the BarCom03 and NoBarCom05 levels for the I-90 location for all of the measured Calm Neutral groups. The BarCom03 and NoBarCom05 microphones were both 69 feet from the center of the near travel lane and 10.4 feet above the roadway surface. The levels in the frequency bands from 20 Hz up through 80 Hz were 0.5 dB to 1 dB higher at BarCom03. For 1 kHz and higher, the BarCom04 levels were approximately 1 dB to 2 dB higher than those at NoBarCom05. The most noticeable differences were in the 250 Hz to 500 Hz bands, where the levels were 2.5 dB to 5 dB (at 400 Hz) higher.

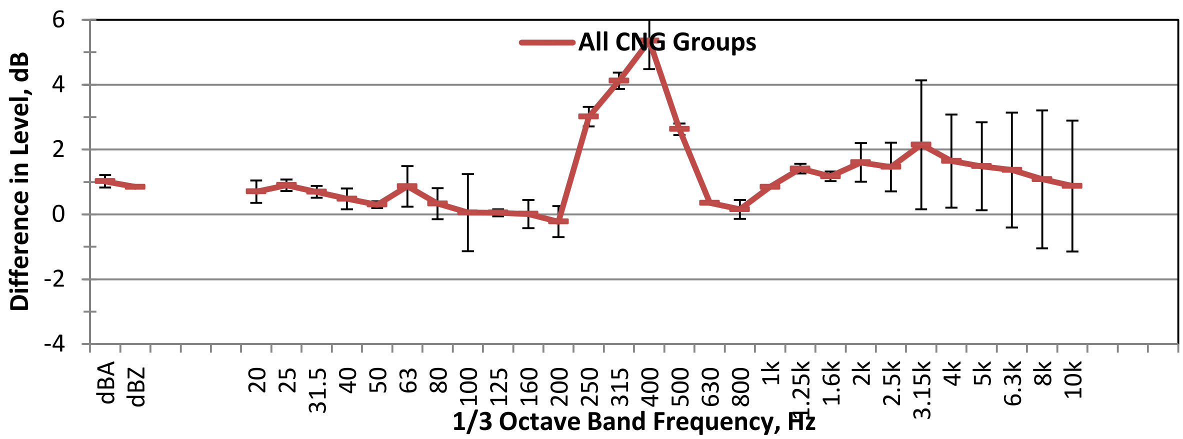


Figure 54. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarCom03 minus NoBarCom05, for all Calm Neutral groups, I-90.

The next location with microphones at two heights is MD-5. All of the groupings of five-minute periods that were judged equivalent for traffic parameters at the MD-5 location fell into four meteorological classes: Downwind Neutral and Downwind Lapse (daytime) and Calm Neutral and Calm Inversion (evening). The potential difference by meteorological class will be addressed later in this chapter. For now, typical sound pressure level spectra are shown in Figure 55 for BarCom03 and

NoBarCom05 for one of the five-minute periods in the Calm Inversion meteorological class. The increase in levels in the mid-range and higher-range frequencies is similar to that observed for the I-24 and I-90 locations.

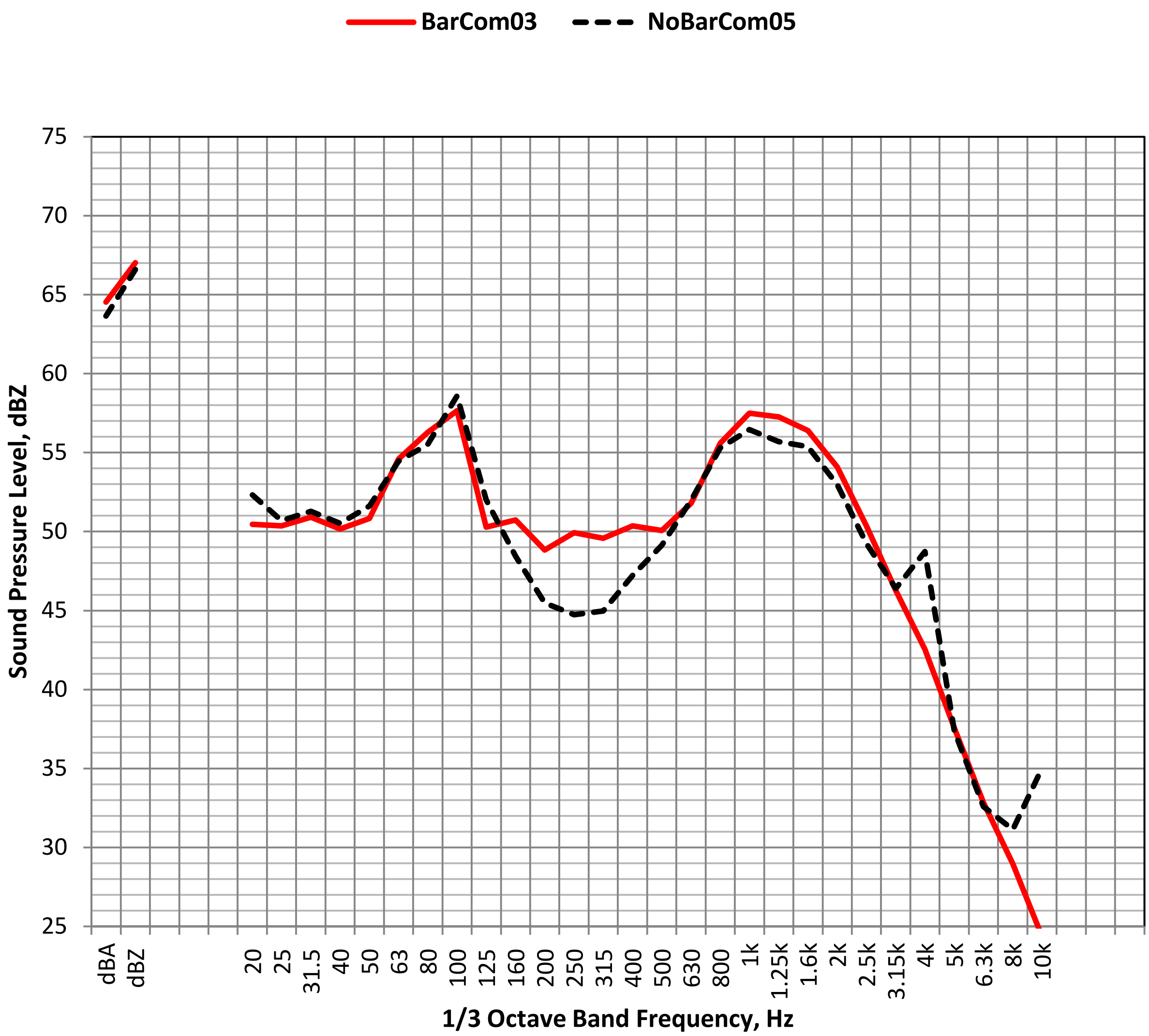


Figure 55. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Calm Inversion Group CIG-3-4, 23:15 (L_{eq}(5min), dBZ).

Figure 56 shows the level difference averages for all of the Calm Inversion classes at the MD-5 location. The results for early-evening Calm Neutral class evening periods are similar. The graph shows the higher BarCom03 levels in the bands from 200 Hz to 500 Hz (with the maximum at 5 dB higher at 250 Hz and 315 Hz). The 4 kHz band is 6 dB higher at NoBarRef02 than BarRef01 due to loud, localized frog noise. A possible explanation for the barrier effect being prominent in the low frequency range (250 to 500 Hz) for BarCom03 at I-90 (Figure 54) and MD-5 (Figure 56) is that direct and reflected sound take different propagation paths. The direct sound at both the Barrier and No Barrier sites is likely experiencing ground effects/wave interference that cause a dip in sound level in that frequency range, as is illustrated in the sample spectra in Figure 52 and Figure 55. The reflected sound at the barrier site is experiencing a different propagation path than the direct sound, with different ground effects and wave interference with ground reflections; a dip in the 250 to 500 Hz range could be non-existent or diminished. As a result, the barrier effect would be pronounced in the 250 to 500 Hz range.

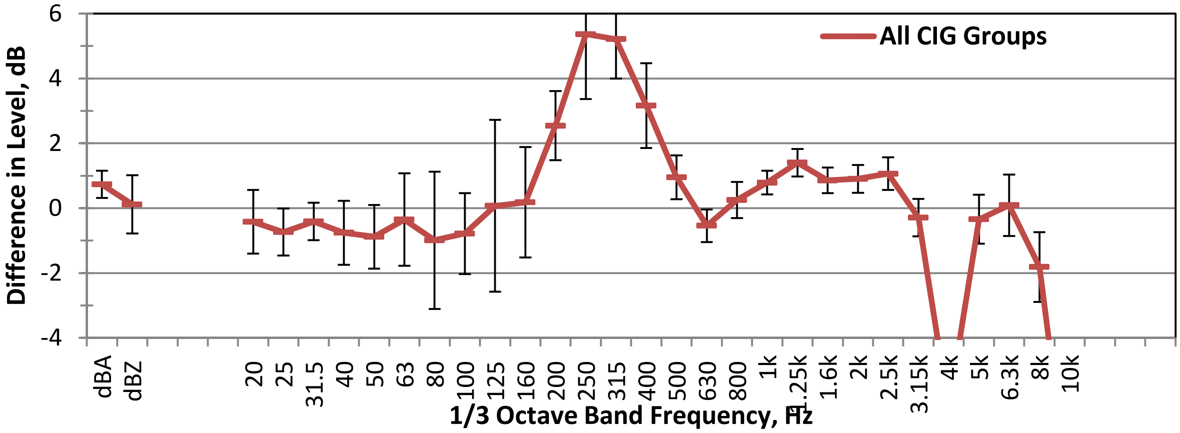


Figure 56. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Inversion groups, MD-5.

Finding 9: Farther back from the road, but still within 100 ft, background level increases in the bands from 630 Hz up through 3.15 kHz, as evidenced at I-90 and MD-5, but not I-24.

First, for I-24, Figure 57 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05. There is not much evidence of the elevated background level at BarCom03 than at BarRef01, not too unexpected given the dominance of the direct sound from the nearby vehicles.

For I-90, Figure 58 presents these same differences. In this case, there is strong evidence of the elevated background level at BarCom03. While the L_{eq}(5min) averages about 0.5 dB to 1 dB higher than NoBarCom05, the L_{90} at BarCom03 are 1 dB to 2 dB higher and the L_{99} at BarCom03 are 1 dB to 4 dB higher.

For MD-5, Figure 59 presents the same differences, computed as BarCom03 minus NoBarCom05. There is evidence of the elevated background level at BarCom03 during the daytime hours. While the L_{eq}(5min) averages about 0.5 dB to 1 dB higher than NoBarCom05, the L_{90}(5min) at BarCom03 range from 9 dB lower to 10 dB higher than NoBarCom05, averaging approximately 2 dB higher. Almost all of the daytime L_{99}(5min) are higher at BarCom03 than NoBarCom05, evidence of an increase in the background level due to reflected sound off the barrier. As noted at the other locations, none of these levels have been edited for contaminating sounds.

One possible reason for the background level increase at the I-90 and MD-5 Barrier microphones and not at the I-24 Barrier microphone is that the barrier at MD-5 and I-90 sits just at the edge of the shoulder, while the I-24 back is set back nearly 100 ft. As a result, there is more likelihood of a sustaining of the pass-by signal due to the reflected sound at the close-in barriers, which elevates the background level.

In the evening at the MD-5 location, the clear trend was for the L_{90}(5min) and L_{99}(5min) at NoBarCom05 to grow larger relative to BarCom03 as the evening got later. This trend is a clear result of the increased level and constancy of frog and insect noise.

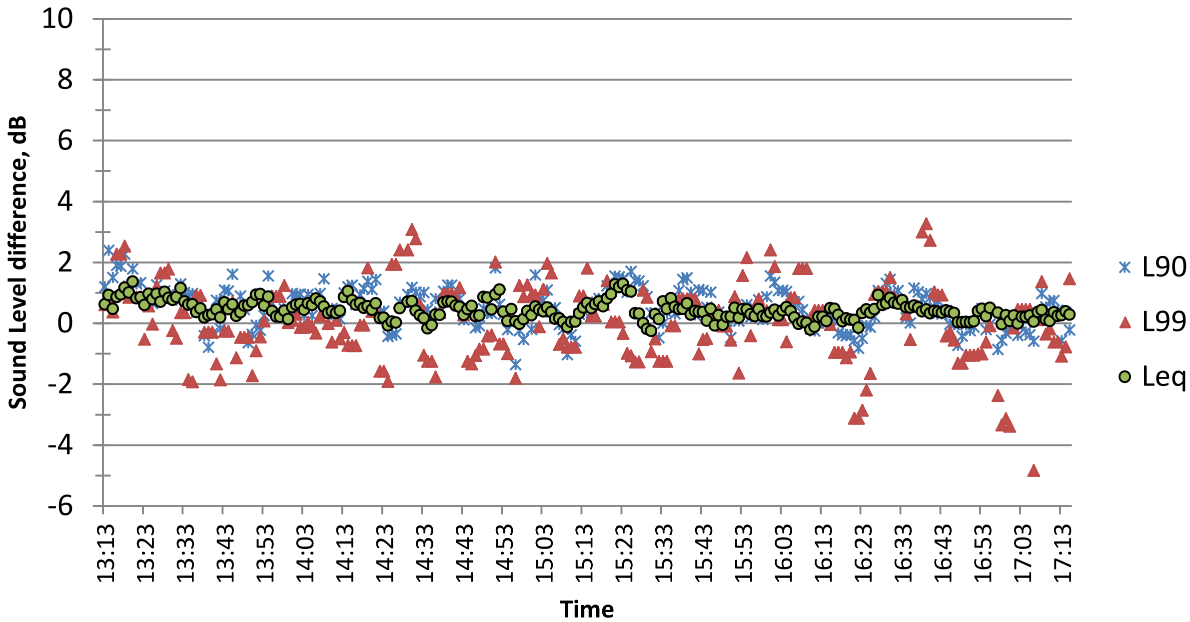


Figure 57. Differences in A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-24, BarCom03 and NoBarCom05.

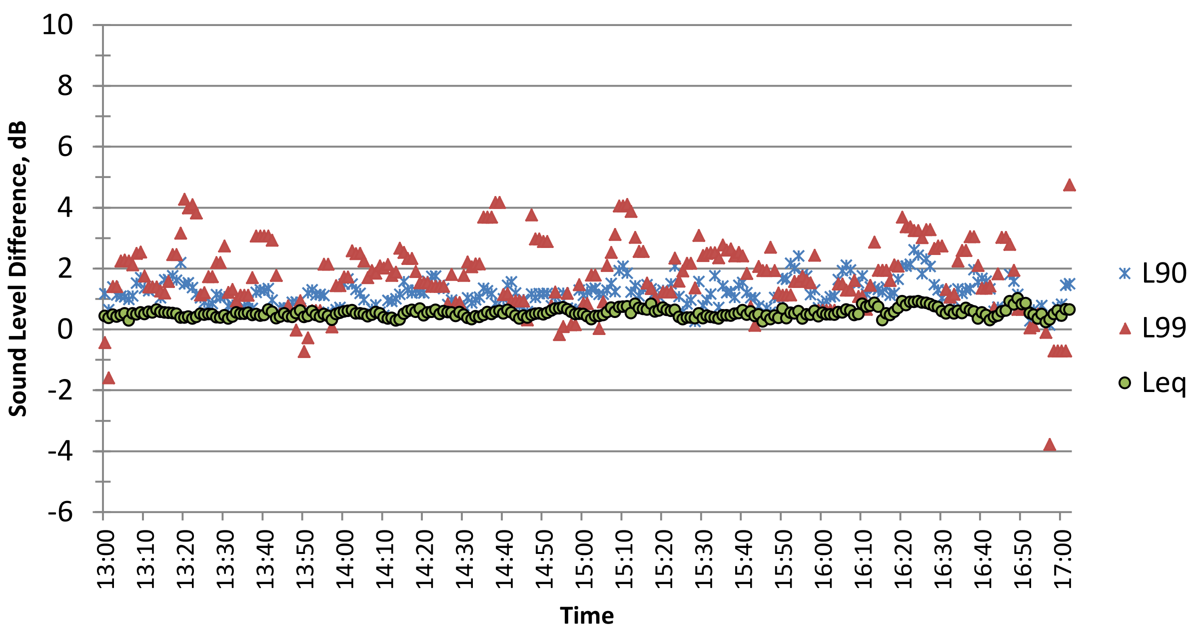


Figure 58. Differences in A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-90, BarCom04 and NoBarCom06.

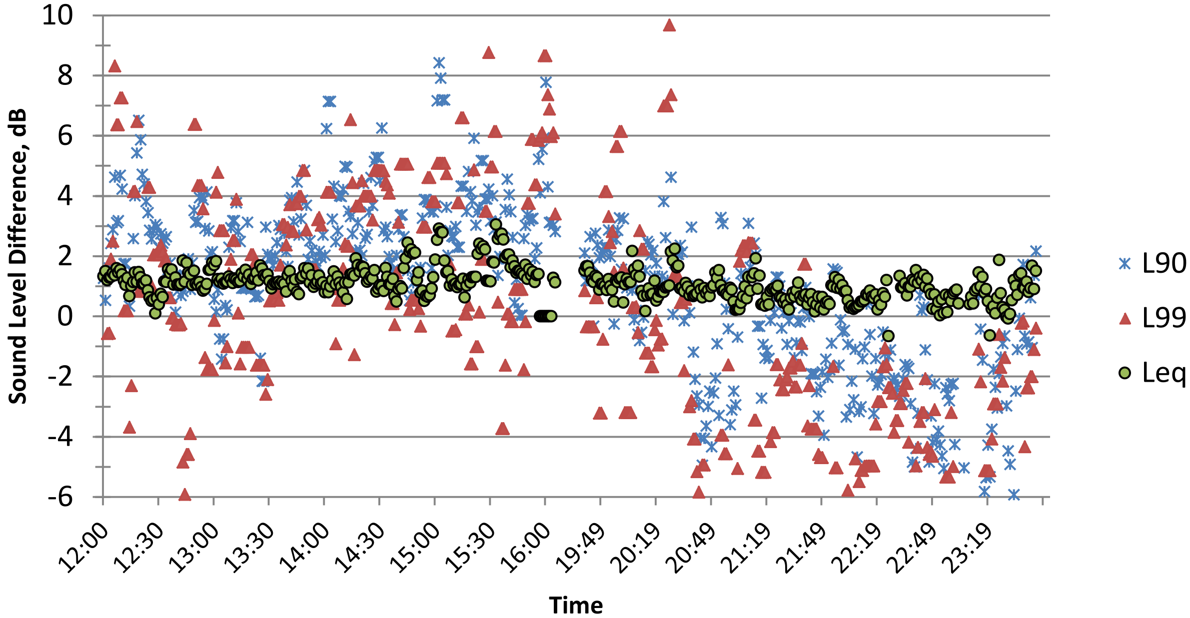


Figure 59. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, MD-5, BarCom03 and NoBarCom05.

Figure 60 shows an example of the 1/3 octave band L_n differences for BarCom03 and NoBarCom05 at I-90 as an example. Similar graphs for the other locations are in Appendix B. The brown color in the 250-500 Hz bands indicate an increase in all of the L_n descriptors means the Barrier levels are higher than the No Barrier levels, which was discussed in Finding 8 (the blue color means the No Barrier levels are higher). The vertical brown streaks on the right sides of the data columns in the frequency bands from 630 Hz up through 3.15 kHz indicate that the BarCom03 background levels are higher than the NoBarCom05 background levels.

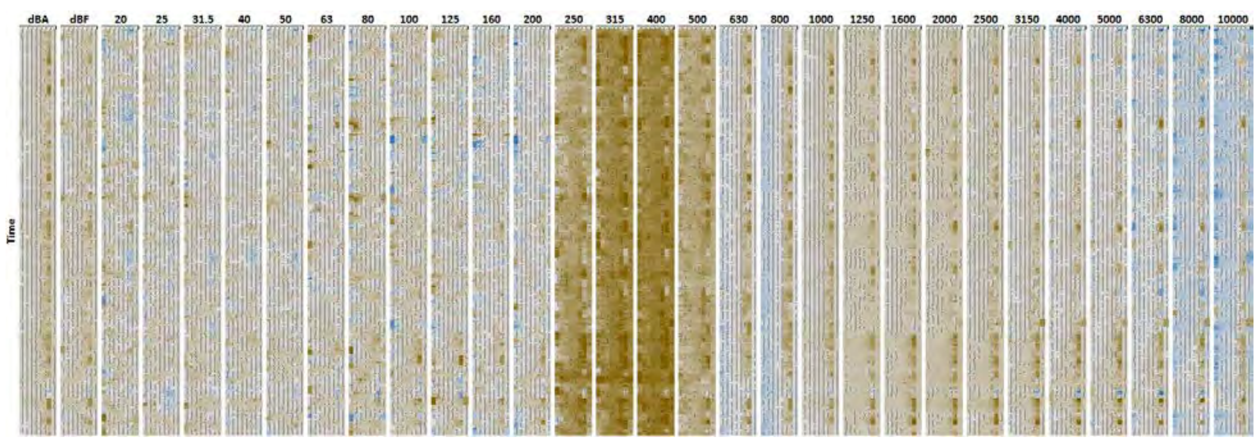


Figure 60. I-90 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom03 and NoBarCom05.

Finding 10: Back at 400 ft from the road, the BarCom04 levels are typically 1 dB to 4 dB higher than at the No Barrier site, as evidenced at SR-71.

Figure 61 shows the differences in the unweighted and A-weighted levels for the BarCom04 and NoBarCom06 microphone pair at SR-71. These microphones were the most distant from the road in the study, at 400 ft. For virtually all of the running five-minute Leq periods, the BarCom04 levels, both unweighted and A-weighted, are higher than the NoBarCom06 levels. The unweighted levels range from 0 dB to 5.5 dB higher than NoBarCom06. The A-weighted levels range from 1 dB to 3.7 dB higher. For both unweighted and A-weighted cases, the average difference was 2.1 dB higher at BarCom04.

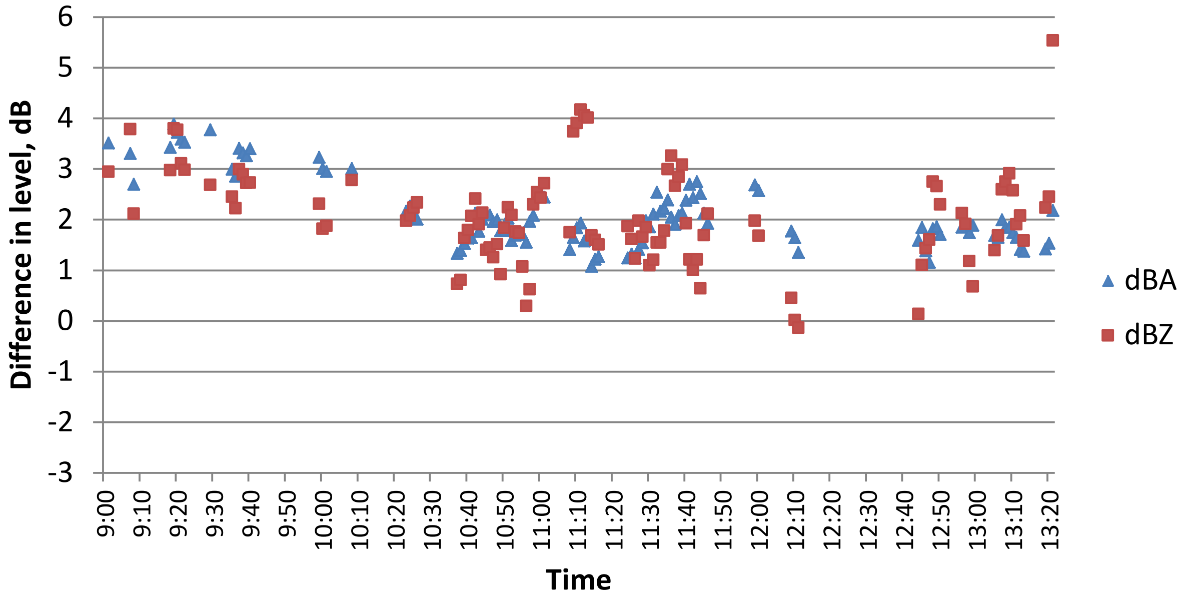


Figure 61. Differences in running L_{eq}(5min), SR-71, BarCom04 minus NoBarCom06.

All of the groupings of five-minute periods that were judged equivalent for the reference L_{eq} and average speeds at the SR-71 location fell into one meteorological class: Downwind Neutral. Figure 62 presents the sound pressure level spectra for BarCom04 and NoBarCom06. The BarCom04 levels are higher in all bands except 100 Hz to 200 Hz where NoBarCom06 is higher. Note that terrain differences between the two sites can affect results below 500 Hz. Differences below 500 Hz are likely attributable to a combination of terrain differences and barrier effects. A simplified FHWA TNM analysis showed that, for some of the frequencies below 500 Hz, the BarCom04 sound levels should be lower due to ground effects. Please refer to the spectrogram results for Site SR-71 in Appendix B for more information.

Figure 63 shows the averages of the differences in the distant BarCom04 and NoBarCom06 levels for all of the Downwind Neutral groups. The levels in the frequency bands from 20 Hz up through 80 Hz were 2 dB to 4 dB higher at BarCom04 compared to NoBarCom06. Then, from 315 Hz through 8 kHz, the BarCom04 levels are 1.5 dB to 3 dB higher than NoBarCom06. In the range of 100 Hz through 250 Hz, the NoBarCom06 levels range from 0 dB to 3 dB (at 200 Hz) higher than the BarCom04 levels.

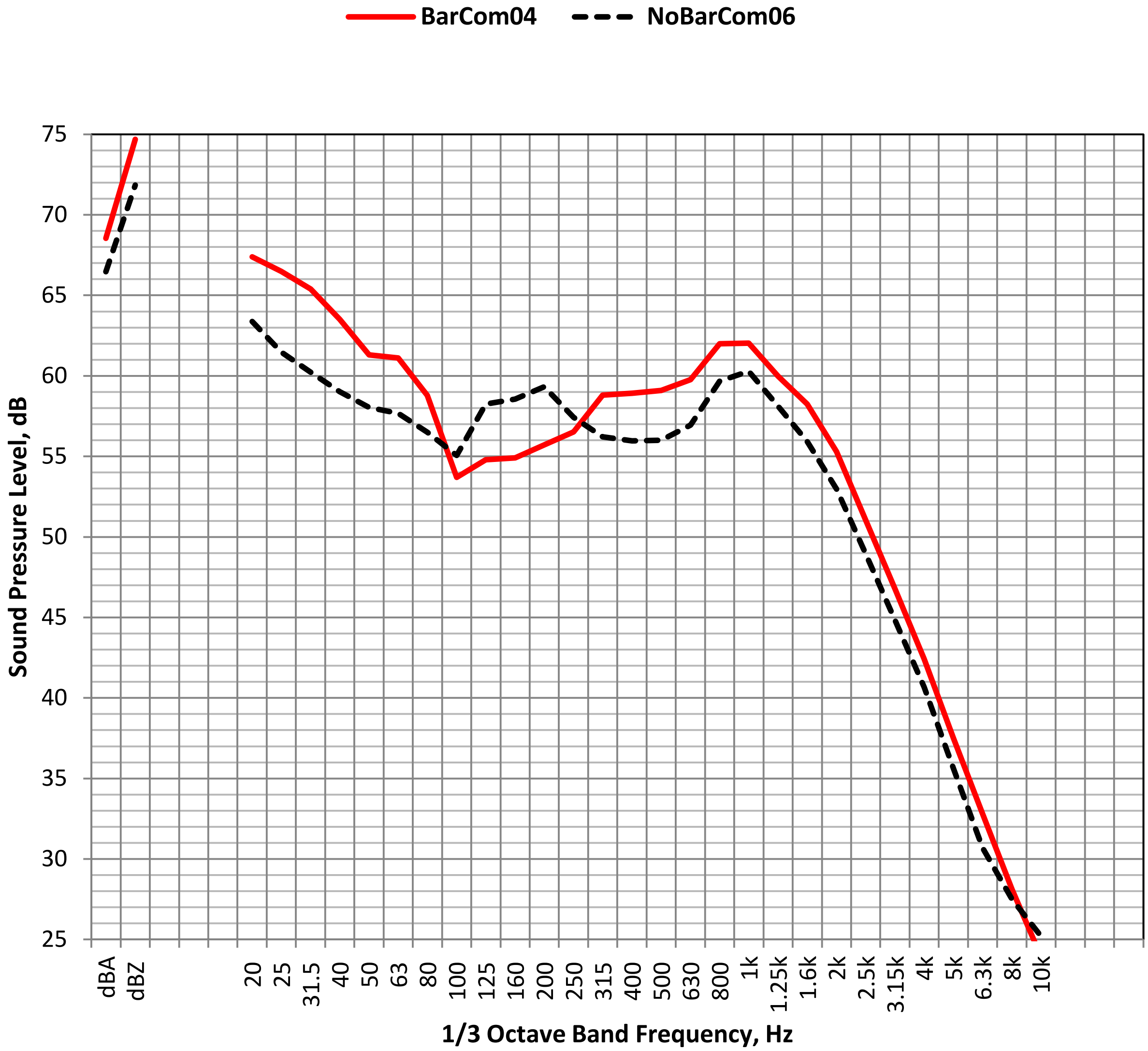


Figure 62. Sample sound pressure level spectra for BarCom04 and NoBarCom06, SR-71, Downwind Neutral group DNG-3-2, 11:38-11:43 (L_{eq}(5min), dBZ).

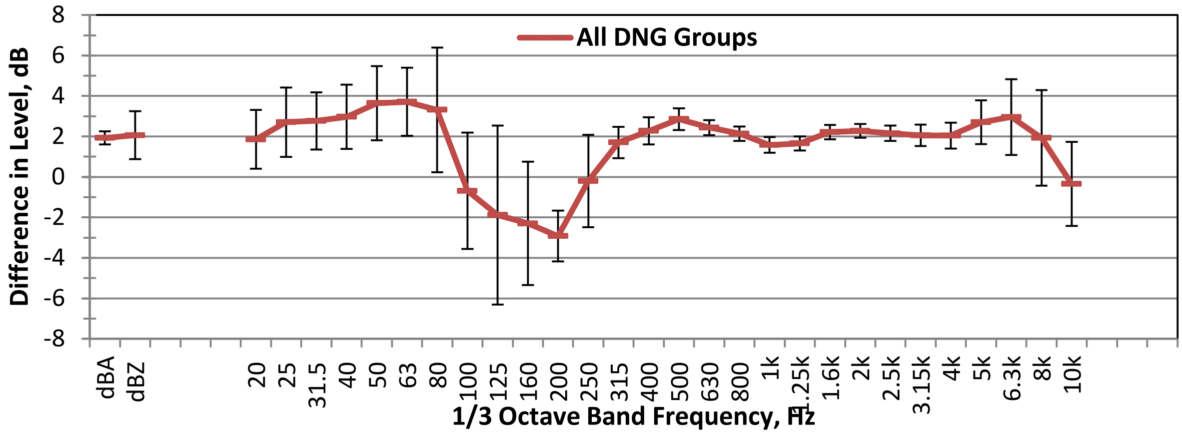


Figure 63. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarCom04 minus NoBarCom06, for all Downwind Neutral groups, SR-71.

Finding 11: Back at 400 ft from the road, all of the L_n descriptors were higher at the BarCom04 site, not just the background levels, as evidenced at SR-71.

Figure 64 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06. Both of these figures start 45 minutes into the measurement period. The was a great deal of what turned out to be roofing nail gun noise that was audible at NoBarCom06 during this period, Rather than trying to edit it all out of the data, this period was just deleted from this L_n analysis.

The results are different for this microphone pair than most of the other pairs across the various study locations because these microphones are the farthest from the road. The BarCom04 L_{eq}(5min) ranged from 2.5 dB to 3.8 dB higher than the NoBarCom06 level for the first 23 minutes of the period shown on the figure. During this time, the meteorological class was Calm Neutral and the L_{90}(5min) and $L_{99(5min)}$ differences ranged from 2 dB to 5 dB higher at BarCom04 than at NoBarCom06.

During the last three hours, the L_{eq}(5min) difference became more variable – 0.5 dB to 2.5 dB higher at BarCom04. During this period, L_{90}(5min) differences also became more variable, being 0 to 3.5 dB higher at BarCom04. The L_{99}(5min) became even more variable, with the BarCom04 values ranging from 1 dB lower than those at NoBarCom06 to 5.4 dB higher. During this time period, the meteorological class was Downwind Neutral. On average over the full measurement period, the BarCom04 L_{eq}(5min), L_{90}(5min) and L_{99}(5min) were 1.7 dB, 2.0 dB and 2.1 dB higher than at NoBarCom06.

These results, taken together, suggest that the overall levels from the traffic noise are higher at the Barrier site, but because the traffic is 400 ft away, there is less overall rise and fall to the levels compared to being in close to the road. As a result, there is little chance for lulls in the noise under the studied traffic flows. Perhaps nighttime measurements when the flow is much lower might show that elevating of the background level at a distant site across from a barrier.

Figure 65 presents the spectral L_n differences for BarCom04 and NoBarCom06. A pattern can be seen of higher broadband A-weighted levels at BarCom04 in the low and mid-to-upper bands, with higher NoBarCom06 levels in the 100 Hz to 250 Hz bands as well as the highest frequency bands. (Note that terrain differences between the two sites can affect results below 500 Hz; please refer to the SR-71 spectrogram results in Appendix B for more information.) This pattern applies across most of the Ln descriptors, not just L_{90}(5min) and L_{99}(5min).

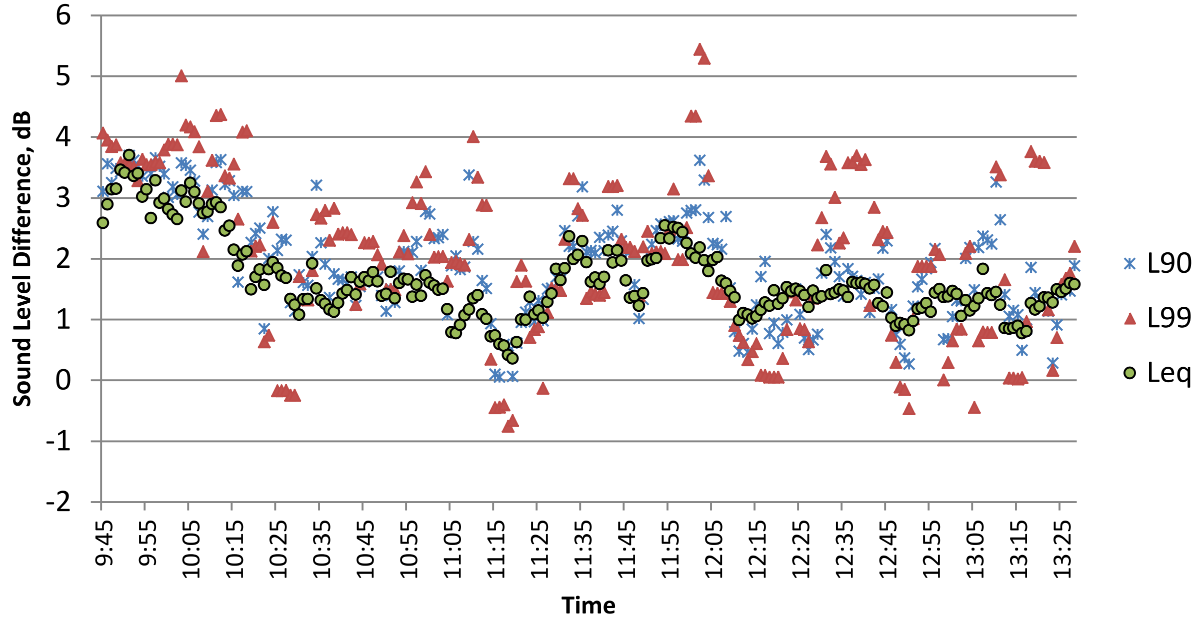


Figure 64. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, SR-71, BarCom04 and NoBarCom06.

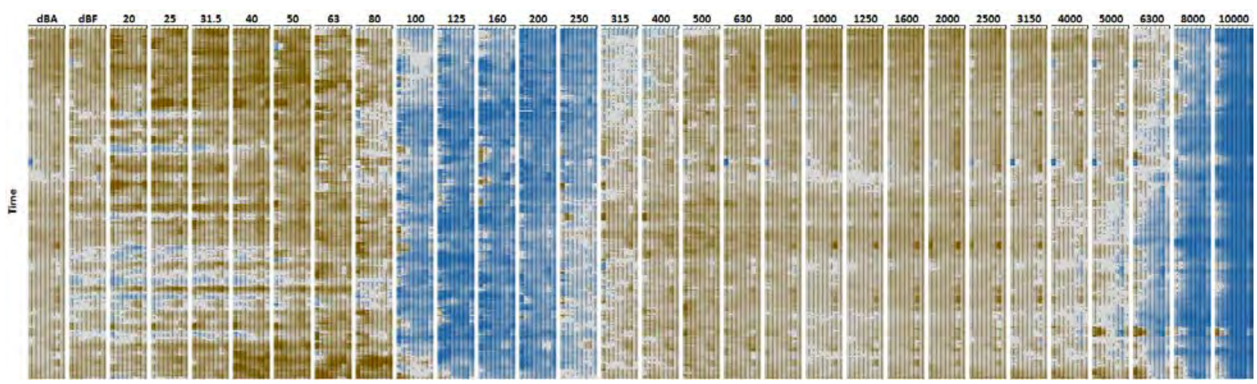
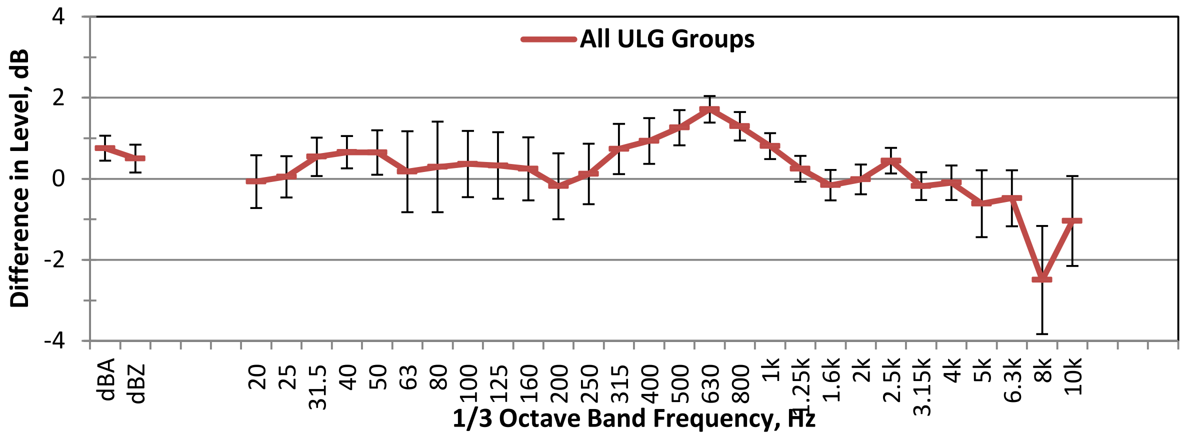


Figure 65. SR-71 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom04 and NoBarCom06.

Finding 12: The increase in levels due to reflections decreased by 1 dB to 2 dB going from a lower-height microphone to a higher microphone, as evidenced at I-24, I-90, and MD-5.

At I-24, BarCom03 and NoBarCom05 were 5 ft above the roadway plane. BarCom04 and NoBarCom06 were 15 ft above the roadway, at the same distant back as the lower microphones. Figure 66 shows the differences in level between the microphone pairs for an average of all of the Upwind Lapse groups. The top graph shows the differences in levels between BarCom03 and NoBarCom05. In general, the BarCom03 levels are equal to or slightly greater than the NoBarCom05 levels over most of the frequency range up through 4 kHz. The increase is less than 1 dB from 31.5 Hz to 250 Hz, and on the order of 1 dB to 2 dB in the bands from 315 Hz to 1 kHz. Above 4 kHz, the levels at NoBarCom05 are higher than the levels at BarCom03. The difference was caused by insects in the vegetation behind the NoBarCom05 microphone that were not present near the BarCom03 site.

The lower graph compares the levels at BarCom04 and NoBarCom06. The results show that the BarCom04 levels in the frequency bands from 20 Hz up through 1.25 kHz were equal to or slightly higher than at NoBarCom06. At 31.5 Hz to 63 Hz, they were approximately 1 dB higher than NoBarCom06. At 1.6 kHz and above, the NoBarCom06 levels were higher than the BarCom04 levels ranging from a fraction of a decibel at 1.6 kHz to 2.5 dB in the 6.3 kHz band. The higher levels at NoBarCom06 in the high-frequency bands are attributed to insect noise in some vegetation behind this microphone.



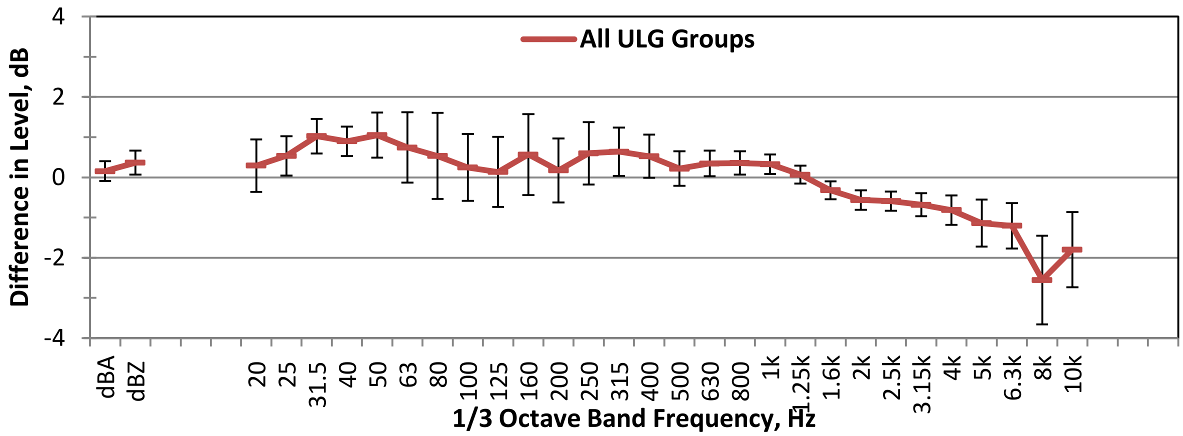
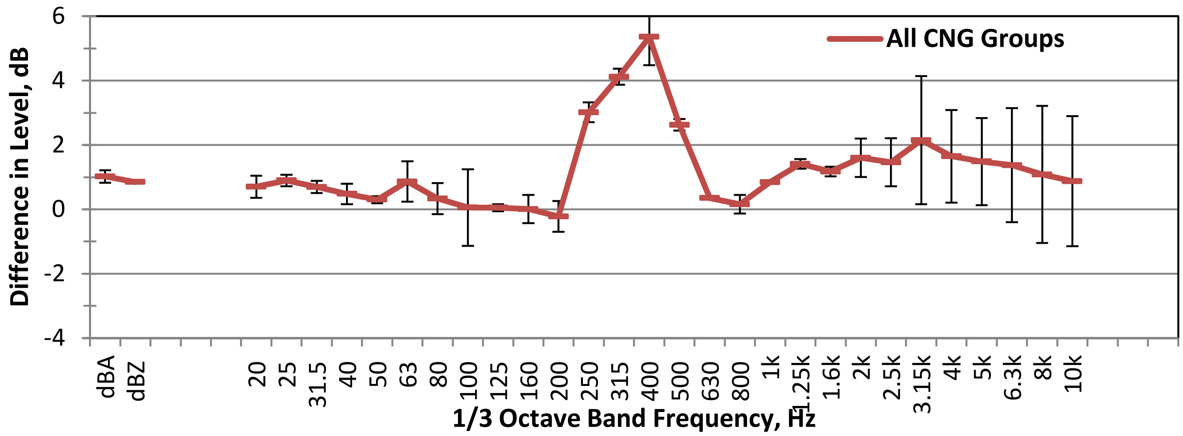


Figure 66. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarCom03 and NoBarCom05 (top) and BarCom04 and NoBarCom06 (bottom), for all Upwind Lapse groups, I-24.

For I-90, Figure 67 shows the averages of the differences in the Barrier and No Barrier microphones' levels for all of the Calm Neutral groups. The upper graph compares the levels at BarCom03 and NoBarCom05, the lower-height microphones, both of which were 69 feet from the center of the near travel lane and 10.4 feet above the roadway surface. The levels in the frequency bands from 20 Hz up through 80 Hz were 0.5 dB to 1 dB higher at BarCom03. For 1 kHz and higher, the BarCom04 levels were approximately 1 dB to 2 dB than those at NoBarCom05. The most noticeable differences were in the 250 Hz to 500 Hz bands, where the levels were 2.5 dB to 5 dB (at 400 Hz) higher.

The lower graph compares the levels at BarCom04 and NoBarCom06, both of which were 93 feet from the center of the near lane and 17 feet above the roadway surface. The levels in the frequency bands from 31.5 Hz up through 250 Hz were 0.5 dB to 1 dB higher at BarCom04. From 1.25 kHz to 3.15 kHz, the BarCom04 levels were approximately 0.5 dB higher. The most noticeable differences were in the 315 Hz to 630 Hz bands, where the levels were 1.5 dB to 3 dB (at 400 Hz) higher.



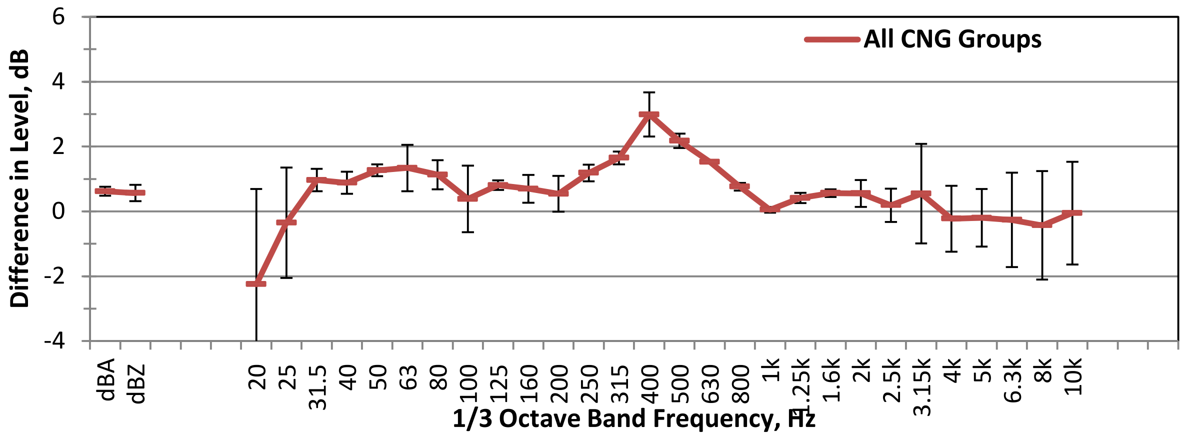


Figure 67. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarCom03, BarCom04, NoBarCom05 and NoBarCom06, for all Calm Neutral groups, I-90.

Similar results were seen at MD-5 where the lower microphones were 5 ft above the roadway plane. Graphs for that data are in Appendix B, as well as graphs and details of the L_n analysis at I-24, I-90 and MD-5.

Although this idea requires further consideration, one possible conclusion that can be drawn from this finding is that barrier reflection effects may be more pronounced closer to the ground due to sound-reducing propagation effects. Closer to the ground, shielding from median barriers/vehicles and ground effects can reduce sound levels at various frequencies. When an opposing barrier is added, the reflected noise likely has energy at those same frequencies, and this energy can become exposed. For receivers higher above the ground, the noise-reducing propagation effects are decreased, so the barrier-reflected noise may be partially masked or diminished.

Finding 13: No effect on the sound level differences was seen as a function of traffic volume, as evidenced at all microphone pairs.

For all sites and among all groups within a meteorological class, there was little correlation found between changes in traffic volumes and changes in the differences in L_{eq}(5min). Although, the Calm Inversion group actually showed a roughly 300% change in Factored Hourly traffic volume across all of the equivalent groups, meaningful conclusions about correlations between traffic volumes and the differences in L_{eq}(5min) could not be established.

Also, in general, the range in speeds for each class was too small to address any relationship between speed sound level difference.

The ranges in volumes and speeds in the studied five-minute equivalent periods are shown Table 13.

Table 13. Ranges in volumes and speeds in the studied five-minute equivalent periods.

Location	Range of Two-Way Factored Hourly Volume*, vph	Range in Average Speeds, mph
I-24	5,700 to 8,212	67 mph to 72 mph for Upwind Lapse groups 68 mph to 72 mph for Calm Lapse groups 69 mph to 71 mph for Calm Neutral groups
I-90	4,779 to 5,488	66 mph to 71 mph for Downwind Lapse 68 mph to 70 mph for Calm Neutral groups
SR-71	3,628 to 3,764	66 mph to 76 mph for Downwind Neutral groups
MD-5	400 to 2,936	58 mph to 63 mph for Downwind Lapse groups 58 mph to 64 mph for Downwind Neutral groups 58 mph to 63 mph for Calm Neutral groups 58 mph to 64 mph for Downwind Neutral groups

*Total two-way volume averaged across the periods in that group and factored up to one hour.

Finding 14: There are slight differences in the sound level differences for different meteorological classes, however there are no clear trends, as evidenced at I-90, I-24 and MD-5. Data collected at greater distances from the road might tell more.

As shown earlier in Table 11, data were collected under a fair range of meteorological classes across all of the locations. There are too many differences from one location to another, such that comparison of meteorological class results from one location to another would not be meaningful. However, comparison of difference meteorological class results at the same location has more validity.

The following comparisons were made:

- Calm Neutral and Downwind Lapse at I-90
- Upwind Lapse, Calm Lapse and Calm Neutral at I-24
- Downwind Lapse, Downwind Neutral, Calm Neutral and Calm Inversion at MD-5

The equivalent-period data at the SR-71 location all fell in the same Downwind Neutral meteorological class, not allowing for comparisons across classes at the most distant microphones in the study. However, the less rigorous comparison of the broadband A-weighted levels shown earlier in Figure 64 under Finding 11 gives evidence of the differences between the BarCom04 and NoBarCom06 levels being 1.5 dB to 2 dB greater during the early Calm Neutral periods than the later Downwind Neutral periods.

At the I-90 location, the results show that the Calm Neutral differences were slightly greater than the Downwind Lapse differences at the community microphones.

The I-24 data show that the Upwind Lapse average differences tend to be:

- Both slightly less and slightly greater than the Calm Lapse average differences in the lower frequency bands, by a few tenths of a decibel; and
- A few tenths of a decibel greater than the Calm Lapse average differences in the higher frequency bands (500 Hz to 4 kHz).

At the MD-5 location (ignoring the frog noise at 4 kHz at the No Barrier microphones), for the lower community microphones (BarCom03 and NoBarCom05), the Calm Neutral differences are:

- 1 dB to 1.5 dB greater than all three of other classes at 125 Hz;
- 0.5 dB to 1.0 dB less than all three other classes at 200 Hz;
- About 1 dB greater than the two Downwind cases at 250 Hz 1 dB to 1.5 dB less than the two Downwind cases at 400 Hz through 630 Hz;
- About a half decibel less than the two Downwind cases at 1kHz through 3.15 kHz.

For the MD-5 upper community microphones (BarCom04 and NoBarCom04), the Calm Neutral differences are:

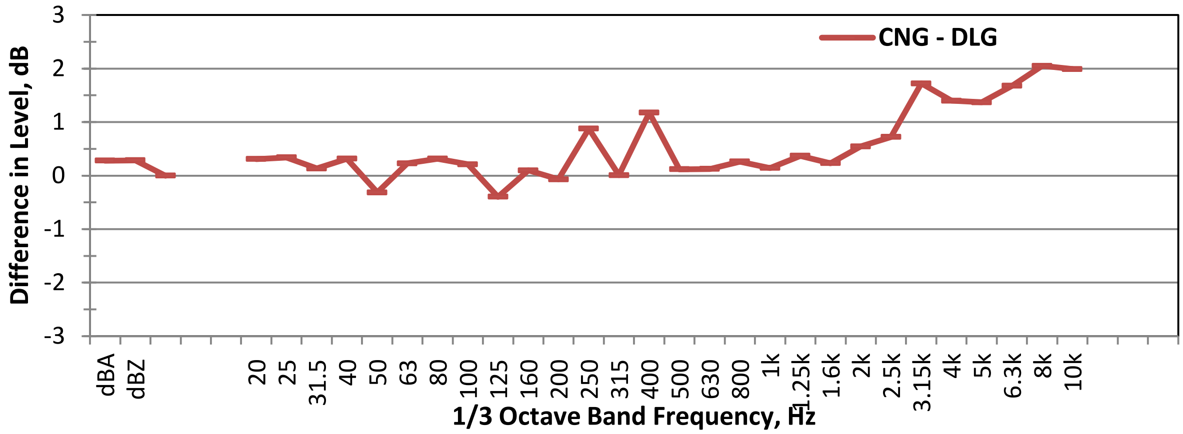
- 1 dB to 2.5 dB greater than all three of other classes at 125 Hz;
- 0.5 dB to 1.0 dB less than all three other classes at 200 Hz;
- About 1 dB less than the Calm Inversion cases at 63 and 100 Hz;
- A half decibel or less different at the rest of the frequency bands compared to all three other meteorological classes.

Supporting figures are shown in the following sections.

I-90 Calm Neutral and Downwind Lapse Comparison

Figure 68 compares the I-90 differences in level for the Downwind Lapse and Calm Neutral classes for BarCom03 vs. NoBarCom05 and BarCom04 vs. NoBarCom06. Again, the data values are the average Calm Neutral differences minus the average Downwind Lapse differences for each frequency band.

The data show that the Calm Neutral average differences tend to be slightly greater than the Downwind Lapse average differences across the frequency spectrum. For both microphone pairs, the Calm Neutral differences are greater than the Downwind Lapse differences by a decibel or less up though 2.5 kHz. (with the exception at 25 Hz, where the difference is 2 dB). At 3.15 kHz and above, the Calm Neutral differences range from 0.5 dB to 2.0 dB higher.



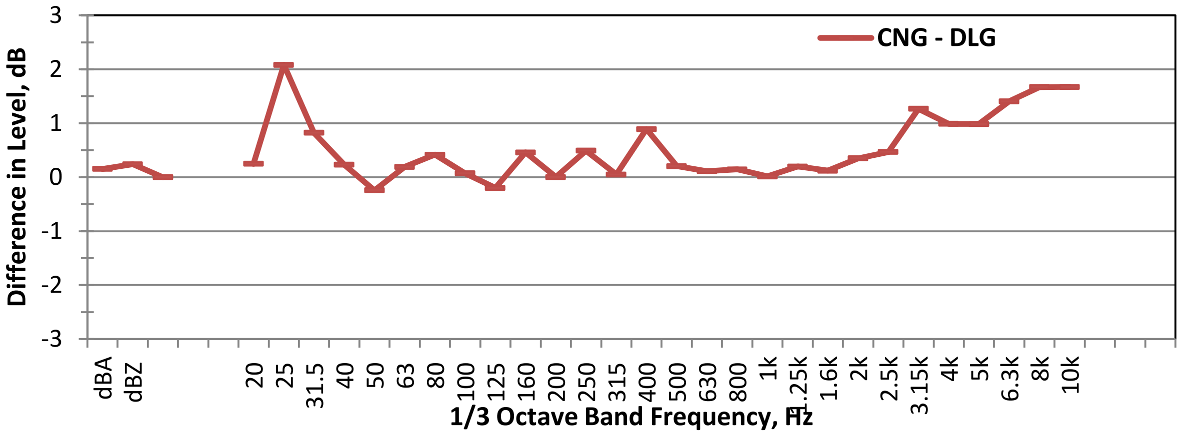
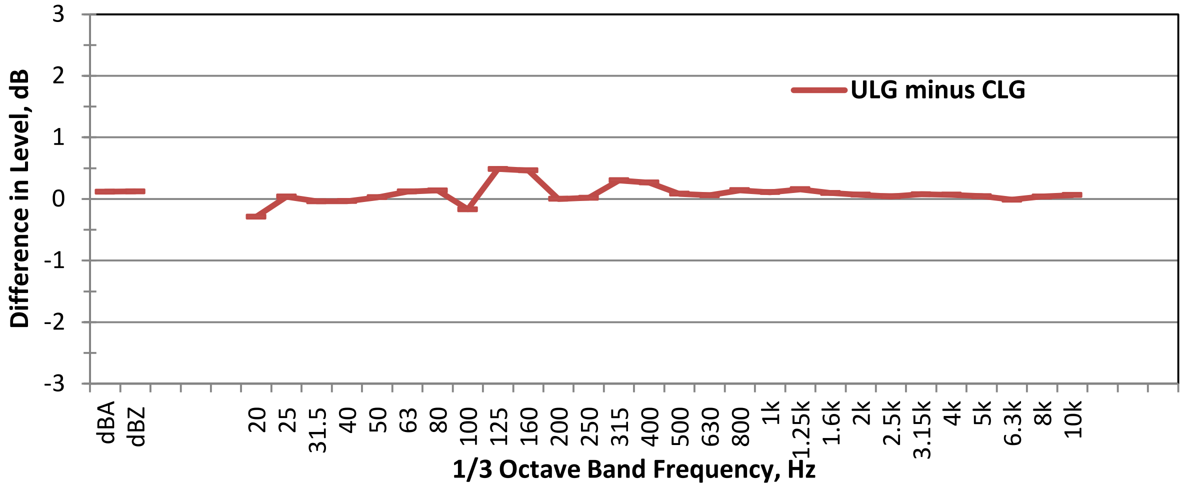
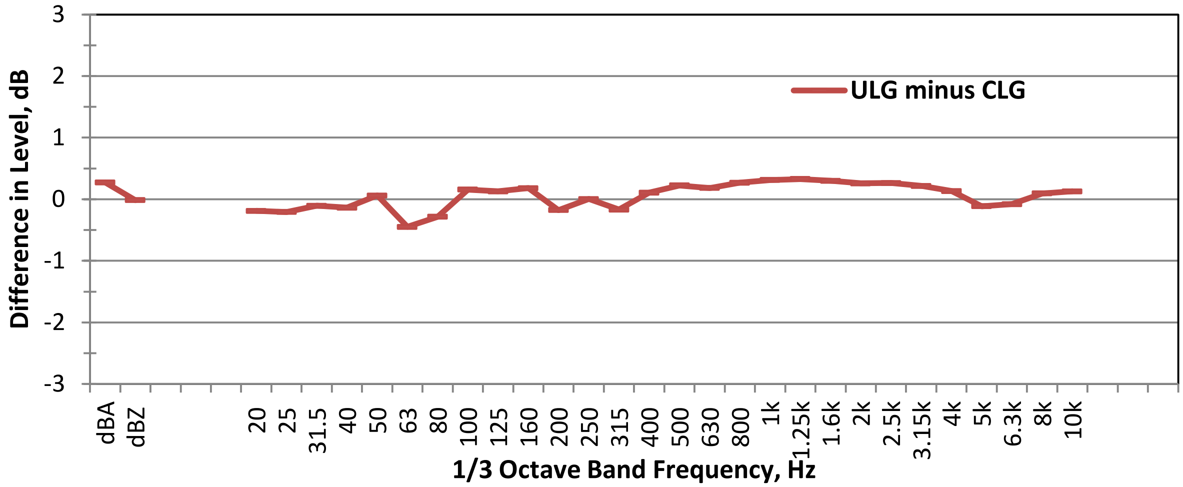


Figure 68. Calm Neutral minus the Downwind Lapse average differences (L_{eq}(5min), BarCom03 minus NoBarCom05 (top) and BarCom04 minus NoBarCom06 (bottom), I-90.

I-24 Upwind Lapse, Calm Lapse and Calm Neutral comparisons

Figure 69 compares the differences in level for the Upwind Lapse and Calm Lapse classes for the four community microphone positions for the I-24 location. The data values are the average Upwind Lapse differences minus the average Calm Lapse differences for each frequency band.





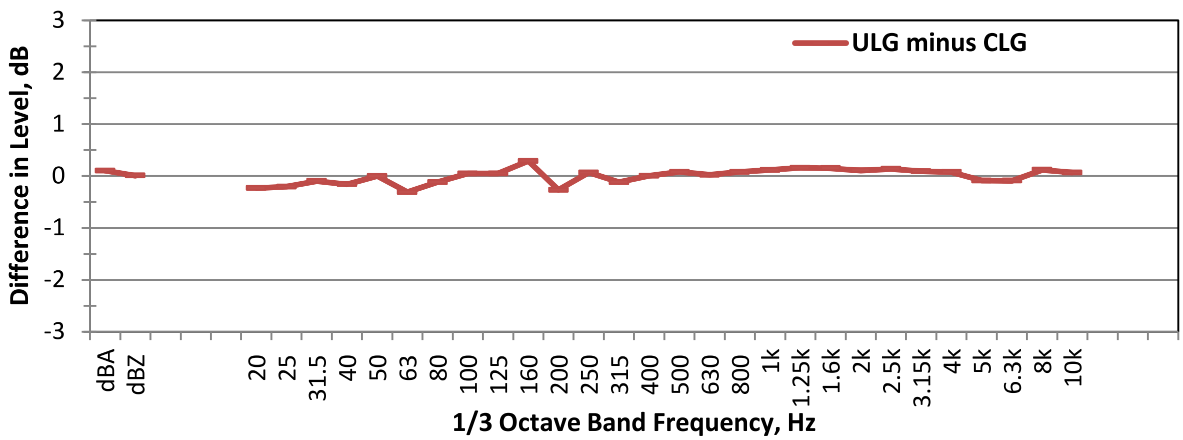


Figure 69. Differences in the Upwind Lapse average differences and the Calm Lapse average differences (L_{eq}(5min) +/- one standard deviation, dB), BarCom03 minus NoBarCom05 (top) and BarCom04 minus NoBarCom06 (bottom), I-24.

MD-5 Downwind Lapse, Downwind Neutral, Calm Neutral and Calm Inversion Comparison

For the MD-5 data, the results are shown by microphone pair. The Downwind cases are in the afternoon measurement session and the Calm cases are in the evening session. In each figure, the top graph is for the differences in the Calm Neutral and Downwind Lapse average difference; the middle graph compares Calm Neutral to Downwind Neutral; and the bottom graph compare Calm Neutral to Calm Inversion. Figure 70 is for BarCom03 minus NoBarCom05 (the lower microphones in the field). Figure 71 is for BarCom04 minus NoBarCom06 (the upper microphones in the field).

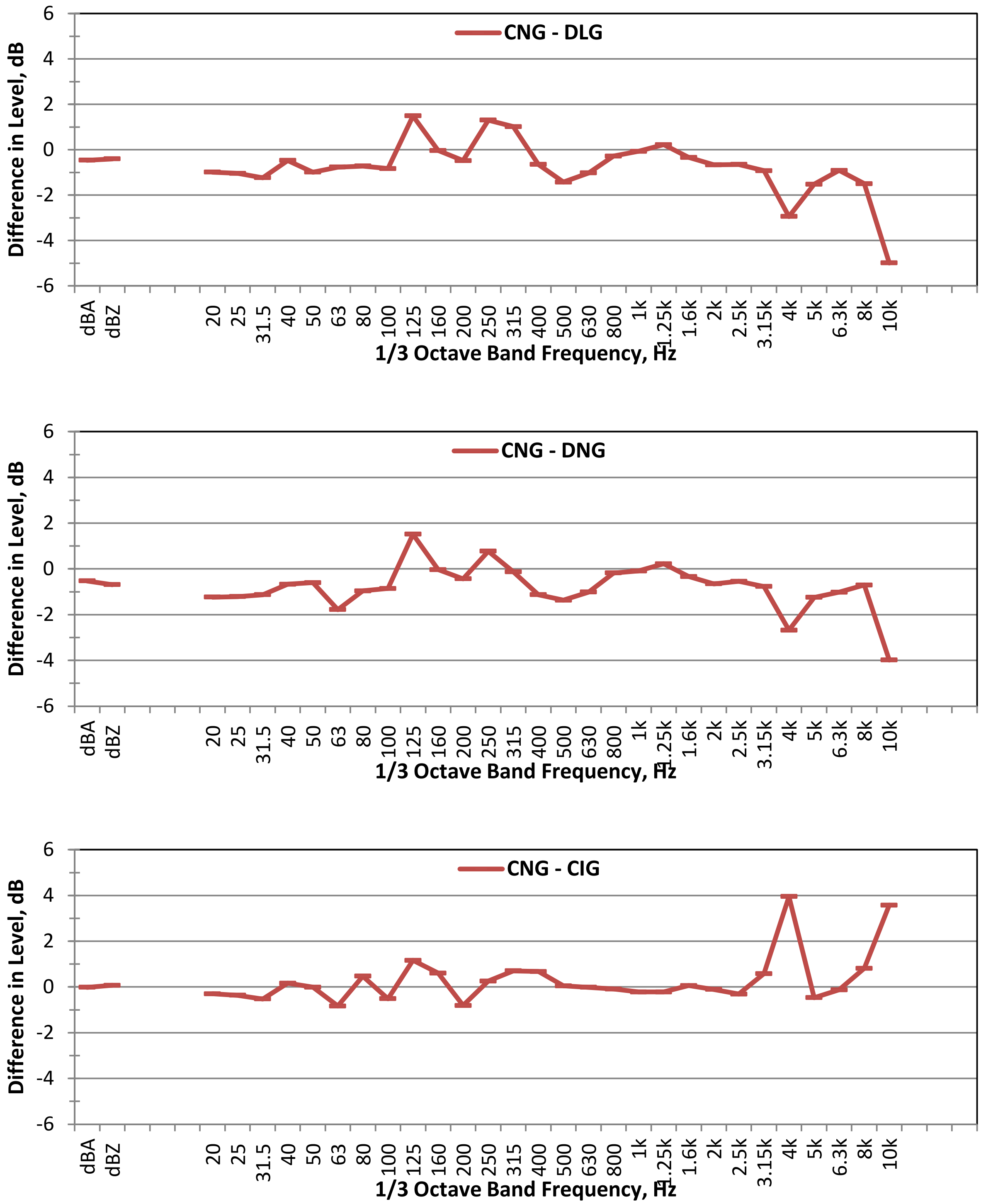


Figure 70. Calm Neutral average differences minus Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq}(5min), NoBarCom05 minus NoBarCom05, MD-5).

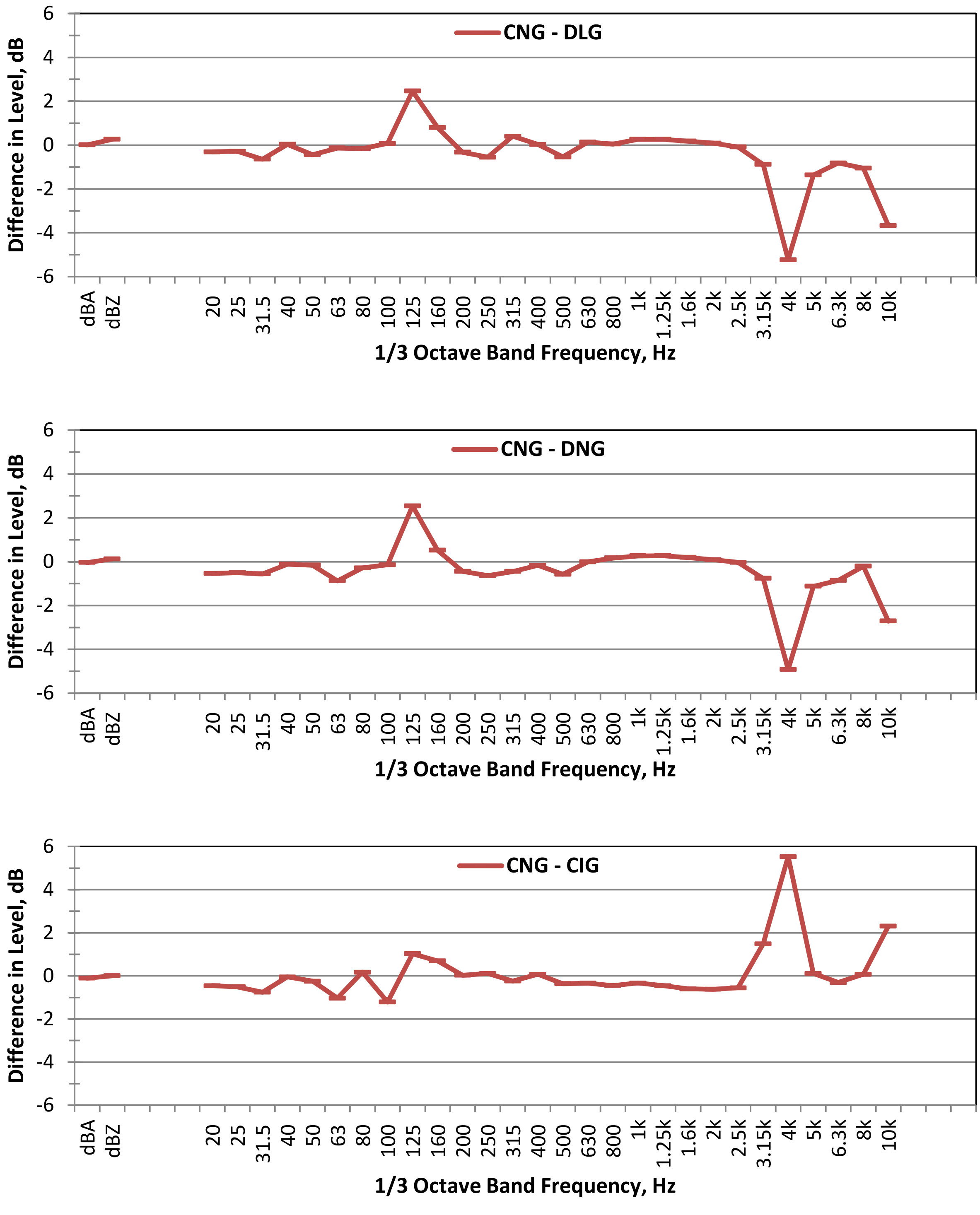


Figure 71. Differences in the Calm Neutral average differences and Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq}(5min), BarCom04 minus NoBarCom06, MD-5.

Spectrogram Findings

Finding 15: Barrier reflections cause sound levels to increase over a broad range of frequencies and cause higher sound levels to be sustained for a longer period of time, as evidenced by the spectrogram results at all locations.

Spectrograms (spectral time histories) were generated for individual or groups of vehicle passby events, as well as samples of highway traffic noise for each of the measurement sites. Examples of the spectrograms are shown in this section. The spectrograms compare data collected at the Barrier site and at an equivalent position at the No Barrier site. This comparison allows for a visual examination of the effect of barrier-reflected noise.

Examples of the vehicle passby events are shown first, followed by example time blocks of highway traffic noise. What can be seen in the spectrogram data when comparing the Barrier to the No Barrier sites is the following:

1. The hot spots (highest sound levels) get hotter (sound levels increase) when there is a barrier present.
2. The hot spots expand (taller and wider) when there is a barrier present. The presence of a noise barrier causes sound levels to increase over a broad range of frequencies and causes higher sound levels to be sustained for a longer period of time.

It should be noted that the above observations apply to vehicles traveling on either side of the road, for a range of distances from the road and heights above the road, and for the vehicle types examined (autos, heavy trucks, and motorcycles). There is evidence that the barrier effect is more pronounced at farther distances from the road. It is assumed that the path length difference between direct and reflected sound is one of the variables controlling the strength of the effect seen from barrier reflections. At farther distances, the path length difference is comparatively smaller, allowing both the direct and reflected sound to contribute to the overall sound level. With larger path length differences, as is the case near the highway, the direct sound would be more dominant than the reflected, and therefore contribute more to the overall sound level, with the reflected sound contributing very little (since it has to travel so much farther than the direct sound). See Chapter 4 on suggested research for more information about this idea.

The first vehicle passby spectrogram example is from the SR-71 site in California (Figure 72). For this example, results are being shown for the distant microphone pair, BarCom04 (top plot) and NoBarCom06 (bottom plot), which was located 400 feet from the road. The passby event is a motorcycle traveling southbound, adjacent to the community side, going by the Barrier site at around 12:10:25 and the No Barrier site around 12:10:50. The barrier effect can clearly be seen when comparing the two spectrograms. For the Barrier site, the hot spots are hotter and also wider and taller for a broad range of frequencies. It is particularly noticeable for frequencies from 250 Hz to 2.5 kHz. Because there were differences in the terrain over the long distance, a brief TNM analysis was conducted to determine how the terrain differences would affect the comparison. Based on the TNM analysis conclusions, the differences seen from 500 Hz to 2.5 kHz can be attributed to the barrier reflections. Below 500 Hz the differences may or may not be attributed to the barrier.

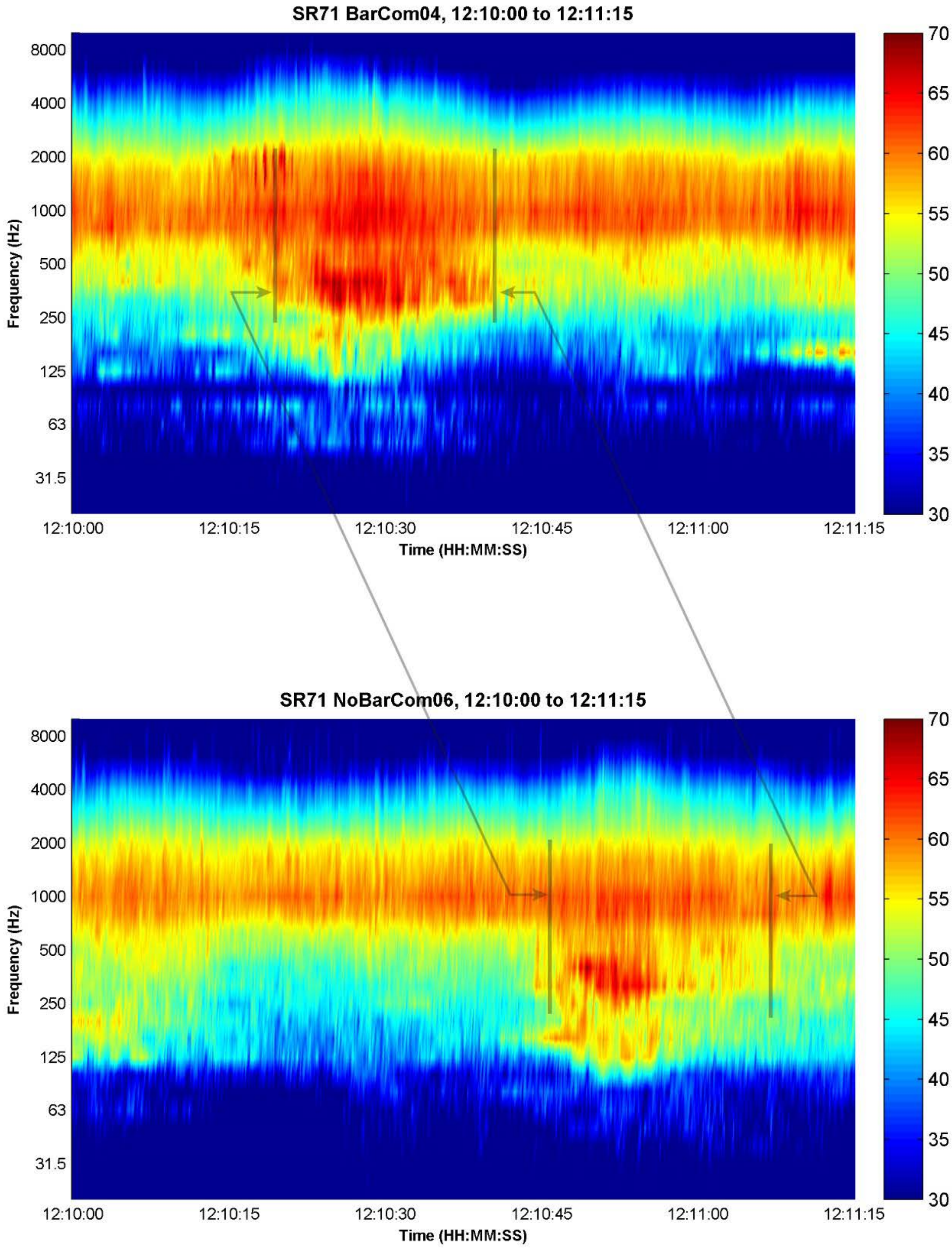


Figure 72. SR-71 spectrograms for motorcycle on southbound (community) side (approximate event times): Barrier site 12:10:25, No Barrier site 12:10:50. Top is BarCom04; bottom is NoBarCom06.

The second vehicle passby spectrogram example is from the MD-5 site in Maryland (Figure 73). For this example, results are being shown for the high microphone pair, BarCom04 (top plot) and NoBarCom06 (bottom plot), which was located 75 feet from the road. The passby event is a pickup truck traveling southbound, adjacent to the barrier side, going by the Barrier site at around 20:09:20 and the No Barrier site around 20:09:35. The barrier effect can clearly be seen when comparing the two spectrograms. The darkest red areas (highest sound levels) fill in more and become wider and taller with the barrier present. The red is centered around 800 or 1000 Hz. The same effect occurs in the surrounding frequency bands, stepping through various colors of the spectrum. The effect is clarified in Figure 74, where the highest levels from the previous figure are extracted and overlaid. The trace from the barrier site (in gray) is taller (broader frequency spread) and wider (more time duration) than the No Barrier site (in red). The intensifying and expanding hot spots indicates that the barrier is causing higher sound levels at frequencies which contribute most to the overall sound level and causing these levels to be sustained for a longer period.

The third vehicle passby spectrogram example is from the I-90 site in Illinois (Figure 75). For this example, results are being shown for the microphone pair closest to the road, BarCom03 (top plot) and NoBarCom05 (bottom plot), which was located about 52 feet from the road. The passby event is a heavy truck traveling southbound, adjacent to the community side, going by the Barrier site at around 13:29:36 and the No Barrier site around 13:29:43. The event can be identified by Doppler Effect, with a distinct yellow/orange band (around 62 dBA) along time shifting from 160 Hz to 125 Hz. The barrier effect can clearly be seen when comparing the two spectrograms. For the Barrier site, the hot spots are wider and taller than for the No Barrier site for a broad range of frequencies. It can be seen that the tallest darkest red band (highest sound level band) centered around 1,000 Hz is both wider and taller, with the same effect occurring in the surrounding frequency bands, stepping through various colors of the spectrum. This difference indicates that the barrier is causing higher sound levels at frequencies which contribute most to the overall sound level and causing these levels to be sustained for a longer period for each vehicle passby event.

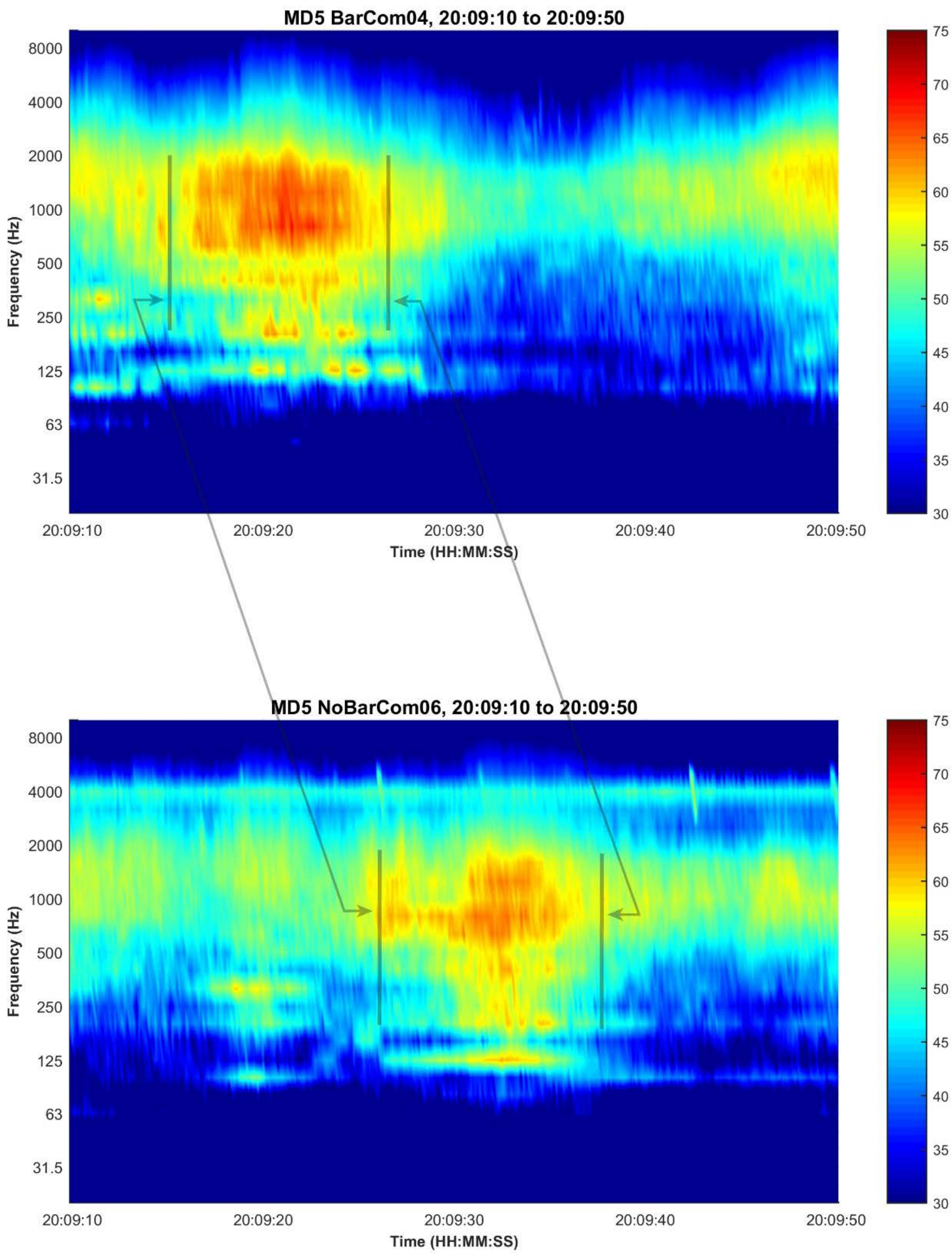


Figure 73. MD-5 spectrograms for a pickup truck on southbound (barrier) side (approximate event times: Barrier site 20:09:20, No Barrier site 20:09:35). Additional vehicle follows the heavy truck. Top is BarCom04; bottom is NoBarCom06.

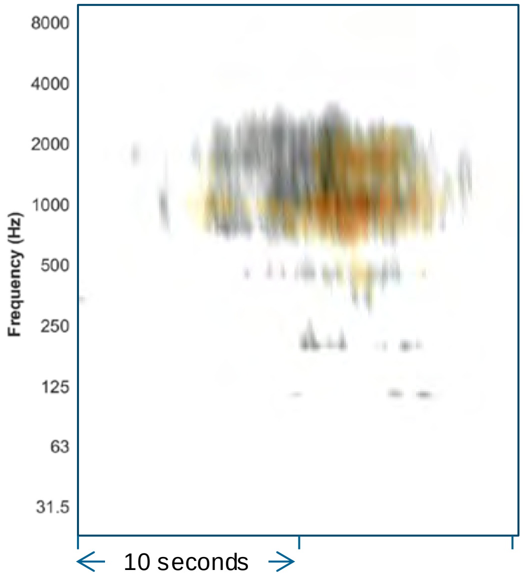


Figure 74. Overlay of MD-5 pickup truck passby hot spots for levels greater than ~60 dBA: BarCom04 (hot spot now represented in gray/black) and NoBarCom06 (hot spot represented in orange/red).

The next two examples show longer periods of traffic noise. In the first of these examples, a four-minute block of data starting at 9:49 for the SR-71 site in California is plotted in Figure 76. For this example, results are being shown for the distant microphone pair, BarCom04 (top plot) and NoBarCom06 (bottom plot), which was located 400 feet from the road. The spectrograms show a clear difference between the Barrier and No Barrier sites. As with the passby data, the clean data blocks show that hot spots are both wider and taller for a broad range of frequencies, particularly for 500 Hz and up, the range to which barrier effects can be attributed (based on the TNM analysis for terrain differences at this site). In the FHWA Method analysis of the overall A-weighted equivalent sound level, several clean data blocks were examined, and it was found that the difference between Barrier and No Barrier A-weighted equivalent sound levels ranged from 1.3 to 3.3 dB. The four-minute block at 9:49 shown in the spectrogram is the case where there was a 3.3 dB difference. (Note: The two "blips" in the spectrogram for BarCom04 at about 09:50:10 and 09:52:30 are due to vehicles on a side road passing closely by the microphone.)

The next example of traffic noise shows a five-minute block of clean data starting at 15:56 for the I-24 site in Tennessee (Figure 77). For this example, results are being shown for two pairs of microphones, in order from top to bottom in the figure: BarRef01 (33 ft from road, barrier side), NoBarRef02 (33 ft from road, barrier side), BarCom04 (66 ft from road, high microphone), and NoBarCom06 (66 ft from road, high microphone). For the reference positions, the spectrograms show a clear indication that there are more occurrences of higher sound levels (dark red) for the barrier case compared to the No Barrier case. In addition, the higher sound level events are broader in frequency and time. Vehicles traveling eastbound (barrier side of road) dominate the sound levels, and during the five-minute block, single events can be tracked from the Barrier site to the No Barrier site about 15 to 20 seconds later. Across the road from the barrier, the high microphone also indicates that the higher sound level events are broader in frequency and time. Vehicles traveling westbound dominate the sound levels (community side of road), and single events can be tracked from the No Barrier site to the Barrier site about 15 to 20 seconds later. The barrier effect trends are not as obvious across the road from the barrier as for the reference positions, but they can be seen by focusing on a series of events and noticing that multiple consecutive events are more blended together in the Barrier case than the No Barrier case. As the higher levels (hot spots) broaden, they blend together more.

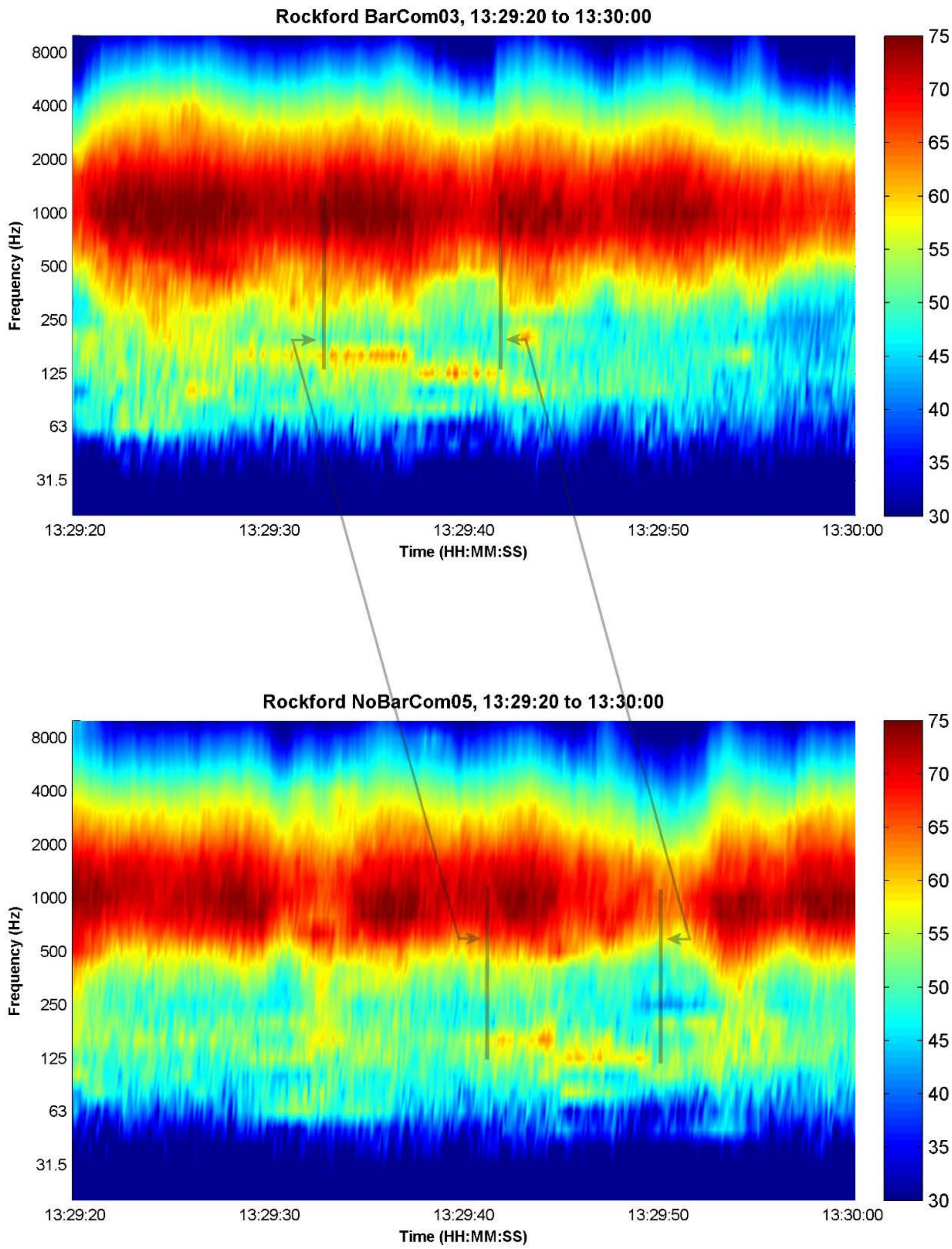
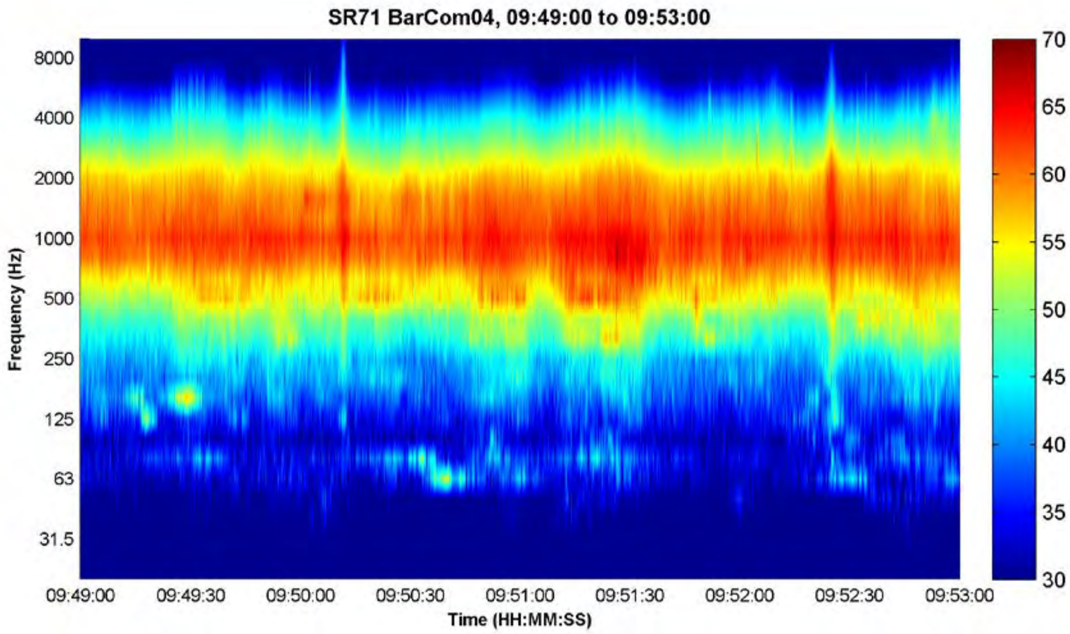


Figure 75. I-90 spectrograms for a heavy truck on southbound (community) side (approximate event times: Barrier site 13:29:36, No Barrier site 13:29:43). Top is BarCom03; bottom is NoBarCom05.



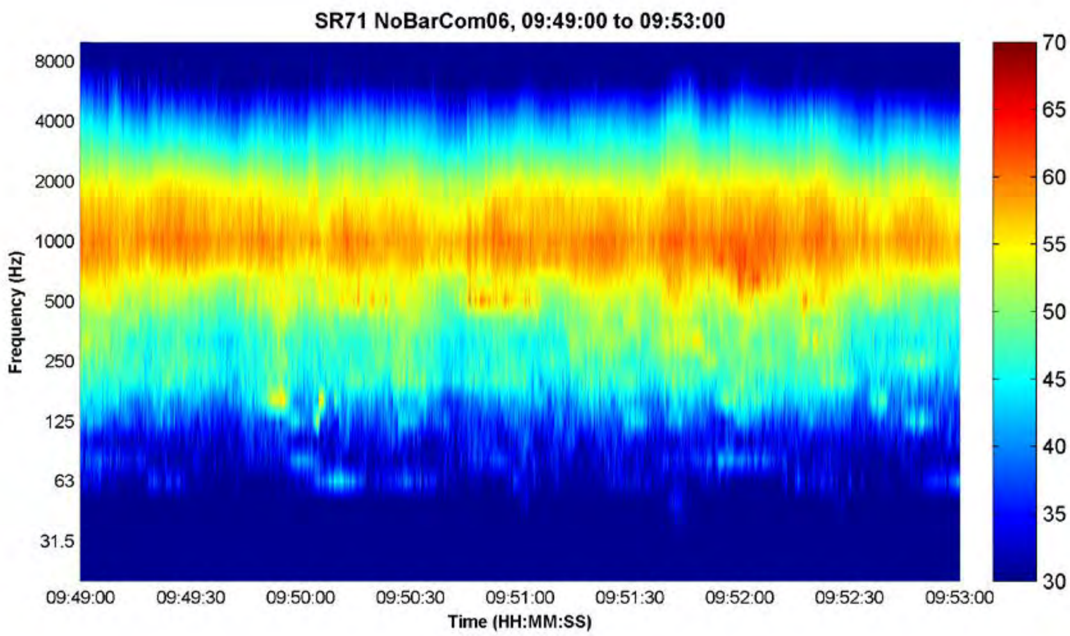


Figure 76. SR-71 spectrograms for 4-minute block of data in the morning at 09:49: top is BarCom04; bottom is NoBarCom06.

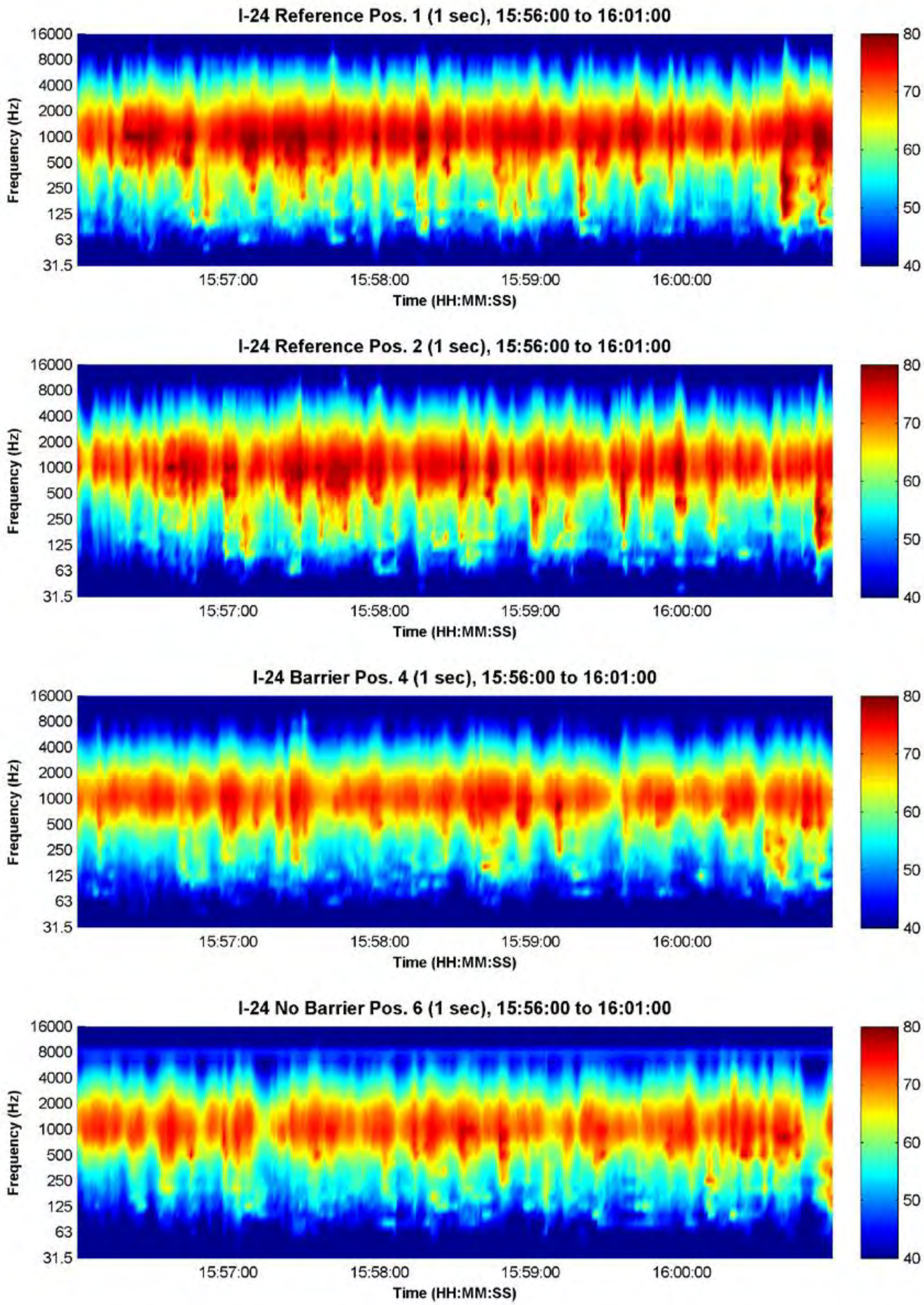


Figure 77. I-24 five-minute spectrograms; top to bottom: BarRef01, NoBarRef02, high mics (BarCom04 and NoBarCom06); for Calm Lapse group CLG-6-1, start time 15:56.

Psychoacoustics Findings

Finding 16: Combined psychoacoustic metrics of Unbiased Annoyance and Psychoacoustic Annoyance yield similar results to one another, while Category Scale of Annoyance does not yield useful indications.

As discussed above, a set of combined psychoacoustic metrics indicating annoyance were applied to the audio recordings for each microphone. Three such annoyance metrics were tested. Of these, the Unbiased Annoyance (UBA) and Psychoacoustic Annoyance (PA) consistently showed similar results. This is to be expected, as they derive from similar approaches in psychoacoustics research. Both of these metrics are dominated by Loudness (measuring total energy and accounting for masking) and Sharpness (an indicator of high-frequency spectral content). The Category Scale of Annoyance (CSA) was ineffective at indicating any differences at all sites and microphone locations. This is most likely due to its simplicity (a simple linear combination of psychoacoustic metrics) and the fact that it was derived from listening studies based on simplified product noise. This result is demonstrated in Figure 78, where the time series and histograms of UBA, PA, and CSA are shown for the upper community microphones.

Finding 17: Annoyance metrics show differences between Barrier and No Barrier sites at moderate distances, but the results are contra-indicative.

The psychoacoustic metrics applied to the audio recordings did not show positive correlation with higher annoyance at the Barrier sites. When simple descriptive statistics are applied to the resulting UBA and PA time series, there are cases where the mean values from the Barrier sites differed to an appreciable level of significance from those at the No Barrier sites. In those cases where the recording microphones were located close to the roadway, the statistics showed no difference between sites. The Loudness and Sharpness at these locations are dominated by direct sound from passing vehicles, and the annoyance metrics, which rely primarily on Loudness, are similarly dominated by direct sound.

The cases where the mean values of annoyance differed to a statistically significant extent tended to occur for the higher microphones, and it was more pronounced for those microphones located at moderate distances from the roadway. This is demonstrated at CA SR-71, as shown in Figure 79. The microphones BarCom03 and NoBarCom05 are located 5 feet above and very close to the roadway, while BarCom04 and NoBarCom06 are 15 feet above and quite far from the roadway. Unfortunately, to the extent that the mean values of annoyance showed significant differences, they were contra-indicative: the annoyance metrics at Barrier sites tended to have lower values than those at the No Barrier sites. An explanation for why this tended to occur was not developed in this work.

Finding 18: Annoyance metrics are less effective in heavy, constant traffic, but show differences in lighter traffic with separated passbys.

The annoyance metrics computed from the recordings at MD-5 are of particular note. The recordings made in the afternoon, with continuous heavy traffic, do not show clear differences between the sites. However, the recordings made at night, when the sound signals consisted mostly of individual vehicle passby events, showed more and more differentiation as the traffic became lighter. This is demonstrated in Figure 80. This may indicate that the psychoacoustic metrics, as applied here, are more applicable to complexities of individual vehicle events than to the general sonic mash of heavy traffic. Note too that the annoyance metrics' dependence on Loudness is revealed in the gradual decrease in traffic toward midnight.

Figure 78. Comparing UBA, PA, and CSA (top to bottom) at the upper community microphones, CA SR-71.

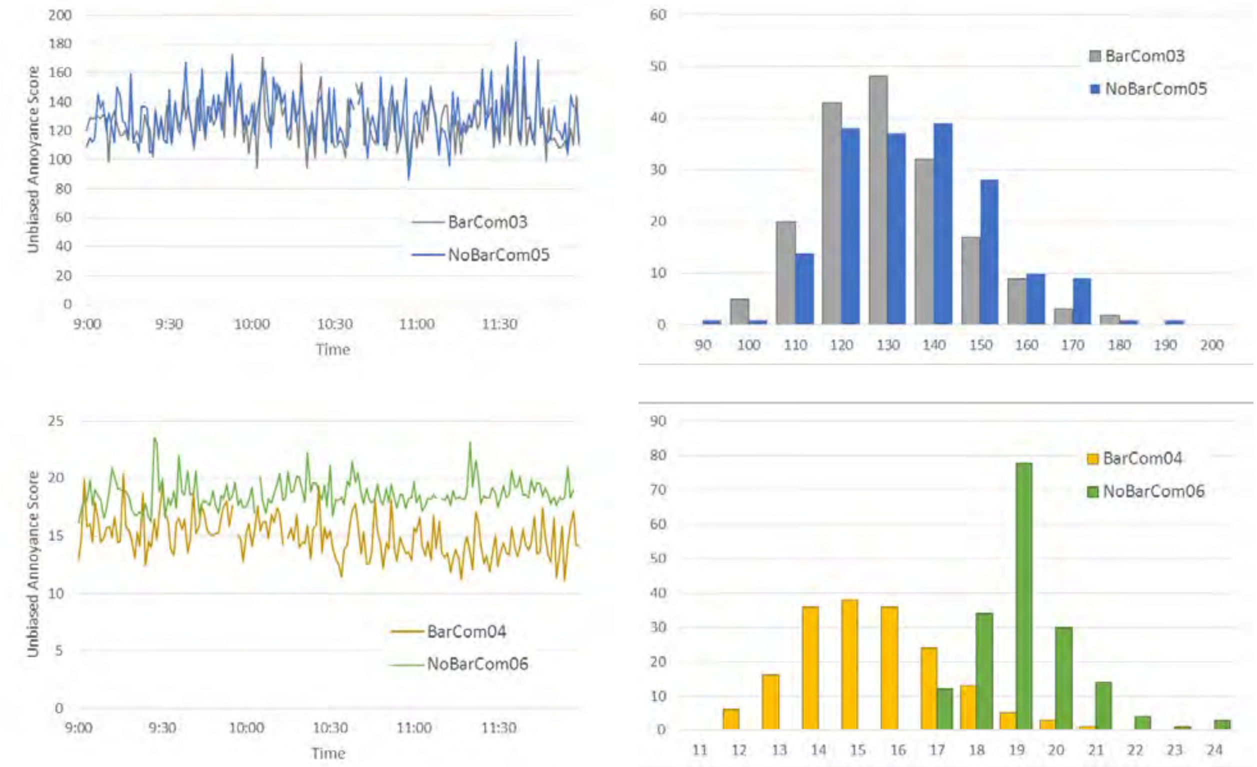


Figure 79. Comparing UBA computed for lower community microphones, close to the roadway, with upper community microphones, distant from the roadway, at CA SR-71.

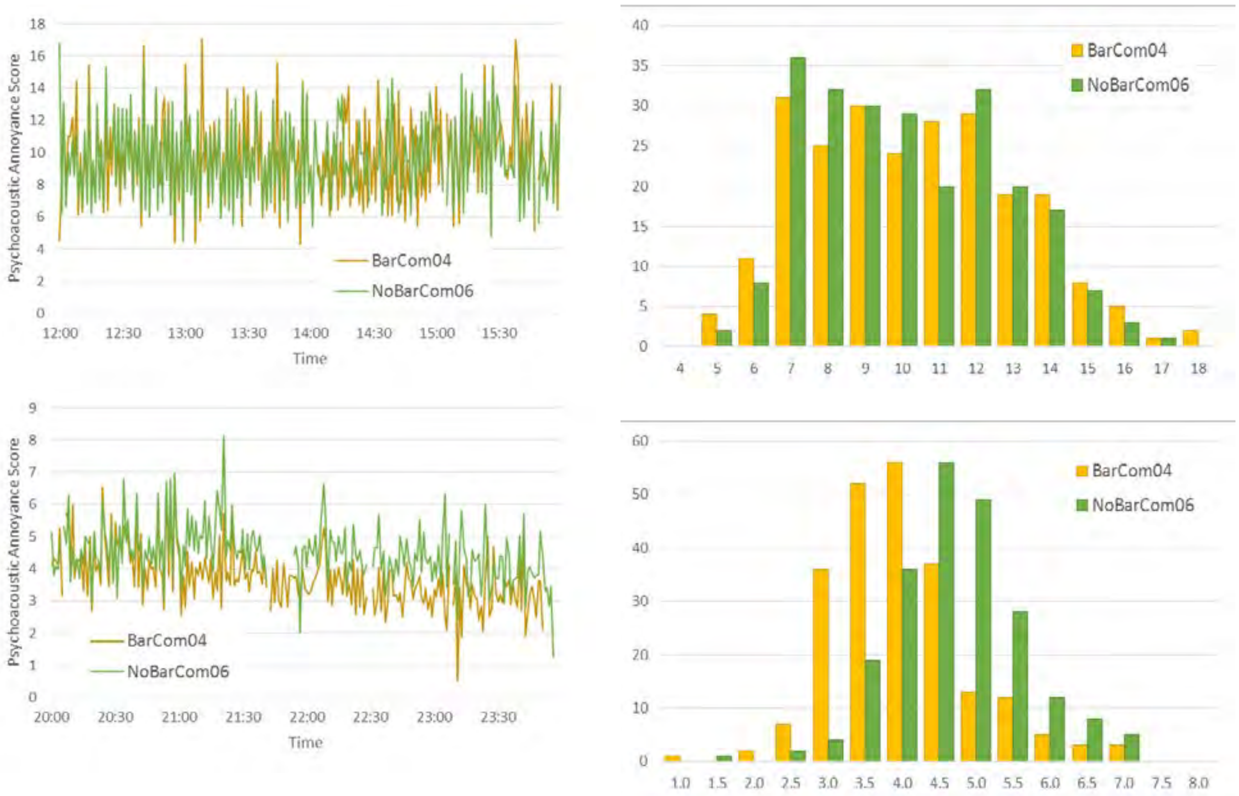


Figure 80. Comparing PA at MD-5 for heavy traffic (above) and light, decreasing traffic (below).

Applications

FHWA Method

The most immediate application of these results is the understanding by traffic noise analysis and abatement practitioners, that traffic sound levels and sound characteristics for receptors across from a proposed single reflective noise barrier can change after the installation of the barrier. The sound level increases can be evident in elevated broadband A-weighted sound levels and unweighted sound pressure levels that are caused by frequency-dependent changes. Also, the traffic noise background levels can be elevated, sustaining the sound of individual vehicle passage, as discussed below for spectrograms.

This understanding can lead to the appropriate specification of sound-absorbing surfaces on these single barriers, especially for highway widenings where the roadway already exists—such as in a Type I widening project or a Type II retrofit noise abatement project (both as defined in current state highway agencies' (SHA) noise policies).

In many cases, the receptors across from a single barrier may have been determined to be impacted by a proposed project in the project's noise study. However, they did not qualify for abatement based on acoustical or physical feasibility reasons or because they did not meet a SHA's noise abatement reasonableness criteria in its traffic noise policy. The specification of sound-absorbing single barriers can be a proactive step to not make the situation worse for such impacted receptors.

In other cases, the receptors may be more distant and not be impacted; nonetheless, the results of this study suggest that such receptors can experience changes in the noise environment due to the introduction of the barrier on the opposite side of the road. While it might be difficult to justify making the barrier sound-absorbing in such a case, the practitioner at least has a better idea of the nature of the phenomenon.

Spectrograms

Spectrograms provide a color-coded visualization of frequency and temporal characteristics of highway traffic noise. Such visualizations can help to reveal differences when comparing a site with and without a noise barrier; this may be useful when trying to explain the effect of barrier reflections—there is a clear visual difference when a barrier is present. Spectrograms may also help to visualize barrier reflections with and without absorption (see recommendations); a comparison could be made among a site without an opposing barrier, one with a reflective barrier, and one with an absorptive barrier. This could help policy makers provide guidance on when it may be effective to use sound-absorbing barriers and help in showing the public what an absorptive barrier could provide.

Psychoacoustics

Because the derived annoyance metrics were either uncorrelated with site location or were contra-indicative for continuous flow traffic, their direct use (as applied in this work) cannot be recommended for indicating increased annoyance due to single barriers in the presence of heavy traffic. However, these metrics are useful in cases where the overall roadway sound is dominated by individual vehicle signatures. This is because time-varying annoyance metrics are dominated by the effects of short-term loud events (N_5).

CHAPTER 5

Conclusions, Recommendations, and Suggested Research

Conclusions

The goal of this research was to investigate the potential change in the sound characteristics opposite a single, reflective highway noise barrier due to the reflection of the traffic noise off that barrier. It is concluded that the sound characteristics are indeed different. The differences are a function of the distance from the road, and to some extent, whether the highway sound is continuous or dominated by individual vehicle passbys.

The first type of change is an increase in the broadband A-weighted sound level and unweighted sound pressure level. Near the road, this increase is higher for receiver positions on the barrier side of the road between the barrier and the road than on the opposite side of the road. There is also evidence that this increase is higher for more distance receivers on the opposite side of the road.

The second type of change is seen in the frequency spectrum of the received sound. The changes appear to be greater at the lower-height microphones than at the higher microphones. There appears to be an enhancement in the spectrum in the 1 kHz to 3.15 kHz bands and in the 250-500 Hz bands, although the results are not entirely consistent.

The third type of change is an increase in the background level due to the lengthening of the signal of a vehicle passby caused by the creation of an image source of the vehicle by the sound reflection off the barrier wall. This increase in the background appears to be greater closer to the road than farther away. In close, the passby signal absent the barrier rises and falls rather quickly. In the presence of the barrier wall, the direct and reflected paths of sound from the vehicle combine to cause the sound to be heard sooner as the vehicle approaches the passby point before its arrival and then last longer after the vehicle passes and is receding away. As a result, the sound level does not have as much time to drop off to a background level before the enhanced sound of the next vehicle is heard (earlier than in a No Barrier situation). The effect is to sustain the background sound level at a higher level than without the reflected sound. The effect on background level appears to decrease with increasing distance from the road and barrier. As distance increases, the effect of other vehicles upstream and downstream from the passby point becomes greater—the rise in level and fall in level during an individual vehicle passage are both made smaller by the effect of distance and the increasingly more important contribution to the total level by upstream and downstream vehicles.

It is concluded that these three changes—level, spectral content and background level—can lead to a listener perceiving a change in the sound. The sound can be louder, different in character and/or last longer than when a barrier was not present. The extent to which any of these three parameters change—and therefore be important to a listener—can vary with distance from the road. It is suggested that the increase in A-weighted sound level alone may not be sufficient to be noticed or trigger a reaction. However, when the change is to the shape of the sound spectrum and/or to the duration of the signal, that change is more readily perceived.

Spectrograms provide a clear visualization of both frequency and temporal effects due to barrier reflections. It can be seen that the presence of the barrier causes sound levels to increase over a broad range of frequencies and causes higher sound levels to be sustained for a longer period of time. The increased sound levels include frequencies that dominate highway traffic noise. These observations apply to vehicles traveling on either side of the road, for a range of distances from the road and heights above the road, and for the vehicle types examined (autos, heavy trucks, and motorcycles). An additional observation is that there is evidence that the barrier effect is more pronounced at farther distances from the road. It is assumed that the path length difference between direct and reflected sound is one of the variables controlling the strength of the effect seen from barrier reflections (smaller difference = greater effect).

The psychoacoustic metrics applied to the audio recordings did not show reliable, positive correlation with higher annoyance at Barrier sites for continuous traffic. The Unbiased Annoyance (UBA) and Psychoacoustic Annoyance (PA) consistently showed similar results. The Category Scale of Annoyance (CSA) was ineffective at all sites and microphone locations at indicating any differences.

When simple descriptive statistics are extracted from the resulting UBA and PA time series, there are cases where the mean values from the Barrier sites differed to an appreciable level of significance from those at the No Barrier sites. These tended to occur for the higher microphones, and it was more pronounced for those microphones located at moderate distances from the roadway. In all cases, metrics derived from microphones located close to the roadway showed no difference between sites. Unfortunately, to the extent that the mean values of annoyance showed significant differences, they were contra-indicative: the annoyance metrics at Barrier sites tended to have lower values than those at the No Barrier sites. However, it was found that with lower traffic volumes, where individual passby events were more noticeable, Psychoacoustic Annoyance did increase opposite the Barrier relative to the No Barrier site.

Recommendations

Several recommendations are made below.

1. The use of sound-absorbing barriers should be considered when there are receptors on the opposite side of the roadway that did not qualify for a barrier based on an agency's noise abatement feasibility and reasonableness criteria in their noise policies.
2. True before/after noise measurement studies should be conducted on the opposite side of the highway from a barrier that is to be constructed as part of a highway widening project. These studies should be done when there are no noise-sensitive receptors on the opposite side, especially if a sound-reflecting barrier is to be built, in order to learn more about the effects of distance, height, cross-section, terrain, meteorological on the change in level spectrum shape and background level.
3. True before/after measurement studies should also be done when there are noise-sensitive receptors on the opposite side of the highway who do not qualify for a barrier, whether or not the barrier is to be made sound-absorbing.
    a. If it is to be sound-absorbing, the before measurements would be important evidence in demonstrating that the noise environment opposite the barrier has not been made worse by the installation of the barrier.
    b. If a sound-reflecting barrier is to be installed, the before measurements provide a base case for learning if the noise environment did change after the barrier installation and in what way and by how much.
    c. Such studies can include a sociological component, surveying residences on both side of the barrier regarding their perceptions.
4. To further understand barrier reflections and evaluate the benefit of sound absorptive barriers, it is recommended to continue the current research using spectrograms, applying the analysis to sites with absorptive barriers.

5. The spectrograms will help in determining frequency ranges of sound reduction attributed to the absorption, as well as whether or not the absorption helps to reduce sustaining of the higher noise levels seen with a reflective barrier.
6. Because the derived annoyance metrics were either uncorrelated with site location or were contra-indicative, their direct use (as applied in this work) cannot be recommended for indicating increased annoyance due to single barriers.
7. A layman's guide to the results should be developed, including using a spectrogram comparison. Spectrograms comparing traffic noise and individual vehicles for sites with and without a barrier be used to help stakeholders visualize and understand the effect of barrier reflections.
8. The findings should be incorporated into the National Highway Institute course NHI 142051, *Highway Traffic Noise* in the *Basic Concepts* and *Noise Barrier* lessons, using figures and spectrograms to explain concepts and high-level findings. The results could also be incorporated into the course's *Public Involvement* lesson, in terms of how to address the issue with the public at a meeting.

Suggested Research

Study Reflections Off Sound-Absorbing Barriers

To further understand barrier reflections and evaluate the benefit of sound absorptive barriers, it is recommended to continue the current research using spectrograms, applying the analysis to sites with absorptive barriers. This research found that it was very difficult and time-consuming to find locations with truly equivalent sites. Any research scoping should consider this fact.

Time-Based Metrics

It is suggested for future research to examine the data collected using time-based metrics, specifically examining the delta between the percentile metrics L_{10} and L_{90}. The percentile metric L_{10} is the sound level exceeded 10% of the time for a specified measurement period, which represents an average level for peak events. The percentile metric L_{90} is the sound level exceeded 90% of the time for a specified measurement period, which represents an average background level. It is suggested that public annoyance can increase with increases in the average noise level or as levels become more variable. The delta L_{10} minus L_{90} is an indication of how variable noise is: the greater the delta, the greater the chance of annoyance.

To see if examining the delta L_{10} minus L_{90} would be worth pursuing, a few example data blocks were analyzed for the data collected at Chino Hills, CA, SR-71 and Hughesville, MD, MD-5. This brief analysis showed that the delta L_{10} minus L_{90} is providing additional information. Both near and far and high and low microphone positions were examined. It was found in all cases that the delta was slightly greater (up to 1 dB) for the Barrier site compared to the No Barrier site. Other data blocks at these two sites and data blocks from other Project sites would need to be examined to confirm the trend and to make any conclusions regarding the delta value in relation to variables such as distance from the road or height above the ground. It would also need to be investigated through literature perceptibility and its relation to an increase in the delta L_{10} minus L_{90}. There are several literature sources from the 1970s that involve the Traffic Noise Index (TNI), which is based on the delta L_{10} minus L_{90}; these articles and others could be examined to help determine if the greater deltas associated with barrier reflections can be tied in with adverse community perception.

Examination of Time-Above Metric

In addition to examining other time-based metrics, it is suggested for future research to also examine time above. The Time-Above (TA) metric represents the amount of time the sound level exceeds a threshold of interest. This metric is applied to a noise event or to a time interval. As an example, the threshold of interest could be speech interference. Since the spectrogram data from the research discussed in this report show that traffic noise is louder and broader (in time) in the presence of an opposing barrier, it is thought that a particular level could be exceeded more often in a community with an opposing barrier compared to one without. The threshold level could be associated with speech interference or related to a site-specific sound level (e.g., existing worst-hour equivalent sound level). Examining the TA along with the amount of exceedance could help to explain adverse public reaction to barrier-reflected noise.

Barrier Reflections Screening Tool

It is suggested for future research to assess a screening tool to help estimate the effect of barrier reflections. Toward the end of this research, a preliminary screening tool was developed to potentially help with determining if reflections need to be considered for a highway project. This tool focuses on a single variable to estimate the barrier-reflected noise effect at receptors opposite a noise barrier: path length difference (comparing the path length for direct sound and for barrier-reflected sound). It is recognized that other variables contribute to the effect; depending on the amount of contribution, estimates for other variables can be combined with the path length screening tool to refine results.

The preliminary screening tool examines the path length difference between direct and reflected sound and calculates the estimated barrier influence in decibels based simply on geometrical spreading of sound assuming a line source. The screening tool needs to be validated with the data collected through the NCHRP 25-44 project and any related subsequent projects.

An example of the validation process is shown below. This example is for the SR-71 site measured in Chino Hills, CA. For the community measurements, data were collected at distances of 25 ft and 400 ft from the center of the near travel lane. Table 14 shows the average measured barrier effect (comparing sites with and without a barrier) and the calculated estimate of the effect using the screening tool. The barrier effect is shown in decibels as the increase in sound level due to barrier reflections. The measured effect is shown with both A-weighting and no weighting applied. It can be seen that the screening tool provides a conservative estimate of the effect determined through measurements.

It is interesting to note that at the far microphones, the estimate matches the unweighted measured effect. This is likely due to these factors:

1. A-weighted levels deemphasize lower frequencies, whereas unweighted does not;
2. Lower frequencies dominate the overall sound level more at far distances than near, since higher frequencies are attenuated more by propagation effects (atmospheric, ground, etc.); and
3. The screening tool does not account for propagation effects other than geometrical spreading.

Table 14. Average measured barrier effect and the calculated estimate of the effect using the screening tool.

Receptor (Distance from Center of Near Travel Lane)	Measured Effect A-weighted (dBA)	Measured Effect Unweighted (dBZ)	Estimated Effect (dB)
SR-71 Near (25 ft)	0.1	0.3	1.1
SR-71 Far (400 ft)	1.8	2.3	2.3

Further work is necessary to validate the screening tool, including examining data from the other project sites. If this simple method is validated as a conservative tool, then it may be possible to assign a rule-of-thumb on when to further evaluate reflected noise and options to abate it (e.g., absorptive treatment on barrier). For example, based strictly on the screening tool, if the reflected path length is greater than four times the direct path length, you can expect less than 1 dB influence from the barrier, and that could be a threshold under which no action is taken. As was mentioned, other contributing variables could be used to refine recommendations. It is also possible to generate a rule-of-thumb list where reflected noise warrants further consideration; the list could include the path length check and evaluation of other variables, such as prevailing meteorological conditions.

Spectral evaluation of propagation effects in relation to barrier-reflected noise

In order to further investigate the barrier reflection effects being greater closer to the ground, an analysis using the FHWA TNM could be conducted to show frequency ranges being affected by shielding from median barriers and highway vehicles and also ground effects. Those frequency ranges could be compared to the frequency ranges showing barrier effects presented in this report. This analysis may help to show that sound-reducing propagation effects help to “expose” barrier-reflected noise.

Listening trials

The use of psychoacoustic annoyance metrics did not result in clear correlations or indications as to expected annoyance response due to the presence of single barriers. However, since the literature regarding single barriers indicates that people do perceive changes, a psychoacoustic preference study could be used to assess the ability of listeners to detect this change. First, in-depth surveys of the residents near single-Barrier sites would be conducted; second, a series of listening trials would be conducted.

The surveys would need to be carefully developed and of large enough sample size to avoid the many confounding non-acoustic factors contributing to human annoyance, as has been experienced, for example, in the case of wind turbines. The results of such surveys would be used to estimate the true extent of the problem of annoyance with single barriers. Key factors that must be explored are the relations of distance, site lines, time of day, and most importantly, listener location if/when annoyed. This latter element is crucial. If residents find themselves annoyed by the noise while indoors, highly-detailed metrics including phase, directionality, and time evolution of spectral content are probably not called for: the structure itself is cleansing the signals of much of this content. If, however, residents are annoyed when outdoors, then it is important to understand how parameters such as distance, direction, and intervening elements contribute.

Listening trials would be used to provide statistical indications of those elements in the single-barrier roadway noise that might in fact contribute measurably to annoyance. From these results, a set of actionable criteria would be extracted to guide road planners.

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APPENDIX A – LITERATURE REVIEW

CONTENTS

EXECUTIVE SUMMARY, APPENDIX A

This Appendix was prepared as a Technical Memorandum in fulfillment of Task No. 2, "Literature Review," for NCHRP Research Project 25-44, "Field Evaluation of Reflected Noise from a Single, Reflective Noise Barrier." The literature review addresses the community noise issues that have led to investigations of noise reflected from barriers, past attempts to quantify the magnitude and effects of noise reflected from barriers, and the success of efforts to reduce noise reflected from barriers.

Community noise issues that have led to the investigations of noise reflected from barriers date back almost as long as the first widespread construction of U.S. highway noise barriers in the 1970s. With a noise barrier on only one side of a highway, reflected sound typically may increase the overall noise level at a receptor opposite the barrier by one to two decibels (dB). While this change generally has been considered too small to be readily perceived,[1] state highway agencies nonetheless have received complaints of increased noise from residents following the construction of reflective noise barriers, including threats of legal action and petitions to have noise barriers removed.[2] As a result of such reactions, some state departments of transportation (DOTs) have invested considerable effort and money researching the magnitude of sound level increases from reflective noise barriers along highways.[3] Other state DOTs, despite the widespread construction of reflective noise barriers, either have had few community complaints due to reflected sound, or have been able to resolve any such issues without extensive investigations.

During this same period there have been numerous attempts to quantify the magnitude and effects of noise reflected from barriers. Although some studies have identified increases in overall A-weighted sound level of 0 to 3 dB as a result of reflections, investigators typically concluded that such changes were insignificant and not perceptible to the human ear. These conclusions were based in part on guidance issued both by FHWA and by state highway agencies.[4] Yet despite study conclusions indicating that increases in noise levels were so small that they should have been imperceptible, in many cases people did respond to reflected sound, or at least to the perception of it. One potential difficulty is that many of the studies focused on the change in the overall sound level; the changes that residents perceived, however, may have been related to more than a simple increase in the overall sound level. Factors other than a change in overall noise levels may increase the likelihood both that listeners will notice changes and perceive the changes as increases attributed to reflections from a new noise barrier. Such factors may include long-term familiarity with the highway noise source followed by an abrupt change, spectral changes in traffic noise due to reflections, or alterations of the temporal characteristics of vehicle passbys.[5] More recently, studies have begun to examine further influences that may be perceived by residents in addition to changes in the A-weighted sound level.

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[1] Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance,* FHWA-HEP-10-025, December 2011, p. 60.
[2] For example: Hendriks, R. and J. Hecker, *Parallel Noise Barrier Report: A Noise Absorptive Demonstration Project, San Diego Freeway (I-405), Los Angeles, CA*, Caltrans District 7, Environmental Investigations Section, July 1989.
[3] Menge, C.W. and D.E. Barrett. "Reflections from Highway Noise Barriers and the Use of Absorptive Materials in the United States, Why Small Increases in Noise Levels may Deserve Serious Consideration," *Transportation Research Record: Journal of the Transportation Research Board, No. 2233*, Transportation Research Board of the National Academies, Washington, D.C., 2011, p. 161.
[4] For example: Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance*, p. 60. Also: Hendriks, R., *General Guidelines for Studying the Effects of Noise Barriers on Distant Receivers*, Technical Advisory TAN-89-01-R9701, California Department of Transportation, November 30, 1998, p. 7.
[5] Menge and Barrett, Op. cit., p. 164.

The success of efforts to reduce noise reflected from barriers has varied across the U.S., in part due to the different approaches pursued by various state highway agencies. While some state DOTs have responded to community concerns about reflected sound by conducting investigations attempting to document perceived increases in noise, other DOTs have addressed similar concerns by adding sound-absorptive materials to barriers after construction. Still others have long-standing practices of installing noise barriers with absorptive surfaces where there is noise-sensitive land use on the opposite side of the highway. Since 2010, FHWA has required state highway agencies to include provisions in their state noise policies for use of absorptive treatment on roadside structures, including noise barriers, retaining walls, bridges, and any other structure the highway agency may consider for application of a sound-absorptive material.[6] In response to this requirement, some states have adopted formal policies requiring the use of absorptive treatment on noise barriers in certain situations. Recent investigations in states including California, Minnesota, and Ohio have continued attempts to measure the benefit provided by the use of sound-absorptive noise barrier materials, either on new barriers or as retrofit treatments.

[6] Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance*, p. 60.

CHAPTER A-1

Introduction to Appendix A

This Technical Memorandum has been prepared in fulfillment of Task No. 2, “Literature Review,” for NCHRP Research Project 25-44, “Field Evaluation of Reflected Noise from a Single Noise Barrier.” The goal of this task is to conduct a review of available literature on reflected noise from single noise barriers addressing the following:

- The community noise issues that have led to investigations of noise reflected from barriers,
- Past attempts to quantify the magnitude and effects of noise reflected from barriers, and
- The success of efforts to reduce noise reflected from barriers.

The memorandum is divided into three sections, addressing in turn each of the three topic areas named above. Each section first provides an overview of the topic area, incorporating information from the various relevant reports, papers, and other sources identified during the literature review. Following each overview section, the memorandum provides a brief summary of relevant material from each of the primary sources. Some of the works cited include information relevant to more than one of the three topic areas. In those cases, related information may be included in more than one section of this memorandum, with a note alerting the reader that additional information from the primary document can be found elsewhere. While acknowledging some redundancy, we believe that this format will be useful for readers desiring both a summary of the entire issue of reflections from single barriers and also more specific information on any of the three individual topic areas.

The primary documents identified during this literature review were gathered from a variety of sources. Many of the documents were provided by state DOT representatives in response to a query from the research team for any relevant studies, investigations, or incidences of complaints due to noise reflected from highway noise barriers in their states. Others were provided by members of the research team based on their many years of collective practice in the field of highway noise, and several of the documents summarized herein previously were identified and discussed in the paper “Reflections from Absorptive Highway Noise Barriers and the Use of Absorptive Materials in the United States.”[7] The research team acknowledges and appreciates the efforts of all who contributed to this literature review.

[7] Menge, and Barrett, Op cit., pp. 161–166.

CHAPTER A-2

Community noise issues that have led to investigations of noise reflected from barriers

Overview

Community noise issues that have led to the investigations of noise reflected from barriers date back almost as long as the first widespread construction of highway noise barriers in the U.S. in the 1970s. By the end of 2010, over 180 million square feet of highway noise barriers had been constructed in the United States, of which approximately 98% are reflective.[8] For many years, on many occasions, and in many different states, communities have complained of sound reflected from highway noise barriers to receptors on the other side of the highway. The problem may occur when the community on one side of a highway qualifies for a barrier but residents on the other side of the highway, for one reason or another, do not qualify. The concern sometimes is exacerbated by the fact that these residents may be impacted by the highway noise yet do not meet certain feasibility or reasonableness criteria for abatement. For them, experiencing a noticeable change in the sound level caused by their neighbors receiving abatement may be further cause for annoyance.

When a reflective noise barrier is present on only one side of a highway, common guidance has said that reflected sound typically may increase the overall noise level at a receptor opposite the barrier by one to two decibels. While this change generally has been considered too small to be readily perceived,[9,10] state DOTs nonetheless have received complaints from residents opposite reflective barriers following their construction. Researchers have recognized since at least the 1940s that under controlled, laboratory situations, listeners have demonstrated sensitivity to immediate changes in levels of broadband noise of less than 0.5 dB."[11] Although conventional wisdom holds that small differences in sound levels are more difficult to perceive in environmental rather than laboratory settings, it also has been suggested that other factors caused by reflected sound may influence listeners' perceptions and sensitivities, increasing the likelihood both that they will notice changes and perceive the changes as increases in level attributed to reflections from a new noise barrier. These factors may include long-term familiarity with the highway

[8] Federal Highway Administration, *Summary of Noise Barriers Constructed by December 31, 2010*, FHWA-HEP-12-044, July 2012.
[9] Federal Highway Administration, *Fundamentals and Abatement of Highway Traffic Noise: Textbook and Training Course*. U.S. Department of Transportation, Sept. 1980.
[10] For example: "Attempts to conclusively measure [the increase in sound level due to a single barrier reflection] have rarely show an increase of greater than 1-2 dB(A), an increase that is not perceptible to the average human ear." Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance*, p. 60.
[11] Miller, George A., "Sensitivity to Changes in Intensity of White Noise and Its Relation to Masking and Loudness," *The Journal of the Acoustical Society of America*, Volume 19, Number 4, July, 1947, p. 609.

noise source followed by an abrupt change, spectral changes in sound due to reflections, or alteration of the temporal characteristics of vehicle passbys.[12]

The California Department of Transportation (Caltrans), one of the leaders in constructing noise barriers for nearly four decades, has received and responded to complaints of reflected sound for almost as long. As a result of such community reactions, Caltrans and other DOTs have spent considerable effort and money researching the magnitude of sound level increases from reflective noise barriers along highways.[13] Since the late 1970s, Caltrans has, for example, responded to complaints of reflected sound in various locations including San Jose, Los Angeles, Alamo, Oakland, and San Rafael.[14] Other state DOTs that have conducted investigations of reflected sound in response to community noise issues include Colorado[15] and Minnesota.[16,17] In a recent instance of community noise issues leading to an investigation of reflected sound, residents of San Clemente, California began to complain of increased noise levels shortly after a 16-foot high reflective noise barrier was constructed in 2011 on the opposite side of Interstate 5. The residents claimed that Caltrans had "failed to comply with the California Environmental Quality Act (CEQA) by not adequately notifying residents on both sides of the freeway when it solicited neighborhood input about putting up the new walls." Even while affirming the legality of the disputed noise barrier, Caltrans offered to work with city and county officials to study the project further, possibly including new noise measurements, and to consider changes.[18]

Other state DOTs, despite the widespread construction of reflective noise barriers, either have received few community complaints due to reflected sound, or have been able to resolve any such issues without extensive investigations. The Florida Department of Transportation (FDOT), in spite of having constructed over 150 miles of noise barriers since the 1980s,[19] is not aware of any studies, investigations, or recent complaints due to noise reflected from highway noise barriers in Florida. Because reflected noise has not been a significant issue in Florida, FDOT has not conducted any research or studies of the issue.[20] The New Hampshire Department of Transportation (NHDOT) acknowledges having received "a few complaints here and there," but was "able to dismiss those mostly by taking measurements and finding that the noise levels were still below the [Noise Abatement Criteria][21] or that the neighborhood lacked a Type I[22] project." To date, NHDOT has not conducted any studies regarding reflected noise.[23]

[12] Menge and Barrett, Op. cit., p. 164.
[13] Ibid., p. 161.
[14] Ibid., pp. 162–163.
[15] Hankard Engineering, *North End Neighborhood Noise Study* (Colorado Springs), 2000.
[16] Roseen, M., *Effects of noise wall located on the East side of TH 100 on noise levels of residences on the Westside of TH 100 in the vicinity of Vernon Avenue*, Minnesota DOT, Environmental Analysis and Compliance Section, Environmental Modeling and Testing Unit, January 22, 2002.
[17] Roseen, M., *Effects of a noise barrier, located on the west side of TH 47 (University Ave.), on the noise levels of residences on the east side of TH 47 located between 45th Ave. N. and 52nd Ave. N.*, Minnesota DOT, Environmental Analysis and Compliance Section, Environmental Modeling and Testing Unit, September 20, 2002.
[18] Shyong, F., "Caltrans offers to consider changes to I-5 sound wall." *Orange County Register*, February 3, 2012, updated August 21, 2013.
[19] Federal Highway Administration, *Summary of Noise Barriers Constructed by December 31, 2010*.
[20] Berrios, Mariano, Florida Department of Transportation. Message to Douglas Barrett. November 7, 2013. E-mail.
[21] The Noise Abatement Criteria (NAC) are the threshold sound levels for each relevant land use type that would require consideration of noise abatement measures on Type I projects.
[22] "Type I" projects include either (1) the construction of a highway on a new location or (2) improvements to an existing facility that include substantial horizontal or vertical alteration, the addition of through traffic lanes, the addition of an auxiliary lane (except for when the auxiliary lane is a turn lane), the addition or relocation of interchange lanes or ramps added to a quadrant to complete an existing partial interchange, restriping existing pavement for the purpose of adding a through-traffic lane or an auxiliary lane, or the addition of a new or substantial alteration of a weigh station, rest stop, ride-share lot or toll plaza. (U.S. Code of Federal Regulations, Title 23: Highways - Part 772: *Procedures for Abatement of Highway Noise and Construction Noise*, June 2010.)

Washington State DOT (WSDOT) also has received complaints regarding noise barrier reflections, but is restricted in its ability to respond in-person to all complaints due to staff time limitations. WSDOT has decided not to conduct detailed investigations because "these situations have fallen outside of their policy guidelines" and also because of "their lack of a funding mechanism to provide additional mitigation."[24]

Summaries of Cited Works (Community noise issues that have led to investigations of noise reflected from barriers)

Menge, C.W. and D.E. Barrett. "Reflections from Highway Noise Barriers and the Use of Absorptive Materials in the United States, Why Small Increases in Noise Levels may Deserve Serious Consideration," *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2233*, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 161–166

This paper "presents historical information on the study of reflections from noise barriers in the U.S., human perception of changes, and also how reflective noise barriers may change the character of noise from highways as heard in communities opposite the barriers." The authors draw two main conclusions: 1) Small changes in sound level associated with barrier reflections can be meaningful to the public and to their conclusions regarding the effectiveness of noise barriers, and 2) the benefit of simply implementing absorptive barrier treatments opposite residential areas outweighs the benefit of researching the issue or conducting detailed analyses to justify the use of absorption.

The paper provides a brief history of community reaction in the U.S. to reflections from noise barriers and to the related responses of state departments of transportation (DOTs) noting that for decades, many DOTs have followed widely-accepted guidance that single reflections of noise from noise barriers to the opposite side of highways are "generally one to two dBA or less, and therefore not perceptible to the average human ear." Despite this guidance, "the outcry from residential communities subject to reflected noise can be quite significant." As a result of such community reaction, some DOTs have spent "significant effort and money spent researching the magnitude of sound level increases both near and far from reflective noise barriers along highways."

As an example of community noise issues that have led to investigations of barrier reflections, the paper describes the "Caltrans Experience." The authors note that for most, if not all of the early decades of highway noise barrier construction, Caltrans led the U.S. in the total length of noise barriers constructed, and nearly all these were of reflective concrete block. "Perhaps as a result of the sheer number of barriers constructed and the large number of homes affected, Caltrans received its share of complaints from residents about increased noise after barriers were constructed." Although many of these residents were located at significant distances from the highways, and were not exposed to noise levels high enough to constitute noise impact or to warrant noise abatement, Caltrans investigated the complaints, in an attempt to understand their basis, and to take appropriate action, if any was deemed appropriate. The investigations described in the paper took place in response to community complaints in San Jose, Los Angeles, Alamo, Oakland, and San Rafael (summaries of these studies follow below).

The paper also addresses the common guidance that changes in sound level of less than 3 dB are not readily noticeable stating that "researchers have known for decades that under controlled, laboratory situations, listeners can detect changes in broadband noise far smaller than the 3 dB considered a

[23] Evans, Jonathan, New Hampshire Department of Transportation. Message to Douglas Barrett. Nov. 1, 2013. E-mail.
[24] Sexton, Timothy, Washington State Department of Transportation. Messages to Douglas Barrett. Nov. 4 and Nov. 25, 2013. E-mail.

threshold of perception for reflected noise."[25] The authors note that "as far back as the late 1940s, experiments confirmed that over 50% of listeners demonstrated sensitivity to changes in levels of broadband noise of less than 0.5 dB."[26] (See the following summary in Section 0.) Although "conventional wisdom holds that small differences in sound levels are more difficult to perceive in environmental rather than laboratory settings," the paper contends that other factors may influence listeners' perceptions and sensitivities, increasing the likelihood both that they will notice changes and perceive the changes as increases in level attributed to reflections from a new noise barrier:

- Long-term exposure to a particular noise source such as a nearby highway may lead to ingrained expectations regarding typical noise levels and heighten sensitivity to even small changes.
- Comparative audio listening tests have demonstrated that frequency shifts as small as 0.1 dB are audible. Residents may discern spectral changes due to reflected sound as a change in sound character and may interpret this change as an increase in level.
- The addition of reflective surfaces adds new sound propagation paths and may change the temporal character of vehicle passbys. For example, residents may notice that truck passbys sound different than previously and may interpret this change as an increase in level.

Section 0 of this memorandum details findings from this paper related to the magnitude of noise reflected from barriers and Section 0 discusses efforts to reduce reflected noise from barriers.

Miller, George A., "Sensitivity to Changes in Intensity of White Noise and Its Relation to Masking and Loudness," *The Journal of the Acoustical Society of America*, Volume 19, Number 4, July, 1947

This paper, referenced in the previous document, shows that as far back as the late 1940s, experiments confirmed that over 50% of listeners demonstrated sensitivity to changes in levels of broadband noise of less than 0.5 dB. The study conducted by Harvard University's Psycho-Acoustic Laboratory examined sensitivity to changes in the intensity of a random noise over a wide range of intensities. The study found that the "just detectable increment" in the intensity of random noise was of the same order of magnitude as for pure tones. For intensities more than 30 dB above the threshold of hearing for random noise, the size of the increment which can be heard 50% of the time was determined to be approximately constant (0.41 dB).

Hatano, M. M., *Evaluation of Noise Barrier Reflection 04-SC1-101-30.7*, Office of Transportation Laboratory, California Department of Transportation Report No. 1970-657287, January 1978

This report describes the earliest instance identified by this literature review of an investigation in response to community concerns of sound reflected from a highway noise barrier.

In 1978, Caltrans conducted an investigation of complaints about increased noise from residents near US Route 101 in San Jose regarding a noise barrier constructed by a developer on state right-of-way to shield a new residential development. Residents claimed "that they noticed a significant increase in noise level due to noise reflections" from a wall constructed in 1975 on the opposite side of the freeway. The residences involved in the study were located several hundred feet from the edge of pavement and, in

[25] See, for example: Harris, Cyril M., *Handbook of Acoustical Measurements and Noise Control*, p. 17.22, 1991.
[26] Miller, George A., "Sensitivity to Changes in Intensity of White Noise and Its Relation to Masking and Loudness," *The Journal of the Acoustical Society of America*, Volume 19, Number 4, July, 1947, p. 609.

some cases, considerably above the road. Based on their measurements, the researchers concluded that "reflected noise from the walls is not significant." Although modeling exercises indicated that theoretical increases in A-weighted noise levels of up to 2 decibels were possible, the report stated that "changes of 2 to 3 dBA from one day to the next cannot be normally perceived by most people."

Results of this study are further described in Section 0.

Hendriks, R. and J. Hecker, *Parallel Noise Barrier Report: A Noise Absorptive Demonstration Project, San Diego Freeway (I-405), Los Angeles, CA*, Caltrans District 7, Environmental Investigations Section, July 1989

Following the construction of parallel, reflective noise barriers along Interstate 405 in the Brentwood section of Los Angeles, Caltrans began to receive complaints about increased noise levels at large distances from the highway. After receiving threats of legal action and a petition by Brentwood residents to remove the noise barriers which were causing an "intolerable increase in noise levels due to reflection in the neighborhoods," the Caltrans District 7 Environmental Investigations Section conducted a study of absorptive noise barrier treatments.

Results of this study are described in Section 0**.**

Hankard Engineering, *North End Neighborhood Noise Study* (Colorado Springs), 2000

As part of a highway widening project, the Colorado Department of Transportation (CDOT) constructed a noise barrier along the west side of Interstate I-25 in Colorado Springs in 1998. The wall was designed to reduce traffic noise levels at residences adjacent to the west side of the highway. Shortly after completion of the noise barrier, CDOT began to receive complaints about traffic noise from residents of a neighborhood east of the highway set back several hundred feet to a few thousand feet and generally at a higher elevation than I-25. Residents complained that "I-25 noise is very bothersome, and noticeably higher since construction of the wall." In 1999, in response to these complaints, CDOT commissioned a noise study for the affected neighborhoods.

Results of this study are described in Section 0.

Roseen, M., *Effects of noise wall located on the East side of TH 100 on noise levels of residences on the Westside of TH 100 in the vicinity of Vernon Avenue*, Minnesota DOT, Environmental Analysis and Compliance Section, Environmental Modeling and Testing Unit, January 22, 2002

Following construction of a noise barrier on the east side of TH 100, a six-lane divided highway in Minneapolis, residents on the west side of the road raised concerns about possible increases in traffic noise levels. Due to this reaction, MnDOT conducted a test to determine if construction of the noise barrier had increased noise levels, and if so, the magnitude of the increases.

Results of this study are described further in Section 0**.**

Roseen, M., *Effects of a noise barrier, located on the west side of TH 47 (University Ave.), on the noise levels of residences on the east side of TH 47 located between 45th Ave. N. and 52nd Ave. N.*, Minnesota DOT, Environmental Analysis and Compliance Section, Environmental Modeling and Testing Unit, September 20, 2002

In a similar situation, residents on the east side of University Ave., a four-lane divided arterial in Minneapolis, were concerned about possible increases in traffic noise levels due to construction of a noise barrier on the west side of the road. In response, MnDOT conducted a test to determine if construction of the noise barrier had increased noise levels, and if so, the magnitude of the increases.

Results of this study are described in Section 0**.**

Burge, P., J. Crawford, and Peter Wasko, "Use of advanced tools and techniques to resolve an atypical parallel noise barrier case," *Proceedings of Noise-Con 2013*, Denver, CO, August 26–28, 2013

As part of a lane addition project along Interstate 94 (I-94), the primary highway link between Minneapolis and St. Paul, Minnesota, an acoustically reflective noise barrier was constructed on the eastbound (southern) side of I-94. The noise impact analysis for the neighborhood north of the highway did not consider possible acoustical reflections, in part because a noise barrier constructed many years earlier on the north side of the highway already was in place. The two walls together formed a parallel barrier condition with the northern neighborhood and barrier at a higher elevation than the southern barrier and community. After the southern wall was constructed, residents north of I-94 complained of increased noise levels. MnDOT commissioned a follow-up study to determine 1) if reflections from the new noise wall were causing perceptively higher noise levels in the adjacent community, and 2) if so, what could be done within project budget constraints to help mitigate the noise level increases.

The results of this study are described in Section 0.

The following three news articles describe the recent reaction of a community to perceived increases in noise levels due to reflected sound and the response from Caltrans.

Swegles, F., "San Clemente to lodge complaints about I-5 wall," *Orange County Register*, December 21, 2011, updated August 21, 2013

The San Clemente, California City Council voted 4-0 to send two letters to Caltrans on behalf of two groups of residents. One group living east of Interstate-5 (I-5) in San Clemente wants Caltrans to dismantle a 16-foot-tall freeway sound wall they say is blocking their ocean views and reflecting freeway noise at their homes. Other "residents west of I-5 say they wish Caltrans had extended the wall farther south to protect their homes from freeway noise. [. . .] In one letter, the council will ask [Caltrans] to reopen environmental analysis of the [noise barrier] that Caltrans built without consulting most residents on the east side of the freeway. City Attorney Jeff Oderman concluded that Caltrans [failed to] comply with the California Environmental Quality Act (CEQA). The council will ask for an environmental meeting in San Clemente, inviting all affected residents, followed by studies of view and noise effects on both sides of I-5. In a second letter, the city will ask Caltrans why the I-5 wall ends at West Avenida Cornelio when residents of West Avenida Junipero less than a quarter-mile south say they were promised that the wall would provide a sound barrier for their homes. People living on both sides of I-5 complained about unbearable noise."

Shyong, F., "Caltrans offers to consider changes to I-5 sound wall," *Orange County Register*, February 3, 2012, updated August 21, 2013

"[Caltrans officials] affirmed the legality of an I-5 sound wall in San Clemente that has triggered complaints from residents and businesses but offered to work with city and county officials to study the project further and consider changes. In a letter to Mayor Jim Evert . . . , Caltrans District 12 Director Cindy Quon wrote, 'The department would like to work with city staff to further define the scope of the study area and establish the project limits.' The re-examination would look at the project's impact area and could include new noise readings. [. . .] Some residents and businesses on the east side of I-5 have appealed repeatedly to the City Council for relief since the wall was erected on the west side of the freeway above Avenida del Presidente. Those on the east side say the 16-foot-tall wall blocks ocean views and [reflects] freeway noise in their direction. [. . .] The city contends the agency failed to comply with the California Environmental Quality Act by not adequately notifying residents on both sides of the freeway when it solicited neighborhood input about putting up the new walls in a $5.3 million project. Caltrans has said the project qualified for a 'categorical exemption' from the Environmental Quality Act because Caltrans concluded the sound walls would not have significant effects. Public-outreach efforts by the Orange County Transportation Authority went beyond state and federal requirements, Caltrans said."

Swegles, F., "A quest for peace and quiet," *Orange County Register*, September 25, 2013

Although Caltrans agreed to use a sound-absorbing concrete block product on noise barriers to be built as part of a $275 million freeway widening that will begin in 2014 in north San Clemente, residents in south San Clemente still are complaining of noise reflected from a 16-foot noise barrier constructed in 2011. According to a south San Clemente resident, "I saw them working on [the noise barrier]," he said. "As the wall got higher, my noise level went higher. It was just like someone turned up a radio."

Residents on the opposite side of I-5 from the noise barrier claim that they were not able to provide comments "because Caltrans never notified them of stakeholder meetings. The meetings targeted residents closest to the then-proposed wall." After construction of the noise barrier, people inland (east) of I-5 claimed they were exposed to reflected noise. "They enlisted the city's help, and the city asked Caltrans to reopen the environmental-review process for the wall, but Caltrans insisted it had followed the state's environmental rules."

"Now that Caltrans will use the sound-absorbing blocks on the new noise barriers in north San Clemente, [south San Clemente residents] hope to see it applied to the wall below their homes, too. [. . .] 'We don't doubt the product,' [the city's transportation engineering manager] said. 'Funding is the challenge.' [. . .] Dave Richardson, Caltrans spokesman, said he could not comment on whether Caltrans might apply the absorptive product to the 2011 wall as the agency is facing a lawsuit over that project."

The following paragraphs summarize correspondence with representatives from three different state DOTs regarding any incidents of complaints due to reflected noise and the DOT's response.

Correspondence with Jonathan Evans, New Hampshire Department of Transportation, November 1, 2013

To date, New Hampshire DOT (NHDOT) has not had any experience or issues regarding noise barrier reflection and has not conducted any studies regarding reflected noise. Although they "have had a few complaints here and there, [NHDOT was] able to dismiss those mostly by taking measurements and finding that the noise levels were still below the [Noise Abatement Criteria] NAC or that the neighborhood lacked a Type I project." For parallel noise barriers, NHDOT has "used the FHWA's parallel barrier width-to-height ratio of 10:1 as a way to indicate an area that could be affected by reflected noise. The Department's ROW's are almost always wide enough that no receptors are located within the area of this 10:1 with-to-height ratio."[27]

[27] FHWA guidance states: "Studies have suggested that to avoid a reduction in the performance of parallel reflective noise barriers, the width to height ratio of the roadway section to the barriers should be at least 10:1. The width is

Correspondence with Mariano Berrios, Florida Department of Transportation, November 7, 2013

FDOT is not aware of any studies, investigations, or complaints due to noise reflected from highway noise barriers in Florida. In the past, "Florida had a couple of 'reflection' related complaints but they were unfounded." Noise reflection has not been a significant issue in Florida, therefore they have not done any research/studies in that area.

Correspondence with Timothy Sexton, Washington State Department of Transportation, November 4 and 25, 2013

Washington State DOT has "received complaints on this topic, but staff time limitations restrict their ability to respond in-person to all complaints." Since these situations have fallen outside of their policy guidelines, WSDOT has decided not to collect measurements or pursue more detailed explanation. This approach is reinforced by their lack of a funding mechanism to provide additional mitigation.

the distance between the barriers, and the height is the average height of the barriers above the roadway." Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance*, p. 60.

CHAPTER A-3

Past attempts to quantify the magnitude and effects of noise reflected from barriers

Overview

Over the past several decades, state highway agencies have made numerous attempts to quantify the magnitude and effects of noise reflected from highway noise barriers. In 1978, in response to complaints about increased noise from residents opposite a newly constructed noise barrier along US Route 101 in San Jose, Caltrans performed one of the first investigations of sound reflected from a highway noise barrier. Although field measurements failed to identify statistically-reliable differences between sound levels with and without reflections, Caltrans determined through modeling that theoretical increases in the A-weighted sound level of up to 2 dB were possible. The researchers concluded that this potential increase was not significant, and noted that “changes of 2 to 3 dBA from one day to the next cannot be normally perceived by most people.”[28]

Approximately 10 years later, Caltrans conducted another study of noise barrier reflections, this time in the Brentwood section of Los Angeles along Interstate 405. Construction of parallel, reflecting noise barriers had generated complaints of an “intolerable increase in noise levels due to reflection in the neighborhoods” at distances 1,000 feet or more from the highway. The study incorporated controlled noise and meteorological measurements with simultaneous traffic counts, including some with highly-absorptive treatment added to the far-side barrier. Acoustical modeling also was conducted and compared with the measurement results. The measurements showed that near the highway, noise levels decreased by an average of about 1 dB under all wind conditions due to the addition of the absorptive material, with the range of measured decreases from 0 to 3 dB. No decreases in noise levels could be reliably determined at the farther distances. The study concluded that because the noise level decreases were less than 3 dB, which “cannot be discerned by the normal human ear,” the treatment was inaudible and therefore not effective.[29]

In 1998, Caltrans issued a Technical Advisory providing detailed guidelines for conducting noise and meteorology measurements in response to complaints about reflected sound from barriers. The primary objective of the studies covered by the document was “to determine through measurements if noise barriers inadvertently increase noise levels at distant receivers” generally located 0.15 to 3 km (about 500 to 10,000 feet) from highways. Along with guidance on methodology, the document also provided direction for interpreting the significance of measurement results, stating that “a change of 3 dBA or less will be considered no change.” The author noted that he had “conferred with many experts across the nation about performing studies involving distant receivers” with the “general consensus . . . that it is not

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28 Hatano, M. M., *Evaluation of Noise Barrier Reflection 04-SC1-101-30.7,* Office of Transportation Laboratory, California Department of Transportation Report No. 1970-657287, January 1978.

29 Hendriks, R. and J. Hecker, *Parallel Noise Barrier Report: A Noise Absorptive Demonstration Project, San Diego Freeway (I-405), Los Angeles, CA,* Caltrans District 7, Environmental Investigations Section, July 1989.

practical to do these studies on a routine basis because of their high cost, both in terms of money and necessary resources."[30]

In 1999, Caltrans conducted another measurement program in conjunction with the construction of new noise barriers along Interstate 680 in Alamo, California using the guidelines described above. To evaluate noise level changes, before and after noise levels were grouped into similar meteorological categories and compared. Measured 1 to 2 dB increases of average highway traffic noise levels were found to be consistent with predictions and were "suspected to be caused by the presence of a single reflecting sound wall." The increases, however, were considered to be insignificant, in accordance with the Caltrans guidelines.[31]

During this period, other state highway agencies were conducting similar investigations of noise barrier reflections. In 1999, the Colorado Department of Transportation (CDOT) commissioned a study in response to complaints of reflected sound in a neighborhood set back several hundred feet to a few thousand feet from I-25 in Colorado Springs. Measured A-weighted sound levels were found to have increased by approximately 1 dB following construction of a reflective noise barrier on one side of the highway. Noting that 3 dB "is considered the minimum perceptible change in noise levels in outdoor environments," the report concluded that application of absorbent material to the east face of the noise barrier "would not provide any perceivable noise reduction" in the affected neighborhood.[32]

Shortly thereafter, in 2001 and 2002, MnDOT conducted measurement studies at two locations in Minneapolis due to community concerns of possible increases in traffic noise levels caused by construction of single, reflective noise barriers. In each case, noise measurements were repeated at four sites where measurements had been prior to construction of the barrier. After normalizing to account for differences in traffic and conducting a statistical analysis of measured sound level differences, MnDOT found with a 95% confidence level that the noise barrier did not cause a statistically significant difference in overall A-weighted L_{10} sound levels at three of four measurement sites in each of the two study areas. In each study area, however, the analysis indicated a statistically significant increase of 1 dBA or less at one of four measurement sites. The report concluded that this was not "a detectable change as judged by human hearing" based on FHWA guidance that "the ability of the human ear to detect noise level change is limited to noise level changes of 3 dBA or more."[33]

Despite the findings of these investigations that increases in noise due to reflected sound were so small that they should have been imperceptible, in each case people did respond to reflected sound, or at least to the perception of it. Although each study was conducted carefully using what was considered to be appropriate methodology, they all focused on the change in the overall A-weighted sound level in the community opposite the barrier. The difficulty is that the changes affected residents perceived may have been related to more than a simple increase in the overall sound level. Assuming unobstructed propagation paths for both the direct and reflected sound, the increase in the total sound level due to the addition of the reflections should be less than the 3 dBA attributable to the doubling of the source energy. As noted above, widespread guidance has held that an increase of less than 3 dBA should not be perceptible under these conditions.[34] As discussed above in Section 0, one hypothesis is that the noticeability and annoyance caused by the reflections might be due to other factors such as long-term

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[30] Hendriks, R., *General Guidelines for Studying the Effects of Noise Barriers on Distant Receivers*, Technical Advisory TAN-89-01-R9701, California Department of Transportation, November 30, 1998.
[31] URS Greiner Woodward Clyde and Illingworth and Rodkin, Inc., *Interstate 680 in Contra Costa County, Pre- and Post Sound Wall Noise Study – Stone-Kemline Sound Walls, Near Stone Valley Road,* June 1999.
[32] Hankard Engineering , *North End Neighborhood Noise Study* (Colorado Springs), 2000.
[33] U.S. Department of Transportation, Federal Highway Administration, Fundamentals and Abatement of Highway Traffic Noise (Textbook and Training Course); Document 2, Sec. 3.5.1 (Sept. 1980).
[34] Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance,* p. 60.

familiarity with the highway noise source followed by an abrupt change, spectral changes in sound due to reflections, or altering the temporal character of vehicle passbys.[35] Therefore, it is possible that the studies, while accurately quantifying the magnitude of the change in overall sound level due to reflections, were not addressing the effects of reflected noise perceived by residents.

Other more recent studies have begun to look at additional factors, including spectral information, that may be perceived by community members. A study conducted on U.S. 101 in Marin County, California between 2007 and 2010 sought to determine the benefits of both absorptive barriers and quieter pavement during a widening project that also included the relocation of an existing noise barrier. Methodologies incorporated in the study included 1/3 octave band measurements at a reference location above the noise barrier and also behind the noise barrier, Onboard Sound Intensity (OBSI) measurements (also 1/3 octave band), and sophisticated modeling using software capable of three-dimensional ray tracing.[36] (See Section 0 for further discussion of the results of this study.)

Also recently, researchers in Texas proposed a new method for in-situ measurement of reflections from a highway noise barrier or retaining wall following its construction. The researchers preferred the results obtainable from an in-situ impulse test, but opted to use a broadband, steady-state excitation signal with the same statistical properties as an ideal impulse, rather than a true impulse source. Synchronous averaging of numerous impulse responses caused moving traffic to "vanish" in the long-term and allowed processing of spectral data. As of this writing, only initial testing had been completed on a large reflective retaining wall along IH-30 in Dallas with plans to test the retaining wall again after application of absorptive material.[37]

In January 2012, the Ohio Department of Transportation (ODOT) issued a Request for Proposals (RFP) that included research into the use of absorptive noise barriers in single-barrier cases stating that "it is unknown if a discernable difference between sound absorptive concrete walls vs. reflective concrete walls exists. Research is needed to determine if there is a discernable acoustic benefit that justifies the added expenditure." The RFP indicated that the project's research plan should include noise measurements comparing sound absorptive and reflective concrete walls "to determine if there is a discernable difference at the receptor and noise sensitive areas opposite the freeway."[38] At a minimum, this leaves open the possibility of investigating other factors in addition to changes in the overall sound level. As of this writing, the results of the research are not yet available.[39]

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[35] Menge and Barrett, Op. cit., p. 164.
[36] Donavan, Paul R. and Dana M. Lodico, *The Influence of Quieter Pavement & Absorptive Barriers on U.S. 101 in Marin County*, Presentation at Transportation Research Board Committee ADC40 Summer Meeting, Asheville, NC, July 2012.
[37] Nelson, David A., Terry Dossey, and Manuel Trevino, "A novel method for measuring highway barrier or retaining wall sound reflections in situ," *Proceedings of Noise-Con 2011*, Portland, Oregon, July 2011.
[38] *Comparison and Testing of Various Noise Wall Materials*, Request for Proposals issued by Ohio Department of Transportation, ODOT RFP 2013-16, Posted January 25, 2012.
[39] Alcala, Noel, Ohio Department of Transportation. Message to Douglas Barrett. Nov. 19, 2013. E-mail.

Summaries of Cited Works (Past attempts to quantify the magnitude and effects of noise reflected from barriers)

Menge, C.W. and D.E. Barrett. "Reflections from Highway Noise Barriers and the Use of Absorptive Materials in the United States, Why Small Increases in Noise Levels may Deserve Serious Consideration"

This paper provides a brief history of community reaction in the U.S. to reflections from noise barriers and the related responses of state DOTs. The portion of the paper discussing community reaction is discussed above in Section 0.

As a result of community reaction to the perception of noise reflected from barriers, some DOTs have spent "significant effort and money spent researching the magnitude of sound level increases both near and far from reflective noise barriers along highways." Perhaps foremost among these has been Caltrans. From the late 1970s on, During the 1980s and 1990s, Caltrans conducted a number of studies of the effects of reflected sound and the potential benefits of sound-absorptive barriers. In describing the "Caltrans Experience," this paper provides brief summaries of several of the Caltrans studies. These investigations are summarized below from the original study documents or from related papers or presentations. Further discussion on this paper is found in Section 0**.**

The four following documents were summarized in the "Caltrans Experience" section of the paper and describe various investigations conducted by Caltrans over a period of approximately 35 years.

Hatano, M. M., *Evaluation of Noise Barrier Reflection 04-SC1-101-30.7*

As introduced in Section 0, in 1978, Caltrans conducted an investigation into complaints about increased noise from residents on the opposite side of US Route 101 in San Jose from a noise barrier constructed by a developer on state right-of-way to shield a new residential development. The residences involved in the study were located approximately 400 feet to 650 feet from the edge of pavement and, in some cases, considerably above the road (approximately 100 feet). The investigators conducted noise measurements in comparable sections of the highway with the noise barrier and without the noise barrier using a Caltrans diesel maintenance truck to provide a relatively uniform controlled noise source. Also, measurements were conducted with the noise barriers draped with rugs hung over them to add some sound-absorbing qualities. The researchers could not measure statistically reliable sound level differences between the cases without the barrier, with the (reflective) barrier, or with the barrier draped with rugs. Based on the measurements, the researchers concluded that "reflected noise from the walls is not significant" and that "field measurements did not show any consistent measurable differences between the covered and bare walls or at the comparable locations with and without walls." The researchers also conducted modeling exercises, finding that theoretical increases in the A-weighted noise levels of up to 2 decibels were possible, given the geometry. They noted, however, that their "measuring instruments were not sufficiently accurate to clearly define the small differences that may have occurred" making it "impossible to verify theory." In addition, the report stated that "changes of 2 to 3 dBA from one day to the next cannot be normally perceived by most people."

Hendriks, R. and J. Hecker, *Parallel Noise Barrier Report: A Noise Absorptive Demonstration Project, San Diego Freeway (I-405), Los Angeles, CA*

This Caltrans study along Interstate 405 in the Brentwood section of Los Angeles (introduced in Section 0) included controlled noise and meteorological measurements with simultaneous traffic counts. Noise levels were measured near the highway as well as in neighborhoods more than 1,000 feet from the highway, where many complaints had originated. After adding sound-absorptive treatment to the noise barrier opposite the affected community, Caltrans conducted follow-up measurements. In addition, acoustical modeling was conducted and compared with the measurement results. The measurements indicated that near the highway, the addition of sound-absorptive material decreased noise levels by an average of about one decibel under all wind conditions, with measured decreases ranging from 0 to 3 dB. No decreases in noise levels could be reliably determined at the farther distances. The study concluded that because the traffic noise level decreases were less than 3 dB, which "cannot be discerned by the normal human ear," the treatment was inaudible and therefore not effective. In addition, the researchers found that wind direction had a greater effect on measured A-weighted levels behind the barrier than any reflection effects.

Although this demonstration project involved parallel noise barriers, rather than a single, reflective noise barrier, some aspects are relevant to investigations of reflected sound from single barriers. In particular, the Caltrans report notes that "daytime noise levels at the far receivers were influenced as much or more by local noise sources, such as lawn mowers pool pumps, construction, and [local street traffic]." Clearly, any measurements to quantify the effects of reflected sound are hindered if the subject highway traffic noise is not the dominant noise source at the measurement locations. In addition, the report notes that "wind speed and direction appear to have a much greater influence on the noise levels at the far receivers than freeway traffic volumes." This finding underscores the requirement for comparable atmospheric conditions to ensure the validity of comparisons between different sets of noise measurements.

Hendriks, R., *General Guidelines for Studying the Effects of Noise Barriers on Distant Receivers*, Technical Advisory TAN-89-01-R9701, California Department of Transportation, November 30, 1998

This Technical Advisory provided detailed guidelines for conducting noise and meteorology measurements in response to complaints about reflected noise from barriers. The primary objective of the before and after noise barrier studies covered by the document was to determine through measurements if noise barriers inadvertently increase noise levels at distant receivers. The guidelines and criteria were written to cover complex, non-routine noise barrier noise studies for receivers generally located 0.15 to 3 km (approximately 500 to 10,000 feet) from highways. At the time of this Technical Advisory, such studies had been performed on a limited basis in the San Francisco Bay Area because of public concern that noise barriers increased noise levels at distances beyond 400 m (approximately 1,300 feet) from freeways.

Along with providing guidance on methodology, the document also presented direction for interpreting the significance of measurement results, stating that "a change of 3 dBA or less will be considered no change." The author noted that "many of the guidelines given should be considered experimental," and also that "additional guidelines may be necessary to cover specific site conditions, and some of the guidelines may have to be changed if experience and future studies show a need for it." In addition, the author stated that he has "conferred with many experts across the nation about performing studies involving distant receivers. The general consensus is that it is not practical to do these studies on a routine basis because of their high cost, both in terms of money and necessary resources."

URS Greiner Woodward Clyde and Illingworth and Rodkin, Inc., *Interstate 680 in Contra Costa County, Pre- and Post Sound Wall Noise Study – Stone-Kemline Sound Walls, Near Stone Valley Road*, June 1999

This report evaluated noise conditions before and after construction of new noise barriers along Interstate 680 in Alamo, California. The measurement program was designed to quantify any differences in noise levels "before" and "after" the installation of the noise barriers at locations relatively distant from the freeway traffic noise source. The measurement program followed guidelines developed by Caltrans (Technical Advisory TAN-9701-R9301, a predecessor to TAN-98-01-R9701), including simultaneous noise, meteorological and traffic data collection before and after the construction of noise barriers. Measured traffic noise levels were normalized for traffic conditions and carefully categorized by meteorological condition. Two receivers were located opposite the barrier at distances of 330 feet (100 m) and 950 feet (290 m) on a hillside elevated above the roadway. The only data reported for these receivers was collected at night with relatively calm winds and clear skies. Before and after noise levels grouped in similar meteorological categories were compared to evaluate noise level changes. Average highway traffic noise levels (L_{eq}) were observed to increase by approximately 1 dB at the closer receiver 2 dB at the more distant receiver. Although the report noted that the measured increases were consistent with sound prediction theory that predicts an increase of 0 to 3 dB "and suspected to be caused by the presence of a single reflecting sound wall," the increases were considered to be insignificant, in accordance with Caltrans Guidelines.

Hankard Engineering, *North End Neighborhood Noise Study*

As discussed earlier in Section 0, CDOT conducted this study to determine the effects of a noise barrier constructed along the west side of Interstate I-25 in Colorado Springs on residents of a neighborhood east of the highway set back several hundred feet to a few thousand feet and generally at a higher elevation than I-25. The study included collection of noise levels, traffic volumes, and meteorological data at six locations from July 1 through September 24, 1999. Analysis of the measurement data indicated that I-25 was the predominant noise source throughout much of the study area, particularly on the west side, closest to I-25. At other locations in the study area, farther from I-25 and closer to busier local streets, noise from local traffic influenced noise levels. At one site, located approximately 1,000 feet from I-25 with an unobstructed line of sight to the roadway, noise levels were measured from January to March 1998, prior to construction of the wall, and again during September and October 1998, following the wall's completion. Noise levels at this location were found to increase by approximately 1 dB following construction of the wall. Noting that 3 dB "is considered the minimum perceptible change in noise levels in outdoor environments," the report concluded that application of absorbent material to the east face of the noise barrier "would not provide any perceivable noise reduction" in the affected neighborhood.

The two following documents describe two similar studies conducted by MnDOT in response to community concerns about noise barrier reflections.

Roseen, M., *Effects of noise wall located on the East side of TH 100 on noise levels of residences on the Westside of TH 100 in the vicinity of Vernon Avenue* Due to the concerns of residents on the west side of TH 100, a six-lane divided highway in Minneapolis, about possible increases in traffic noise levels due to construction of a noise barrier on the east side of the road, MnDOT conducted a test to determine if construction of the noise barrier had increased noise levels, and if so, the magnitude of the increases (see also Section 0). In 2001, following construction of the barrier, noise measurements were repeated at four sites opposite the barrier where measurements had been conducted in 2000, prior to construction of the barrier. Traffic classification counts were conducted during both sets of measurements, and the measured before/after traffic noise levels were normalized to account for differences in traffic using FHWA's STAMINA 2.0 traffic noise prediction model. The analysis found with a 95% confidence level that the noise barrier did not cause a statistically significant difference in overall A-weighted L_{10} sound levels at three of the four measurement sites. At the fourth site, however, the analysis indicated a statistically significant increase of approximately 0.5 dBA due to construction of the noise barrier. The report concluded that this increase was not "a detectable change as judged by human hearing" based on FHWA guidance that "the ability of the human ear to detect noise level change is limited to noise level changes of 3 dBA or more."[40]

Roseen, M., *Effects of a noise barrier, located on the west side of TH 47 (University Ave.), on the noise levels of residences on the east side of TH 47 located between 45th Ave. N. and 52nd Ave. N.*

As introduced in Section 0, residents on the east side of University Ave., a four-lane divided arterial in Minneapolis, were concerned about possible increases in traffic noise levels due to construction of a noise barrier on the west side of the road. Using the same methods as in Section 0, MnDOT conducted a test to determine if construction of the noise barrier had increased noise levels, and if so, the magnitude of the increases. In 2002, following construction of the barrier, noise measurements were repeated at four east-side residences where measurements had been conducted in 2000, prior to construction of the barrier. Traffic classification counts were conducted during both sets of measurements, and the measured before/after traffic noise levels were normalized to account for differences in traffic using FHWA's STAMINA 2.0 traffic noise prediction model. The analysis found with a 95% confidence level that the noise barrier did not cause a statistically significant difference in overall A-weighted L_{10} sound levels at three of the four measurement sites. At the fourth site, however, the analysis indicated a statistically significant increase of approximately 1 dBA due to construction of the noise barrier. The report concluded that this increase was not "a detectable change as judged by human hearing" based on FHWA guidance that "the ability of the human ear to detect noise level change is limited to noise level changes of 3 dBA or more."[41]

Comparison and Testing of Various Noise Wall Materials, Request for Proposals issued by Ohio Department of Transportation, ODOT RFP 2013-16, Posted January 25, 2012

This Request for Proposals (RFP) from Ohio DOT provides another example of a sate DOT funding research to better understand the magnitude and effects of sound reflected from noise barriers.

The RFP included three research topics concerning highway noise barriers; the second topic addressed the use of absorptive barriers in single-barrier cases. The problem statement was as follows:

> ODOT's current noise policy is to use sound absorptive material if there are noise sensitive areas opposite the freeway. This results in additional costs to ODOT for the inclusion of the sound absorptive materials. It is unknown if a discernable difference between sound absorptive concrete walls vs. reflective concrete walls exists. Research is needed to determine if there is a discernable acoustic benefit that justifies the added expenditure. Durability of this material is a potential issue as well. Research relative to the durability of this material over time is needed on existing noise walls.

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[40] U.S. Department of Transportation, Federal Highway Administration, Fundamentals and Abatement of Highway Traffic Noise (Textbook and Training Course); Document 2, Sec. 3.5.1, Sept. 1980.
[41] Ibid.

The RFP indicated that a comprehensive research plan should be developed to address this topic as follows:

> Perform noise measurements on sound absorptive concrete walls vs. reflective concrete walls to determine if there is a discernable difference at the receptor and noise sensitive areas opposite the freeway. Statistically validate the findings. Research the durability of this material on existing noise walls. Provide recommendations on the most appropriate use of sound absorptive materials that will ensure ODOT a return on investment from the initial higher construction costs of these types of walls.

The results of this research will be used by decision makers to determine if, and when, to use sound absorptive materials on concrete noise walls. As of this writing, the results of the research are not yet available.[42]

Nelson, David A., Terry Dossey, and Manuel Trevino, "A novel method for measuring highway barrier or retaining wall sound reflections in situ," *Proceedings of Noise-Con 2011*, Portland, Oregon, July 2011

This paper proposes a new method for measuring reflections from a highway noise barrier or retaining wall following its construction. In a recent project it became necessary to determine the sound-reflective properties of such a wall before and after the installation of sound-absorbing material in order to assess the performance of the absorbing material. More conventional methods, such as impedance tube testing and impulse testing, were deemed undesirable because of small area coverage and the potential for startling drivers. Attempts to measure absorptive properties by observing sound level differences due to live traffic passing in front of reflective and absorptive sections must consider changes in traffic volume, speed, vehicle mix, or lane selection. Laboratory tests also have limitations because they are not able to fully address reflection properties of an extended surface or the potential differences in performance of field-installed treatments.

The authors preferred the results obtainable from an in-situ impulse test, but desired that the "impulse" be generated in some other manner other than a true impulse. The use of maximum-length sequence (MLS or m-sequence) analysis, which uses a broadband, steady-state excitation signal with the same statistical properties as an ideal impulse, was employed to determine the impulse response of reflections off the wall. Synchronous averaging of numerous impulse responses causes moving traffic to "vanish" in the long-term. Results have been shown to be comparable to impedance tube tests. Although the method is "conceptually robust and straightforward," it can be affected by various factors requiring careful consideration. Initial tests were performed on a large retaining wall along IH-30 in Dallas, TX, to fine-tune the method into its current form.

The initial testing showed that it is possible to directly measure reflections from extended surfaces, using the MLS method to obtain impulse responses without resorting to impulsive sources. As of this writing, only initial testing had been completed on the reflective retaining wall, with plans to test the retaining wall again after its treatment to assess the reduction in noise level.

[42] Alcala, Noel, Ohio Department of Transportation. Message to Douglas Barrett. Nov. 19, 2013. E-mail.

McNerney, Michael, S.M. Bucsak, E.J. Haden, and K. Liapa, *Relational Database of Texas Noise Barriers and Effectiveness of Absorptive Treatments Applied to Noise Barriers*, Center for Transportation Research, The University of Texas at Austin, Project 0-2112 Summary Report, August 2001

As part of a project to develop a GIS-based relational database of Texas noise barriers, the authors also conducted research to construct a database of acoustically absorptive treatments on noise barriers. Four different manufacturers participated with noise barriers along IH 610 in Houston. Three of the noise barriers included absorptive materials; the fourth was reflective. To evaluate the effectiveness the sound absorptive materials, the researchers placed a microphone within 15 cm (approximately 6 inches) of the front of the wall. The sound source for the test was the existing traffic flow from the highway. The use of an artificial sound source was ruled out during preliminary tests, and a controlled natural sound source was not feasible because heavy traffic along IH 610. The results were normalized for differences in source strength using a reference microphone. The reflective noise barrier was taken as the control, and the measured difference in sound pressure level between it and each of the three absorptive barriers was attributed to the absorptive surfaces . Compared to the reflective noise barrier, sound levels measured near the absorptive barriers ranged from about 1.5 dB to about 4 dB lower. Note that these measurements were conducted within the roadway right of way immediately in front of the reflective barrier, as opposed to at a community location outside of the right of way across the highway from the reflective barrier.

CHAPTER A-4

The success of efforts to reduce noise reflected from barriers

Overview

The success of efforts to reduce noise reflected from barriers has varied across the U.S., in part due to the different approaches pursued by various state highway agencies. As described in Section 0, some DOTs have responded to community concerns about sound reflected from noise barriers by conducting investigations to attempt documenting perceived increases in noise. Other DOTs have chosen to address similar community concerns by adding sound-absorptive materials to barriers after construction, while still others have long-standing practices of using barriers with absorptive surfaces where there is noise-sensitive land use on the opposite side of the highway. During the 1980s and 1990s, DOTs in several states, including Massachusetts, New York, New Jersey, Maryland, and Virginia, started to specify sound-absorbing barriers opposite residential areas when confronted with complaints from residents regarding reflected sound. "Although these states did not institute formal policies, they adopted informal, but widespread practices, of specifying sound-absorptive barriers in locations where reflected sound was of concern – where there was residential land use or another barrier on the opposite side of the roadway." [43]

Since 2010, FHWA has required state highway agencies to include provisions in their state noise policies for use of absorptive treatment on roadside structures, including noise barriers, retaining walls, bridges, and any other structure the highway agency may consider for application of a sound absorptive material.[44] In response to this requirement, some states have adopted formal policies either requiring or considering the use of absorptive treatment on noise barriers in some situations:

- Since 1988 the Wisconsin DOT (WisDOT) Transportation Facilities Development Manual has required that if noise abatement is found to be reasonable and feasible and is proposed for installation, absorptive noise barrier surfaces are required for use "on the roadway side of a single-side-of-roadway noise wall, when residential or other noise-sensitive receptors are located opposite from the roadway wall face." [45]
- Ohio DOT (ODOT) permits installation of sound-absorptive noise barriers when approved by its Office of Environmental Services. Typical uses for sound-absorptive noise barriers have been where there are noise sensitive areas across from a proposed noise wall or where parallel barriers are proposed. However in "isolated areas with no noise sensitive land use on the opposite side of the roadway" the use of reflective barriers is required.[46]

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[43] Menge and Barrett, Op. cit., p. 164.
[44] Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance*, p. 60.
[45] *Wisconsin Department of Transportation Facilities Development Manual*, Chapter 23 "Noise," Section 35 "Noise Abatement Measures," February 15, 1988.
[46] *Ohio Department of Transportation Highway Traffic Noise Analysis Manual, Analysis and Abatement of Traffic Noise*, Ohio Department of Transportation, Office of Environmental Services, February 2013, p. VII-3.

- In its Environmental Procedures Manual, Tennessee DOT (TDOT) acknowledges that "noise reflections off of a noise barrier on one side of a highway can . . . increase sound levels on the opposite side of the highway." While stating that "in most cases, these increases are less than 3 dB which is usually the smallest change in hourly sound levels that people can detect without specifically listening for the change," TDOT may consider specifying single noise barriers as absorptive if there are noise-sensitive land uses on the opposite side of the road from the noise barrier.[47]
- "Depending on the specifics of the transportation improvement project," the Virginia Department of Transportation (VDOT) may recommend absorptive noise barrier surfaces in the presence of "an extremely sensitive receptor(s) on the side opposite the highway from the proposed noise barrier" or in the "presence of impacted receptors on the side opposite the highway for whom a noise barrier was not determined to be feasible or reasonable." In these cases, the determination of whether to use absorptive materials is guided by the ratio of the barrier-to-receiver distance compared to the height of the barrier.[48]

A long-term success story in reducing reflected noise and related community complaints through a policy promoting widespread use of sound-absorptive barriers comes from Ontario, Canada. The Ontario Ministry of Transportation (MTO) has "an aggressive policy in dealing with unwanted reflections from single [and parallel] noise barriers," and has constructed approximately 104 km (65 miles) of absorptive noise barriers since 1978. As a result of this practice, barrier reflections are "just not a problem" in Ontario. [49]

In addition to the investigations described in Section 0 that focused on measuring the magnitude and effects of noise reflected from barriers, other studies have attempted to measure the success of efforts to reduce reflected noise. A 1999 study in Oakland, California evaluated a progression of noise abatement treatments including noise barriers and sound-absorbing panels along a section of I-580. In this project, noise barriers were constructed on one side of the freeway and on a median retaining wall, but were not feasible for residences on the opposite side due to a large elevation difference between the homes and the road. Following construction of the noise barriers, the insertion loss was found to be only 3 to 4 dB, not sufficient noise reduction for the barrier to be considered effective. The median retaining wall and noise barrier then were covered with sound-absorbing panels and the insertion loss was measured to be 5 dB, sufficient to be considered effective. This is an example of where an "imperceptible" one- to two-decibel change made the difference between an ineffective and effective barrier.[50]

Another California study, this one conducted during a widening project on U.S. 101 in Marin County between 2007 and 2010, investigated the benefits of both absorptive barriers and quieter pavement. Prior to the project, noise barriers existed on both sides of the highway, however the addition of a 16-foot wide multi-use path necessitated relocating one barrier farther from the roadway. Because of residents' concerns about reflected sound, absorption was added to the barriers on both sides. Although attempts to measure the benefit of the absorptive materials were inconclusive due to changes in geometry and varying pavement during different project phases, modeling indicated that the absorptive materials could reduce noise levels by 3 to 5 dB at distant (those over 500 feet from road) and elevated receptors. The benefit

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[47] Tennessee Department of Transportation Environmental Procedures Manual, *Guidelines for Preparing Environmental Documents for Federally Funded and State Funded Transportation Projects*, Section 5.3.4.10 "Final Noise Barrier Design," Spring 2011.
[48] *Virginia Department of Transportation Highway Traffic Noise Impact Analysis Guidance Manual (Version 4)*, Section 10.4 "Applications for Absorptive Noise Barriers," August 6, 2013, p. 32–33.
[49] Blaney, Christopher, Ontario Ministry of Transportation. Message to Douglas Barrett. Nov. 4, 2013. E-mail.
[50] Woodward-Clyde and Illingworth & Rodkin, Inc., *Noise Abatement Evaluation: Interstate 580 Oakland*, Reference 4-ALA-580, HP 311 Program, November 1999.

would be less (1 to 2-1/2 dB) at closer receptors.[51] This project involved parallel barriers, but some of the finding are relevant to measurement studies of single-barrier reflections. In particular, (1) the influence of whether or not the receptor had a clear line of sight to either the roadway and/or the reflective noise barrier and (2) the importance of controlling any variability in conditions between measurements of "no barrier" and "with barrier" cases.

Finally, a recent study commissioned by MnDOT investigated potential causes and solutions to community noise complaints following construction of a new noise barrier. As part of a lane addition project along Interstate 94 (I-94) between Minneapolis and St. Paul, a reflective noise barrier was installed across from a noise barrier constructed many years earlier. The study found that the new noise barrier was creating unshielded acoustical reflections to some receivers previously protected by the existing barrier, with the largest increases for those receiver locations with direct line of sight to the new barrier. The study recommended that the most effective and cost efficient mitigation option was to add "backless" acoustical panels, which would provide acoustical absorption without the added cost and weight provided by a solid back panel, to the new noise barrier.[52]

Summaries of Cited Works (The success of efforts to reduce noise reflected from barriers)

Menge, C.W. and D.E. Barrett. "Reflections from Highway Noise Barriers and the Use of Absorptive Materials in the United States, Why Small Increases in Noise Levels may Deserve Serious Consideration"

(This paper is also discussed in Sections 0 and 0)

Since the 1970s, some DOTs have responded to community concerns by conducting investigations to attempt to document the effects (or not) of noise reflected from barriers. Other DOTs have attempted to address similar community concerns by adding sound absorptive materials to barriers after construction, while still others have long-standing practices of using barriers with absorptive surfaces wherever there is noise-sensitive land use on the opposite side of the highway. During the 1980s and 1990s, DOTs in several states, including Massachusetts, New York, New Jersey, Maryland, and Virginia, started to specify sound-absorbing barriers opposite residential areas when confronted by complaints from residents regarding reflected sound. "Although these states did not institute formal policies, they adopted informal, but widespread practices, of specifying sound-absorptive barriers in locations where reflected sound was of concern – where there was residential land use or another barrier on the opposite side of the roadway." The authors note that "public funds spent on sound-absorptive barriers are perceived as benefiting the public whereas funds spent disputing or attempting to disprove residents' claims may be perceived as opposing the public." In addition, the authors contend that the benefit of simply implementing absorptive barrier treatments opposite residential areas outweighs the benefit of researching the issue or conducting detailed analyses to justify the use of absorption, even if that use comes at a modest cost premium.

[51] Donavan, Paul R. and Dana M. Lodico, *The Influence of Quieter Pavement & Absorptive Barriers on U.S. 101 in Marin County*, Presentation at Transportation Research Board Committee ADC40 Summer Meeting, Asheville, NC, July 2012.
[52] Burge, P., J. Crawford, and Peter Wasko, "Use of advanced tools and techniques to resolve an atypical parallel noise barrier case," *Proceedings of Noise-Con 2013*, Denver, CO, August 26–28, 2013.

Correspondence with Chris Blaney, Ontario Ministry of Transportation, November 4, 2013

The Ontario Ministry of Transportation (MTO) provides an example of an agency with a long-standing policy of using sound-absorptive barriers to reduce or eliminate the effects of reflected noise. Ontario has "had an aggressive policy in dealing with unwanted reflections from single [and parallel] noise barriers," having always used absorptive noise barriers in those situations. MTO does not build a single sound reflective noise barrier where there are noise sensitive areas on the opposite side of the highway. In addition, they generally try "to construct noise barriers on both sides of the highway at the same time to avoid the perception of reflections." As a result, "this is just not a problem" in Ontario.

MTO's official policy states that the use of sound absorptive noise barriers is recommended in retrofit barrier sites where parallel sites are being constructed or where there are single sites being constructed where the unwanted reflection may cause problems. It is only a practice (i.e., not policy) for sites constructed for environmental mitigation purposes. MTO is in the process of changing their policy and generally follows the guidance provide in the Caltrans Noise Protocol and the Technical Noise Supplement.

MTO started constructing sound absorptive walls in 1978 because they "were aware of the problem." Since that date, MTO has constructed approximately 104 km (65 miles) of absorptive walls. All noise barriers must be pre-approved for use by MTO and must have a Noise Reduction Coefficient (NRC) greater than or equal to 0.70 to be considered as sound absorptive. Although MTO has had complaints due to perceived reflections despite the use of absorptive materials, the complaints "generally go away once [MTO] explains that over 70% of the sound is absorbed by the walls." MTO acknowledges that "there may however be cases where even small reflections may cause changes to the tone of the noise rather than the absolute sound levels."

The four following selections provide examples of the formal policies or guidance of four state DOTs (Ohio, Tennessee, Wisconsin, and Virginia) addressing the use of sound-absorptive noise barrier materials.

Ohio Department of Transportation Highway Traffic Noise Analysis Manual, Analysis and Abatement of Traffic Noise, Ohio Department of Transportation, Office of Environmental Services, February 2013

Ohio DOT permits installation of sound absorptive noise barriers when approved by its Office of Environmental Services. Typical uses for sound absorptive noise barriers have been where there are noise sensitive areas across from a proposed noise wall or where parallel barriers are proposed. The manual notes that, in the case of parallel noise barriers, if the width to height ratio of the roadway section to the noise barrier is at least 10:1, the use of absorptive materials on noise walls is not required, based on FHWA guidance and research. For example, this means that the use of absorptive material for two parallel barriers 10 feet tall and 120 feet apart, is not required. In "isolated areas with no noise sensitive land use on the opposite side of the roadway" the use of reflective barriers is required, including in locations where future development may result in a noise sensitive land use on the opposite side of the roadway. In addition, reflective barriers are required in locations with industrial or commercial use on the opposite side of the roadway.

Tennessee Department of Transportation Environmental Procedures Manual, Guidelines for Preparing Environmental Documents for Federally Funded and State Funded Transportation Projects, Section 5.3.4.10 "Final Noise Barrier Design," Spring 2011

In its Environmental Procedures Manual, TDOT provides guidance for use of sound absorptive noise barrier materials. In the case of parallel barriers, TDOT requires a detailed noise reflections analysis using TNM's "Parallel Barriers" module. If noise reflections are predicted to "substantially degrade" the predicted design year noise reductions, TDOT will absorptive noise barrier materials. TDOT also acknowledges that "noise reflections off of a noise barrier on one side of a highway can also increase sound levels on the opposite side of the highway." While stating that "in most cases, these increases are less than 3 dB which is usually the smallest change in hourly sound levels that people can detect without specifically listening for the change," TDOT may consider specifying single noise barriers as absorptive if there are noise-sensitive land uses of the opposite side of the road from the noise barrier.[53]

Wisconsin Department of Transportation Facilities Development Manual, Chapter 23 "Noise," Section 35 "Noise Abatement Measures," February 15, 1988

WisDOT states in its Transportation Facilities Development Manual that "the principles of acoustics indicate that sound reflected from the surface of a noise wall has the potential of increasing sound levels at existing noise sensitive receptors located on the opposite side of the roadway from the proposed noise wall project. Specifying an absorptive noise wall will reduce reflected sound levels by eighty percent or more, thereby reducing reflected sound to below the level noticeable to the healthy human ear."

If noise abatement is found to be reasonable and feasible and is proposed for installation, absorptive noise barrier surfaces are required for use on any of the following noise wall installations:

- Roadway side of parallel noise walls, when installed initially as a pair, or separately as part of an approved, multi-year noise abatement plan;
- Roadway side of a single-side-of-roadway noise wall, when residential or other noise-sensitive receptors are located opposite from the roadway wall face; and,
- Residential side of the noise wall, when residential or other noise-sensitive receptors may be affected by reflected noise from other sources located on the residential side of the noise wall.

In addition, if reflected noise has the potential to impact lands which are currently undeveloped, the designer must consider proposed land uses for the undeveloped lands when selecting the noise wall surface type. For purposes of these criteria, WisDOT defines an "absorptive noise wall surface" as a noise wall system having a composite Noise Reduction Coefficient (NRC) of at least 0.80 on the roadway side of the noise wall and 0.70 on the residential side, as applicable.

[53] TDOT has opted to specify absorptive treatment for single noise barriers on three projects where noise-sensitive land uses existed opposite the noise barrier: I-40 eastbound between I-65 South and I-65 North in Nashville, I-240 northbound between Poplar Avenue and Walnut Grove Road in Memphis, and I-65 southbound south of Wedgewood Avenue in Nashville.

1.1.1 *Virginia Department of Transportation Highway Traffic Noise Impact Analysis Guidance Manual* (Version 4), Section 10.4 "Applications for Absorptive Noise Barriers," August 6, 2013, p. 32-33

VDOT may recommend absorptive noise barrier surfaces "depending on the specifics of the transportation improvement project . . . to optimize the benefits of the proposed highway traffic noise abatement." Such cases may include:

- A parallel noise barrier system;
- Presence of an extremely sensitive receptor(s) on the side opposite the highway from the proposed noise barrier;
- Presence of a retaining wall with a reflective surface on the side opposite the highway from the proposed reflective-surfaced noise barrier;
- Presence of impacted receptors on the side opposite the highway for whom a noise barrier was not determined to be feasible or reasonable; and
- A bifurcated highway system.

In the case of a single barrier parallel to residential noise sensitive receptors:

- If the distance from the barrier to the receptors is greater than 20 times the barrier height, a reflective barrier shall be used.
- If the distance from the barrier to the receptors is between 20 times and 10 times the barrier height, consideration will be given to using absorptive barriers.
- If the distance from the barrier to the receptors is less than 10 times the barrier height, an absorptive barrier shall be used.

The next two selections describe two more examples in the series of Caltrans investigations into the effects of reflections from noise barriers. They are included in this section because they focus on potential mitigation measures.

Noise Abatement Evaluation: Interstate 580 Oakland, Reference 4-ALA-580, HP 311 Program, prepared by Woodward-Clyde and Illingworth & Rodkin, Inc., November 1999

This study evaluated a progression of noise abatement treatments including noise barriers and sound-absorbing panels along a section of I-580 in Oakland. This portion of I-580 has super-elevated lanes, where the eastbound lanes are about 1 to 4 meters (about 3 to 14 feet) higher than the westbound lanes. The two directions of travel are separated by a retaining wall. Noise abatement was designed to reduce noise levels at residences along the westbound side; noise reduction was not feasible for residences along the eastbound side due to a large elevation difference with the homes located above the freeway. Detailed noise and meteorology measurements were conducted at several sites behind the barrier (westbound side) and at a site representative of the closest residences opposite the barrier (eastbound side). Noise abatement measures included a noise barrier located at the edge of the westbound lane, a second noise barrier located on top of the median retaining wall, and application of sound-absorbing panels to the median retaining wall and the new median noise barrier.

Following construction of the noise barriers, an increase of 2 dB was measured at the receiver opposite the edge-of-pavement barrier (eastbound side). Behind the barrier (westbound side), the insertion loss was found to be only 3 to 4 dB, not sufficient noise reduction for the barrier to be considered effective. The median retaining wall and noise barrier then were covered with sound-absorbing panels and barrier insertion loss was measured to be 5 dB, sufficient to be considered effective. The authors note that this is an example of where an "imperceptible" one- to two-decibel change makes the difference between an ineffective and effective barrier. Although the application of sound-absorbing panels to the median walls improved the noise reduction for residences on the westbound side, unprotected residences on the eastbound side were left with the 2 dB increase attributed to sound reflected from the new noise barrier.

Donavan, Paul R. and Dana M. Lodico, *The Influence of Quieter Pavement & Absorptive Barriers on U.S. 101 in Marin County*, Presentation at Transportation Research Board Committee ADC40 Summer Meeting, Asheville, NC, July 2012

As noted in Section 4.1, a study was conducted to determine the benefits of various noise abatement measures during a 2007 widening project on U.S. 101 in Marin County, California. Prior to the project, noise barriers existed on both sides of the highway. The project added a high-occupancy vehicle (HOV) lane added in each direction and also a 16-foot wide multi-use path on the southbound side. The multi-use path necessitated relocating the barrier in the southbound direction farther from the roadway. In addition, because of residents' concerns about reflected sound, absorption was added to the barriers on both sides. As a result of the project, overall sound levels dropped by about 6 to7 dB. Onboard Sound Intensity (OBSI) measurements indicated that most of the improvement was due to the new pavement.

Attempts to measure the benefit of the absorptive noise barrier materials were inconclusive due to changes in geometry and varying pavement during different project phases. The effect of the absorptive treatment therefore was modeled using both a spreadsheet approach and SoundPLAN's implementation of the 1978 FHWA traffic noise prediction algorithm. The modeling indicated that the absorptive materials could reduce noise levels by 3 to 5 dB at distant (those over 500 feet from road) and elevated receptors. The benefit would be less (1 to 2.5 dB) at closer receptors.

This project involved parallel barriers, but some aspects are relevant to the situation with a single reflective barrier. Modeling indicated that the effects of reflections were dependent upon both the distance and height of receptors relative to the roadway. In addition, whether or not the receptor had a clear line of sight to either the roadway and/or the reflective barrier influenced the modeled results. Finally, the difficulty in obtaining conclusive measurement results emphasizes the importance of eliminating all variability, to the extent possible, between "no barrier" and "with barrier" conditions.

Burge, P., J. Crawford, and Peter Wasko, "Use of advanced tools and techniques to resolve an atypical parallel noise barrier case," *Proceedings of Noise-Con 2013*, Denver, CO, August 26–28, 2013

As discussed on Section 0, as part of a lane addition project along Interstate 94 (I-94), the primary highway link between Minneapolis and St Paul, Minnesota, a reflective noise barrier was constructed on the eastbound (southern) side of I-94 opposite a noise barrier constructed many years earlier on the north side of the highway. The two walls together formed a parallel barrier condition with the northern neighborhood and barrier at a higher elevation than the southern barrier and community. MnDOT commissioned a study to determine 1) if reflections from the new noise wall were causing perceptively higher noise levels in the adjacent community, and 2) if so, what could be done within project budget constraints to help mitigate the noise level increases.

The study indicated that in addition to a moderate increase in noise due to the additional traffic lanes, the new southern wall was creating new unshielded acoustical reflections to some receivers previously protected by the existing barrier. Although the influence of the added traffic lanes was fairly consistent among all receivers (approximately 1 dBA due to the approximate 33% increase in traffic capacity), the influence of the new barrier reflection was greater and less consistent, with second-row receivers receiving a predicted average 4.3 dBA increase versus an average 2.6 dBA increase for first-row receivers. The analysis indicated the largest increases for those receiver locations with direct line of sight to the new barrier.

The study found that the most the most effective and cost efficient mitigation option was to add acoustical absorption to the south wall. Several materials and products were investigated including prefabricated acoustical panels, spray-on material, and a “backless” acoustical panel, which included a lightweight perforated front panel, acoustically absorptive material behind, but no solid back panel. The cost/benefit analysis showed that the backless panel design would provide the required acoustical absorption to reduce reflected noise to a “less than noticeable” level increase at the most economical cost. The advantage of the backless panel is that it would provide acoustical absorption without the added cost and weight provided by a solid back panel, which was not needed due to the mass of the existing barrier.

Although this study involved parallel barriers, rather than a single barrier, some of the findings are relevant to investigations of reflections from single barriers. In particular, the study showed that construction of a reflective barrier may provide new, unshielded sound propagation paths that may dominate overall sound levels at some locations. Even in single barrier situations, terrain, retaining walls, or other structures may block the direct line of sight to traffic, and construction of a noise barrier on the opposite side of the road may cause new unshielded paths. In addition, the recommended mitigation approach of the “backless” acoustical panel may also prove effective in single barrier cases.

CHAPTER A-5

Conclusions for Appendix A

This review of available literature regarding reflected noise from single, reflective barriers has focused on (1) the community noise issues that have led to investigations of noise reflected from barriers, (2) past attempts to quantify the magnitude and effects of noise reflected from barriers, (3) and the success of efforts to reduce noise reflected from barriers. Based on this review, the project team offers the following conclusions:

- Community complaints of sound reflected from highway noise barriers date back nearly as long as the first widespread construction of noise barriers in the United States in the 1970s. For many years, on many occasions, and in many different states, communities have complained of sound reflected from highway noise barriers to receptors on the other side of the highway.
- Over the past several decades, there have been numerous attempts to quantify the magnitude and effects of noise reflected from barriers. Generally these studies have identified 0 to 3 dB increases in overall A-weighted sound level as a result of reflected sound.
- In some cases, depending upon geometry, even a single reflection may increase sound levels by more than 3 dB, particularly when construction of a noise barrier creates new, unshielded sound propagation paths.
- Despite conclusions that increases in noise levels caused by reflections were so small that they should have been imperceptible, in many cases people did respond to reflected sound, or at least to the perception of it.
- It is likely that factors in addition to the increase in overall sound level contribute to residents' perception of increased noise due to reflected sound. Accordingly, investigations of reflected sound should examine additional factors such as spectral changes or alterations of the temporal characteristics of vehicle passbys.

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APPENDIX B – DETAILED PROTOCOLS AND RESULTS

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CHAPTER B-1

Introduction to Appendix B

This appendix presents the details of the research data collection and analysis protocols and the results at five studied single-barrier locations. It does not provide background on the subject, overall findings, applications, recommendations or suggested research. Those topics are covered in the main report.

The purpose of the measurements and analysis was to see if sound levels increased on the opposite side of the road from a noise barrier due to sound reflections off that barrier, as illustrated in Figure 1, and whether differences could be detected using spectrogram analysis or psychoacoustic metrics.

The analysis was done using: (1) a modification to a method in a Federal Highway Administration (FHWA) noise measurement manual ("FHWA Method"); (2) acoustical spectrograms, which show the frequency content of sound as a function of time; and (3) the psychoacoustic measures of Loudness, Sharpness, Roughness, and Fluctuation Strength combined into metrics of Annoyance. Additionally, changes in the statistical exceedance (Ln) descriptors were also addressed. Broadband unweighted sound pressure levels and A-weighted sound levels were studied as well as 1/3 octave band sound pressure levels.

In this appendix, the unit of dB refers to a change in level, both for unweighted sound pressure levels (designated as dBZ per the International Standards Organization (ISO)) and A-weighted sound levels (dBA).

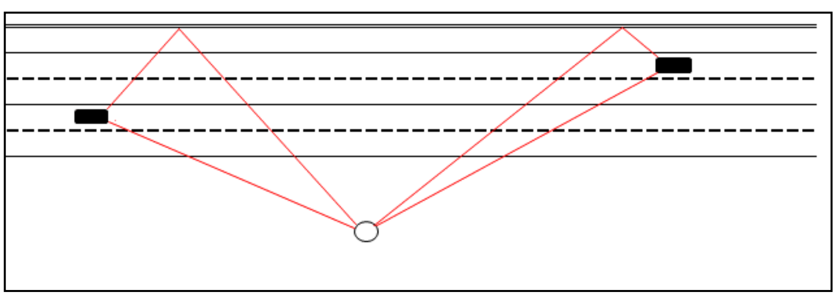


Figure 1. Plan view of the relationship between direct and reflected sound paths to a receptor across the highway from a noise barrier.

The next chapter addresses the research approach. The subsequent chapters then focus on the results, with one chapter for each measurement location. Each of these chapters presents details on the location, the microphone positions, observations made during the measurement, and the results.

The results are presented first in terms of differences in the raw 5-minute broadband equivalent sound levels (L_{eq}(5min)), both for the unweighted sound pressure level and the A-weighted sound levels. Then, the 5-minute periods found to be equivalent to each other in terms of source and meteorological class are identified and studied for 1/3 octave band sound pressure level differences at the microphone pairs. Sample 1/3 octave band unweighted sound pressure level spectra are also presented for comparison at the microphone pairs. Analysis of the L_{90} and L_{99} statistical descriptors is also presented for the broadband unweighted and A-weighted levels, as well as 1/3 octave band analysis of seven Ln statistical measures ranging from L_1 to L_{99}. Finally, results for the spectrograms and psychoacoustic metrics are presented.

There is some duplication of material contained herein with that in the Final Report, especially as related to the measurement locations. The goal was to make this appendix enough of a standalone document so that frequent referral back to the Final Report would not be necessary.

Appendix C of the Final Report includes photos of the microphone positions, meteorological station and traffic data collection site for each location.

CHAPTER B-2

Research Approach

Study Location Selection Criteria and Process

The location selection criteria were developed primarily based on the information needed for judging if a Barrier site and its potentially "equivalent" No Barrier site are indeed equivalent. The criteria were incorporated in a Preliminary Site Evaluation Form prepared by the researchers. These forms were then used by each team member in a desktop identification of potential study locations. Twenty-one potential locations were identified.

These potential locations were reviewed by the researchers, and a list of ten preliminary study locations was developed, considering these variables:

- Comparable Barrier and No Barrier locations: Sections of road with a consistent pavement type, either a reflective or absorptive barrier on one side, and a nearby section with no barrier; similar geometry and topography so that monitors could be placed at the same distances and heights relative to the barrier; paired simultaneous measurements could then be conducted under the same traffic and meteorological conditions with no normalization of data needed for varying traffic conditions.
- Noise sources: Sites without other significant noise sources
- Roadway type/classification: Types of roadway and number of lanes
- Road cross-section: At-grade, elevated (on fill), or depressed (in cut)
- Pavement type: Asphalt or concrete
- Traffic mix: Traffic volumes and vehicle mix (i.e., percent trucks)
- Noise barrier type: Absorptive and/or reflective
- Noise barrier height: Different barrier heights, to the extent feasible.
- Noise barrier location: Locations at the shoulder (near the source) or at the right-of-way (near the receiver)

Field reviews were then conducted at the most promising locations. A final set of eight acceptable locations was identified.

Selected Locations

The selected locations are listed below:

1. BA-1, I-24, Murfreesboro, TN.
2. BA-3, Briley Parkway (SR 155), Nashville, TN.
3. ATS-3, SR-71, Chino Hills, CA.
4. BA-4, I-240, Memphis, TN.
5. EA-4, Hampstead Bypass, Hampstead, MD.
6. EA-5, MD Route 5, Hughesville, MD.

7. RSG-3, US 3/FE Everett Turnpike, Nashua, NH.
8. SID-1, I-90, north of Spring Creek Rd Rockford, IL.

The originally selected California location was ATS-2, SR-99 in Bakersfield, CA. Before the measurements could be conducted, a roadway construction project was started at the ATS-2 location. An alternative location that had also been studied in Task 3, ATS-3 on SR-71 in Chino Hills, CA, was selected to replace ATS-2.

Table 1 summarizes the characteristics of the eight locations. The first two locations were studied as part of Task 4 of the research. The others were identified for potential study in Task 5. At the project's Interim Meeting, the decision to continue with the spectrogram and psychoacoustics analyses meant that the BA-4 and RSG-3 locations would not be studied for budgetary reasons. Then, during final inspection, it was determined that the EA-4 location was sound-absorbing and, being a depressed highway, was not the best location to include as a sound-absorbing site. Instead, the decision was made to conduct extended monitoring at the EA-5 location with the goal of nighttime or off-peak sampling that would allow individual vehicle passbys to be studied. Thus, in Task 5, three locations were studied: SID-1 (I-90), ATS-3 (SR-71) and EA-5 (MD Route 5).

The final five locations offered a wide variety of characteristics:

- Daily traffic volumes range from 18,000 to 80,000 vehicles per day;
- The cross-sections range from a total of four lanes to eight lanes;
- Four locations are on freeways and one is on an arterial;
- Four of the sites are essentially at-grade with surrounding terrain and one is on retaining wall.
- Truck percentages range from 7% up to 14%;
- Four of the pavements are dense-graded asphalt and one is concrete;
- Barrier offset distances from the edge of the near travel lane range from 9 feet to 96 feet;
- All barriers are sound reflective: three are precast concrete post-and-panel designs, one is cast-in-place concrete, and one is concrete block atop an earthen berm; and
- Barrier heights range from approximately 12 feet to 19 feet.

Most of the measurement points were within the highway right-of way, meaning that most of the distances to the community microphones were within approximately 100 ft of the center of the near travel lane. The exception was the SR-71 site where the more distant microphones were able to be set up approximately 400 ft from the center of the near travel lane. It would have been desirable to measure farther back at other locations, but site conditions – mainly developed land uses and terrain – eliminated the ability to have distant Barrier and No Barrier sites that were equivalent in terms of the intervening terrain. The exception was made for SR-71 where simplified modeling with FHWA Traffic Noise Model version 2.5 (TNM) demonstrated site equivalence for frequencies of interest.

The community microphone positions were as follows:

- I-24: two heights above the roadway surface at the same distance from the center of the near travel lane
- Briley: two heights at the same distance from the center of the near travel lane
- I-90: two heights at different distances from the center of the near travel lane
- SR-71: two heights at different distances from the center of the near travel lane
- MD-5: two heights at approximately the same distance from the center of the near travel lane

Table 1. Selected locations.

Location	Roadway	City, State	Road Class	Lanes	Pavement Type	Geometry Relative to Adjacent Land Uses	AADT (veh/day)	Percent Trucks	Barrier Location	Barrier Material	Barrier Height at Study Site
ATS-3*	SR-71, south of Soquel Canyon/Central, north of Pine Ave.	Chino Hills, CA	Freeway	6	Concrete (Longitudinal grooving)	At-Grade	60,000	7%	ROW	Concrete Block atop Berm	13 feet (7-ft wall atop 6-ft berm)
BA-1*	I-24, between Old Fort Pkwy/ New Salem Rd.	Murfreesboro, TN	Freeway	8	Asphalt (DGAC)	At-Grade	78,140	14%	ROW	Precast Concrete	16-19 feet
BA-3*	Briley Pkwy (SR 155), between Brick Church Pike and Dickerson Pike	Nashville, TN	Freeway	6	Asphalt (DGAC)	Fill (Retaining Wall)	45,820	8%	Shoulder	Cast-in-Place Concrete	12-13 feet
BA-4	I-240, between Getwell and Perkins Roads	Memphis, TN	Freeway	10	Asphalt (DGAC)	Slight Fill	151,700	11%	ROW	Precast Concrete	18 feet
EA-4	Hampstead Bypass (MD Rt 30), at N. Houcksville Rd.	Hampstead, MD	Arterial	2	Asphalt (DGAC)	Cut	18,000	9.4%	ROW	Precast Concrete	5-12 feet
EA-5*	MD Route 5, at Carrico Mill Rd and Alex St.	Hughesville, MD	Arterial	4	Asphalt (DGAC)	At-Grade	34,160	8%	Shoulder	Precast Concrete	16 feet
RSG-3	US 3 / FE Everett Turnpike, west of Dunstable interchange	Nashua, NH	Freeway	8-9	Asphalt (Not determined)	At-Grade	100,000	2.8%	ROW	Wood	15 feet
SID-1*	I-90, Illinois Tollway, north of Spring Creek Rd	Rockford, IL	Freeway	6	Asphalt (Not determined)	At-Grade	53,470	9.7%	Shoulder	Precast Concrete	15 feet

*Locations ultimately measured.

The selected locations provided good opportunities to study the noise barrier reflections issue. Each location is described briefly below. More details, including aerial and cross-sectional views of each location, can be found in the Results chapter for each location. More photos for each location are in the appendix.

Location BA-1, I-24, Murfreesboro, TN

I-24 is an 8-lane freeway with dense-graded asphalt pavement that carries 78,000 vehicles per day with 14 percent trucks. The barrier is a reflective post-and-panel concrete wall located approximately 96 ft from the center of the near travel lane, and is 19 ft tall. See Figure 2. The measurement plan placed the community microphones at approximately 84 ft from the center of the near travel lane at two different heights above the pavement: 5 ft and 15 ft. Local businesses on a parallel local road precluded going back farther than near the ROW line at the Barrier site.

Because of the large barrier offset from the road and the fact that this location was the first to be studied, it was decided to move the reference microphones closer to the road – 51 ft from the center of the near travel lane (33 ft from the edge of shoulder) and 45 ft in front of the barrier at the Barrier site. During the field review, near-direction traffic dominated the noise being heard at the community microphones. By moving the reference microphone to be between the barrier and the road, it provided an opportunity to see if a microphone at such a close position to the barrier experiences a sound level increase due to reflections.

Figure 2. No Barrier (left) and Barrier (right) views at BA-1, I-24. (Source: research team members.)

Location BA-3, Briley Parkway (SR 155), Nashville, TN

Briley Parkway is a six-lane freeway with dense-graded asphalt pavement. It carries 46,000 vehicles per day with 8 percent trucks. The barrier is a reflective cast-in-place concrete wall, located approximately 16 ft from the center of the near travel lane. It is 13 ft tall. See Figure 3. This road carries relatively light traffic in the nighttime hours and is being considered for the nighttime measurements in hopes of measuring individual vehicle passages.

Briley Parkway is elevated on a retaining wall in the Barrier and No Barrier areas. The microphone support poles needed to be tall enough to get the at least one community microphone at each site above the top of the parapet on the retaining wall. The measurement plan placed the community microphones at approximately 90 ft from the center of the near travel lane (75 ft from the retaining wall). One microphone at each site was 10 ft above the pavement. The other was near the ground in backyards of single family residential lots, one at 5 ft above ground and one at 12 ft above ground so that both were approximately 14 ft below the pavement. The houses precluded measuring farther from the road.

Because of the height of the retaining wall at the No Barrier reference microphone location, the needed tripod height was too great to be stable and safe. It was proposed and accepted not to measure at this point. As noted earlier, FHWA's *Measurement of Highway-Related Noise* does not require reference microphones. Because the No Barrier site is adjacent to the Barrier site, there was very little chance, if any, that the "source" would not be equivalent at both sites for the same 5-minute blocks of time being used in the analysis.

Figure 3. No Barrier (left) and Barrier BarRef01 (right) views at BA-3, Briley Parkway. (Source: research team members.)

Location SID-1, I-90, north of Spring Creek Rd Rockford, IL

I-90 is part of the Illinois Tollway system and is a six-lane freeway with dense-graded asphalt pavement. It carries 53,500 vehicles per day with 9.7 percent trucks. The barrier is a reflective post-and precast concrete wall, located 20 ft from the center of the near travel lane. It is 15 ft tall. See Figure 4 for a roadside view of the barrier.

Figure 4. No Barrier (left) and Barrier (right) views at SID-1, I-90. (Source: research team members.)

Location ATS-3, SR-71, Chino Hills, CA

SR-71 is a six-lane freeway in Chino Hills, CA, with longitudinally grooved concrete pavement. It carries 60,000 vehicles per day with 7 percent trucks. The barrier is 13 ft high, consisting of a 7-ft high reflective concrete block atop a 6-ft high earthen berm wall near the right-of-way line at distance of approximately 50 ft from the center of the near travel lane. See Figure 5.

Figure 5. No Barrier NoBarCom05 (left) and Barrier BarRef01 (right) views at ATS-3, SR-71. (Source: research team members.)

Location EA-5, MD Route 5, Hughesville, MD

MD Route 5 (MD-5) is a four-lane arterial freeway with dense-graded asphalt pavement. It carries 34,200 vehicles per day with 8 percent trucks. The barrier is a reflective post-and-panel precast place concrete wall, located approximately 15 ft from the center of the near travel lane. It is 16 feet tall. See Figure 6. This road carries relatively light traffic in the nighttime hours and was studied in the evening as well as the daytime in an attempt to measure individual vehicle passages.

Figure 6. No Barrier NoBarCom05 and NoBarCom06 (left) and Barrier from meteorological station (right) views at EA-5, MD Route 5. (Source: research team members.)

Data Collection Protocol

Three types of data analysis were used in this study:

- FHWA Method (based on the Indirect Measured procedure in Chapter 6 of FHWA's Measurement of Highway-Related Noise (Ref. 1), where simultaneous measurements are made at the Barrier site and an "equivalent" No Barrier site)
- Spectrograms
- Psychoacoustics

A single data collection process yielded the data for use in all three analyses, and is discussed first. Then the data processing steps are outlined. Finally, the data analysis methodology for each type of data is discussed.

In addition to the sound level data, the data collection for the FHWA Method included recording of calibrated .wav audio files at each microphone position. These files are used in this study for processing and analysis of the spectrograms and the psychoacoustics parameters.

The two locations in Task 4 were analyzed by all three methods above. At the Interim Meeting, the technical panel decided that more work should be done using the spectrograms and psychoacoustics analysis as part of Task 5. An objective was to measure at night at Briley in addition to daytime in order to study individual vehicle passbys, with particular interest in the change in the signature of the noise level of the passby in the presence of the far wall reflected sound. Nighttime measurements were also made at MD-5 to study single events.

The FHWA Method calls for equivalence of site geometry, noise sources and meteorological parameters. Two factors that affect the sound level and frequency spectrum produced by traffic are the pavement and the roadway grade; these factors were considered in site selection. Two other source characteristics that can affect the sound level and frequency spectrum are the volume and speed of the traffic. Because one goal in site selection was to avoid interchanges or intersections between the Barrier and No Barrier sites and because the Barrier and No Barrier measurements were to be made simultaneously, any potential variations in traffic volume and speed between the two sites was minimized. However, traffic volumes and speeds vary over time. Likewise, experience indicates that meteorological conditions, particularly the wind speed and direction, can change even over relatively short periods of time.

Measurement of Highway-Related Noise recommends a minimum of three "measurement repetitions" per site (with a preferred number of six repetitions) under equivalent source and meteorological conditions. The challenge is that it can be very difficult and time-consuming while in the field collecting data to demonstrate source equivalence and meteorological equivalence real-time. As a result, the field protocol was:

- Collect four hours of data at each site, to be averaged in one-minute periods;
- Video-record the traffic and measure speeds with a laser speed gun; and
- Collect wind speed and direction and temperature data at two heights, to be averaged in one-minute periods.

Then, as part of the data processing protocol, the four hours of data were divided into 5-minute periods of equivalent source and meteorological conditions at the No Barrier and Barrier sites. Each period represents one "measurement repetition" for a unique combination of equivalent source and meteorological conditions.

To accomplish this assignment of the data into periods, the initial goal was to count and classify traffic at each site from the video recording and to merge that data with the speed data to determine periods of equivalent source conditions over the four-hour measurement period, in what will be called "traffic classes." Unfortunately, the video data was not collected at the BA-3 Briley Parkway site. An alternative method of determining period equivalency – based on the reference microphone sound levels and the average speeds by direction of travel – was found that worked very well and was adopted for the rest of the study.

In Technical Memorandum No. 2 prepared for the study, the researchers used FHWA TNM 2.5 sensitivity testing to establish maximum allowable changes in volume, mix and speed before one measurement period is judged not equivalent to other periods. Given the small sound level changes due to reflections that are being considered in this study, the maximum allowable change due to a source variable was initially established to be 0.5 dB, unless this change proved to be too restrictive when classifying the data, which turned out to be the case with I-24 because of variations in total traffic and heavy truck volumes. However, when the source equivalence determination was shifted to working directly with the measured reference microphone data, the maximum allowable change was able to be reduced to 0.3 dB or less across all of the locations.

The wind data were processed to determine a vector wind speed (component of wind speed perpendicular to the road) and corresponding wind class (Upwind, Calm, or Downwind) for each period. The temperature data was also processed to determine the corresponding temperature gradient class (Lapse, Neutral, or Inversion) for each period. These data were merged with the source data and sorted to determine the combined equivalent source and meteorological data period repetitions.

Equipment and Sound Level Descriptors

A standardized data collection equipment package was used at all of the sites, consisting of:

- Six Type I sound level analyzers with 1/3 octave band measurement capabilities with data loggers and audio recorders;
- Meteorological data collection station with precision temperature sensors and precision quality anemometers capable of measuring wind speed in three dimensions at two heights (5 ft and 15 ft) above the ground;
- Video camera and laser speed gun; and
- Accessories including a 94-dBZ calibrator, extension cables, windscreens, microphone tripods and stands, extension poles and guy wires.

Depending on site characteristics and goals at any of the measurement locations, the community microphones could be located at two different distances from the road or at two different heights at the same distance.

Regarding the naming of the microphones, when two microphones were at different heights at the same distance, at the Barrier site, the lower microphone was named BarCom03 and the upper one BarCom04. At the No Barrier site, NoBarCom05 was the lower microphone and NoBarCom06 was the upper microphone. The reference microphones on the barrier side of the road were named BarRef01 and NoBarRef02.

Measurements were made in terms of the equivalent sound level, L_{eq}, for the broadband (overall) A-weighted sound level and unweighted sound pressure level and individual one-third octave band sound pressure levels. Statistical exceedance descriptors, specifically L_1, L_5, L_{10}, L_{33}, L_{50}, L_{90} and L_{99}, were computed for the 5-minute periods based on the 1-second data. These "L_n" descriptors were used in determining the sound level range in a sample period and in diagnosing data on individual passbys and the possible sustaining of the background level due to sound reflections off the barrier.

Meteorological Data

At each location, the meteorological station was set up in an open area near the No Barrier site. The wind data were used to determine a vector wind speed in the direction from the roadway to the microphones in order to be able to determine the appropriate wind class for the measurements (i.e., upwind, calm, and downwind). Temperature data were used to determine the appropriate gradient class for the measurements (i.e., inversion, neutral, and lapse). Cloud cover class was determined by the person responsible for the meteorological station as a back-up for the temperature gradient data.

Measurement Procedures

Prior to going into the field, the measurements were planned in detail using the field review report as a guide. All needed equipment, accessories, batteries, data sheets, radios and tools were inventoried and checked out. Analyzer data collection settings were confirmed on each analyzer and the audio output from the analyzers to the data loggers was tested. Clock times were synchronized across all analyzers, the meteorological station, the video camera, the speed gun, and team members' watches.

On the measurement day, the team set up and calibrated the sound level analyzers and deployed the microphones via extension cables on tripods or guyed towers. In addition to calibration, the electronic noise floor of the entire acoustic instrumentation system was established. The initial calibration tone and final calibration check tones were recorded as .wav files for use in the data analysis. The meteorological station (oriented to the north) and the traffic video camera and speed gun were also set up, and the team filled out field data sheets and took site photographs.

Approximately four hours of simultaneous data were then collected at all of the microphones. One-second broadband A-weighted levels and unweighted sound pressure levels and 1/3-octave band unweighted sound pressure levels between 12.5 Hz and 20,000 Hz were saved, and were later processed into 1-minute intervals. The audio signal was also recorded. Analysis of the initial data led to a decision to only present data in the 20 Hz to 10 kHz bands to eliminate the distraction of data irrelevant to the study and undue influence on the broadband unweighted sound pressure levels and A-weighted sound levels. These broadband levels were recomputed after the very low and high bands were deleted. The meteorological data were saved as one-second wind speed and direction and temperature for later processing into one-minute averages, time-synched to the sound level data.

Each noise measurement person kept field logs of events, with the time of occurrence of vehicles of interest (typically heavy trucks) and any unrepresentative sounds or events that might affect the one-minute measurements. These latter events were studied for possible elimination of the 1-minute data intervals from the analysis. A team member also made informal observations of wind speed and direction and cloud cover every 15 minutes as a back-up check for the meteorological station's data.

Loss of the traffic video at the Briley location prevented the subsequent counting of traffic. As noted above, an alternative approach to determining source equivalence between periods was adopted, relying on the A-weighted L_{eq} at the Barrier Reference site at Briley and the speeds being in a 5-mph range. The NoBarRef02 levels were used at the other locations to help determine source equivalence to avoid possible influences of truck body reflections at the Barrier site.

Samples of vehicles speeds were stored in a file in the laser gun and were also recorded manually on data sheets to identify the vehicle type (and linked back to the file by an ID number). Speeds varied by lane, as expected. For consistency, for roads with more than two lanes in each direction – the condition at both locations – the majority of speeds were measured in the second lane from the outside. Additionally, samples of speeds were made in the other lanes to the extent possible. It was attempted to shoot all speeds at the same angle. However, since these angles varied during the course of the measurement, it was necessary to adjust the speeds afterwards. In addition to speed, the laser gun reports the range in feet to the vehicle when the speed was sampled. By using the gun to also measure and record the offset distances from the gun to the point in each lane where the vehicles pass closest to the gun (perpendicular to the road), these distances and each speed shot's range were used to compute angles and corresponding speed adjustments for each speed sample during data processing.

At the end of the measurements, the calibration was checked for sound level analyzers, with the audio of the calibration tone recorded.

All of the data were then downloaded onto personal computers, with a common file-naming convention for all of the files. For the sound level data, there was one file per sound level analyzer per day, including calibration tones and any annotation notes. The meteorological data were stored in one file per sensor height. The audio files were extremely large, yet each contained only approximately eleven minutes of audio, meaning the download took considerable time. When two microphones were at the same site (e.g., BarCom03/BarCom04 or NoBarCom05/NoBarCom06), there was only one audio file with each microphone's audio being on its own track in the file.

The traffic video recording files were transferred from the camera's SD card to a computer. Vehicle classification counts (automobiles, medium trucks, heavy trucks, buses and motorcycles) were made in 1-minute intervals that matched the sound level measurement intervals. The counts were then entered into a traffic spreadsheet. When the traffic camera was not right at the microphone sites, there was a time difference between when a vehicle was counted and when it passed the microphones. This difference resulted in the time periods for the counts being adjusted upward or downward by as much as a minute to give a better representation of the counts near the microphones during any given minute. These adjustments were useful in determining the equivalence of traffic in the different 5-minute sample periods.

The speed files from the laser gun's SD card were transferred to a computer and renamed. The speed data were entered into the speed spreadsheet by ID number and vehicle type. The speeds were adjusted to account for the angle of speed shooting off of head-on, using the distance range recorded by the gun for each sample. When the speed site was not at the microphone sites, there was a time difference between when a vehicle passed the microphones and when its speed was sampled. In such cases, the speed samples were time-adjusted forward or backward to represent the time of passage of a point midway between the Barrier and No Barrier sites.

Photographs were downloaded and renamed. All field data sheets were scanned and assembled into one or more PDF files.

FHWA Method Data Processing

Data processing involved three major steps: creation of data spreadsheets, elimination of time periods with unrepresentative events that affected the measured sound levels, and identification of equivalent time periods in terms of meteorological class and traffic parameters.

First, the sound level and meteorological data were processed into a single standardized spreadsheet format for both the "raw" 1-second data and 1-minute interval (or "period") data averaged from the 1-second data. There was one spreadsheet of the 1-second data for each measurement location with worksheets for each microphone position (BarRef01, NoBarRef02, BarCom03, BarCom04, NoBarCom05 and NoBarCom06). There was also one spreadsheet of the 1-minute data for each measurement location with worksheets for each microphone position and the meteorological data.

Each worksheet used one row per each second or minute of data. The sound level data included the A-weighted sound level and unweighted sound pressure level plus the 1/3 octave band sound pressure levels. The meteorological data included the average wind speed, wind direction, temperature, and relative humidity at each sensor (high and low heights of 15 ft and 5 ft). The vector component of the average wind velocity in a perpendicular line from the highway to the reference microphone was computed for each period, as well as the temperature gradient.

Each period was classified by wind class based on Table 2 (which is Table 3 from *Measurement of Highway-Related Noise*), using a class called *Invalid-wind* for periods outside the wind limits.

Table 2. Classes of wind conditions.

Wind Class	Vector Component of Wind Velocity, m/s
Upwind	-1 to -5 (-2.2 to -11 mph)
Calm	-1 to +1 (-2.2 to +2.2 mph)
Downwind	+1 to +5 (+2.2 to +11 mph)

Each period was also classified by temperature gradient class, per Table 3. These classes are based on data collected by ATS from the Arizona Transportation Research Project (Ref. 2) several years ago. The Neutral conditions are based on the graphs presented in that report.

Then, based on the wind class and temperature gradient class, each 1-minute period of sound level data was put into one of ten meteorological classes (Upwind Lapse, Calm Lapse, Downwind Lapse, Upwind Neutral, Calm Neutral, Downwind Neutral, Upwind Inversion, Calm Inversion, Downwind Inversion and *Invalid-wind* (for vector components over +/- 11 mph)).

Table 3. Classes of temperature gradients.

Temperature Gradient Class	Gradient= (Temp_upper – Temp_lower) divided by Vertical distance between sensors
Inversion	positive > 0.1
Neutral	-0.1 to 0.1
Lapse	negative < -0.1

Based on the field notes, the data were screened for any potentially bad or unrepresentative events at each microphone position (e.g., loud non-traffic noises, periods of stopped traffic flow, etc.). As needed, the 1-second data and 1-minute averaged data were reviewed to see if the events affected the levels.

The next step was to determine 5-minute periods that were equivalent to each other for inclusion in a measurement repetition "group." First, 5-minute running averages of the vector wind component were computed for each minute of the 4-hour block (excluding those 5-minute periods that had one or more bad 1-minute periods). "Five-minute running averages" means that each consecutive minute is the starting minute of a 5-minute period including its data and the data in the next four minutes. For example, 12:01-12:06, 12:02-12:07, and 12:03-12:08 would be three consecutive running 5-minute periods. The use of 5-

minute running averages gives more flexibility when trying to determine periods that have equivalent sources and meteorological conditions.

Each 5-minute period was assigned to a meteorological class, based on a requirement that at least three of the five minutes be in the same class. All of the 5-minute periods in the same meteorological class that were not overlapping in time with each other were then tested for traffic equivalence. An example of overlapping periods would be 13:45 to 13:50 and 13:47 to 13:52, whereas 13:45 to 13:50 and 13:50 to 13:55 would be non-overlapping.

Next traffic equivalence was determined. Initially, plans were to use the, 5-minute running classification counts for the five vehicle types were derived from the 1-minute traffic counts starting with each minute in the 4-hour measurement block. Five-minute running average speeds were also computed starting with each minute. The average speeds were computed for four conditions: (1) all vehicles in the second westbound lane; (2) all vehicles in the second eastbound lane; (3) the average speed of all westbound vehicles sampled in all lanes; and (4) the average speed in each direction of all eastbound vehicles sampled in all lanes.

Based on sensitivity tests with the FHWA Traffic Noise Model (TNM), Version 2.5, the following criteria were established for determining if two or more 5-minute periods were in the same a traffic class.

- **Traffic volume**: A change in volume of 10% or less for heavy trucks in each direction and total volume in each direction. After finding very few periods that were equivalent, this criterion was relaxed to 15%. (A change in volume of 10 percent or less should result in no more than a 0.4 dB change in the L_{eq}(1h).)
- **Traffic speed**: The average speeds had to fall within 5 mph of each other for each averaging condition (by second lane by direction and all lanes by direction). (Generally the change in speed to keep the change in the L_{eq}(1h) below 0.5 dB is only 1 mph to 2 mph for autos and 2 mph to 3 mph for heavy trucks. However, speed variations from lane-to-lane in any given 5-minute period can easily be greater than these ranges. Because of the error involved with not measuring every vehicle in every lane, the 5 mph criterion was adopted, understanding that there can be a sound level change greater than 0.5 dB between the periods being compared.)

The above protocol was used for the first location, I-24. However, for the second location – Briley Parkway – because there were no traffic counts, the traffic equivalency of the 5-minute periods was determined based on the BarRef01 L_{eq}(5min) and the 5-minute running average speeds.

For L_{eq}(5min), an allowable range of 0.2 dB between periods was first considered, which worked well for the Calm Inversion periods. For the Calm Lapse and Calm Neutral periods, this allowable range was expanded to 0.3 dB.

This alternative was then tested on the I-24 data and found to be an acceptable procedure to use for all of the locations, using the levels at the No Barrier reference microphone (NoBarRef02).

FHWA Method Data Analysis Protocol

After the equivalent 5-minute periods were determined for the different meteorological classes and traffic conditions, each grouping of non-overlapping equivalent periods was used to compute the sound level increases between the Barrier and No Barrier microphones, as described in the next section.

The data analysis procedure in *Measurement of Highway-Related Noise* was used, with some adjustment. The first step was to determine any needed calibration adjustments prior to data analysis. What was proposed in Technical Memorandum No. 2 is an improvement to the method in Section 3.1.4 of *Measurement of Highway-Related Noise*. Instead of simply averaging the differences in the initial and final calibration levels to adjust the levels, a linear change in the sound level was assumed between the initial and final calibrations. An adjustment was computed for each minute in the 4-hour measurement block and applied to the A-weighted sound level and unweighted sound pressure levels in that minute.

Thus, if the final calibration level for a particular microphone was 0.3 dB lower than the initial calibration level, an adjustment for each minute was computed as -0.3 dB x (1 minute / 240 minutes) x (the number of minutes from the starting time). All of the final calibration levels at all of the microphones at both the I-24 and Briley locations were within -0.3 dB to 0.0 dB of the initial calibration levels.

The procedure in Section 6.6.3 of *Measurement of Highway-Related Noise* was adapted for levels measured opposite the noise barrier rather than behind the barrier, and for analysis in 1/3 octave bands. The basic equation when reference levels have been measured at the Barrier and No Barrier sites and are being used to adjust the levels at the community microphones for source equivalency is:

$$SLI_{i,j} = [L_{NoBarRef(j)} - L_{NoBarCom(i,j)} - (L_{BarRef(j)} - L_{BarCom(i,j)})] \text{ in dB}$$

where:

$SLI_{i,j}$ is the sound level *increase* (or sound pressure level *increase*) at the Barrier site for the i^{th} community receiver in the j^{th} 1/3 octave band, where i=03, 04, 05 or 06);
$L_{NoBarRef(j)}$ and $L_{BarRef(j)}$ are, respectively, the No Barrier and Barrier reference levels (adjusted as needed for calibration shift) in the j^{th} 1/3 octave band; and
$L_{NoBarCom(i,j)}$ and $L_{BarCom(i,j)}$ are, respectively, the No Barrier and Barrier community microphone levels (adjusted as needed for calibration shift) at the i^{th} community receiver in the j^{th} 1/3 octave band.

For example:

$L_{NoBarRef(j)}$ = 70.2 dBA
$L_{NoBarCom(i,j)}$ at community microphone 05 = 69.5 dBA
$L_{BarRef(j)}$ = 71.1 dBA
$L_{BarCom(i,j)}$ at community microphone 03 = 71.4 dBA

Therefore:

$$SLI_{03,j} = (70.2 – 69.5) - (71.1 -71.4) = 0.7 - (-0.3) = 1.0 \text{ dB}$$

For the I-24 and SR-71 locations, the BarRef01 and NoBarRef02 microphones were located in between the barrier and the road as their own test for reflection sound level increases. Thus, it would not be valid to adjust the Com microphone levels by the differences in the reference microphone levels. This set-up simplified the sound level increase calculations to three comparisons:

$$SLI_{01,j} = L_{BarRef01(j)} - L_{NoBarRef02(j)} \text{ in dB}$$
$$SLI_{03,j} = L_{BarCom03(j)} - L_{NoBarCom05(j)} \text{ in dB}$$
$$SLI_{04,j} = L_{BarCom04(j)} - L_{NoBarCom06(j)} \text{ in dB}$$

For the Briley location, the NoBarRef02 position was not measured, simplifying the sound level increase calculations to two comparisons:

$$SLI_{03,j} = L_{BarCom03(j)} - L_{NoBarCom05(j)} \text{ in dB}$$
$$SLI_{04,j} = L_{BarCom04(j)} - L_{NoBarCom06(j)} \text{ in dB}$$

For the I-90 and MD-5 locations, the barrier was very close to the road. It was felt that the BarRef01 levels could be elevated by reflected noise between the wall's surface and the vehicle sides, especially heavy truck trailers. Therefore, any adjustment to the community microphones' levels for differences between the BarRef01 and NoBarRef02 levels would be incorrect. Thus, the sound level increase calculations for these two locations also used the equations used for I-24 and SR-71.

These equations were applied to the different groups of equivalent 5-minute periods. The mean A-weighted sound level increase and unweighted sound pressure level increases for each 1/3 octave band were computed for each group by arithmetically averaging the differences from the individual 5-minute periods. A standard deviation was computed for each sound level increase and the results were plotted.

The average differences by frequency band were then computed for all equivalent 5-minute periods that were analyzed within a meteorological class occurring at each location. Differences of these averages differences were also computed to allow study of the possible effect of meteorological class on the results. After study of the average differences for each equivalent group for each meteorological class, it was decided that the average differences by meteorological class represented the individual groupings' difference quite well. Thus, these latter average differences by meteorological class are presented in this appendix. All of the graphs and tables of the average differences by the groups of equivalent 5-minute periods are in the spreadsheets in the project record.

Additionally, the differences results were examined to see if the differences were related to the total two-way volume in the 5-minute periods.

Spectrogram Data Processing and Analysis Protocol

A spectrogram analysis allows an examination of spectral (frequency) content over time, whether it is a specified time block (e.g., 5 minutes) or a vehicle pass-by event.

The research team screened the master raw data spreadsheet files from the measured sound level data files and identified bad or invalid data periods. Clean data blocks were identified for the spectrogram analysis; the length of these data blocks varies among the sites, based on the frequency of intrusive noise events and also whether or not it was desirable to examine the same 5-minute data blocks as were examined with the standard analysis. Example data blocks for each site are shown in this report.

In addition, vehicle pass-by events were identified for investigation. The vehicle pass-by events were first identified using the site logs, where potential isolated events were noted. Multiple events were examined for each site and only ones that could be clearly identified at both the Barrier and No Barrier sites were retained. Example vehicle pass-by events for each site are shown in this report.

The audio .wav files were processed and examined in 1/3 octave bands in 1/8-second intervals. The data were then displayed using spectrogram-type graphs. In-house MATLAB code allows for the spectrogram processing and the flexibility to compare selected time blocks of data among different microphones at each site.

For the data blocks and vehicle pass-by events, pairs of microphones were compared, where each pair consisted of one microphone at the Barrier site and an equivalent microphone at the No Barrier site. For all sites, spectrogram data were examined for the community microphone pair BarCom03/NoBarCom05 and the community microphone pair BarCom04/NoBarCom06. The spectrograms for these two pairs show the effect of the barrier noise reflected back across the highway to communities opposite a noise barrier. At some of the sites, the reference microphones were strategically placed between the road and the barrier to capture barrier reflections on the barrier side of the highway. In these cases, microphones BarRef01 and NoBarRef02 were compared to show the effect of the barrier reflected noise close to the reflecting surface.

Upon examination of the spectrograms, spectral shapes and values were compared for the equivalent microphone pairs, and trends were noted. Where results were similar between microphone pairs, only one pair is presented.

Psychoacoustics Processing and Analysis Protocol

Basic Sound Quality Metrics

We define the basic, stationary metrics of sound quality, introduced in Ref. (3): Loudness, Sharpness, Roughness, and Fluctuation Strength. These metrics are computed over a frequency spectrum divided into so-called critical bands (z) whose widths are measured in “barks”. Spanning the frequency range of normal human hearing, these 24 bands are similar to 1/3-octave bands, but they vary in frequency width in a way more representative of the human hearing mechanism. Definitions of the three annoyance metrics used in this study follow; they generally depend on some combination of the fundamental metrics, weighted to fit regressions over reported annoyance from listening trials.

Loudness (N)

Loudness (N) is one of the defining metric for sound quality. Methods for determining the Loudness of a stationary signal are defined in Ref. (4). Loudness, measured in “phons”, is based on tables derived from empirical data with relatively flat spectra (no pure tones) and diffuse sound fields. Loudness levels, measured in “sones”, are computed for each octave band (Stevens Mark VI) or 1/3-octave band (Stevens Mark VII), from which a composite Loudness can then be derived from the following expression:

$$N = 0.7N_{i,\max} + 0.3\sum_i N_i$$

Zwicker Loudness is similar to the Stevens Mark VII method but also accounts for the masking of higher-frequency sound by stronger, lower-frequency sound. It can also accommodate complex sounds with broadband and/or pure tone components. It uses 1/3-octave bands and can account for frontal or diffuse sound fields. Zwicker Loudness has become the most commonly used metric for indicating sound quality.

Sharpness (S)

Sharpness is an indicator of “tone color”. It is derived from the spectral distribution of Loudness. Measured in “acums”, Sharpness is a weighted integral of specific Loudness over critical bands. The weighting emphasizes higher-frequency noise in the sound spectrum; a sound with more high-frequency content will sound “sharper” or more aggressive than another sound of similar overall Loudness but less high-frequency content. Sharpness has not been defined in an international standard; the expression most commonly implemented is due to Aures:

$$S = 0.11\frac{\int_0^{24} N'(z)g(z)z\,dz}{\log\left({}^{N}/_{20} + 1\right)}$$

where the weighting kernel *g(z)* is an exponential function that gently slopes upward with increasing frequency,

$$g(z) = e^{0.171z}$$

In these expressions, *z* represents the critical band (numbered 0 through 24), *N'* represents the specific Loudness in any one critical band, and *N* is the composite Loudness over all bands as described above. The constants in the expression are selected such that one acum is equivalent to a sound pressure level of 60 dB within the critical band centered at 1,000 Hz.

Roughness (R)

Roughness (R) is a measure of high-rate temporal modulation of a sound. Expressed in "aspers", it is an integral over the "modulation depth" of sound level (ΔL) in each critical band *z*, multiplied by the dominant modulation rate f_{mod} in that band. As with Sharpness, Roughness has not been defined in an international standard; (Zwicker & Fastl, 1990) (eq. 11.1) define it as:

$$R = 0.0003 f_{\mathrm{mod}} \int_0^{24} \Delta L(z) dz$$

where

$$\Delta L = 20\log\left[\frac{N_1{}'}{N_{99}{}'}\right]$$

is the "masking depth" as a function of critical band, and *N'* represents the specific Loudness in each critical band. The term $N_1{}'$ is the 99th percentile loudness (exceeded 1% of the time) and the term $N_{99}{}'$ is the first-percentile loudness (exceeded 99% of the time). This masking depth becomes larger for lower modulation frequency.

The constant in the expression is selected such that one asper is the Roughness generated by a 1,000 Hz tone of 60 dB modulated 100% at 70 Hz. Perceived Roughness is directly proportional to the modulation frequency. A perceived change in Roughness occur when the metric changes by more than about 17 percent.

Fluctuation Strength (FS)

Fluctuation Strength (FS), expressed in "vacils", is similar to Roughness as measure of temporal variation of sound. However, Fluctuation Strength reaches a maximum at modulation frequencies of about 4 Hz, much "slower" than the modulations attributed to Roughness. Like Roughness, Fluctuation Strength is computed over the "modulation depth" of sound level ΔL. It is computed as the logarithm of the ratio of the first-percentile Loudness to the 99th percentile Loudness. As with Sharpness and Roughness, Fluctuation Strength has not been defined in an international standard, but the typical implementation is:

$$FS = 0.032 \sum_0^{24} \frac{\Delta L(z) \Delta z}{\left[\frac{f_{\mathrm{mod}}}{4} + \frac{4}{f_{\mathrm{mod}}}\right]}$$

where

$$\Delta L = 20\log\left[\frac{N_1{}'}{N_{99}{}'}\right]$$

is the “masking depth”, and *N’* represents the specific Loudness in any one critical band. The term $N_1{}'$ is the 99th percentile loudness (exceeded 1% of the time) and the term $N_{99}{}'$ is the first-percentile loudness (exceeded 99% of the time). This masking depth becomes larger for lower modulation frequency.

The constants in the expression are selected such that one vacil is equivalent to a 1,000 Hz tone of 60 dB modulated 100% at 4 Hz.

Annoyance

Traditionally, annoyance scales are directly related to the physical properties of isolated noise. These physical properties are expressed as noise metrics or noise ratings. There are many noise ratings, for example, energy-based ratings such as equivalent-continuous A-weighted sound level $L_{AEQ(t)}$, Day-Night sound level L_{DN} (a weighted form of L_{AEQ} over 24 hours), A-weighted exposure level L_{AE}, or ratings directly related to the sound pressure level at a particular moment, such as L_A and L_{Amax}. The problem with these level-based metrics is that studies have shown weak correlation between them and reported annoyance.

Three measures of annoyance were applied to the audio data in this project:

- Unbiased Annoyance (UBA);
- Psychoacoustic Annoyance (PA); and
- Category Scale of Annoyance (CSA)

These metrics are based on combinations of the basic sound quality metrics outlined above. The combinations were created to fit and explain reported annoyance to various types of sound in human listening trials.

Ref. (1) defined noise annoyance as a multi-component concept, using several psychoacoustical variables. This definition was an effort to avoid variable noise sensitivity, and was named Unbiased Annoyance (UBA). In their original model, the value of UBA was calculated from 90th percentile Loudness N_{10}, mean Sharpness, and mean Fluctuation Strength, together with a day-night correction, as demonstrated in Ref. (5).

Unbiased Annoyance (UBA) is a function of:

- Loudness exceeded 10% of the time (N_{10}) in sones,
- Mean Sharpness (S) in acums, and
- Mean Fluctuation Strength (F) in vacils.

$$UBA = d\,(N_{10})^{1.3}\left[1 + (0.25S - 1)\log(N_{10} + 10) + 0.3\left(F\frac{1 + N_{10}}{N_{10} + 0.3}\right)\right]$$

In the second (1999) and third (2007) editions of Ref. (1), Zwicker and Fastl introduce a modified formula for the UBA, called Psychoacoustic Annoyance, (PA). It is formed from the root mean square of a Sharpness criterion and a combined Fluctuation Strength and Roughness criterion, each again weighted by 95th percentile Loudness (N_5).

Psychoacoustic Annoyance (PA) is a function of:

- Loudness exceeded 5% of the time (N_5) in sones,

- Mean Sharpness (S) in acums,
- Mean Fluctuation Strength (F) in vacils, and
- Mean Roughness (R) in aspers.

$$PA = N_5\left(\sqrt{\omega_S^2 + \omega_{FR}^2}\right)$$

where:

$$\omega_S = \begin{cases}(S - 1.75)0.25\log(N_5 + 10), & S > 1.75 \text{ acum} \\ 0, & S < 1.75 \text{ acum}\end{cases}$$

$$\omega_{FR} = \frac{2.18}{(N_5)^{0.4}}(0.4F + 0.6R)$$

There is a similarity between this expression and that of Unbiased Annoyance. In each case, an overall Loudness (figure of merit) is weighted with a combination of the sound's high-frequency content (Sharpness) and temporal variation (Fluctuation Strength and Roughness). Each of these, in turn, is weighted by the Loudness in a "slower-than-linear" way.

In Ref. (6), another multi-component metric for annoyance was introduced, called "Category Scale of Annoyance" (CSA). Their work was based on "neutralized" product sounds in an effort to explore subjective interpretation of a sound's affective meaning. As with the other metrics, CSA was based on a regression analysis of listener responses to a set of recorded sounds. (In this case, the sounds were altered electronically in order to reduce their "identifiability" by the listeners.) However, unlike UBA and PA, CSA is a simple linear regression of terms, and lacks a component due to Fluctuation Strength.

Category Scaling of Annoyance (CSA) is a function of

- Loudness exceeded 5% of the time (N_5) in sones,
- Sharpness exceeded 50% of the time (S_{50}) in acums, and
- Mean Roughness (R) in aspers.

$$CSA = 8.07 + 0.563N_5 + 3.022S_{50} + 2.175R$$

Processing of Audio Data for Annoyance Metrics

The analog audio signal from each microphone at a site was fed to a digital recorder, where it was sampled at 48 kHz with a 16-bit sample word size. These data were saved directly (without compression) in Windows Audio format (WAV). These data were used to calculate the basic sound quality metrics of Loudness, Sharpness, Roughness and Fluctuation Strength. Magnitudes of the WAV files were scaled using recordings of the 94 dB calibration tone at 1 kHz applied to each microphone prior to each monitoring period.

Sound quality processing software was developed by Nelson Acoustics, Inc. specifically for this project. The metrics were computed according to the equations listed above. Metrics were accumulated into 1-minute blocks (2.88 million samples per block), from which were extracted a mean value and five percentiles (99%, 90%, 50%, 10%, 1%). Note that the sound quality software did not directly compute the 95th percentile Loudness, $N_{5;}$ instead, the recordings were re-processed to 1-second blocks of Loudness (48,000 samples), from which the 95th percentile values for each one-minute interval were extracted using MS Excel. The one-minute interval metrics were exported to MS Excel spreadsheets for further processing.

For each one-minute interval, the resulting sound quality metrics were combined using the equations for Unbiased Annoyance, Psychoacoustic Annoyance, and Category Scale of Annoyance within MS Excel. The resulting time series were plotted in pairs: the low-height microphones (BarCom03 and NoBarCom05) and the raised-height microphones (BarCom04 and NoBarCom06). From these time series graphs, outliers could be identified as well as trends in the data over the duration of each monitoring period.

Further, simple descriptive statistical analyses were applied to each time series, in order to identify the centroid and distribution of each annoyance metric at each location. The accompanying histograms (distributions of annoyance metric magnitude over the monitoring duration) were plotted in paired bar graphs. These plots were used to explore whether or not a statistically meaningful difference could be found between the annoyance metrics computed in the presence and absence of the barrier, respectively.

CHAPTER B-3

Results - I-24, Murfreesboro, TN (Location BA-1)

The I-24 measurements were conducted from 13:13 to 17:20 on August 13, 2014 (all times will be based on a 24-hour clock). The weather was partly cloudy, with alternating periods of direct sun and clouds. Temperatures were in the upper-70° F range. Winds were calm to moderate, generally coming from the northeast through the northwest. The road runs in a northwest-to-southeast direction with the Com microphones on the northeast side of the road. Thus, most of the 1-minute measurement periods were in an Upwind or Calm wind class.

Six sound level analyzers were deployed at the BA-1 I-24 location, three each at the Barrier and No Barrier sites:

- A reference microphone located roughly midway between the barrier and the edge of the near travel lane (BarRef01), and at a similar offset and height at the No Barrier location (NoBarRef02). The initial plan was to locate the reference microphones five feet above the top of the noise barrier at the Barrier site and at the same distance and height above the roadway at the No Barrier site. However, because of the noise barrier set-back, this first location gave a good opportunity, to study a point that clearly ought to be influenced by reflected noise with less masking by the direct traffic noise than the microphones across the road.
- Two "community" microphones on the opposite side of the road from the barrier at the Barrier site (BarCom03 and BarCom04) and the No Barrier site (NoBarCom05 and NoBarCom06).

Figure 7 shows the microphone positions at the I-24 location. Appendix C of the Final Report includes site photographs. Figure 8 shows cross-sections at the Barrier and No Barrier sites. The cross-section at the No Barrier site was virtually identical, but without the barrier and with the ground behind NoBarRef02 staying at the same elevation rather than rising up like at BarRef01.

The microphone positions were as follows:

Table 4: Microphone positions at I-24 site

Mic Name	Side of Road	Distance from Center of Near Travel lane (ft)	Height above Roadway Plane (ft)
BarRef01	EB	51*	10 (16 ft above ground, near midpoint of barrier)
NoBarRef02	EB	51*	10 (16 ft above ground)
BarCom03	WB	84	5 (9 ft above ground)
BarCom04	WB	84	15 (19 ft above ground)
NoBarCom05	WB	84	5 (9 ft above ground)
NoBarCom06	WB	84	15 (19 ft above ground)

*96 feet to barrier

A concrete median barrier at both the Barrier and No Barrier sites shielded the view of the vehicle tires and automobile engines and exhausts at the 5-ft high BarCom03 and NoBarCom05 microphones. It could have also shielded the BarCom03 microphone from some of the reflected noise.

Figure 7. I-24 microphone positions. (Source: Google Earth.)

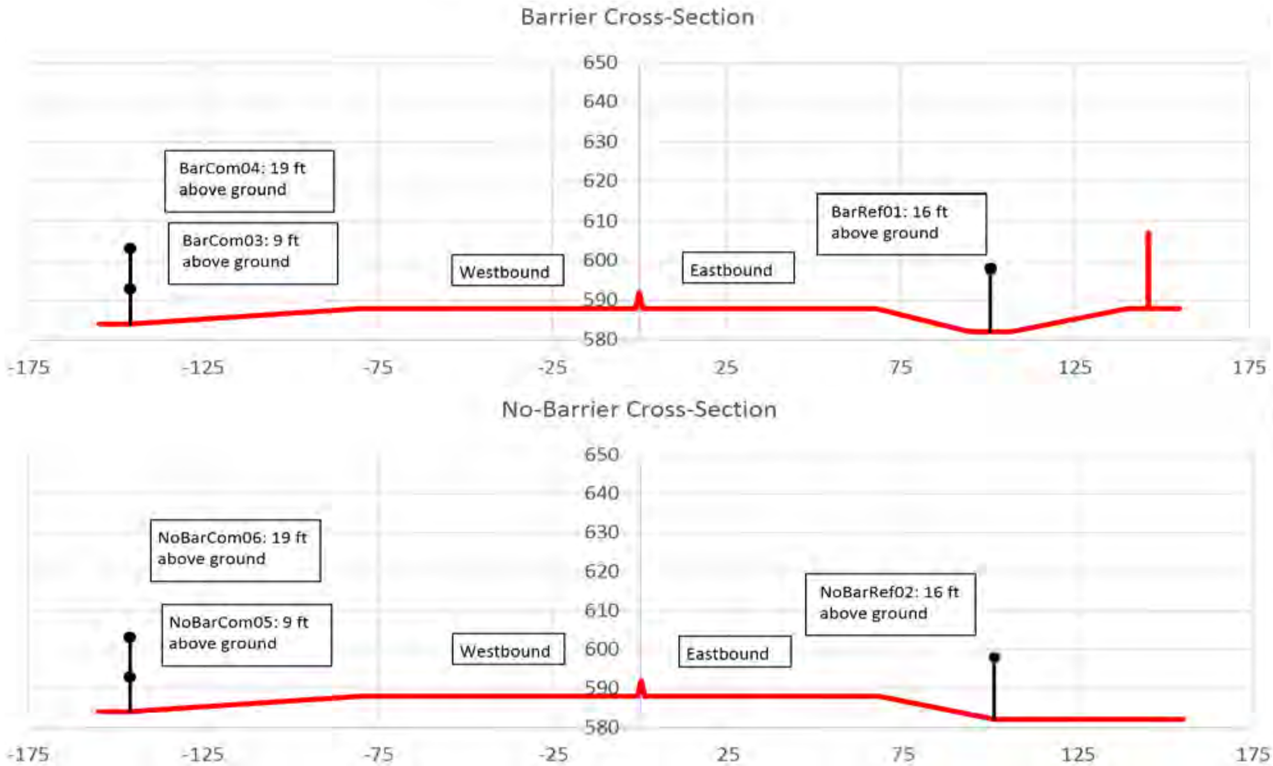


Figure 8. Cross-sections at the I-24 Barrier (top) site and No Barrier (bottom) sites.

Measurement Observations

As observed at the traffic count and speed site (in the center of an overpass about a mile southeast of the No Barrier site), initially, the traffic volumes appeared roughly equal in each direction. However, the eastbound lane volumes seemed to increase more as rush hour approached. Traffic was typically free-flowing and there were few brief lulls in traffic (mostly on westbound side). Some occasional platooning was observed. The inside lane in each direction was a high-occupancy vehicle (HOV); these lanes were the least occupied, and after 16:00 (the start time of HOV restriction for eastbound traffic), more vehicles were noticed using – and also exiting – the eastbound HOV lane. Heavy trucks tended to use the outer two lanes (this stretch of I-24 was signed to restrict trucks to the two right lanes). Towards the end of the measurement (just before 17:00), an atypical lull in traffic on the eastbound side was noted.

During the measurement period, speeds were generally easier to acquire for receding vehicles than oncoming vehicles, and motorcycles were the most difficult overall. Medium trucks, buses and motorcycles were infrequent and an attempt was made to acquire their speeds whenever present, regardless of their lane of travel. Automobiles and heavy trucks dominated the traffic flow, while medium trucks, buses and motorcycles were infrequent. Speeds typically ranged from 65-70 mph, with no difference by direction being noticed. Automobile speeds tended to be near 70 mph, while heavy truck speeds were usually slightly slower (around 65 mph). Inside lane speeds were generally higher than outside lane speeds.

At the NoBarRef02 site, Observer 1 noticed a police car stopped at the bridge abutment about halfway between the Barrier and No Barrier sites at 16:58, resulting in eastbound traffic slowly down from around 70 mph to 55 mph back by the Barrier site, while not slowing near the No Barrier site. At around 17:03, eastbound speeds picked back up to the 70 mph range. Observer 3 at the BarCom03/04 site also noted that eastbound traffic slowed in the 16:55-17:01 period. At the No Barrier site, Observer 2 noticed that the eastbound traffic appeared to be slowing around 15:46 for a minute, again briefly at 15:50, and again briefly at 16:24.

Observer 1 at BarRef01 moved to NoBarRef02 halfway through the measurement. He noted that the sounds at Bar Ref Mic 1 and NoBar Ref Mic 2 seemed very similar; however, the ground at his position was six feet below the roadway elevation, which would not put him in a good position to hear reflected sound. The main source at both sites was I-24 traffic; little else was audible.

Observer 2 was at the BarCom03/04 site for the first half of the measurement and noted that the noise was dominated by the near-lane (westbound) traffic, particularly heavy trucks. The ground at the observer was about 4 ft below the road surface. Eastbound heavy trucks were audible when there were no westbound trucks, but even a stream of westbound automobiles could mask some eastbound heavy truck noise. During moments of lulls in westbound traffic, eastbound automobile noise could barely be heard, largely because of the shielding provided by the median barrier at the observer's elevation. While not able to be proven, it is considered likely that eastbound automobile noise was more audible at BarCom04 at a height of 15 ft above the road than at NoBarCom05, 5 ft above the road surface.

Observer 2 also noted that a good deal of tire noise could be heard from receding westbound vehicles at the BarCom03/04 site well after they passed the site when there were no other westbound vehicles passing by the site at the time. This phenomenon seemed even more noticeable when Observer 2 moved to the NoBarCom05/06 site halfway through the measurement. The receding vehicle noise seemed to have a higher-frequency nature compared to the immediate passby.

Upon moving to NoBarCom05/06, Observer 2 felt that the sound at the BarCom03/04 site seemed a bit "brighter" in terms of the higher frequencies than at the NoBarCom05/06 site, despite noting that there was some high frequency insect noise coming from the wooded area behind the microphones at the ROW line at the NoBarCom05/06 site.

Observer 3 was at the NoBarCom05/06 site for the first half of the measurement, switching to the BarCom03/04 site for the second half. At the NoBarCom05/06 site, he felt, in comparison to the BarCom03/04 site, that the overall sound of the traffic noise was spread across a broader spectrum. This site sounded "wide open" and louder. Insects in the foliage along the ROW fence near the NoBarCom05/06 site became audible in the higher frequencies (8,000 Hz 1/3-octave band) around 14:30 although they did not affect the overall level, which was dominated by the I-24 traffic noise. He also felt that vehicles were audible longer at this site than at the Bar Mics 3-4 site.

At the BarCom03/04 site, Observer 3 subjectively described the traffic noise character as more "confined and softer" than at the NoBarCom05/06 site, in contrast to Observer 2's observation. Observer 3 did not feel that he was hearing as much tire/pavement noise at the BarCom03/04 site. The far-side eastbound heavy trucks were typically identifiable without visual observation. Eastbound auto traffic was generally heard but unless specific autos were loud they were difficult to identify. Generally, all westbound vehicles were easily identifiable by their sound. He also observed at the BarCom03/04 site that: eastbound heavy trucks were typically identifiable without visual observation; eastbound automobile traffic was generally heard but unless specific automobiles were loud they were difficult to identify; and, generally, all westbound vehicles were easily identifiable by their sound.

Measured Broadband Levels and Level Differences for I-24

The running L_{eq}(5min) for each site are presented in the following figures to give an overall picture of the measured levels, both in terms of unweighted sound pressure levels and A-weighted sound levels:

- BarRef01 and NoBarRef02 - Figure 9 (unweighted) and Figure 10(A-weighted); then Figure 11 shows the differences in the unweighted and A-weighted levels for this mic pair;
- BarCom03 and NoBarCom05 - Figure 12 (unweighted) and Figure 13 (A-weighted); then Figure 14 shows the differences in the unweighted and A-weighted levels for this mic pair; and
- BarCom04 and NoBarCom06 - Figure 15 (unweighted) and Figure 16 (A-weighted); then Figure 17 shows the differences in the unweighted and A-weighted levels for this mic pair.

The following observations are prior to any attempt to group data into equivalent periods. In general, both the unweighted sound pressure levels and A-weighted sound levels are higher at the Barrier microphones than at the No Barrier microphones.

For virtually all of the running 5-minute L_{eq} periods, the BarRef01 levels, both unweighted and A-weighted, are higher than the NoBarRef02 levels by a range of 0.5 to 1.5 dB. These higher levels were expected because the BarRef01 microphone was located halfway between the barrier and I-24.

For a large majority of the running 5-minute L_{eq} periods, the BarCom03 levels, both unweighted and A-weighted, are higher than the NoBarCom05 levels by a range of 0.0 to 1.0 dB, with some differences as much as 1.5 dB.

For most of the running 5-minute L_{eq} periods, the BarCom04 levels, both unweighted and A-weighted, are higher than the NoBarCom06 levels by a range of 0.0 to 0.5 dB, with some differences as much as 1.0 dB. For the other periods, the A-weighted levels at NoBarCom06 are 0 dB to 0.5 dB higher than the BarCom04 levels.

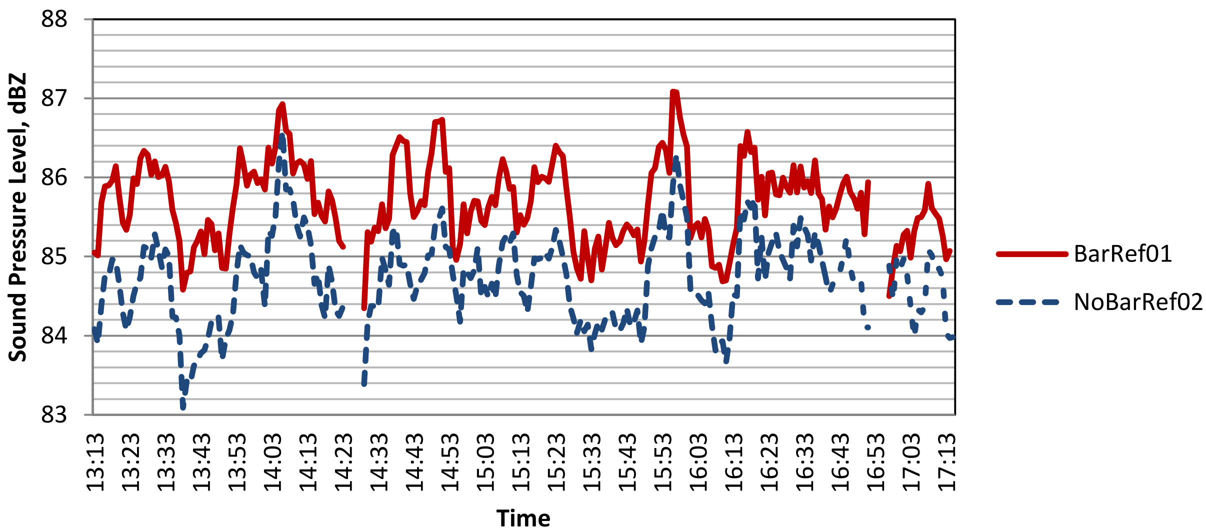


Figure 9. Running L_{eq}(5min), I-24, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

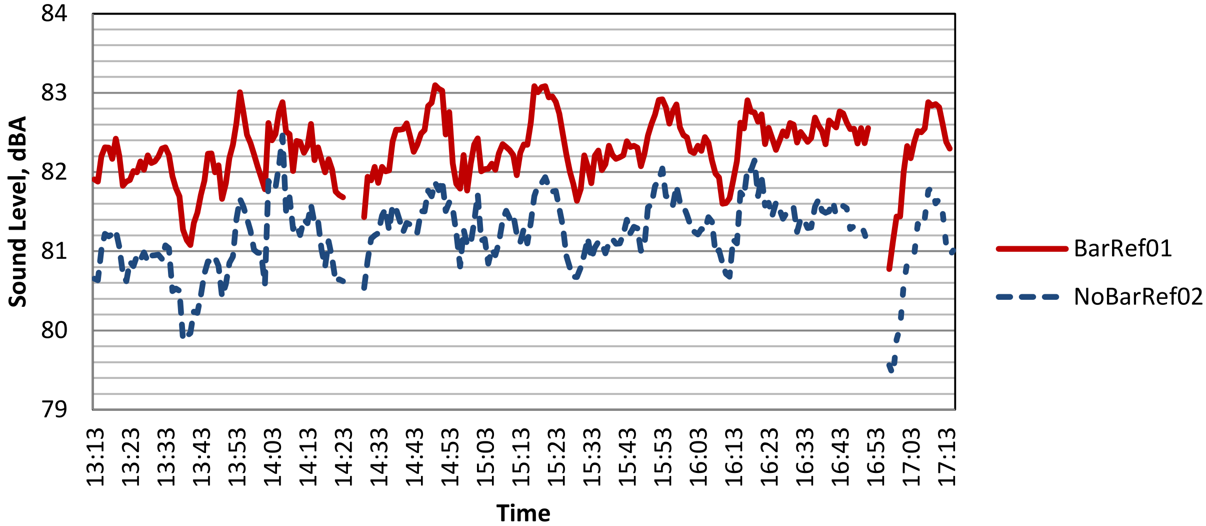


Figure 10. Running L_{eq}(5min), I-24, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

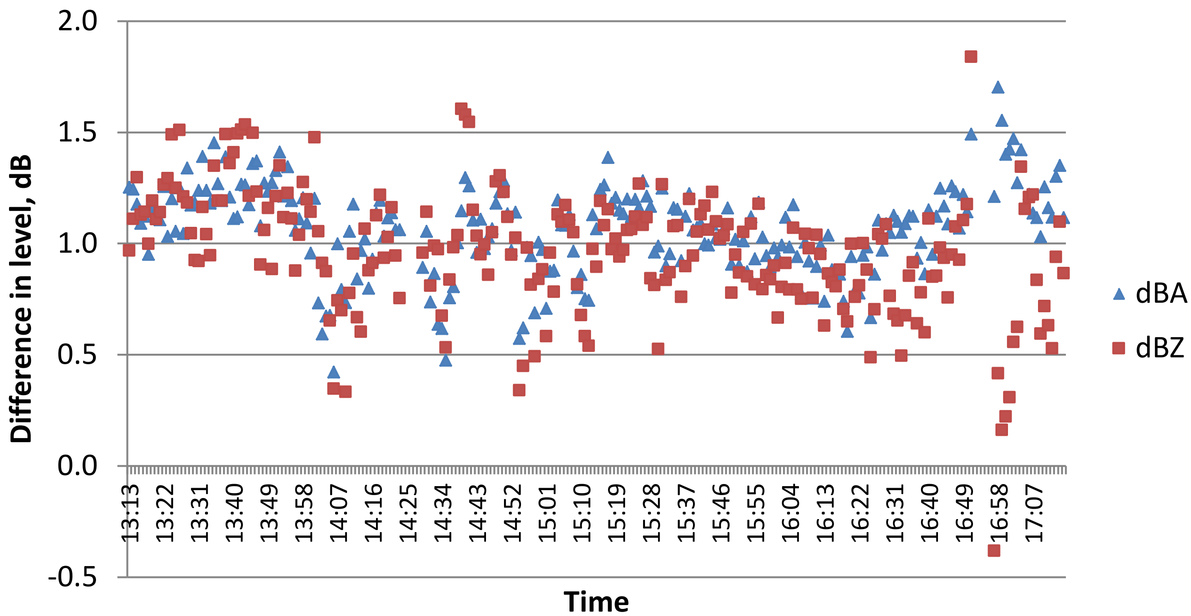


Figure 11. Differences in running L_{eq}(5min), I-24, BarRef01 minus NoBarRef02.

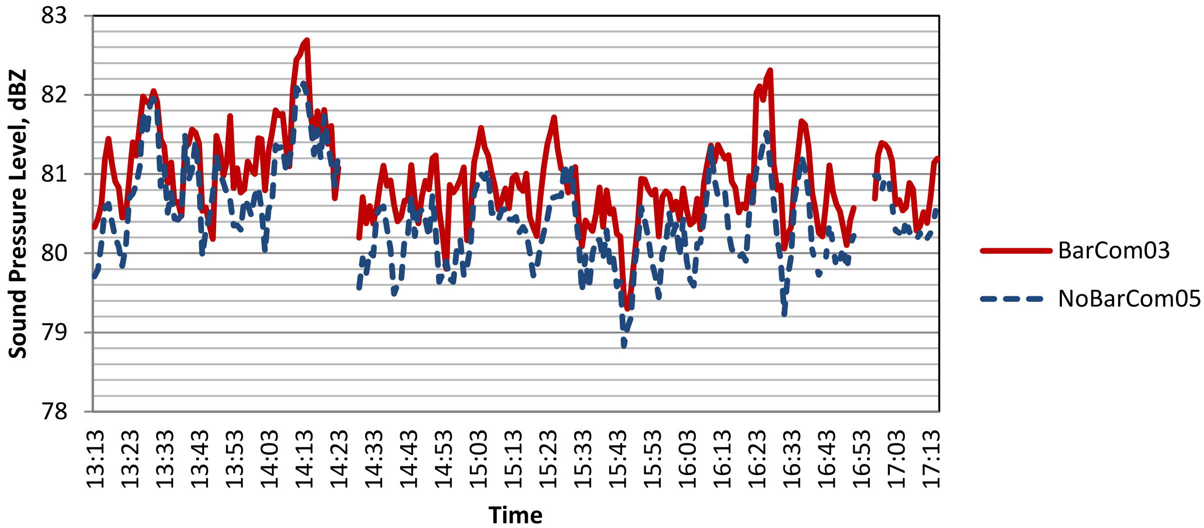


Figure 12. Running L_{eq}(5min), I-24, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

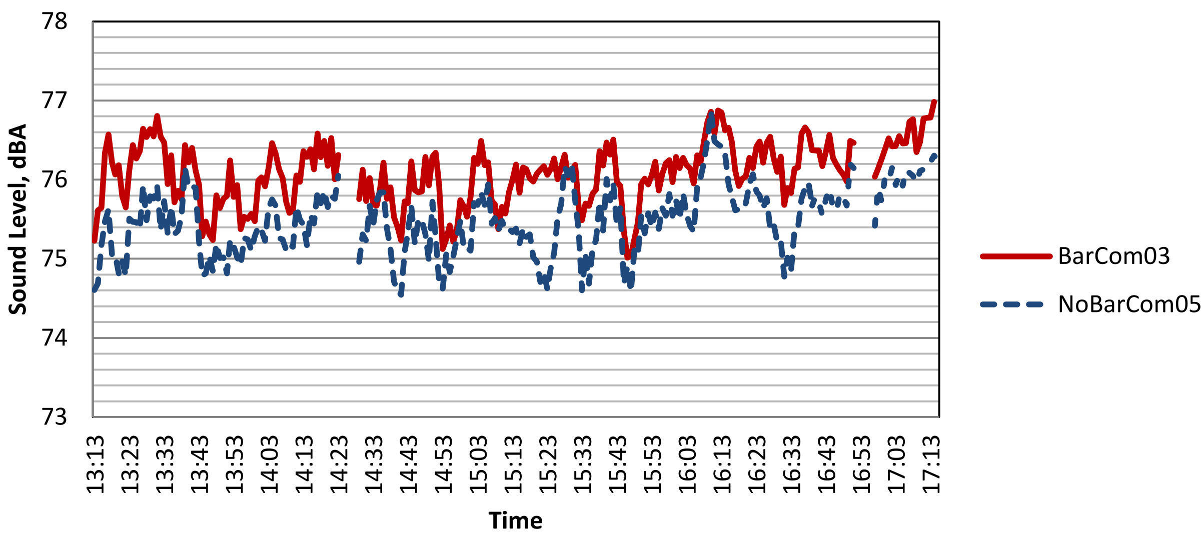


Figure 13. Running L_{eq}(5min), I-24, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

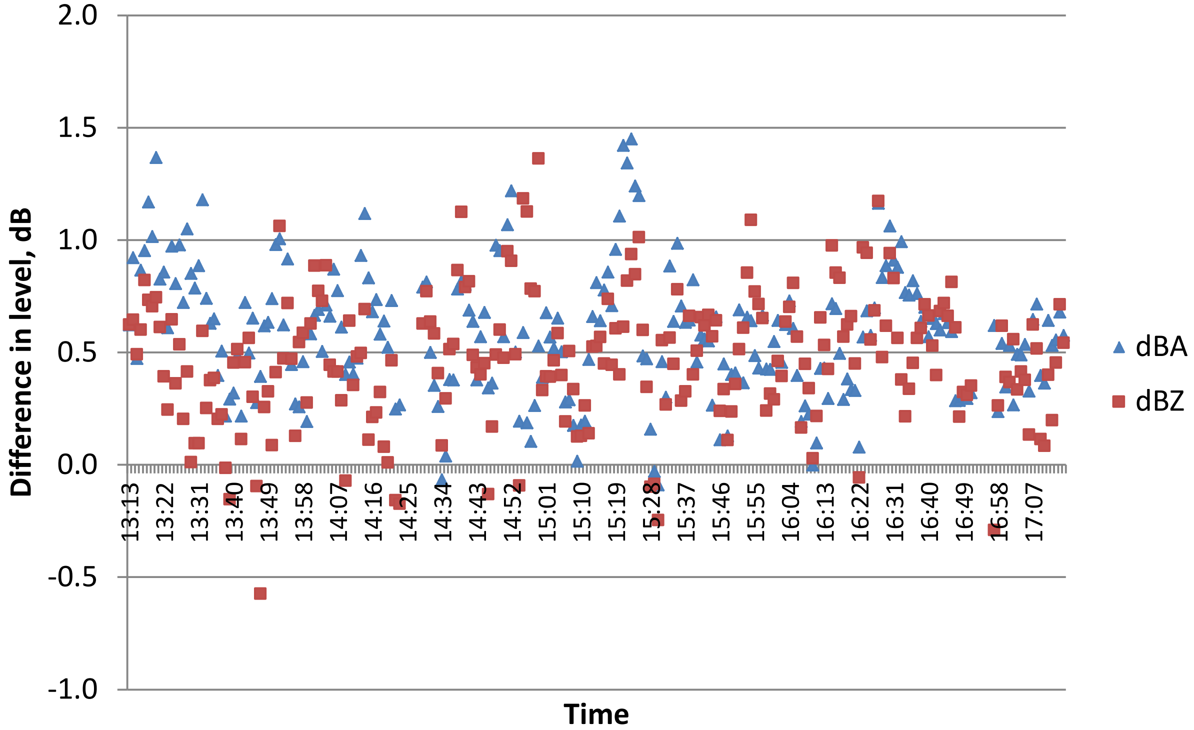


Figure 14. Differences in running L_{eq}(5min), I-24, BarCom03 minus NoBarCom05.

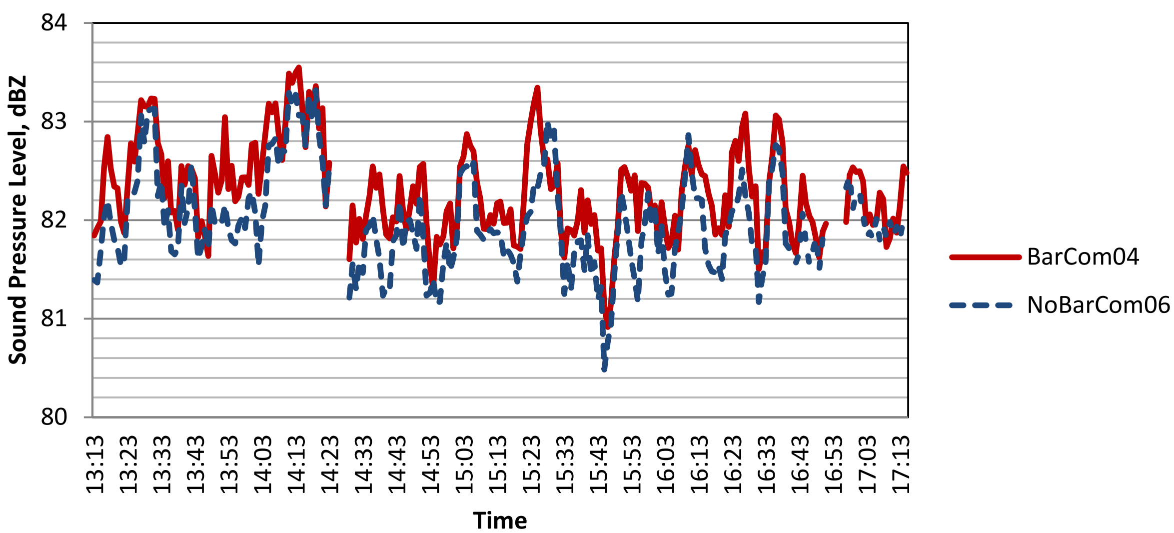


Figure 15. Running L_{eq}(5min), I-24, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

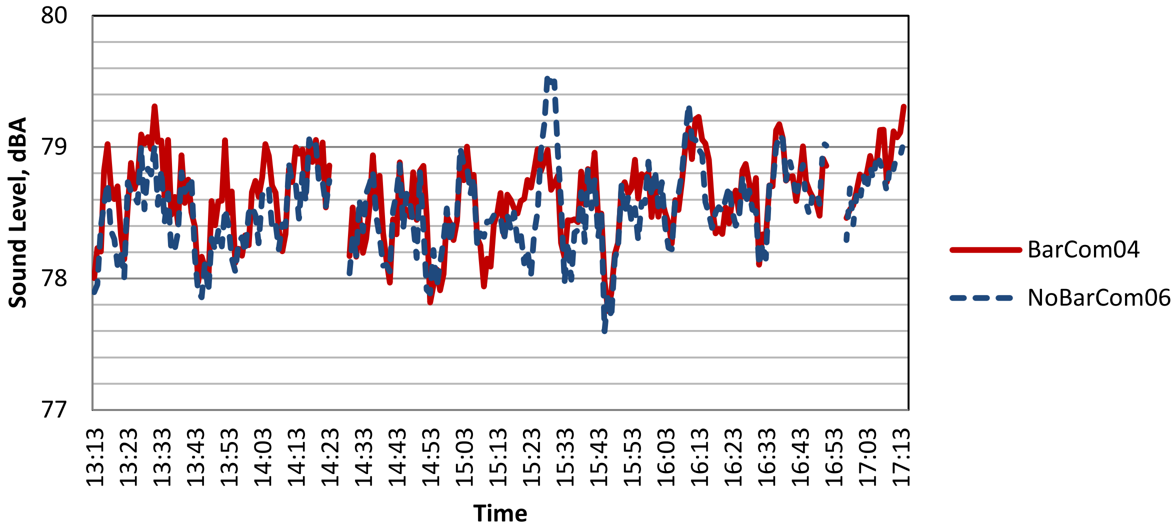


Figure 16. Running L_{eq}(5min), I-24, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

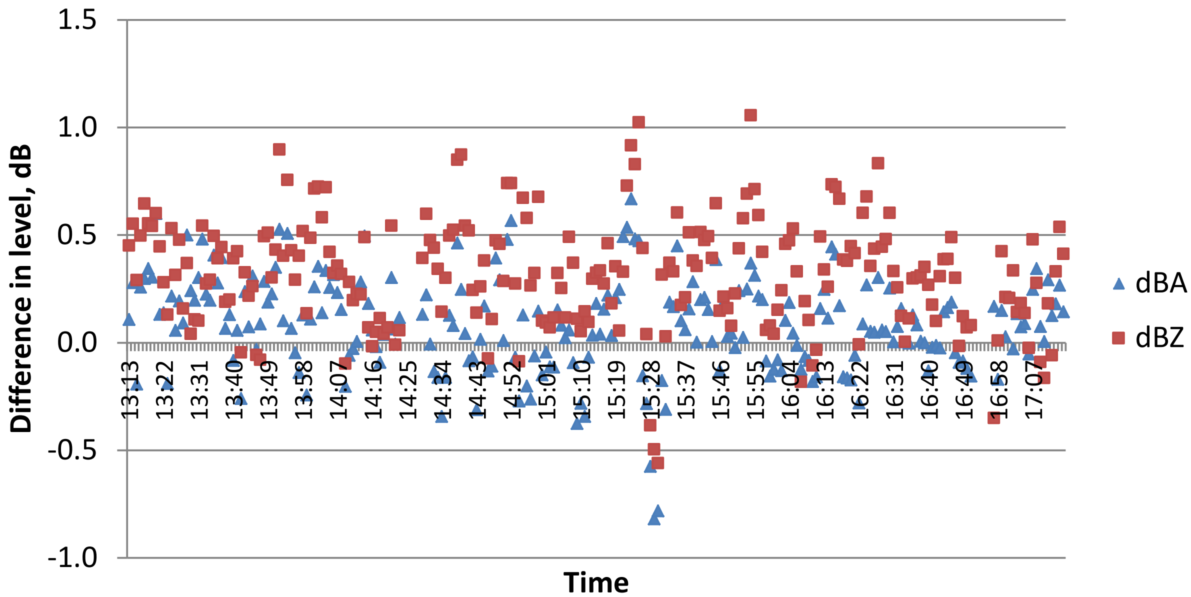


Figure 17. Differences in running L_{eq}(5min), I-24, BarCom04 minus NoBarCom06.

Data Analysis for I-24 - FHWA Method

Equivalent Groups

All of the groupings of 5-minute periods that were judged equivalent for traffic parameters at the I-24 location fell into three meteorological classes: Upwind Lapse, Calm Lapse, and Calm Neutral. There were 31 groupings in the Upwind Lapse class, each with three to six 5-minute equivalent periods; 13 groupings in the Calm Lapse class, each with three to six 5-minute equivalent periods; and four groupings in the Calm Neutral class, each with exactly three 5-minute equivalent periods.

Figure 18 shows these groupings graphically for the Upwind Lapse class. The times along the top represent the starting minute of each 5-minute period. Figure 19 and Figure 20 show the same for the Calm Lapse and Calm Neutral groups, respectively. Each group has a unique name, starting with "ULG-," "CLG-," or "CNG-". Note that while all of the 5-minute periods in a group are non-overlapping in time, the same 5-minute periods often appear in multiple equivalent groups.

These periods had varying traffic volumes, as show in Table 5, which ranks first the Upwind Lapse groups, then the Calm Lapse groups, and finally, the Calm Neutral groups by total two-way volume averaged across the periods in that group (i.e., Factored Hourly Volume, vph). For the Upwind Lapse class, the volumes of the highest group were roughly 21% greater than the volumes of the lowest group. For the Calm Lapse class, the highest group was approximately 13% greater than the lowest group. For the Calm Neutral Group, the highest group was approximately 6% higher than the lowest group. In terms of equivalent hourly volumes, the overall range was from 5,700 vph to 8,212 vph.

Speeds were much more consistent, ranging from averages of 67 mph to 72 mph for the Upwind Lapse groups, 68 mph to 72 mph for the Calm Lapse groups, and 69 mph to 71 mph for the Calm Neutral groups.

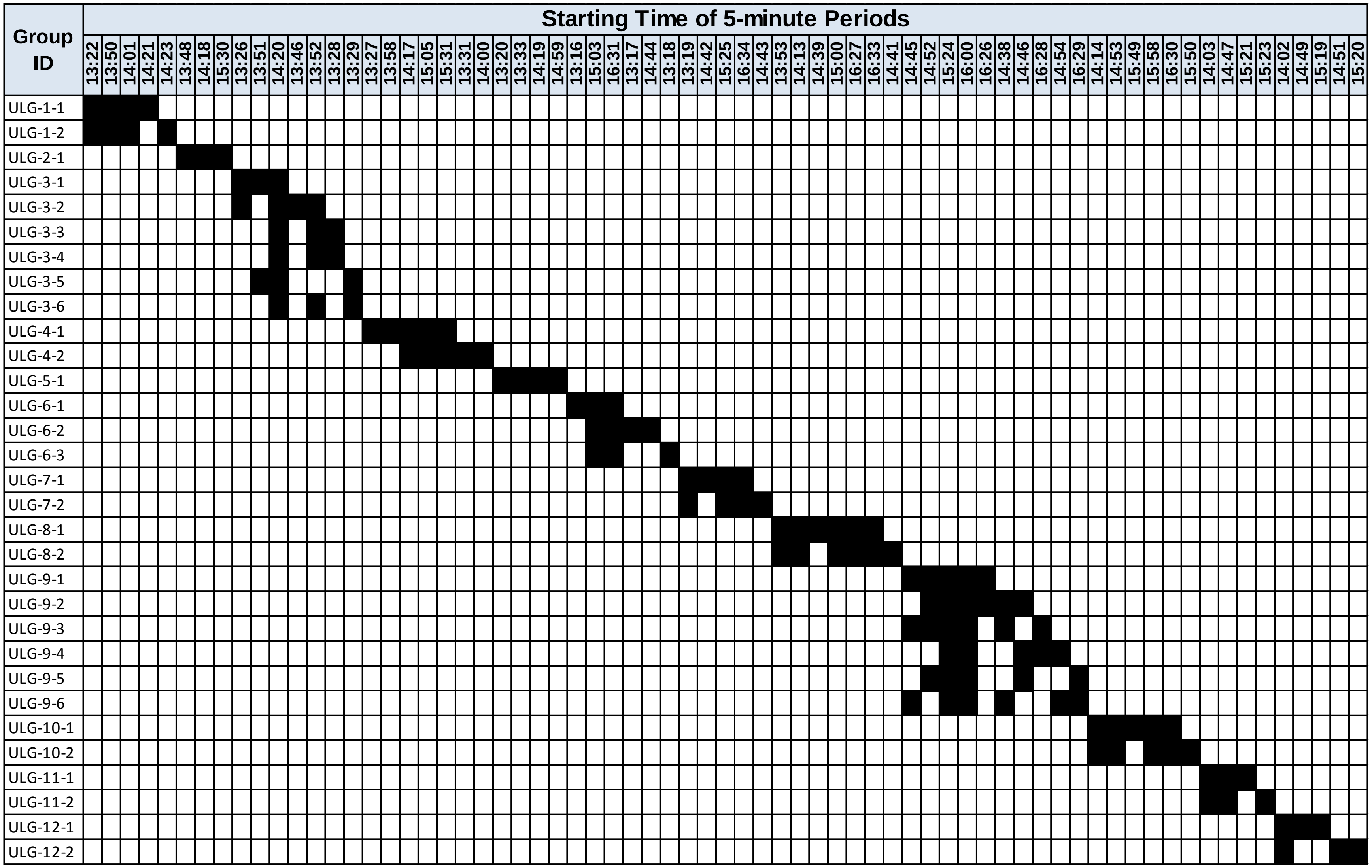


Figure 18. Equivalent 5-minute periods for Upwind Lapse groups at I-24.

Group ID	Starting Time of 5-minute Periods																																
	13:23	13:54	13:56	13:57	14:08	14:09	14:11	14:15	14:16	14:30	14:31	14:32	14:55	14:57	14:58	15:06	15:07	15:08	15:10	15:14	15:15	15:17	15:44	15:45	15:46	15:55	16:01	16:06	16:13	16:14	16:15	16:20	16:24
CLG-1-1	■									■						■																	
CLG-2-1															■		■												■				
CLG-2-2															■		■				■									■			
CLG-3-1							■				■		■										■										
CLG-3-2							■					■	■										■										
CLG-4-1				■		■								■						■				■			■						
CLG-4-2				■		■								■						■				■									
CLG-4-3				■		■								■						■					■								
CLG-5-1			■															■										■					■
CLG-5-2			■						■									■										■					■
CLG-5-3			■					■											■									■					■
CLG-6-1		■			■																	■				■					■		
CLG-6-2		■			■																	■				■						■	

Figure 19. Equivalent 5-minute periods for Calm Lapse groups at I-24.

Group ID	Starting Time of 5-minute Periods								
	16:11	16:47	17:02	17:03	17:04	17:06	17:13	17:14	17:15
CNG-1-1	■		■					■	
CNG-1-2	■			■				■	
CNG-2-1		■			■		■		
CNG-2-2		■				■			■

Figure 20. Equivalent 5-minute periods for Calm Neutral groups at I-24.

Table 5. Two-way traffic volumes in 5-minute periods, by equivalent group for Upwind lapse, Calm Lapse, and Calm Neutral conditions, sorted by factored hourly volume, I-24.

Group	Two-Way Traffic Volumes (5 minutes)						Factored Hourly Volume (vph)
	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	
Upwind Lapse							
ULG-10-2	504	550	613	598	642		6,977
ULG-9-5	563	550	570	592	617		6,941
ULG-9-2	568	563	550	570	592	625	6,936
ULG-9-1	552	550	570	592	625		6,934
ULG-9-4	563	539	570	592	623		6,929
ULG-9-3	568	552	550	570	592	623	6,910

ULG-10-1	504	550	579	598	642		6,895
ULG-9-6	568	552	539	570	592	617	6,876
ULG-8-2	507	513	539	562	613	618	6,704
ULG-8-1	507	513	535	562	613	618	6,696
ULG-7-1	461	557	556	657			6,693
ULG-12-1	488	554	623				6,660
ULG-7-2	461	522	556	657			6,588
ULG-12-2	488	547	610				6,580
ULG-6-2	462	555	543	604			6,492
ULG-11-2	489	561	573				6,492
ULG-11-1	489	561	572				6,488
ULG-6-1	449	543	604				6,384
ULG-6-3	433	543	604				6,320
ULG-4-1	511	497	497	552	546		6,247
ULG-4-2	494	497	497	552	546		6,206
ULG-3-6	521	514	501				6,144
ULG-3-5	521	494	501				6,064
ULG-2-1	479	475	552				6,024
ULG-3-3	488	514	501				6,012
ULG-3-4	488	514	501				6,012
ULG-5-1	437	505	504	539			5,955
ULG-3-2	481	476	514	501			5,916
ULG-3-1	481	494	501				5,904
ULG-1-1	425	491	495	511			5,766
ULG-1-2	425	491	495	489			5,700
Calm Lapse							
CLG-2-2	526	583	583	668			7,080
CLG-5-1	481	611	642	616			7,050
CLG-2-1	526	583	629				6,952
CLG-6-1	523	494	611	610	651		6,934
CLG-6-2	523	494	611	610	618		6,854
CLG-5-2	481	471	611	642	616		6,770
CLG-5-3	481	488	588	642	616		6,756
CLG-3-2	526	523	523	623			6,585
CLG-4-1	502	503	511	593	585	584	6,556
CLG-3-1	526	491	523	623			6,489
CLG-4-2	502	503	511	593	585		6,466
CLG-4-3	502	503	511	593	584		6,463
CLG-1-1	470	493	598				6,244
Calm Neutral							
CNG-2-1	659	686	708				8,212
CNG-2-2	659	665	680				8,016
CNG-1-1	599	722	680				8,004
CNG-1-2	599	662	680				7,764

Sound Pressure Level Spectra

Before discussing the differences in levels between the Barrier and No Barrier sites, typical sound pressure level spectra are shown to give some perspective on the data upon which the differences are based. One of the 5-minute periods in the one of the Upwind Lapse groups was chosen as typical.

Figure 21, Figure 22 and Figure 23 present the sound pressure level spectra for, respectively, BarRef01/NoBarRef02, BarCom03/NoBarCom05 and BarCom04/NoBarCom06.

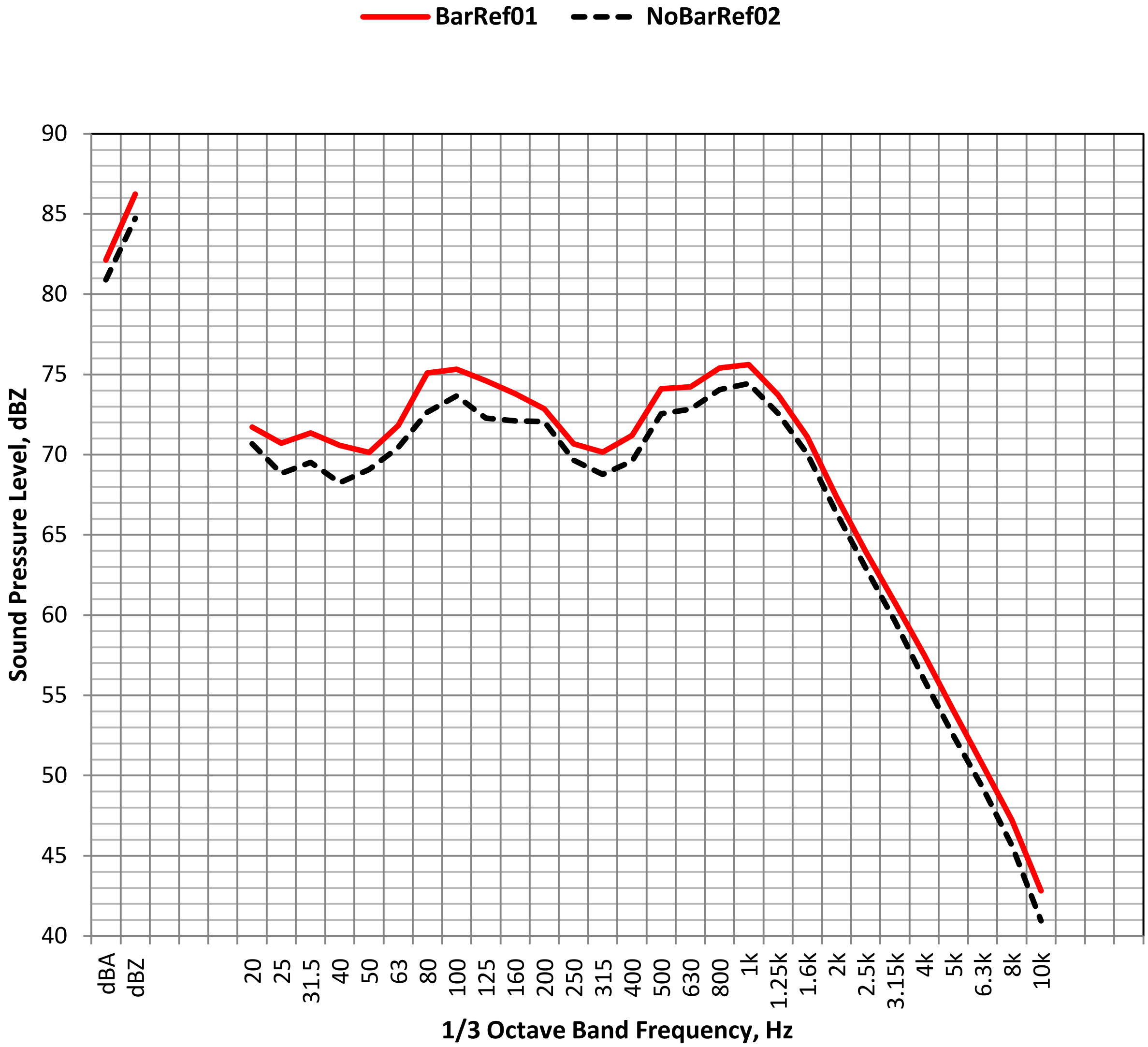


Figure 21. Sample sound pressure level spectra for BarRef01 and NoBarRef02, I-24, Upwind Lapse group ULG-3-2, 13:26-13:31 (L_{eq}(5min), dBZ).

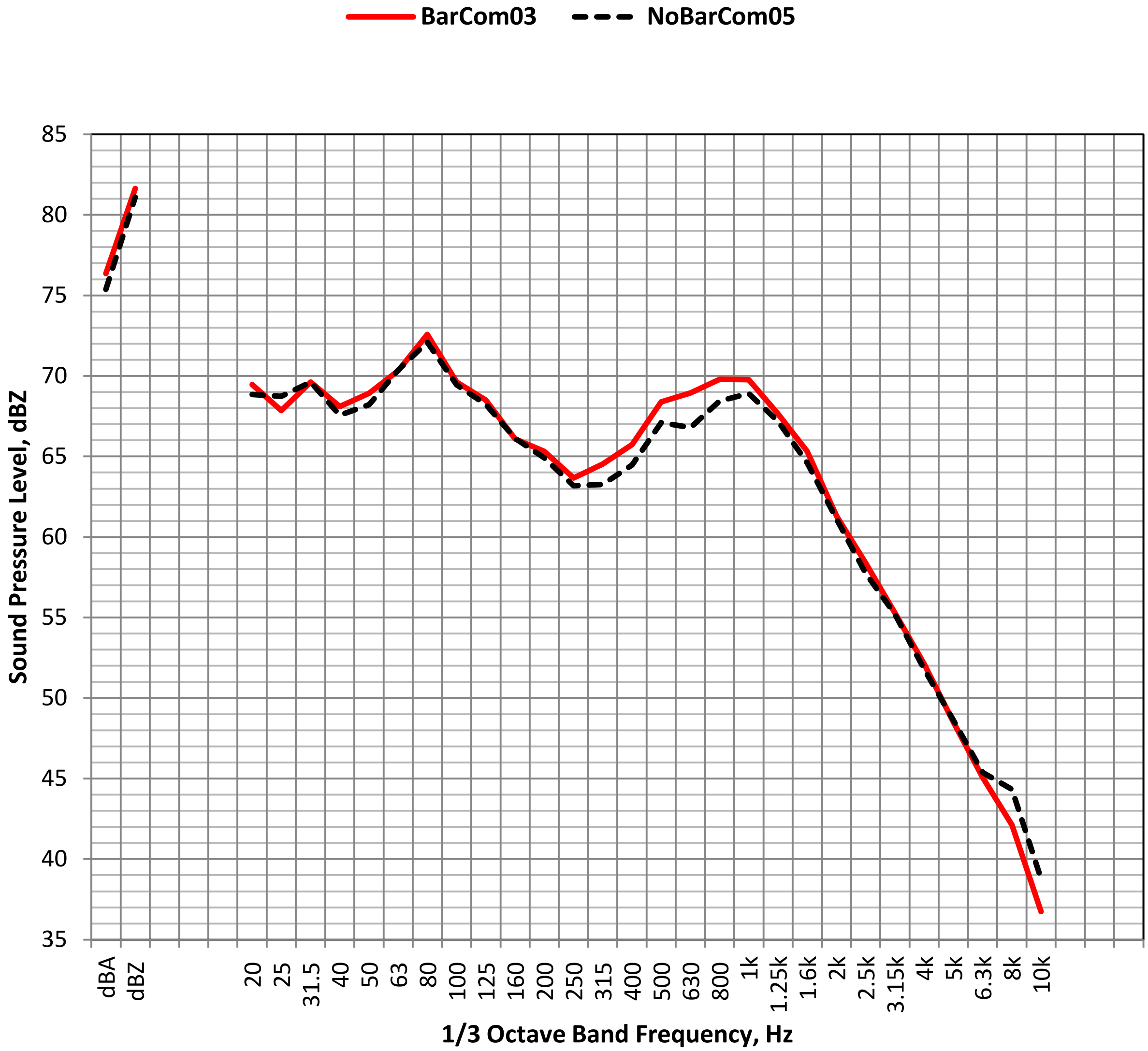


Figure 22. Sample sound pressure level spectra for BarCom03 and NoBarCom05, I-24, Upwind Lapse group ULG-3-2, 13:26-13:31 (L_{eq}(5min), dBZ).

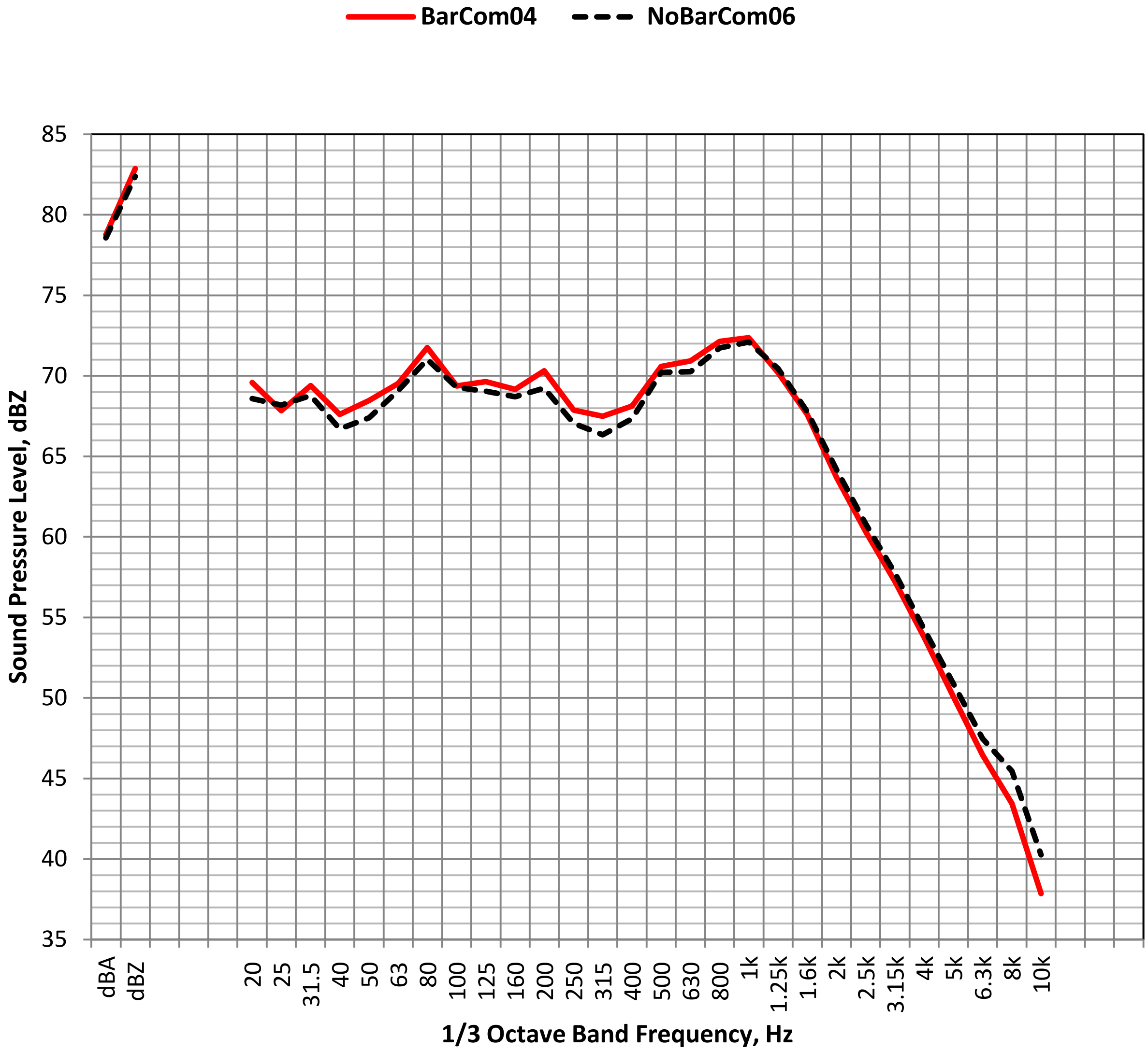


Figure 23. Sample sound pressure level spectra for BarCom04 and NoBarCom06, I-24, Upwind Lapse group ULG-3-2, 13:26-13:31 (L_{eq}(5min), dBZ).

Upwind Lapse Class

Figure 24 shows three graphs of the differences in level between comparable microphones for an average of all of the Upwind Lapse groups, with their error bars. The error bars are +/- one standard deviation for each average value. This figure compares the following:

- BarRef01 and NoBarRef02 in the upper graph;
- BarCom03 and NoBarCom05 in the middle graph; and
- BarCom04 and NoBarCom06 in the lower graph.

Each graph shows the averages of the average level differences for the A-weighted sound level, the unweighted sound pressure level and the 1/3 octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all of the individual Upwind Lapse groups are in spreadsheet files in the project record. The trends across the 1/3 octave band frequencies, described below, are generally similar in these individual groups of equivalent periods, with some differences likely related to background noise and the uniqueness of vehicle noise sources in each period.

Figure 24 shows in the upper graph that, in general, the BarRef01 levels are roughly 0.9 dB to 1.3 dB higher than the NoBarRef02 levels across the entire spectrum. At 25 Hz, the difference is 2 dB; at 200 Hz and 250 Hz, it is approximately 0.5 dB. Higher levels at BarRef01 are expected since the microphone is between the barrier and the road.

The middle graph shows the differences in levels between BarCom03 and NoBarCom05, both of which were five feet above the roadway elevation. In general, the BarCom03 levels are equal to or slightly greater than the NoBarCom05 levels over most of the frequency range up through 4 kHz. The increase is less than 1 dB from 31.5 Hz to 250 Hz, and on the order of 1 dB to 2 dB in the bands from 315 Hz to 1 kHz. Above 4 kHz, the levels at NoBarCom05 are higher than the levels at BarCom03. The difference was caused by insects in the vegetation behind the NoBarCom05 microphone that were not present near the BarCom03 site.

The lower graph compares the levels at BarCom04 and NoBarCom06, both of which were 15 feet above the roadway surface. The results show that the BarCom04 levels in the frequency bands from 20 Hz up through 1.25 kHz were equal to or slightly higher than at NoBarCom06. At 31.5 Hz to 63 Hz, they were approximately 1 dB higher than NoBarCom06. At 1.6 kHz and above, the NoBarCom06 levels were higher than the BarCom04 levels ranging from a fraction of a decibel at 1.6 kHz to 2.5 dB in the 6.3 kHz band. The higher levels at NoBarCom06 in the bands are attributed to insect noise in some vegetation behind this microphone.

While all of the 5-minute periods in all of the groups were not equivalent in traffic volume and speed across all of the groups, these average differences show consistency with the results in the individual groups.

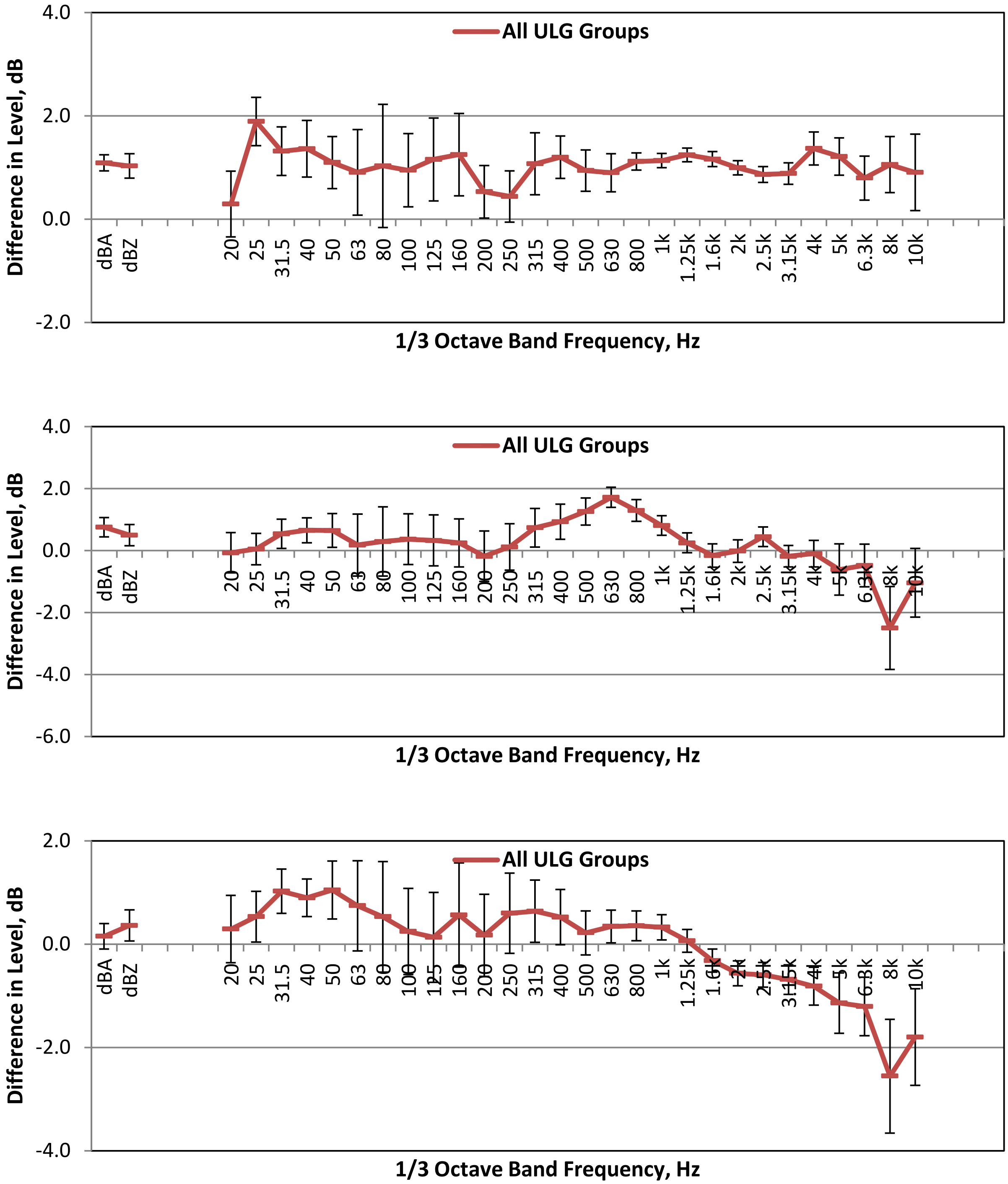


Figure 24. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Upwind Lapse groups, I-24.

Calm Lapse Class

Figure 25 shows the averages of the average level differences between the Barrier and No Barrier microphones' levels for all of the Calm Lapse groups, with error bars, in the same manner as the Upwind Lapse groups. Other than some minor variations, the Calm Lapse differences are very similar to those for the Downwind Lapse class for all three microphone pairs.

As with the Upwind Lapse case, while all of the 5-minute periods in all of the groups were not equivalent in traffic volume and speed across all of the groups, these average differences show consistency with the results in the individual groups. Graphs for all of the individual Calm Lapse groups are in spreadsheet files in the project record.

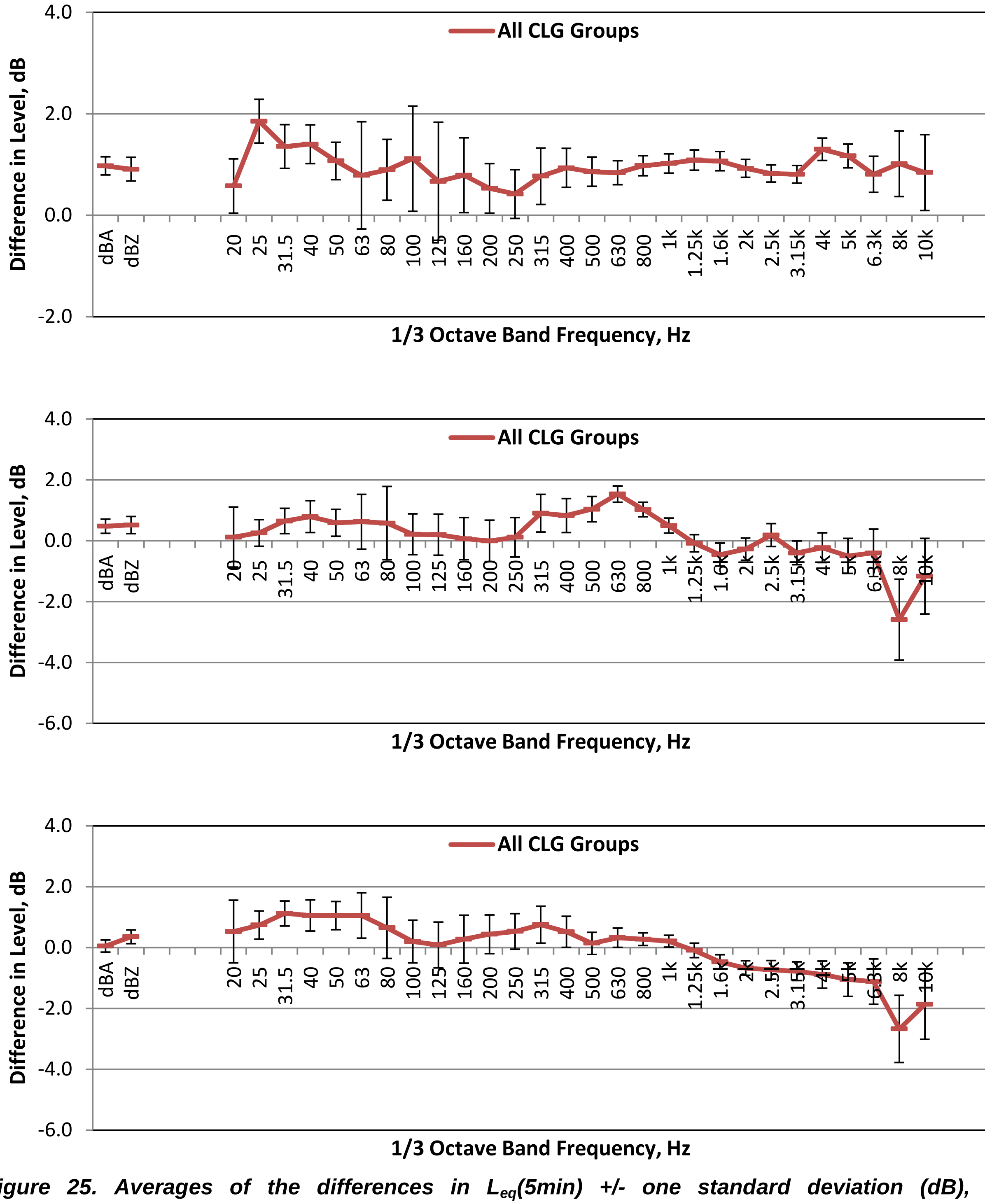


Figure 25. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Lapse groups, I-24.

Calm Neutral Class

Figure 26 shows the averages of the average level differences between the Barrier and No Barrier microphones' levels for all of the Calm Neutral groups, with their error bars. Graphs for all of the individual Calm Neutral groups are in spreadsheet files in the project record.

The upper graph shows generally similar trends to the Upwind Lapse and Calm Lapse graphs for BarRef01 and NoBarRef02, with three variations: (1) the difference at 125 Hz decreased from 1.0 dB to 0.5 dB; (2) the difference at 1.6 kHz decreased from 1.5 dB to 1.0 dB; and (3) the difference at 8 kHz increased from -0.5 dB to 1.0 dB.

The middle graph compares BarCom03 and NoBarCom05 (lower microphones) for the Calm Neutral group. It again shows generally similar trends to the Upwind Lapse and Calm Lapse graphs, with three variations: (1) the difference at 125 Hz changed from -1.0 dB to 0 dB; (2) the difference at 6.3 kHz changed from -2.6 dB to -1.0 dB; and (3) the difference at 8 kHz changed from -4.0 dB to -3.0 dB.

The lower graph compares the levels at the BarCom04 and NoBarCom06 (upper) microphones for this Calm Lapse group. This graph shows generally similar trends to the Upwind Lapse and Calm Lapse graphs, with four slight variations: (1) the difference at 100 Hz decreased from 1.0 dB to 0 dB; (2) the difference at 125 Hz increased from -1.0 dB to 0 dB; (3) the difference at 200 Hz decreased from 0.5 dB to 0 dB; and (4) the difference at 8 kHz changed from -4 4 dB to -2.5 dB (NoBarCom05 being higher in all three classes).

As with the Upwind Lapse case, while all of the 5-minute periods in all of the groups were not equivalent in traffic volume and speed across all of the groups, these average differences show consistency with the results in the individual groups.

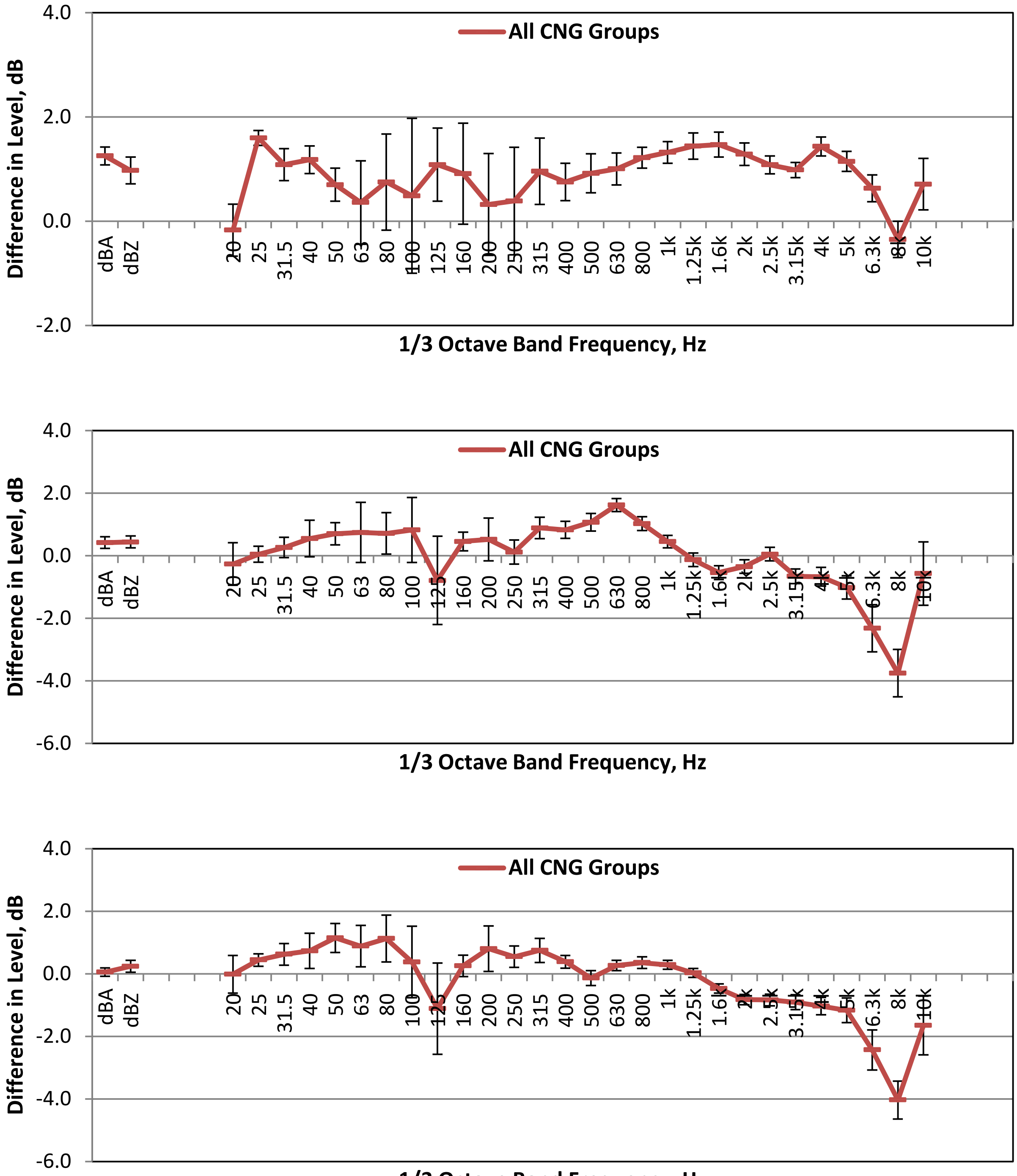


Figure 26. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Neutral groups, I-24.

Comparison of Upwind Lapse and Calm Lapse Results

Figure 27 compares the differences in level for the Upwind Lapse and Calm Lapse classes for the six microphone positions. The data values are the average Upwind Lapse differences minus the average Calm Lapse differences for each frequency band.

The data show that the Upwind Lapse average differences tend to be:

- slightly smaller than the Calm Lapse average differences in the lower frequency bands; and
- slightly larger than the Calm Lapse average differences in the higher frequency bands.

These differences in the average differences are typically on the order of a few tenths of a decibel.

Effects of Traffic Volume and Speed

No trends were evident when considering the differences in sound level as a function of two-way traffic volume for the Upwind Lapse, Calm Lapse and Calm Neutral classes. Also, the range in speeds for each class was too small (5 mph) to address any relationship between speed sound level difference.

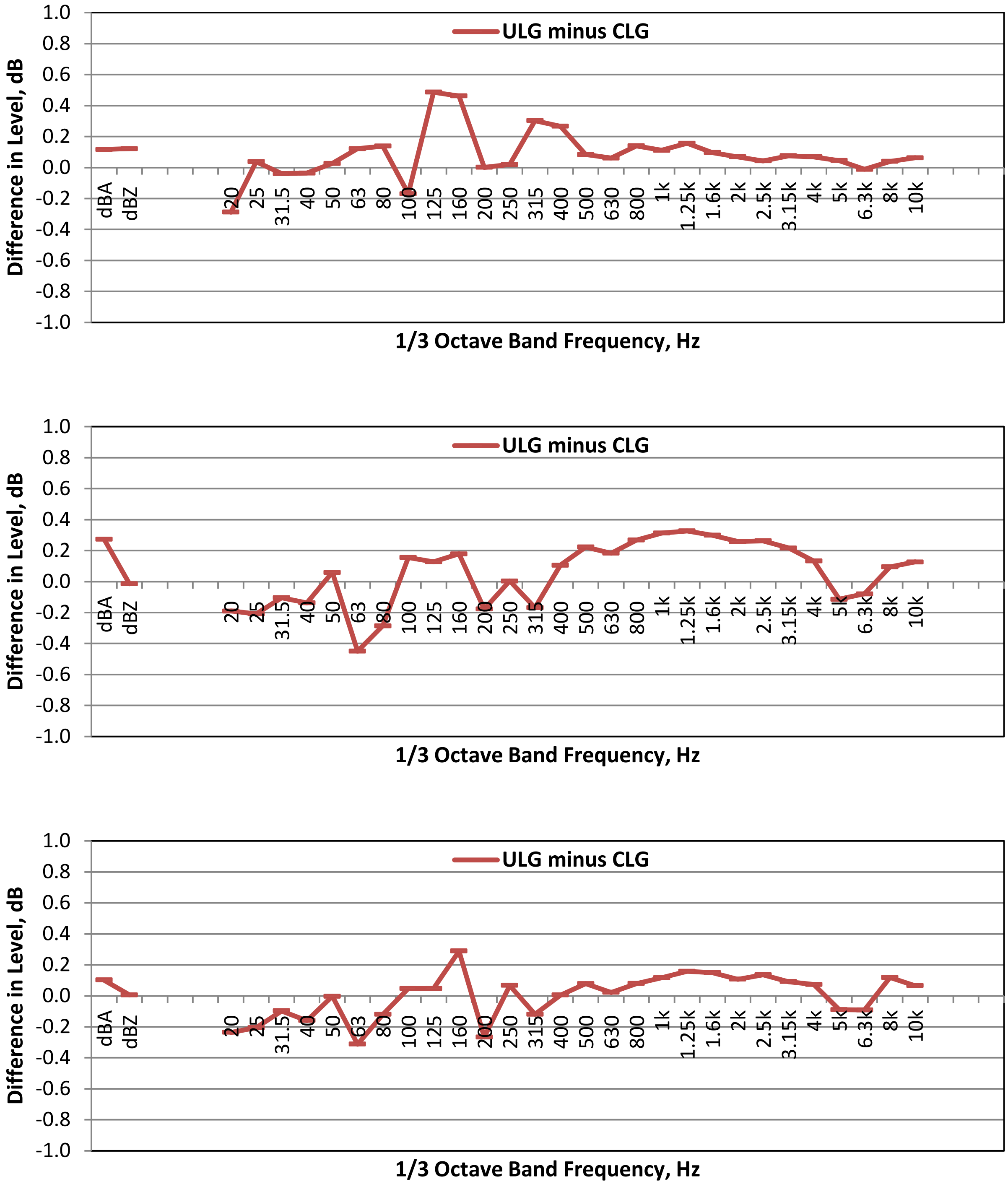


Figure 27. Differences in the Upwind Lapse average differences and the Calm Lapse average differences (L_{eq}(5min) +/- one standard deviation, dB), all microphones, I-24.

Additional Sound Level Analysis for I-24 – L_n Descriptors

In addition to the examination of the differences in levels for the equivalent pairs of running 5-min L_{eq} data, an investigation was made of the differences in the L_n descriptors for the overall data without segregation into equivalent periods, focusing on the possible change in the background level in the presence of the noise barrier.

Figure 28 presents the L_{90}(5min) and L_{99}(5min) for BarRef01 and NoBarRef02, in terms of overall A-weighted sound levels and unweighted sound pressure level. The upper graphs are L_{90} (A-weighted on the left and unweighted on the right). The lower graphs are L_{99} (A-weighted on the left and unweighted on the right).

Then, Figure 29 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min),computed as BarRef1 minus NoBarRef2 for the A-weighted sound levels.

The results show that while the L_{eq}(5min) averages about 1 dB higher at BarRef01 than at NoBarRef02, the L_{90} and L_{99} at BarRef01 are much higher than at NoBarRef02. This effect on these two descriptors is evidence of an increase in the background level in front of the barrier that could be attributed to the presence of reflected sound rays reaching the mic in addition to the direct rays from the passing vehicles.

The results support the idea of not only a reflection component during the moment of passage, but also approach and receding components of the reflections. Thus, the sound level rises sooner and recedes later for each vehicle. This sustaining of the sound for a single vehicle overlaps with the same pattern for other vehicles, elevating the background level and reducing the time during which the background level might decrease between vehicle passages.

Figure 30 presents the same data – L_{90}(5min) and L_{99}(5min) – for BarCom03 and NoBarCom05 (the lower microphones across from the barrier), again for overall A-weighted sound levels and unweighted sound pressure level. Figure 31 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05. There is less evidence of the elevated background level at BarCom03 compared to NoBarCom05, not unexpected given the dominance of the direct sound from the nearby vehicles.

Then, Figure 32 presents the L_{90}(5min) and L_{99}(5min) for BarCom04 and NoBarCom06 (the upper microphones across from the barrier) for overall A-weighted sound levels and unweighted sound pressure level. Figure 33 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06. There is more evidence of the elevated background levels at BarCom04 compared to BarCom03 because of the elevated position of the microphone leading to less shielding of the reflected noise by the median parapet, but not as much evidence as at BarRef01.

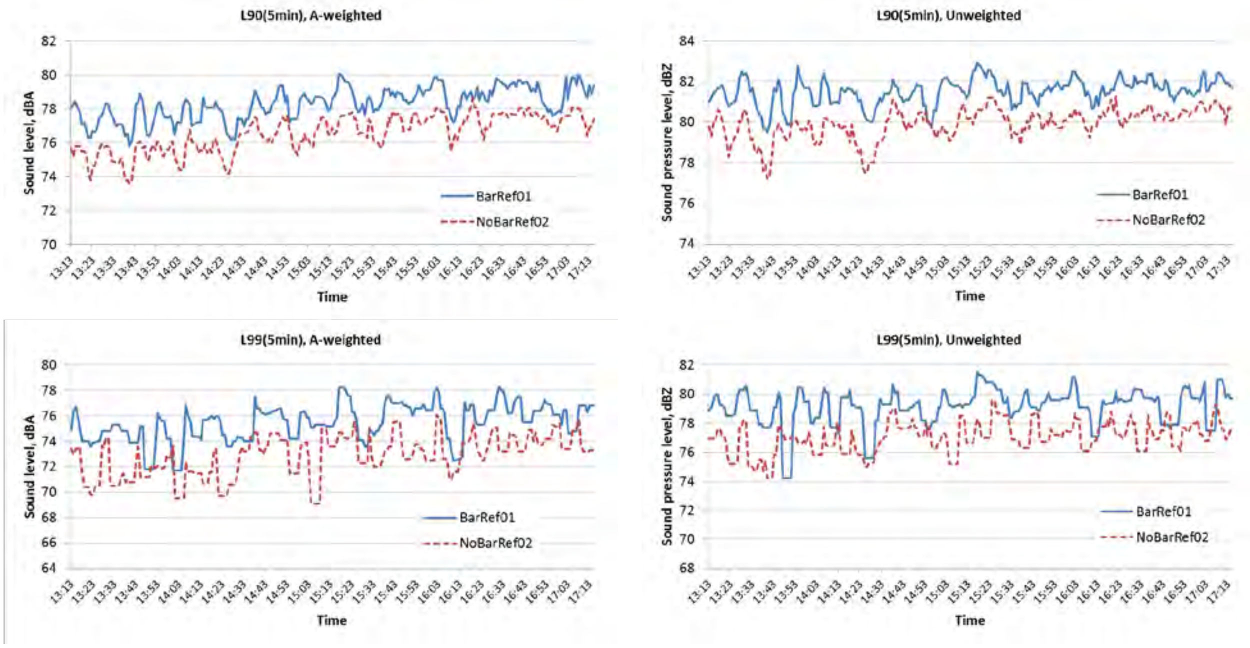


Figure 28. L_{90}(5min) and L_{99}(5min), I-24, BarRef01 and NoBarRef02 – broadband A-weighted sound level and sound pressure level

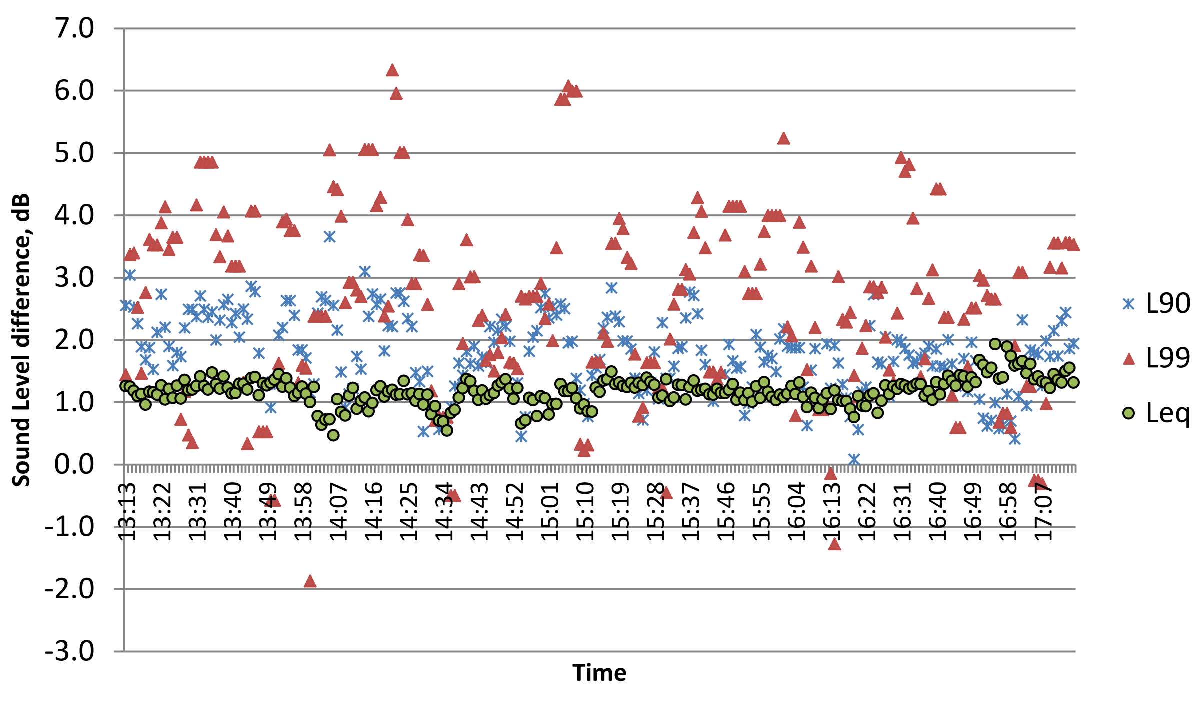


Figure 29. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-24, BarRef1 and NoBarRef2

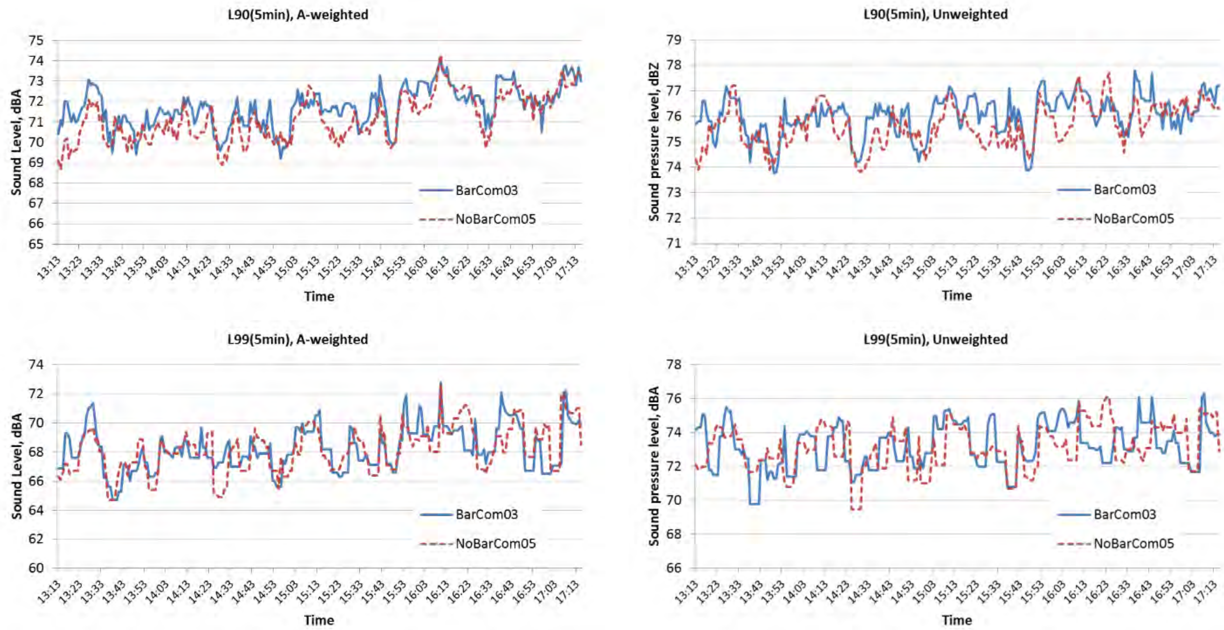


Figure 30. L_{90}(5min) and L_{99}(5min), I-24, BarCom03 and NoBarCom05 – broadband A-weighted sound level (left) and sound pressure level (right).

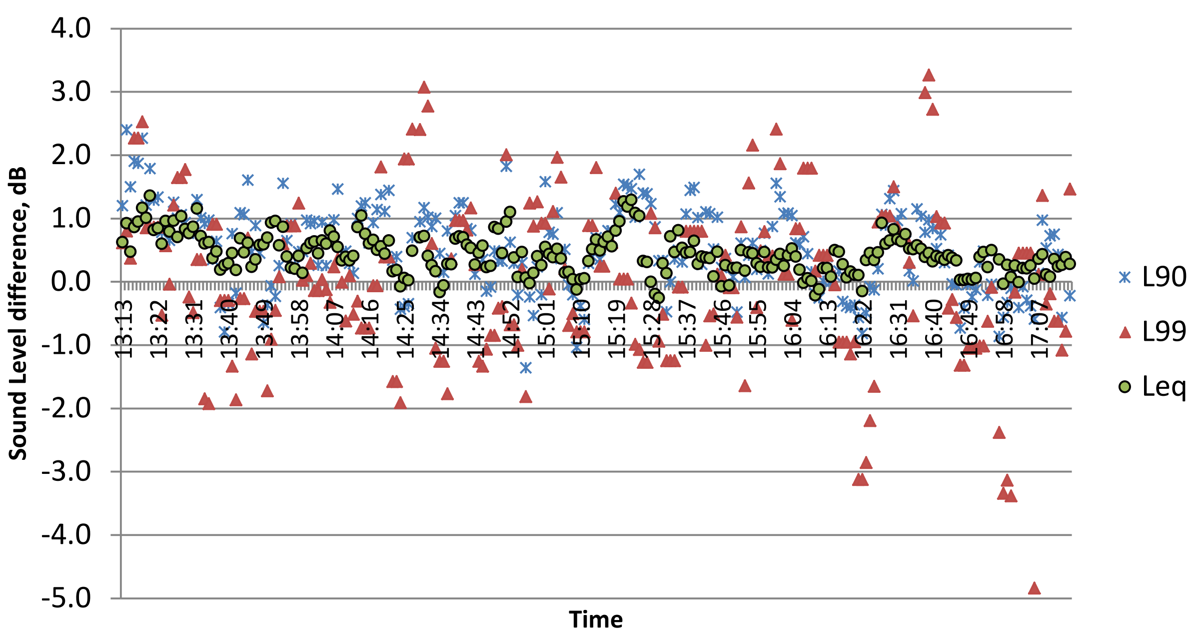


Figure 31. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-24, BarCom03 and NoBarCom05

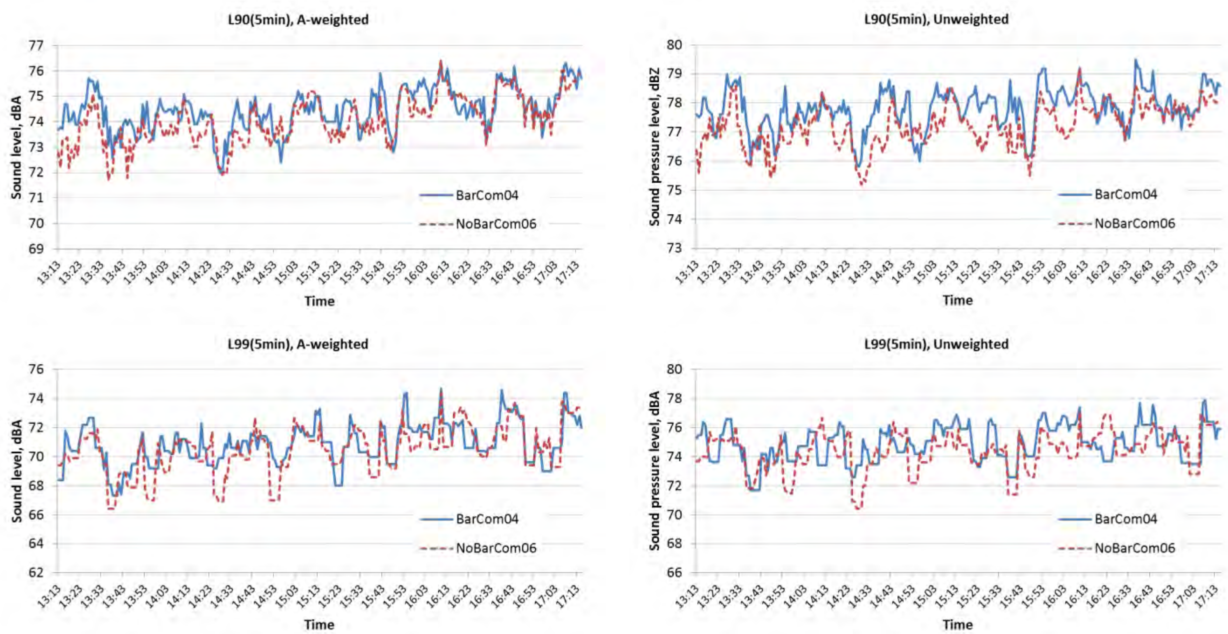


Figure 32. L_{90}(5min) and L_{99}(5min), I-24, BarCom04 and NoBarCom06 – broadband A-weighted sound level (left) and sound pressure level (right)

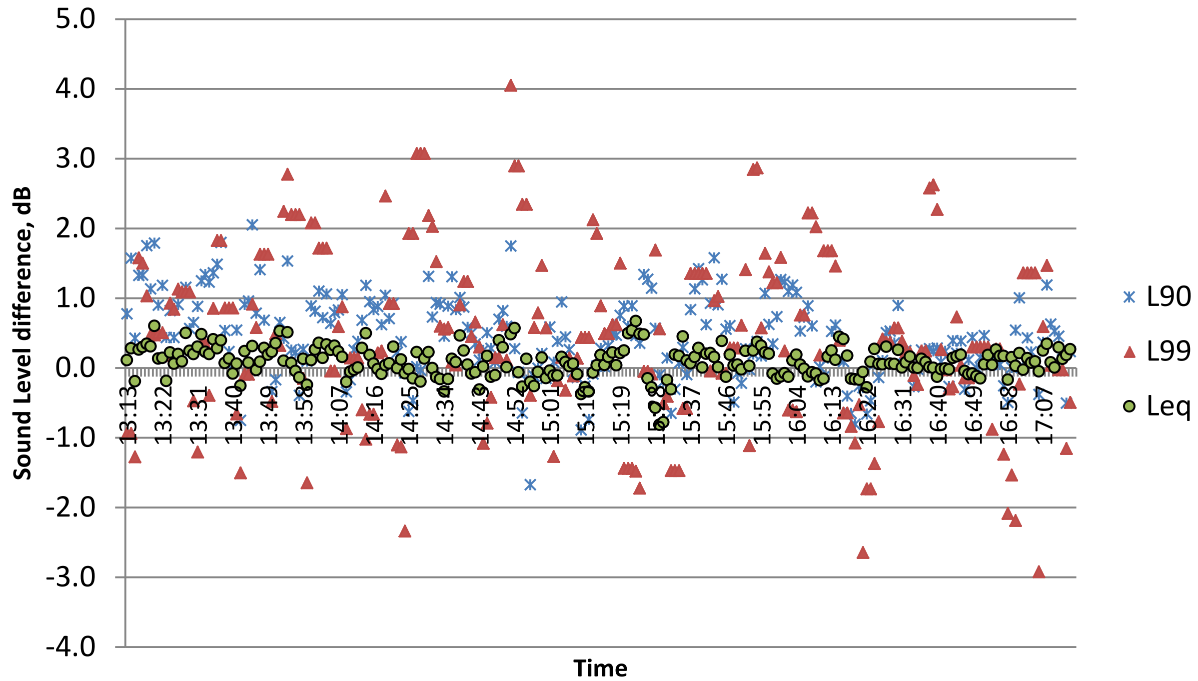


Figure 33. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-24, BarCom04 and NoBarCom06

The above graphs were for the broadband A-weighted sound levels and unweighted sound pressure levels only. Figure 34, shown below, broadens the analysis to include the individual 1/3 octave bands by use of color shading. The brown color means that the BarRef01 levels are higher than the NoBarRef02 levels and blue means that NoBarRef02 is higher. In the graph, time runs from top to bottom (increasing as one moves down each figure, with each row representing the starting minute of a running five-minute period) and the total block representing approximately four hours. The 1/3 octave bands run across from left to right, with the broadband A-weighted sound levels and unweighted sound pressure levels on the far left. Within each band's column of data are the differences for seven Ln sound pressure level Ln values (L_1, L_5, L_{10}, L_{33}, L_{50}, L_{90} and L_{99}) and L_{eq} in the order illustrated in Figure 35 for a single 1/3 octave band.

Vertical brown streaks are on the right sides of the data columns (representing L_{90}(5min) and L_{99}(5min)) in the frequency bands from 400 Hz up through 2 kHz for most of the sample period and up through 5 kHz for the first half of the sample period. These brown streaks mean that the BarRef01 background levels are higher than the NoBarRef02 background levels, evidence of a sustaining of a vehicle's passby noise due to the creation of an image source for each vehicle as the sound reflects off the barrier. In contrast, the vertical blue streaks in the 8 kHz band are evidence of elevated background levels at the NoBarRef02, likely attributable to insect noise in the vegetation behind this position.

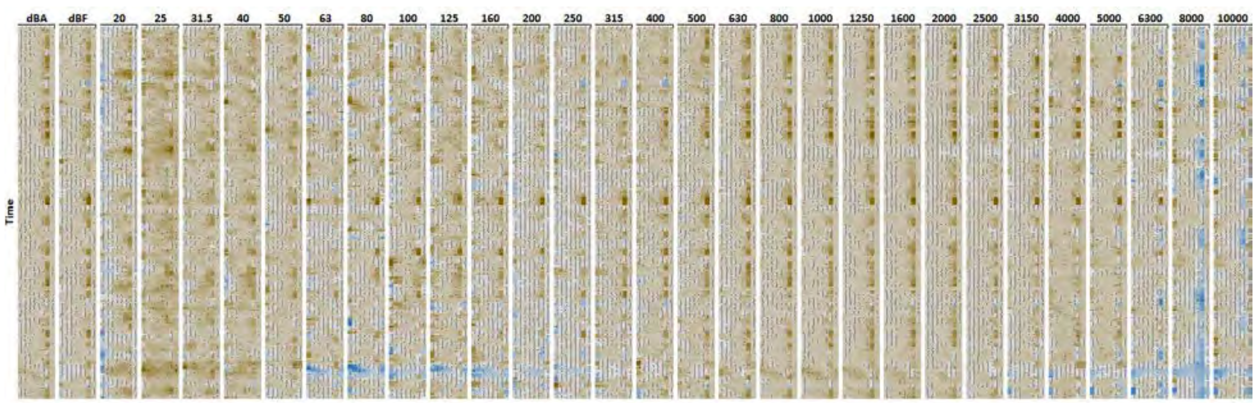


Figure 34. I-24 Differences in L_n(5min) by 1/3 octave frequency bands: BarRef01 and NoBarRef02

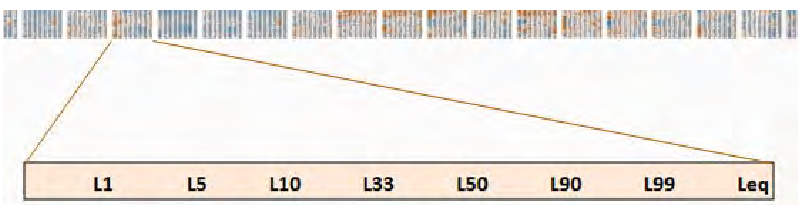


Figure 35. Order of statistical levels for a single 1/3 octave band

Figure 36 presents the L_n differences for BarCom03 and NoBarCom05, while Figure 37 presents the L_n differences for BarCom04 and NoBarCom06. Again, brown means Barrier levels are higher and blue means the No Barrier levels are higher. There is some evidence of slightly higher L_n values at BarCom03 in the 315 Hz to 800 Hz bands and at BarCom04 over much of the lower frequency range. The strong blue streaks in the 6.3 kHz and 8 kHz bands are evidence of elevated background levels at the No Barrier microphones due to the observed insect noise in the vegetation behind these microphones. Two horizontal streaks occur because of missing 1-sec data at start of the 5-minute period.

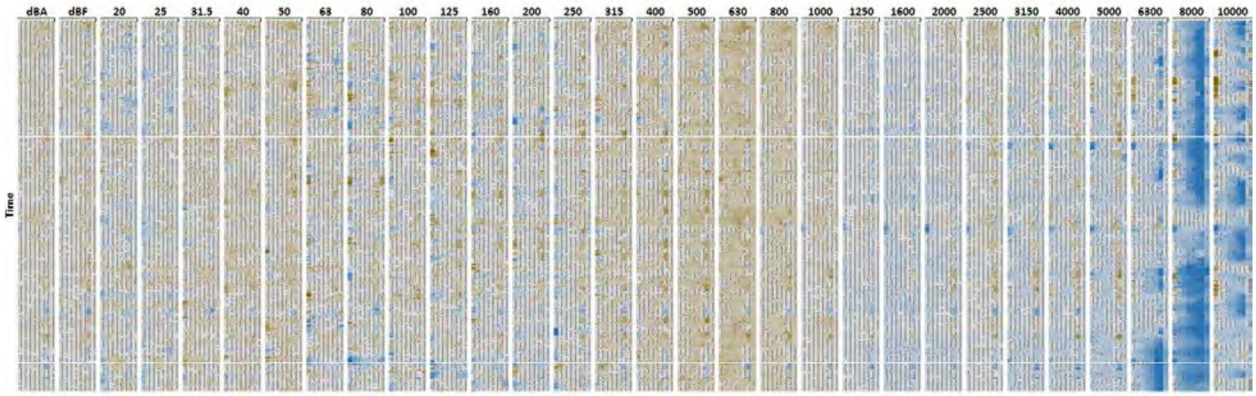


Figure 36. I-24 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom03 and NoBarCom05

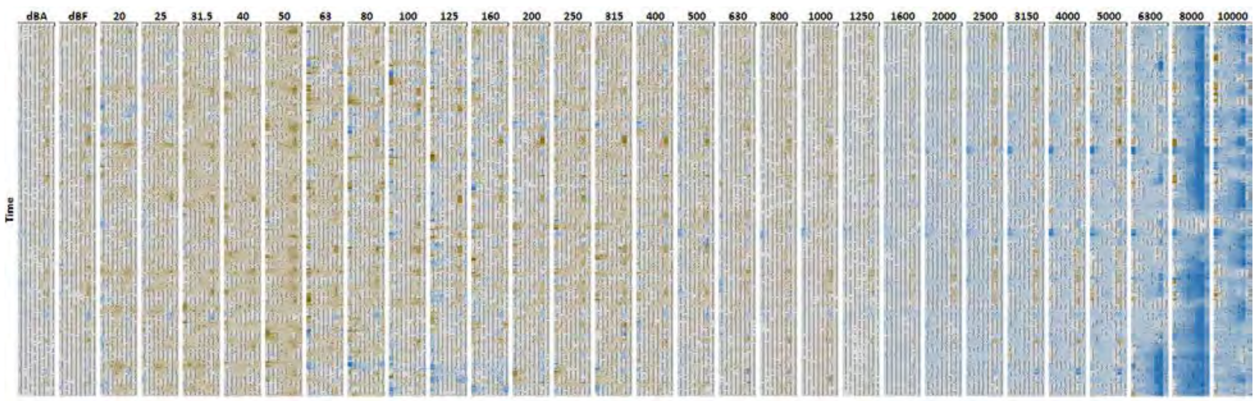


Figure 37. I-24 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom04 and NoBarCom06

Data Analysis – Spectrograms for I-24

Spectrograms show the frequency content of sound as a function of time. This section presents results of the spectrogram analysis. As with the FHWA Method data analysis, data for the spectrogram analysis were examined in the Upwind / Temperature Lapse group and the Calm Wind / Temperature Lapse group, the two prevalent meteorological conditions at the I-24 site. Data presented here are for 5-minute time blocks as well as vehicle pass-by events.

The 5-minute data blocks are presented first. An example of the Upwind Lapse group can be seen in Figure 38 and Figure 39; this is for group ULG-9-1, start time 14:45 (one of the times blocks presented in the FHWA Method data analysis section). Shown in Figure 38 are spectrograms for the reference positions and the high microphone positions, comparing the barrier and no barrier sites. Figure 39 shows the same for the low microphone positions.

An example of the Calm Lapse group can be seen in Figure 40 and Figure 41**Error! Reference source not found.**; this is for group CLG-6-1, start time 15:56 (one of the times presented in the FHWA Method data analysis section). Shown in Figure 40**Error! Reference source not found.** are spectrograms for the reference positions and the high microphone positions, comparing the Barrier and No Barrier sites. Figure 41shows the same for the low microphone positions.

An example of the Calm Neutral group can be seen in Figure 42 and Figure 43; this is for group CNG-2-1, start time 17:05 (one of the times presented in the FHWA Method data analysis section). Shown in Figure 42 are spectrograms for the reference positions and the high microphone positions, comparing the Barrier and No Barrier sites. Figure 43 shows the same for the low microphone positions.

The 5-minute data block spectrograms indicate the following trends:

1. For the reference positions, there is a clear indication that there are more occurrences of higher sound levels (dark red) for the Barrier case compared to the No Barrier case. In addition, the higher sound level events are broader in frequency *and* time. Vehicles traveling eastbound dominate the sound levels, and during the 5-minute blocks, single events can be tracked from the Barrier site to the No Barrier site about 15-20 seconds later.

2. For the high and low microphone positions across the highway from the barrier, there is indication that the higher sound level events are broader in frequency and time. Vehicles traveling westbound dominate the sound levels, and single events can be tracked from the No Barrier site to the Barrier site about 15-20 seconds later. The trend is not as obvious across the road from the barrier as for the reference positions, but it can be seen by focusing on a series of events and noticing that multiple consecutive events are more blended together in the Barrier case than the No Barrier case. As the higher levels (hot spots) broaden, they blend together more.

No clear trends are identified comparing upwind and calm conditions.

There is further evidence of higher sound level events being broader in frequency and time with closer examination of vehicle pass-by events. An example is shown in Figure 46 which shows a two-minute time block that includes a group of eastbound heavy trucks. The hot spots are broader in frequency and time.

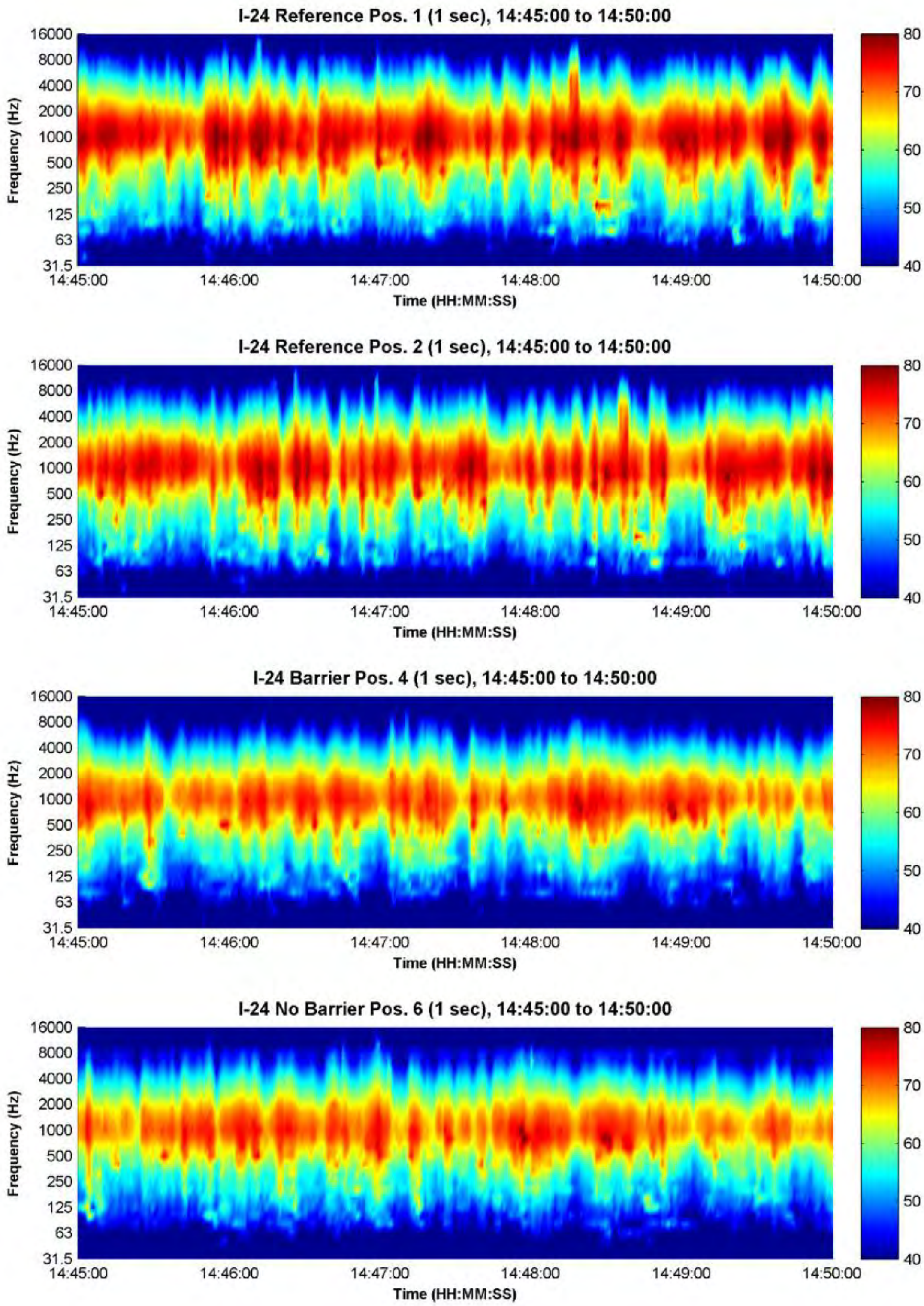


Figure 38. I-24 5-minute spectrograms; top to bottom: BarRef01, NoBarRef02, and high mics (BarCom04 and NoBarCom06); for Upwind Lapse group ULG-9-1, start time 14:45.

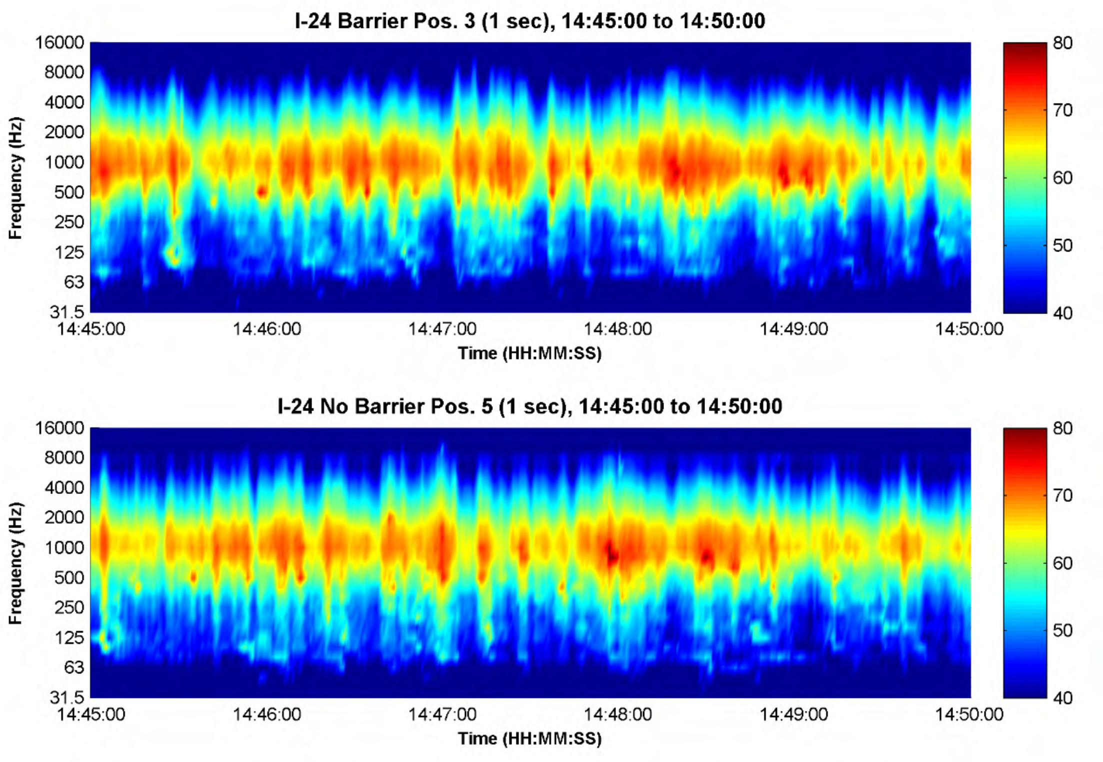


Figure 39. I-24 5-minute spectrograms; top to bottom: low mic BarCom03 and NoBarCom05; for Upwind Lapse group ULG-9-1, start time 14:45.

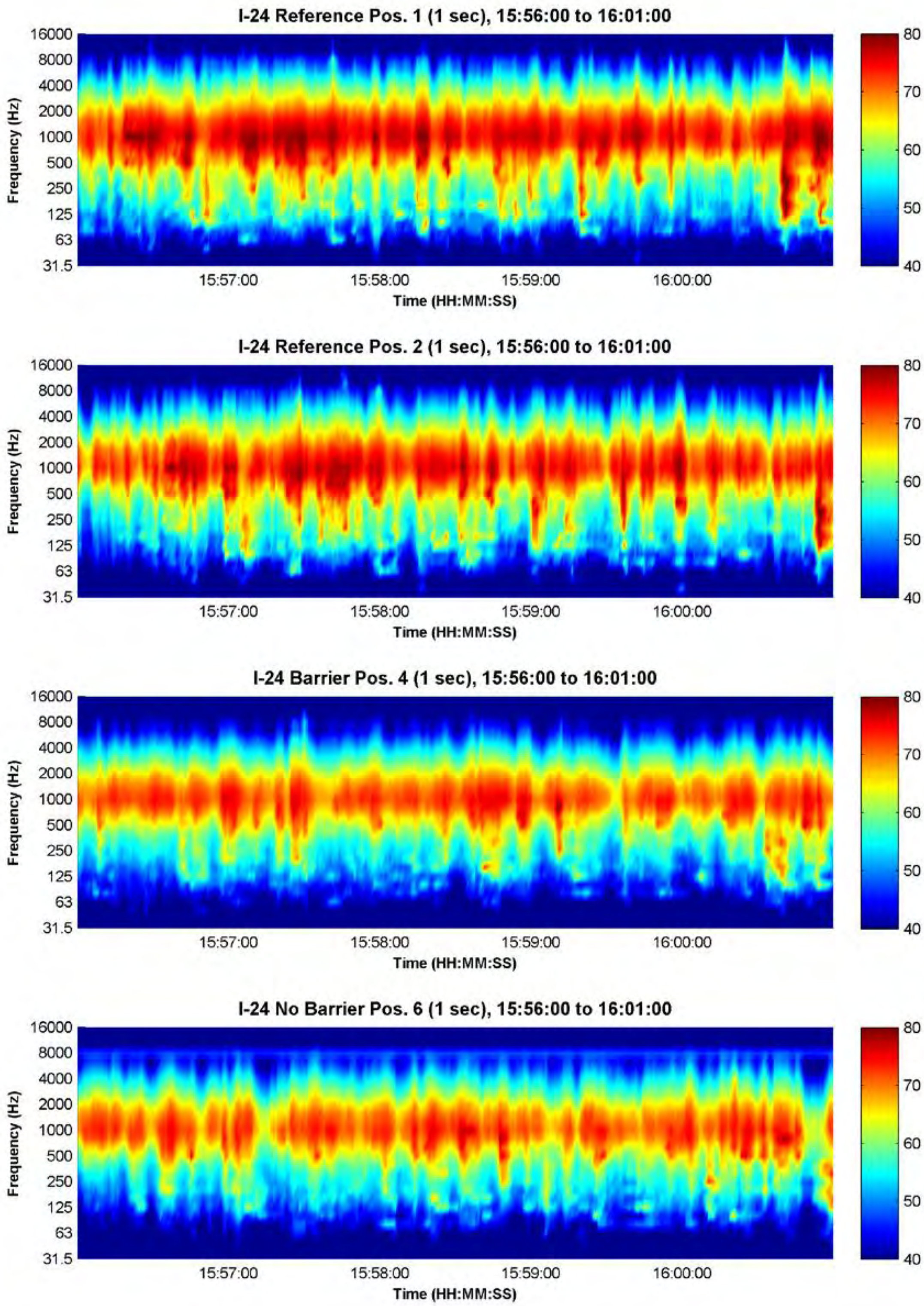


Figure 40. I-24 5-minute spectrograms; top to bottom: BarRef01, NoBarRef02, high mics (BarCom04 and NoBarCom06); for Calm Lapse group CLG-6-1, start time 15:56.

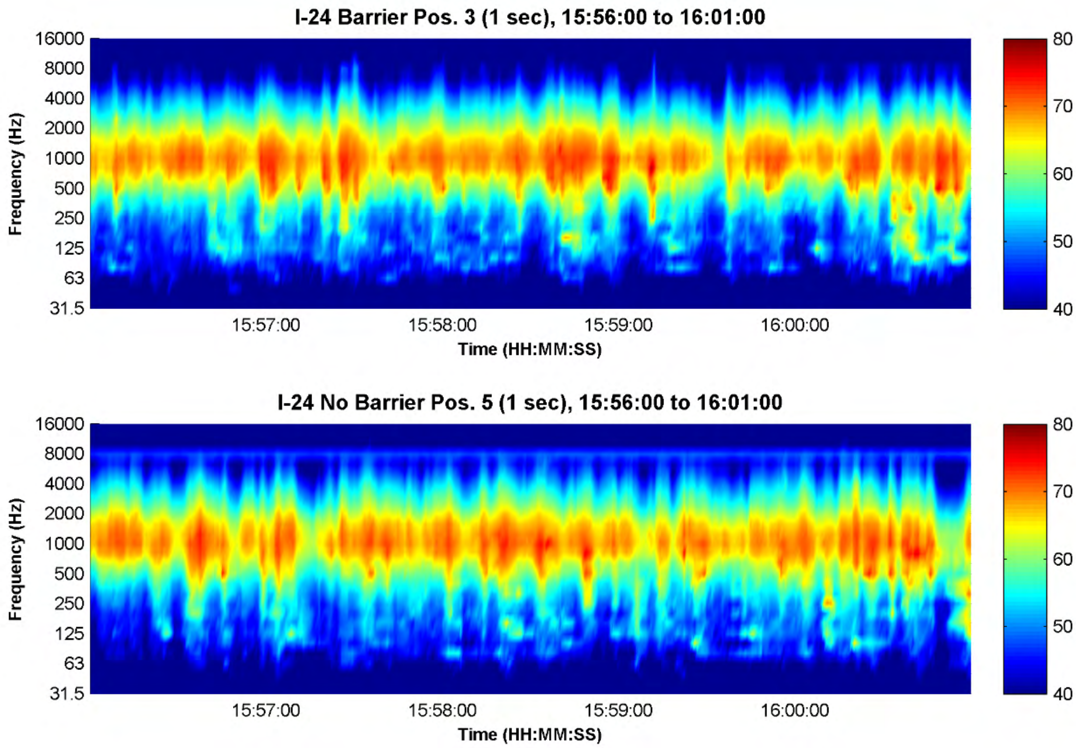


Figure 41. I-24 5-minute spectrograms; top to bottom: lows mics BarCom03 and NoBarCom05; for Calm Lapse group CLG-6-1, start time 15:56.

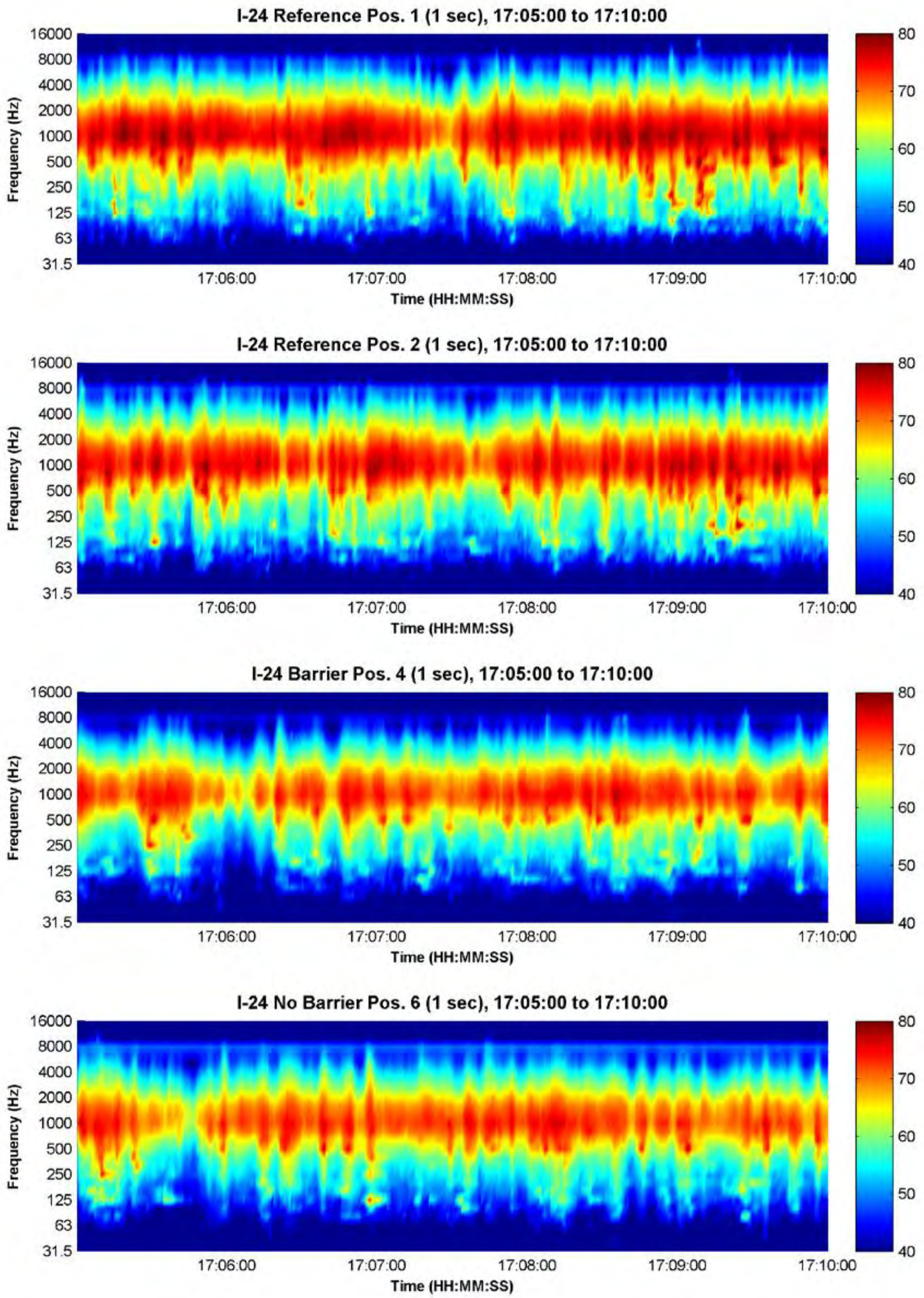


Figure 42. I-24 5-minute spectrograms; top to bottom: BarRef01, NoBarRef02, high mics (BarCom04 and NoBarCom06); for Calm Neutral group CNG-2-1, start time 17:05.

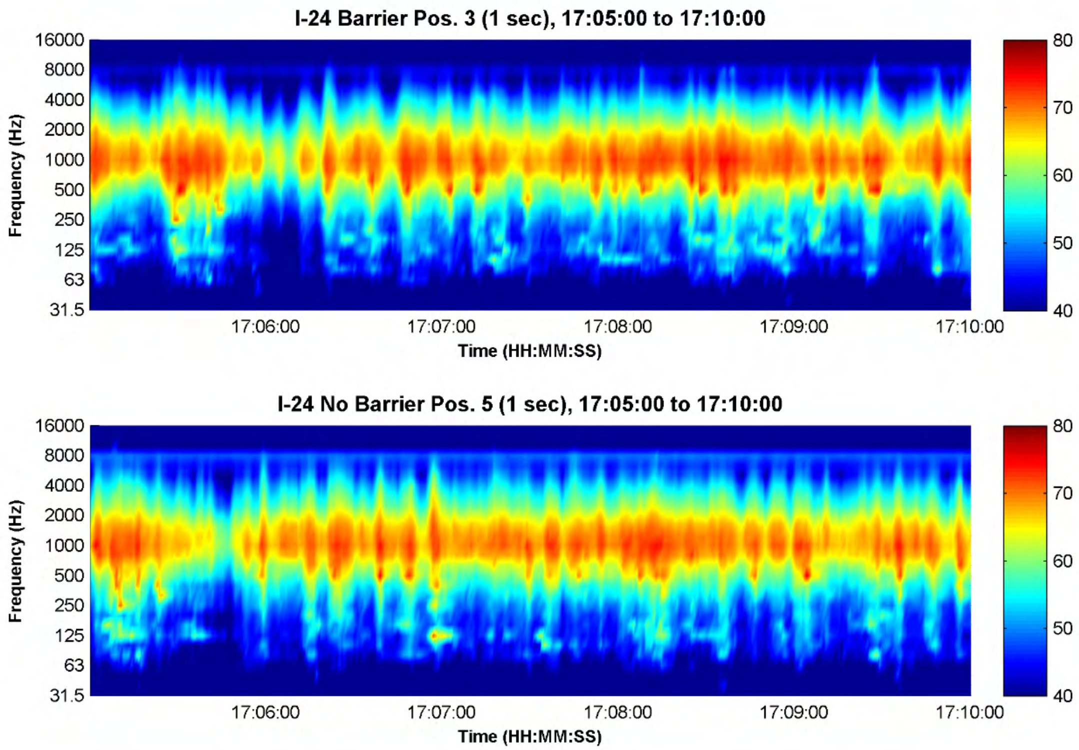
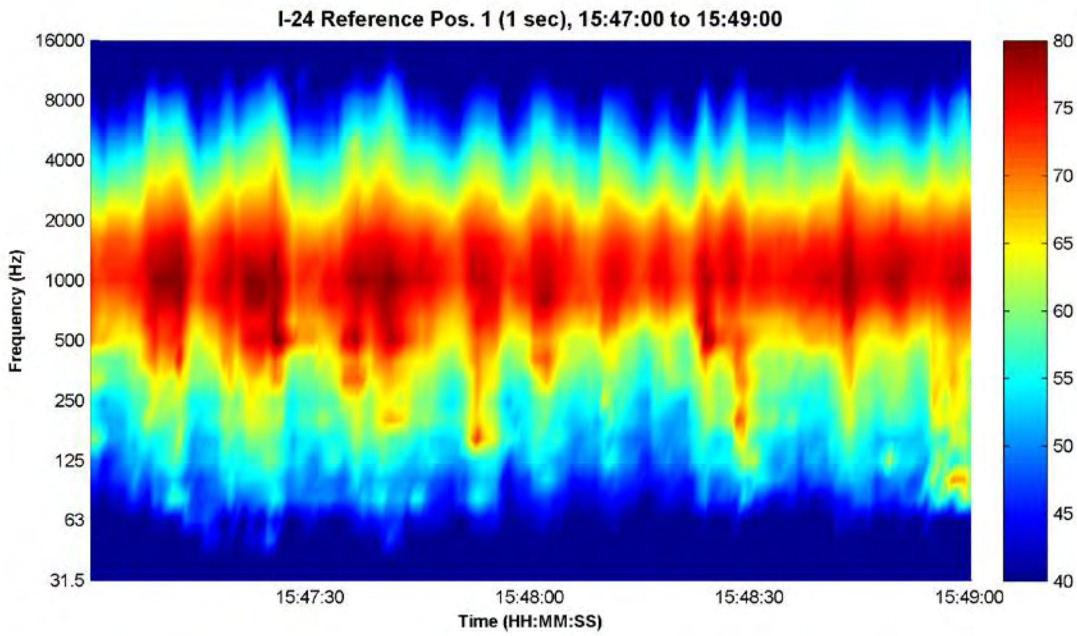


Figure 43. I-24 5-minute spectrograms; top to bottom: lows mics BarCom03 and NoBarCom05; for Calm Neutral group CNG-2-1, start time 17:05.



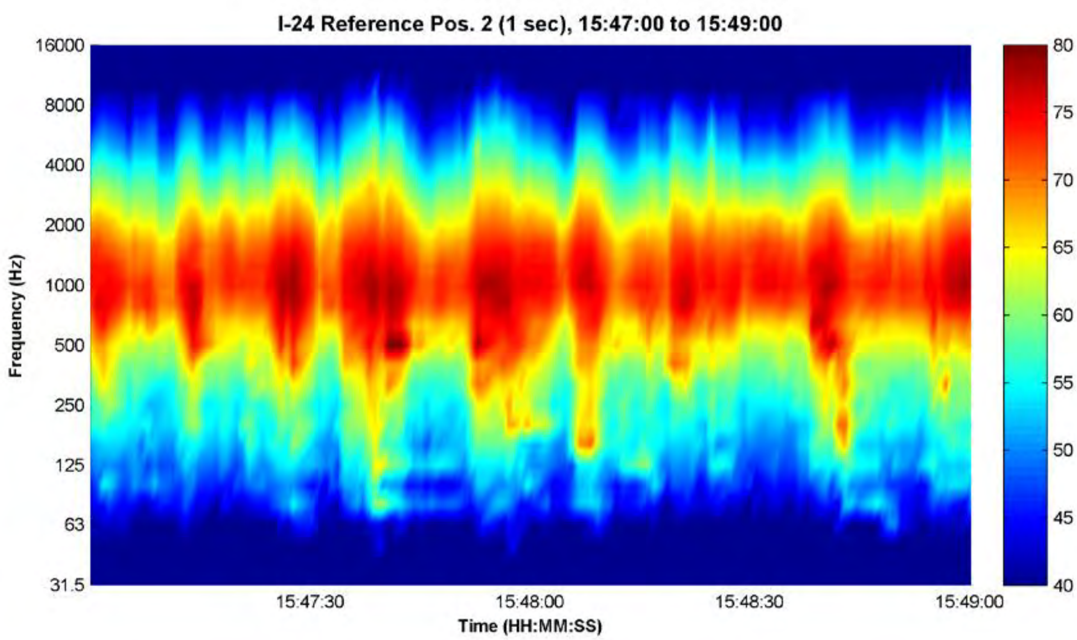


Figure 44. I-24 spectrograms for a group of heavy trucks; top to bottom: BarRef01, NoBarRef02.

Data Analysis - Psychoacoustics for I-24

Descriptive statistics for the computed annoyance metrics at I-24 are summarized in Table 6. The associated histograms in each of the subsequent Figures relate the distribution of magnitudes for each metric at each microphone to the descriptive statistics in the Table. There was significant electronic noise contamination at very high frequencies throughout the audio recordings. The contamination differed for each microphone channel. The contamination strongly influenced by the high-bark Loudness and the Sharpness, thus biasing the computed Annoyance metrics. As a result, filters including narrow notches and high-frequency taper were applied to the recordings prior to analysis.

The Unbiased Annoyance (UBA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 46. The Psychoacoustic Annoyance (PA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 47. The Category Scale of Annoyance (CSA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 48.

There is a clear difference in the means of the Unbiased Annoyance between the Barrier and No Barrier locations for both the higher and lower microphones. The same difference is seen in the Psychoacoustic Annoyance. Since the microphones at this site were stacked and share the same moderate distance to the roadway, the similarity it deviations of the means (slightly less than one standard deviation) may indicate a true difference in the metrics. However, it can be seen that the Barrier microphones have lower mean annoyance than do the No Barrier microphones; therefore, neither the UBA nor the PA substantiate an assumption of increased annoyance due to the presence of the barrier at this site.

There is no significant difference in the means of the Category Scale of Annoyance for either pair of microphones. The simple linear regression that forms CSA, and its derivation from product noise, do not apply well to highway traffic noise.

Table 6. Descriptive statistics of annoyance metrics, I-24.

Metric	Location	Mean	Std. Dev.	Skewness	Kurtosis
UBA	BarCom03	62.3	6.3	-0.036	-0.205
	NoBarCom05	67.0	6.3	0.005	0.625
	BarCom04	61.7	6.3	-0.048	-0.177
	NoBarCom06	67.0	6.2	0.082	0.651
PA	BarCom03	16.6	1.8	-0.091	-0.252
	NoBarCom05	17.9	1.8	-0.226	0.273
	BarCom04	17.4	2.0	0.127	-0.040
	NoBarCom06	19.0	1.9	-0.001	0.121
CSA	BarCom03	43.5	1.5	-0.052	-0.088
	NoBarCom05	42.3	1.5	0.213	0.586
	BarCom04	43.7	1.8	-0.011	-0.503

	NoBarCom06	44.2	1.7	0.083	0.826

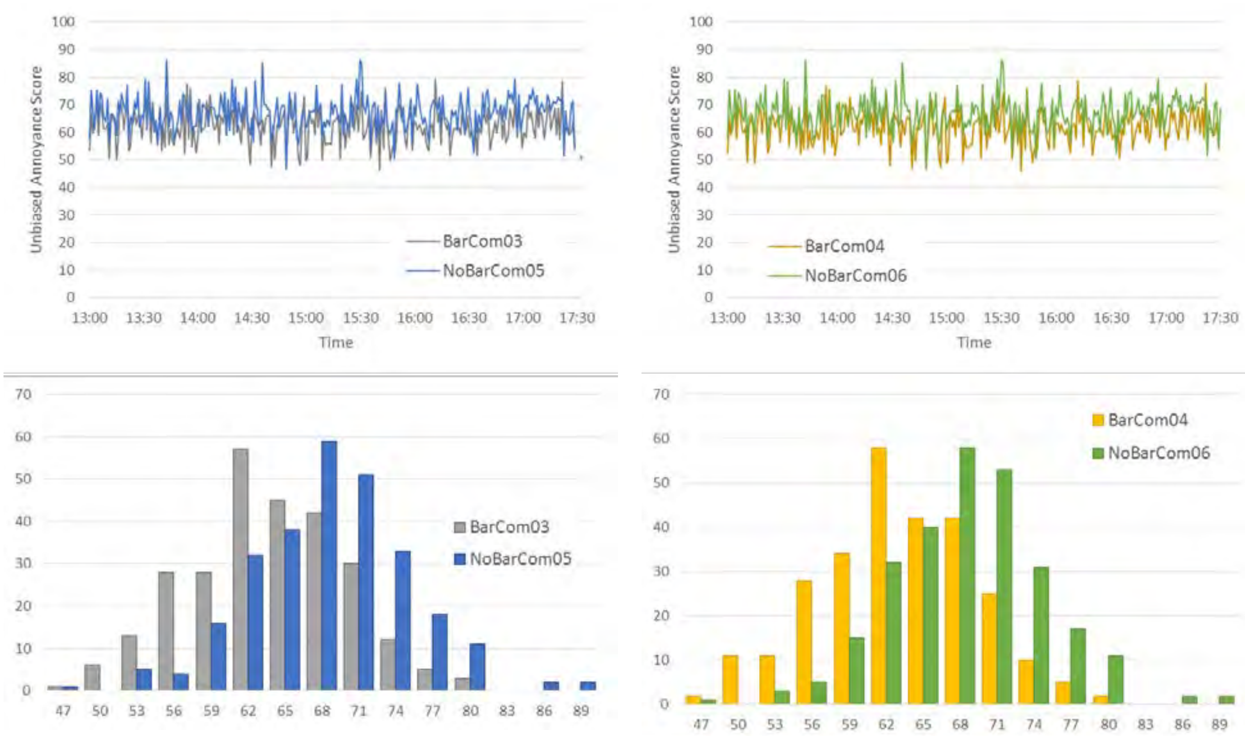


Figure 46. Unbiased annoyance metric vs. time and histograms, I-24.

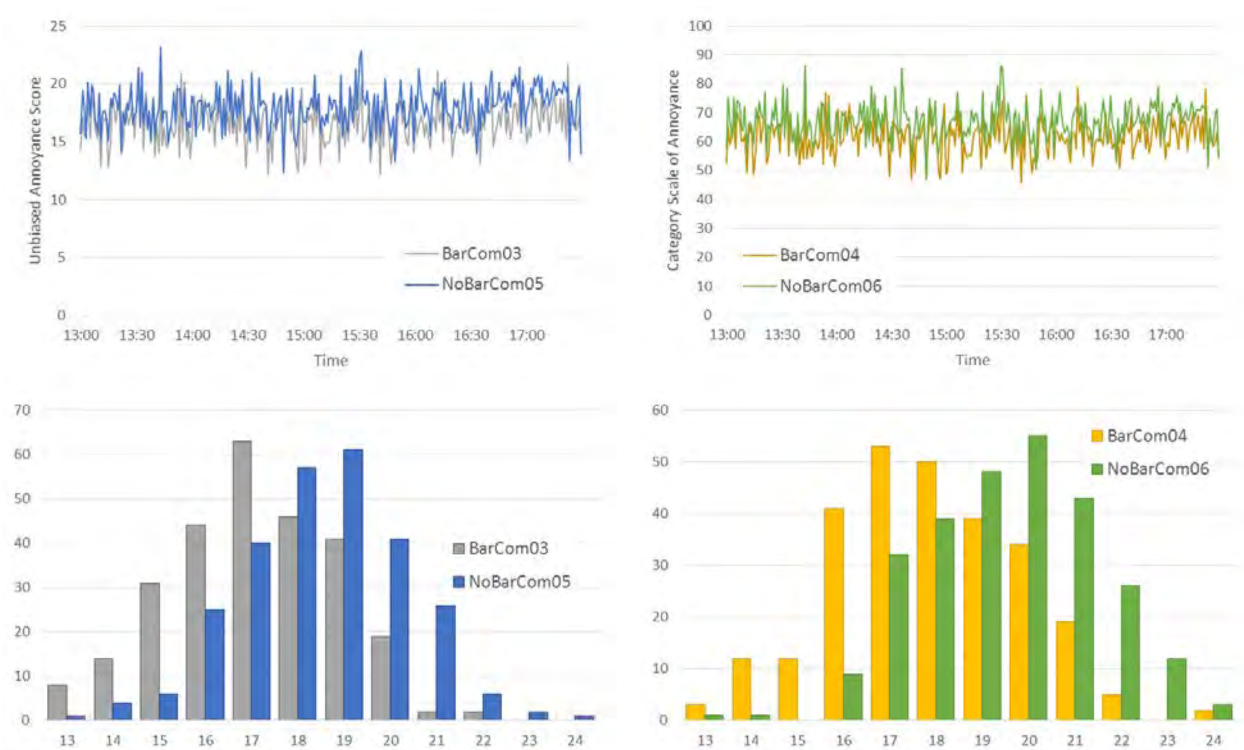


Figure 47. Psychoacoustic annoyance vs. time and histograms, I-24.

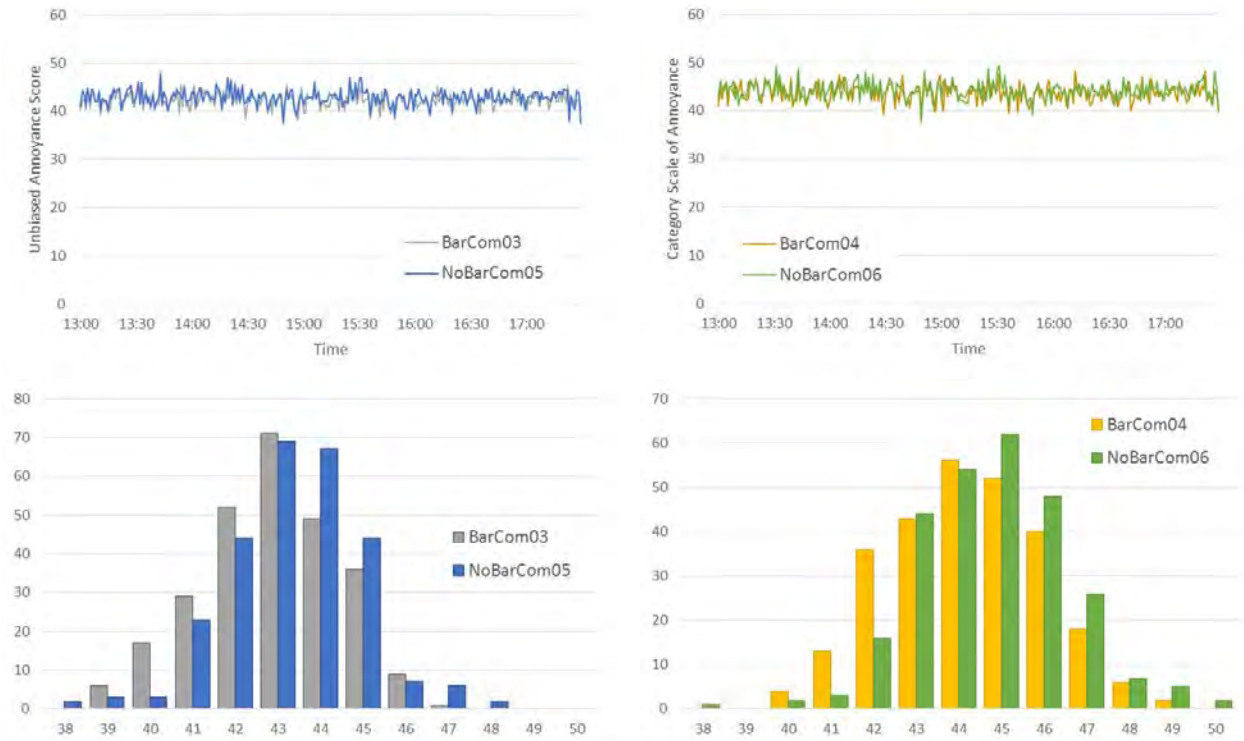


Figure 48. Category scale of annoyance vs. time and histograms, I-24.

CHAPTER B-4

Results - Briley Parkway (SR-155), Nashville, TN (Location BA-3)

The Briley Parkway ("Briley") noise measurements and traffic speed measurements began at 17:04 on August 14 and ended at 21:04. Operator error caused no video to be recorded. The weather was mostly calm and warm, with afternoon temperatures in the low-80 degree range, dropping into the low-70 degree range after dark. Winds were calm throughout the measurement period.

Only five sound level analyzers were deployed at the Briley location. The No Barrier reference microphone (NoBarRef02) was not deployed because the road was on a retaining wall that was too tall to locate a microphone safely at the needed height above the roadway, and a microphone could not be placed safely on the road-side of the barrier.

Because the Barrier and No Barrier sites were close together at the Briley location, it was felt that the No Barrier reference microphone was not essential for demonstrating source equivalence with the Barrier site. Also, within the FHWA Method, one use of the No Barrier reference microphone is to adjust the No Barrier community microphone levels by the difference between the Barrier and No Barrier reference sound levels. At the Briley location, the noise barrier is at the edge of a 10-ft wide shoulder. There was concern that any differences in the Barrier and No Barrier reference sound levels might be caused by sound reflections between truck trailer bodies and the noise barrier, not by differences in the noise sources themselves.

Figure 49 shows the microphone positions at the Briley location. Appendix C of the Final Report includes site photographs. Figure 50 shows cross-sections at the Barrier and No Barrier sites.

The microphone positions were as follows:

Table 7: Microphone positions for Briley Parkway site

Mic name	Side of road	Distance from Center of Near Travel lane (ft)	Height above roadway plane (ft)
BarRef01	EB	16	+18 (5 ft above top of barrier)
NoBarRef02	na	na	na
BarCom03	WB	91*	-14 (5 ft above ground)
NoBarCom05	WB	91*	-14 (30 ft above ground)
BarCom04	WB	91*	+11 (12 ft above ground)
NoBarCom06	WB	91*	+11 (37 ft above ground)

*To retaining wall, which was topped by a safety-shaped parapet at the edge of shoulder

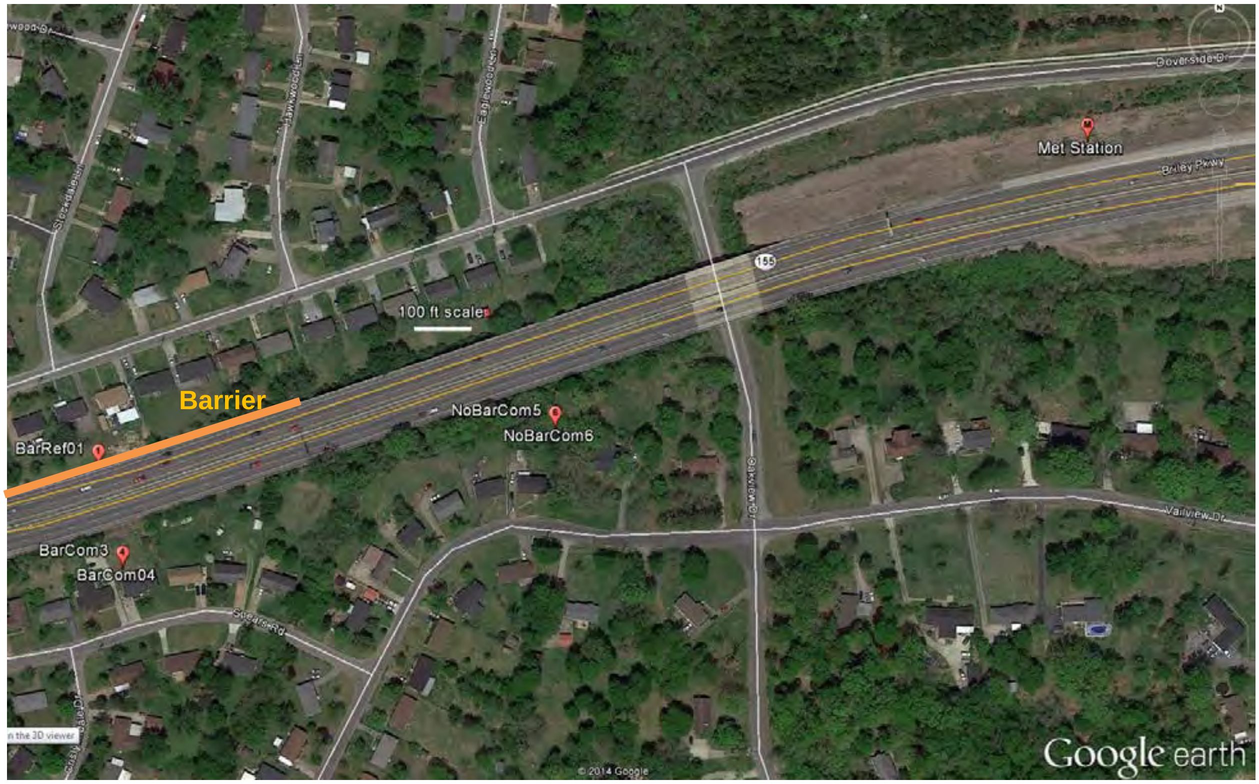


Figure 49. Briley microphone positions. (Source: Google Earth.)

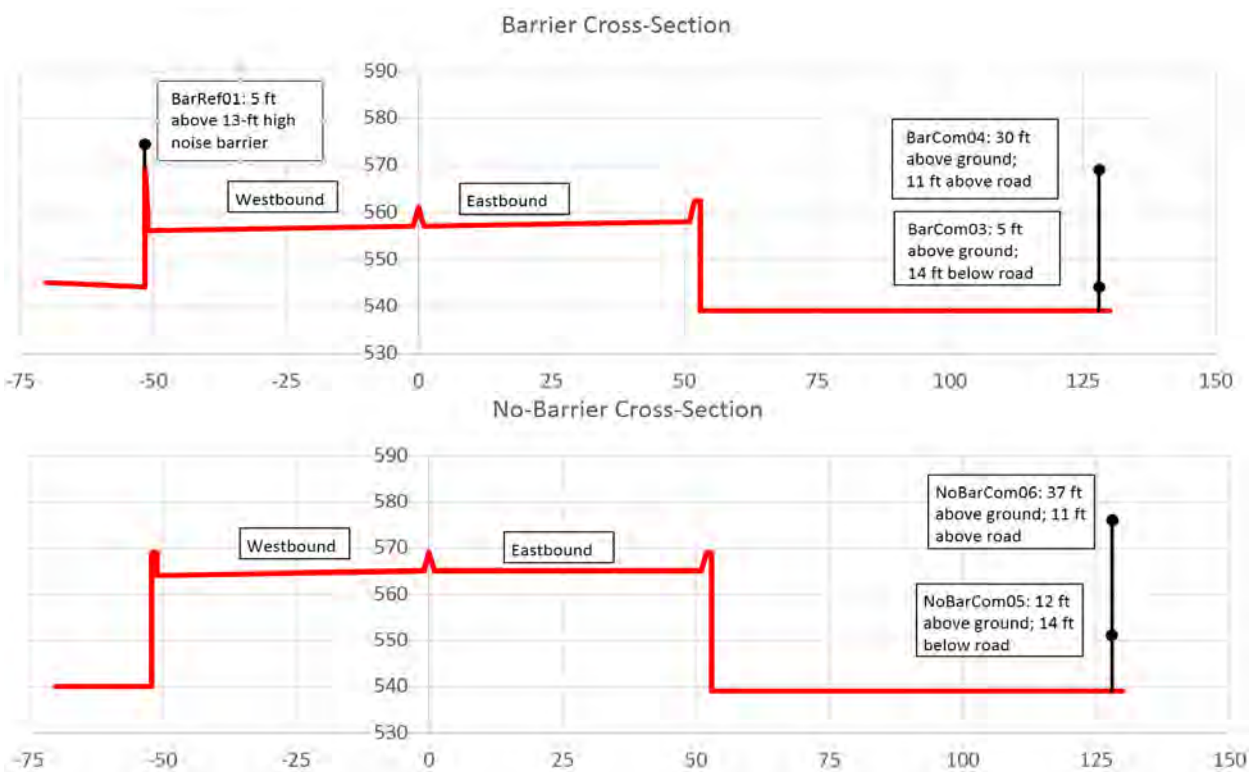


Figure 50. Cross-sections at the Briley Parkway Barrier (top) and No Barrier (bottom) sites.

Measurement Observations

Traffic was observed from an overpass about a half-mile west of the Barrier site. Automobiles and heavy trucks dominated the flow, while medium trucks, buses and motorcycles were infrequent. Speeds typically ranged from 55 to 60 mph. The westbound traffic (traveling from the No Barrier and Barrier sites) seemed to move slightly faster than the eastbound traffic (heading toward the Barrier and No Barrier sites).

Westbound traffic volumes appeared to be higher than eastbound volumes throughout the measurements, and lulls in eastbound traffic were not uncommon. Traffic was consistently free-flowing in both directions, and no incidents affecting the flow of traffic were observed. Heavy trucks used the outer lanes more frequently than the inner lanes.

Briley Parkway is elevated above the community by a retaining wall at both the Barrier and No Barrier sites. The BarCom03/04 and NoBarCom05/06 sites were closest to the eastbound traffic on Briley Parkway. The BarRef01 microphone was closer to the westbound Briley Parkway traffic. There was no microphone at NoBarRef02 due to the unmanageably tall microphone height that would have been required.

At the BarRef01 microphone, sources in the community were not having any effect at the microphone because of its closeness to the westbound traffic atop the barrier. While insect noise was audible at Observer 1’s position behind the barrier in the residential yard, there was no vegetation near the microphone, and the insect noise did not appear to interfere with traffic noise, based on observations of the sound level spectrum on the sound level analyzer display. All frequencies rose with traffic at the microphone and fell when traffic was absent. Individual and multiple truck passbys in both directions were distinguishable, by vehicle type and by direction, even though the vehicles could not be seen.

At the BarCom03/04 site, Observer 2 noted that while this section of the road was on top of a retaining wall and was elevated above the residential backyard by 20 ft or more, eastbound heavy trucks in the outer two lanes were typically audible and easily identified. Eastbound heavy trucks in the inside lane were not visible but were often identifiable. Louder eastbound automobiles were identifiable if they were in the outermost lane, closest to the microphones. Eastbound automobiles in the other two lanes were audible and were part of the overall noise environment but distinguishing individual vehicles in those lanes was difficult. Automobiles in the westbound lanes were occasionally audible but typically only identifiable only as an element of the overall noise environment. Louder westbound heavy trucks were identifiable. Exposure time to traffic noise coming from the east seemed longer than from the west, perhaps because once past the study sites, the road elevation to the east began to rise. Crickets were audible starting shortly after 18:00.

When Observer 3 moved from the NoBarCom05/06 site to the BarCom03/04 site halfway through the measurements, he noted that the westbound traffic noise was more audible than at NoBarCom05/06 site and that westbound heavy truck pass-bys could be more readily identified. Eastbound automobiles were also more easily identified that at the NoBarCom05/06 site. Part of the reason for them sounding louder is that the ground the observer was standing on was seven feet higher relative to Briley Parkway at the BarCom03/04 site than at the NoBarCom05/06 site, although the microphone heights were set relative to the roadway elevation at each site. Some eastbound vehicle tire noise was audible at the BarCom03/04 site, which was not the case at the NoBarCom05/06 site. Eastbound truck passby noise also seemed to last longer, perhaps due to the sparser traffic in the last two hours of the measurements. After the sun set, some of the noise from vehicle tires hitting the bridge expansion joint on Briley Parkway at the Oakview Road overpass, approximately 1,050 ft to the west of the overpass, could be heard at the BarCom03/04 site when traffic was light.

Starting at the NoBarCom05/06 site at the beginning of the measurements, Observer 3 noted that it was easy to identify eastbound passages of heavy trucks, although it could not always be determined if there was a single truck or multiple trucks passing. Trucks in the outside eastbound lane were visible from a position located 5 ft above the ground near NoBarCom05. In general, it was not that easy to distinguish when a westbound heavy truck passed by even when there was little eastbound traffic at the time. It also was not easy to identify westbound vehicles by their type. However, there were occasional periods at the NoBarCom05/06 site when no eastbound vehicles were passing and westbound vehicles were audible.

Also, noise was audible from vehicle tires hitting the bridge expansion joint on Briley Parkway at the Oakview Road overpass located approximately 300 ft from the mics. Observer 3 noted that there were two distinct sounds: a higher frequency “ba-dock” and a lower frequency “bunk”. While the vehicles hitting the joint could not be seen, it sounded as if these two sounds were caused, respectively, by lighter vehicles and heavy trucks.

After moving to the NoBarCom05/06 site, Observer 2 noted that eastbound heavy trucks in the outer lane were typically audible and easily identified. Heavy trucks in that lane could be seen through the trees and foliage. Eastbound heavy trucks in the two inside lanes were not visible but were often identifiable. Louder eastbound autos were identifiable if they were in the outermost lane. Eastbound automobiles in the other two lanes were occasionally audible but more often perceived as only part of the overall noise environment. Automobiles in the westbound lanes were not individually audible and typically only identifiable as an element of the overall noise environment. Louder westbound heavy trucks were identifiable but typically only because of elevated stack noise. The noise of vehicle tires hitting the bridge expansion joint at the Oakview Road overpass was audible and consistent to the east of the site.

From the early stages of the measurements at the No Barrier site, some 8 kHz insect noise could be heard in the vegetation between the mics and the barrier, at a level of around 43 dBZ at NoBarCom05. Around 17:37, some louder 5 kHz insect or frog noise could be heard intermittently coming from the wooded areas to the east of NoBarCom05/06 and toward the retaining wall, at a level of approximately 47 dBZ to 48 dBZ at NoBarCom06. In the last two hours of measurements, Observer 2 noted that the insect noise at NoBarCom05/06 was continuous and after 20:00, the frog noise became more continuous. Every few minutes, the insect/frog noise would get louder for part of a minute and then quiet down. This cycling became more frequent after 20:30.

Other audible noise sources at NoBarCom05/06 included commercial jets departing from Nashville International Airport, higher altitude flyovers, some bird chirping in the 2,500 Hz range at around 18:30, and a small dog barking (800-1,200 Hz) at around 18:33 to 18:35.

Measured Broadband Levels and Level Differences for Briley Parkway

The running L_{eq}(5min) for each site are presented in the following figures to give an overall picture of the measured levels, both in terms of unweighted sound pressure levels and A-weighted sound levels:

- BarRef01 (5 feet above the barrier top) - Figure 51 and Figure 52;
- BarCom03 and NoBarCom05 (14 feet below the roadway) - Figure 53 and Figure 54; and
- BarCom04 and NoBarCom06 (11 feet above the roadway) - Figure 55 and Figure 56.

In general, the figures show how the running L_{eq}(5min) decreased over time as the traffic decreased from the evening rush hour into the later evening. The unweighted sound pressure levels at BarCom03 are typically higher than at NoBarCom05, from a few tenths of a decibel to just over 2 dB. However, the A-weighted sound levels at BarCom03 are generally 1.5 dB to 2 dB *lower* than the NoBarCom05 levels in the first three hours of the measurement and 2 dB to 3 dB *lower* in the last hour. Figure 57 shows these level differences.

The results are different for the upper microphones. Figure 58 shows that the differences in the unweighted sound pressure levels at BarCom04 and NoBarCom06 vary from positive to negative over most of the measurement period, and becoming generally negative (NoBarCom06 *higher* than BarCom04) later in the evening. The A-weighted sound levels at NoBarCom06 tend to be slightly higher than at BarCom04 in the early part of the measurement, with the difference increasing as the measurement period moved later into the evening. Insect and frog noise from trees near NoBarCom05 and NoBarCom06 became major sound contributors starting early in the evening.

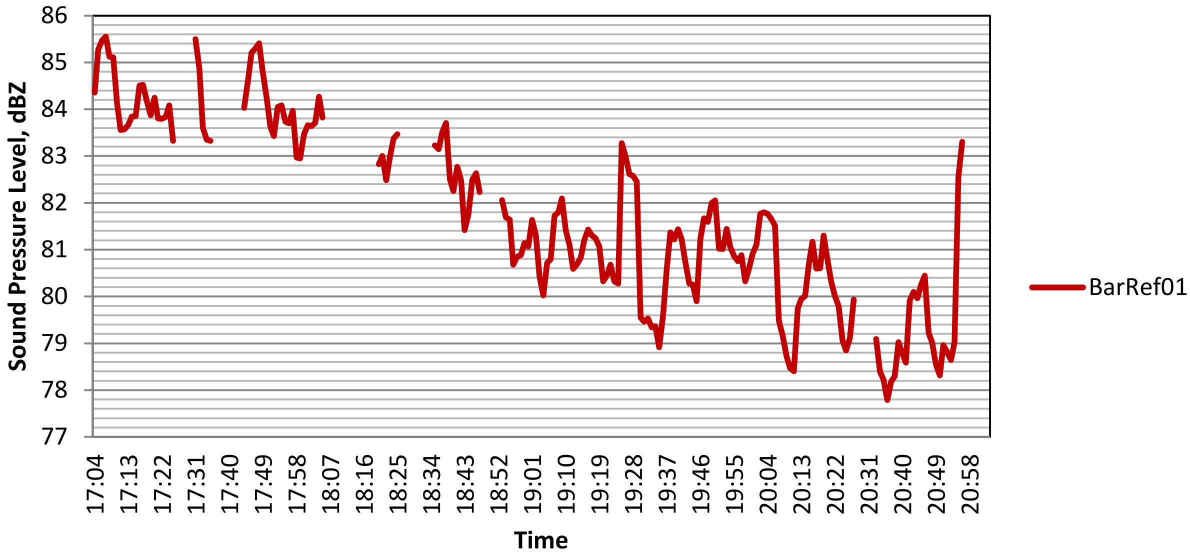


Figure 51. Running L_{eq}(5min), Briley, unweighted sound pressure level, dBZ, BarRef01.

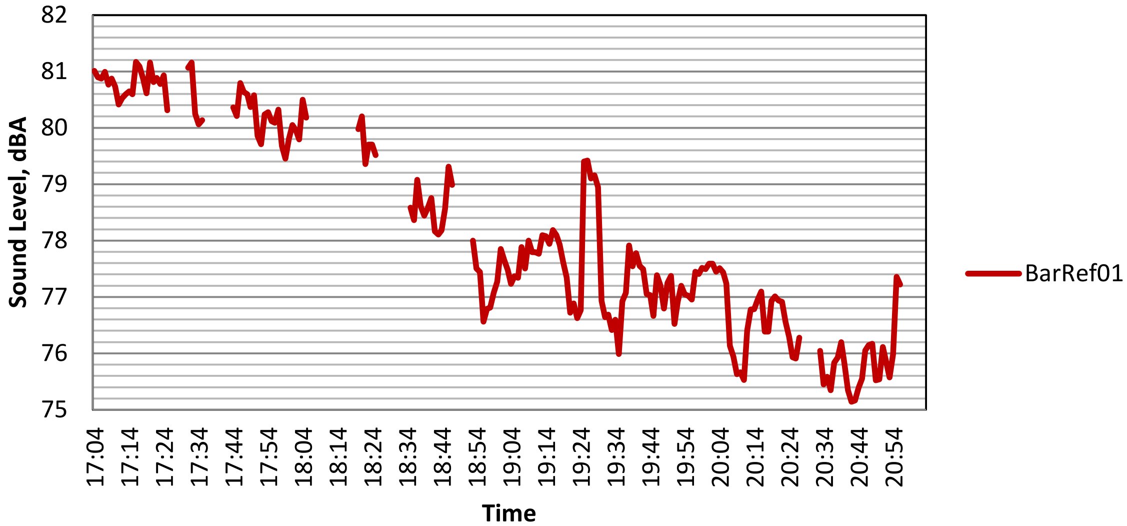


Figure 52. Running L_{eq}(5min), Briley, A-weighted sound level, dBA, BarRef01.

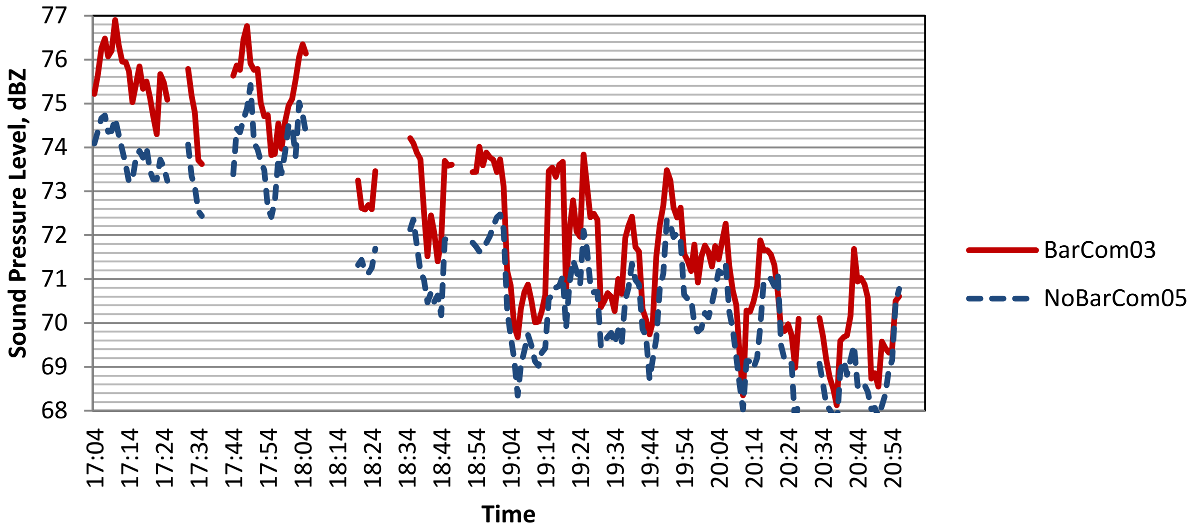


Figure 53. Running L$_{eq}$(5min), Briley, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

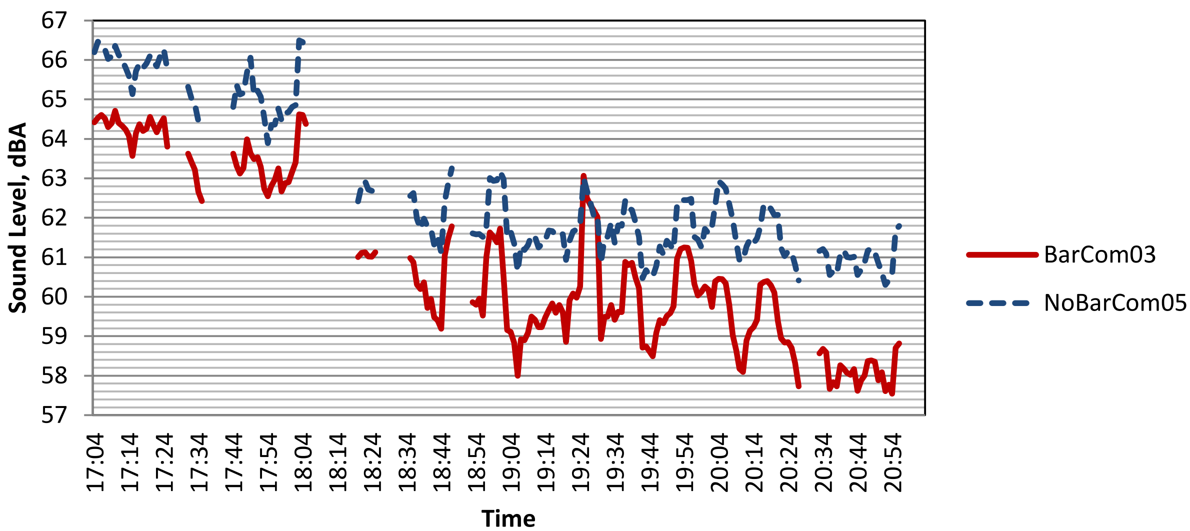


Figure 54. Running L$_{eq}$(5min), Briley, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

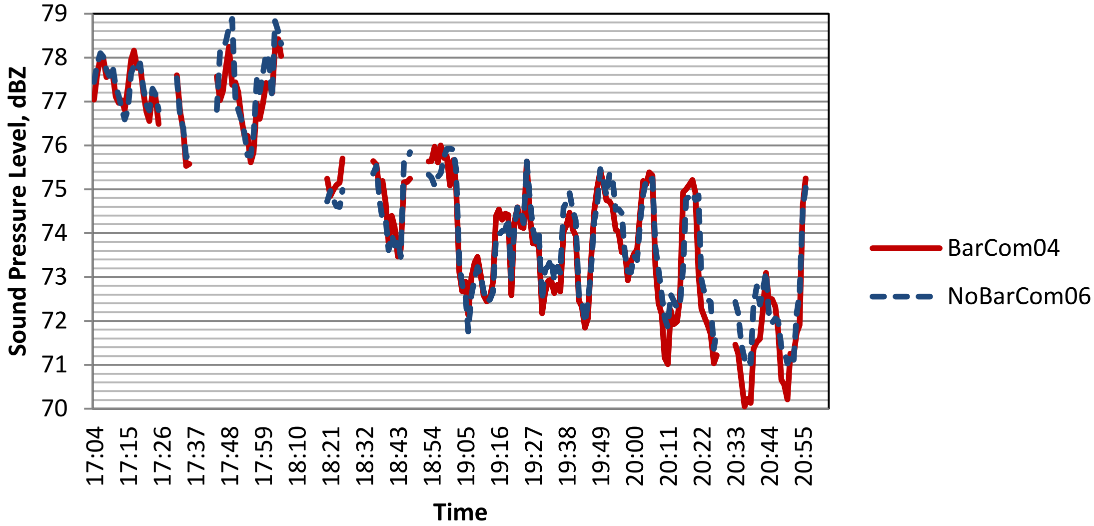


Figure 55. Running L_{eq}(5min), Briley, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

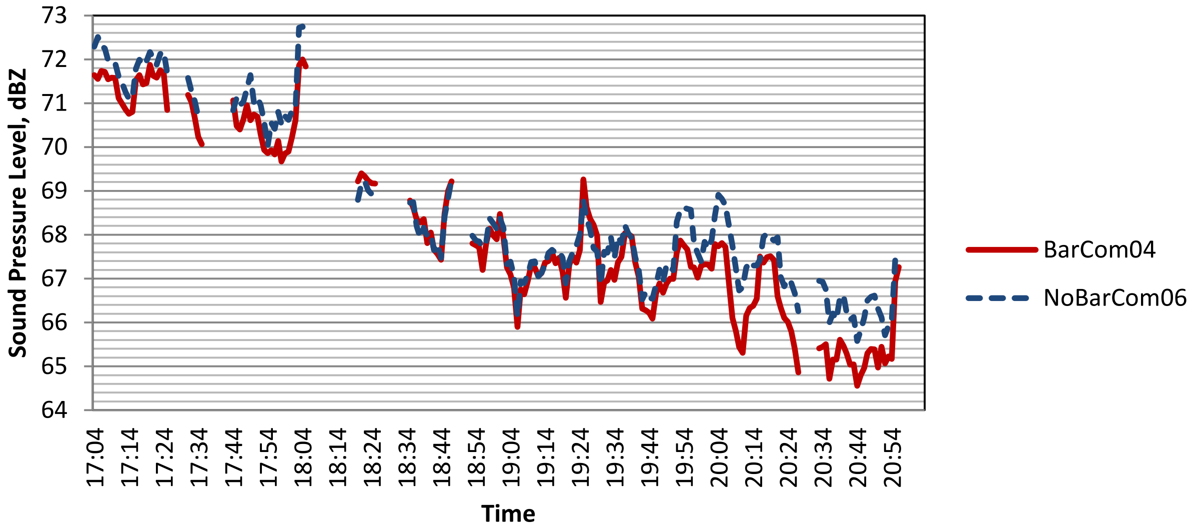


Figure 56. Running L_{eq}(5min), Briley, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

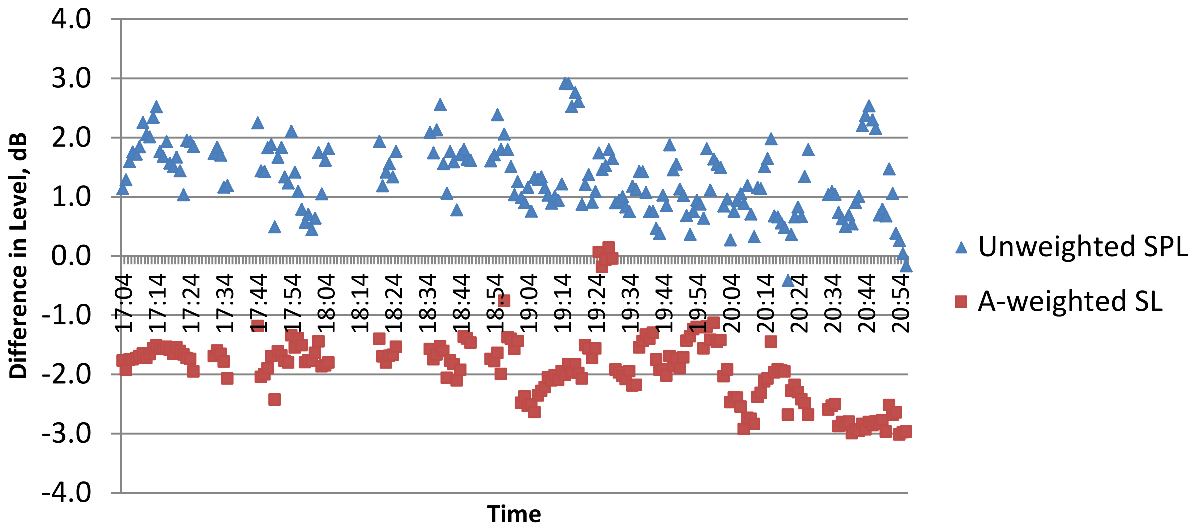


Figure 57. Difference in running L_{eq}(5min), BarCom03 minus NoBarCom05, Briley Parkway, dB

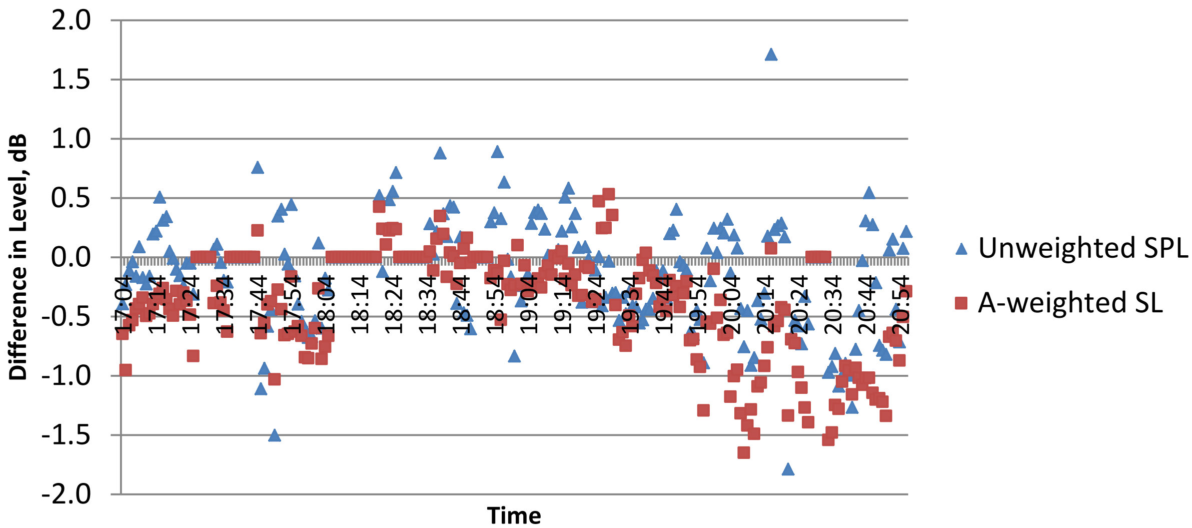


Figure 58. Difference in running L_{eq}(5min), BarCom04 minus NoBarCom06, Briley Parkway, dB

Data Analysis for Briley Parkway - FHWA Method

All of the Briley Parkway data was in the Calm wind class and in the Lapse, Neutral or Inversion temperature gradient classes. Each of the four Calm Lapse groups had three equivalent 5-minute periods. The four Calm Neutral groups had five or six equivalent periods. The thirty-one Calm Inversion groups each had from three to seven equivalent 5-minute periods.

Figure 59 shows the starting times for the 5-minute periods in the Calm Lapse groups, Figure 60 shows the period starting times for the Calm Neutral groups, and Figure 61 shows the starting times for the Calm Inversion groups' periods. As with the I-24 data, many of these groups shared one or more of the 5-minute periods although none of the groups had overlapping 5-minute periods within them.

Group ID	Starting Time of 5-minute Periods							
	17:04	17:09	17:14	17:19	17:08	17:13	17:17	17:18
CLG-1-1				■	■	■		
CLG-1-2			■	■	■			
CLG-2-1	■	■					■	
CLG-2-2	■	■						■

Figure 59. Equivalent 5-minute periods for Calm Lapse groups at Briley Parkway.

Group ID	Starting Time of 5-minute Periods							
	17:44	17:49	17:54	18:21	17:25	17:33	17:53	17:45
CNG-1-1	■	■	■	■	■	■		
CNG-1-2	■	■		■	■	■	■	
CNG-1-3			■	■	■	■		■
CNG-1-4				■	■	■	■	■

Figure 60. Equivalent 5-minute periods for Calm Neutral groups at Briley Parkway.

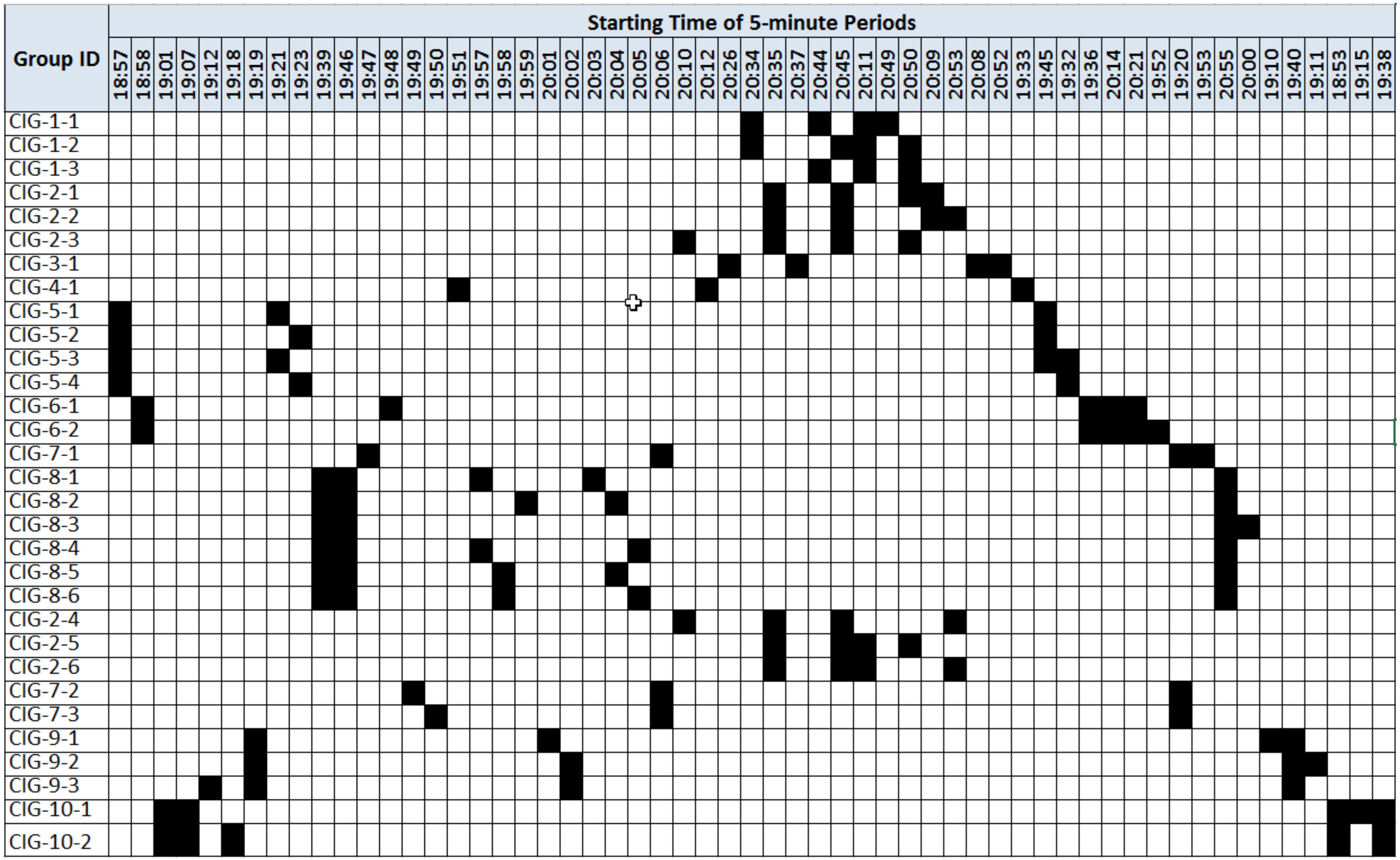


Figure 61. Equivalent 5-minute periods for Calm Inversion groups at Briley Parkway.

Calm Lapse Class

Figure 62 shows an example of the averages of the sound level differences across all of the Calm Lapse groups.

The lower graph of Figure 62 compares the upper microphones at the Briley Barrier and No Barrier sites: BarCom04 and NoBarCom06. These microphones were elevated substantially above the existing ground to be positioned approximately 11 feet above the elevated roadway surface. There was also a standard-height concrete safety-shape parapet wall atop the highway retaining wall in both areas. The lower graph compares the two lower microphones at the Barrier and No Barrier sites: BarCom03 and NoBarCom05. These microphones were approximately 14 feet below the roadway surface in the residential backyards adjacent to the roadway.

These two graphs show substantially different pictures of the differences in levels at the Barrier and No Barrier sites. Part of the reason for these differences could be the fact that the upper microphones were elevated above the roadway surface while the lower microphones were below the roadway surface. As a result, the upper microphones had a clear view of the noise barrier and all of the traffic in both directions even though there was blockage of much of the tire noise by the parapet wall and the concrete median barrier.

In contrast, the lower microphones were deep in the shadow zone of the parapet atop the Parkway retaining wall. At these positions, the upper halves of the near-lane eastbound heavy trucks could be seen by the microphones, and portions of the heavy trucks in the other eastbound lanes may have been visible from these microphones. No westbound traffic was visible. Being deep in the shadow zones, these microphones would experience substantial attenuation of any high-frequency noise coming from either the Barrier or the No Barrier sites' traffic. Likewise, any localized noise from insects or tree frogs would be much more audible because of the shielding of the traffic noise than at the elevated microphones. Also, the insect and tree frog noise was louder at the No Barrier site due to the presence of nearby trees and ground vegetation, which were not present at the Barrier site, although cricket noise could still be heard coming from the residential backyard lawn at the Barrier site.

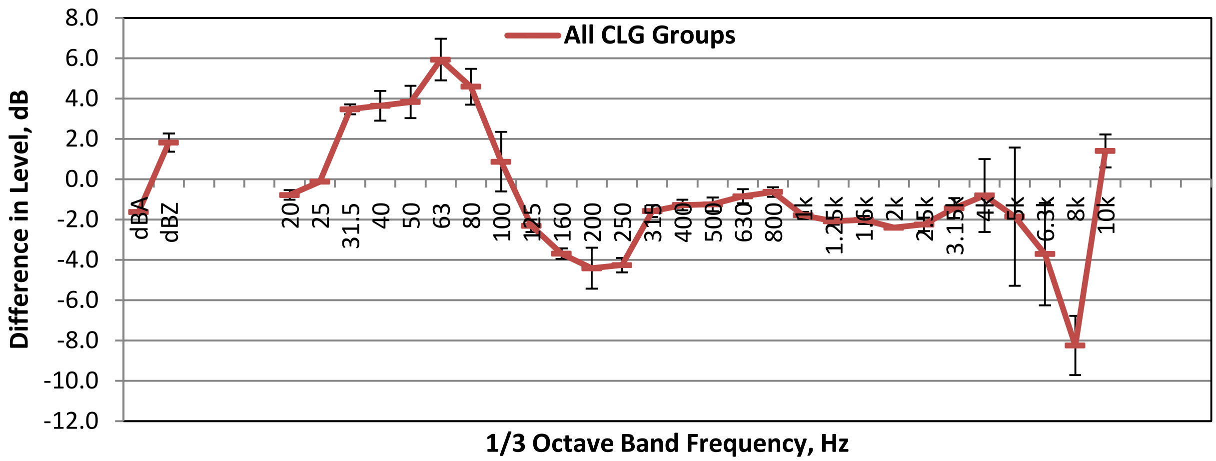
The above factors may help to explain the following differences in the sound levels at the Barrier and No Barrier sites as well as the differences between the upper and lower microphones.

At the upper microphones, as shown in the lower graph in Figure 62, the BarCom04 levels were higher than the NoBarCom06 levels in the 80 Hz band by approximately 1.5 dB and the bands from 2 kHz to 6.3 kHz by a range of 1 dB to 5 dB (at 5 kHz). The BarCom04 levels were also 7 dB higher in the 10 kHz band, a very high frequency not usually associated with traffic noise. However the raw 1-second sound level data showed that heavy truck passbys did indeed occasionally cause an increase in this band (along with the lower bands). It is not clear what truck noise sources might produce sound levels in these high frequencies.

The NoBarCom06 levels were *higher* than the BarCom04 levels in the 31.5 Hz and 40 Hz bands by 2 dB and 1 dB, respectively. The NoBarCom06 levels were also higher from 250 Hz through 1.25 kHz by a range of 0.5 dB to 1.5 dB. The reason for the higher levels at NoBarCom06 in these mid-range frequencies is not apparent. The No Barrier level was also louder in the 8 kHz band, which is attributed to insect noise in the trees and to some extent in the grass.

The upper graph in Figure 62 – for the lower microphone heights – shows a different pattern than for the upper microphones in the lower graph. BarCom03 shows higher levels than NoBarCom05 in the

31.5 Hz through 100 Hz bands by as much as 6 dB at 63 Hz. However, BarCom03 shows *lower* levels than NoBarCom05 for the rest of the frequencies up through 8 kHz. The differences range is from less than a decibel at 800 Hz up to 4.5 dB at 200 Hz and 250 Hz, and 8 dB at 8 kHz. The higher levels at NoBarCom06 at 5 kHz and above are likely due to the insect noise and tree frog noise in the No Barrier area.



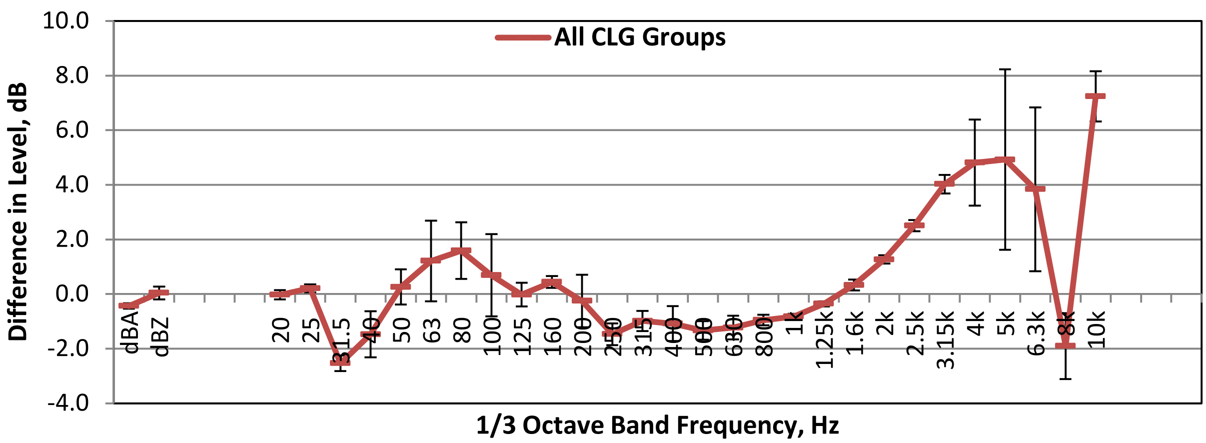


Figure 62. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Lapse groups, Briley Parkway.

Calm Neutral Class

Next is an example for one of the Calm Neutral groups at Briley. First, to give some perspective on the levels, Figure 63 and Figure 64 present the sound pressure level spectra for, respectively, BarCom03/NoBarCom05 and BarCom04/NoBarCom06 for one of the 5-minute periods in the group chosen as typical.

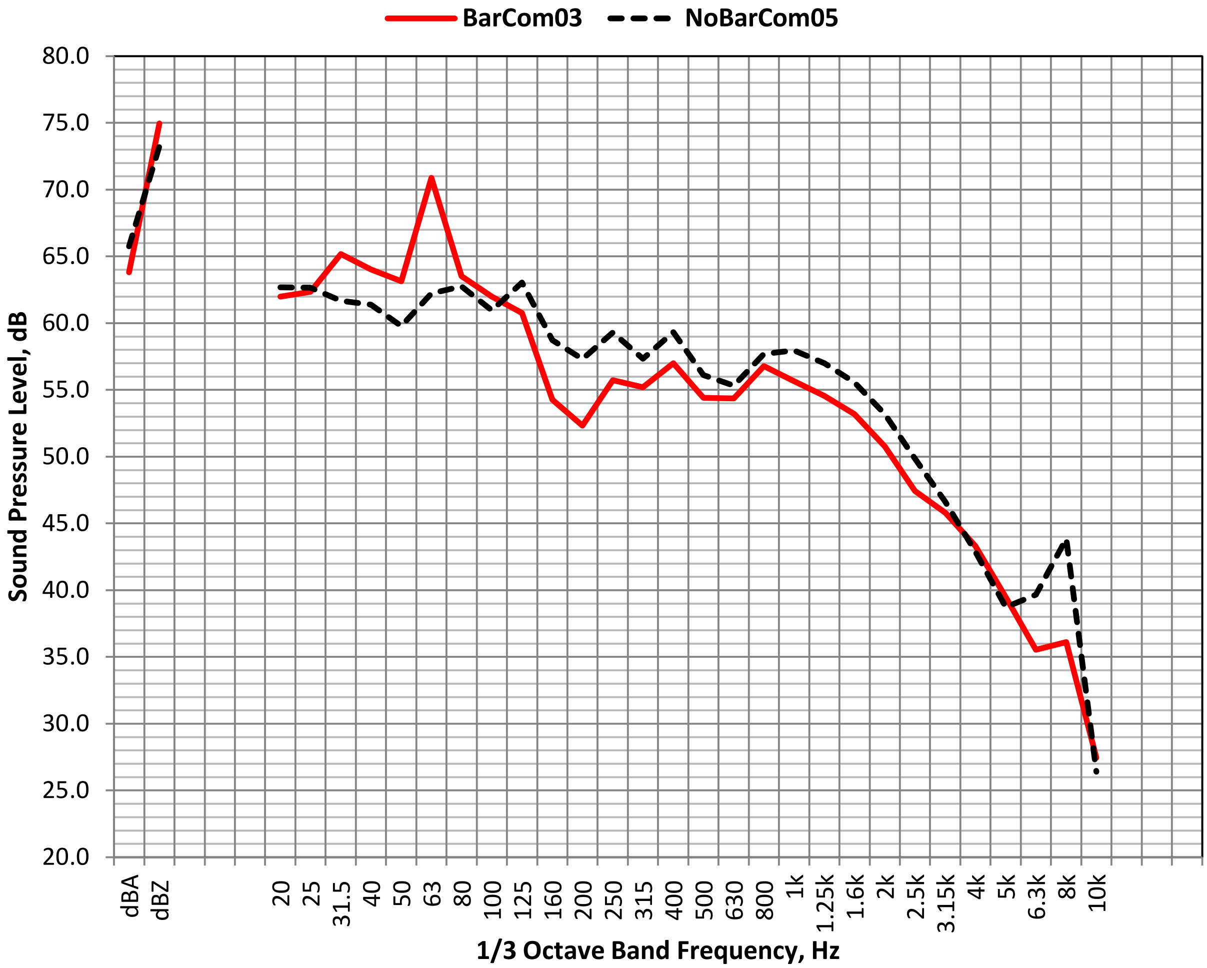


Figure 63. Sample sound pressure level spectra for BarCom03 and NoBarCom05, I-24, Calm Neutral group CNG-1-4, 17:25-17:30 (L_{eq}(5min), dBZ).

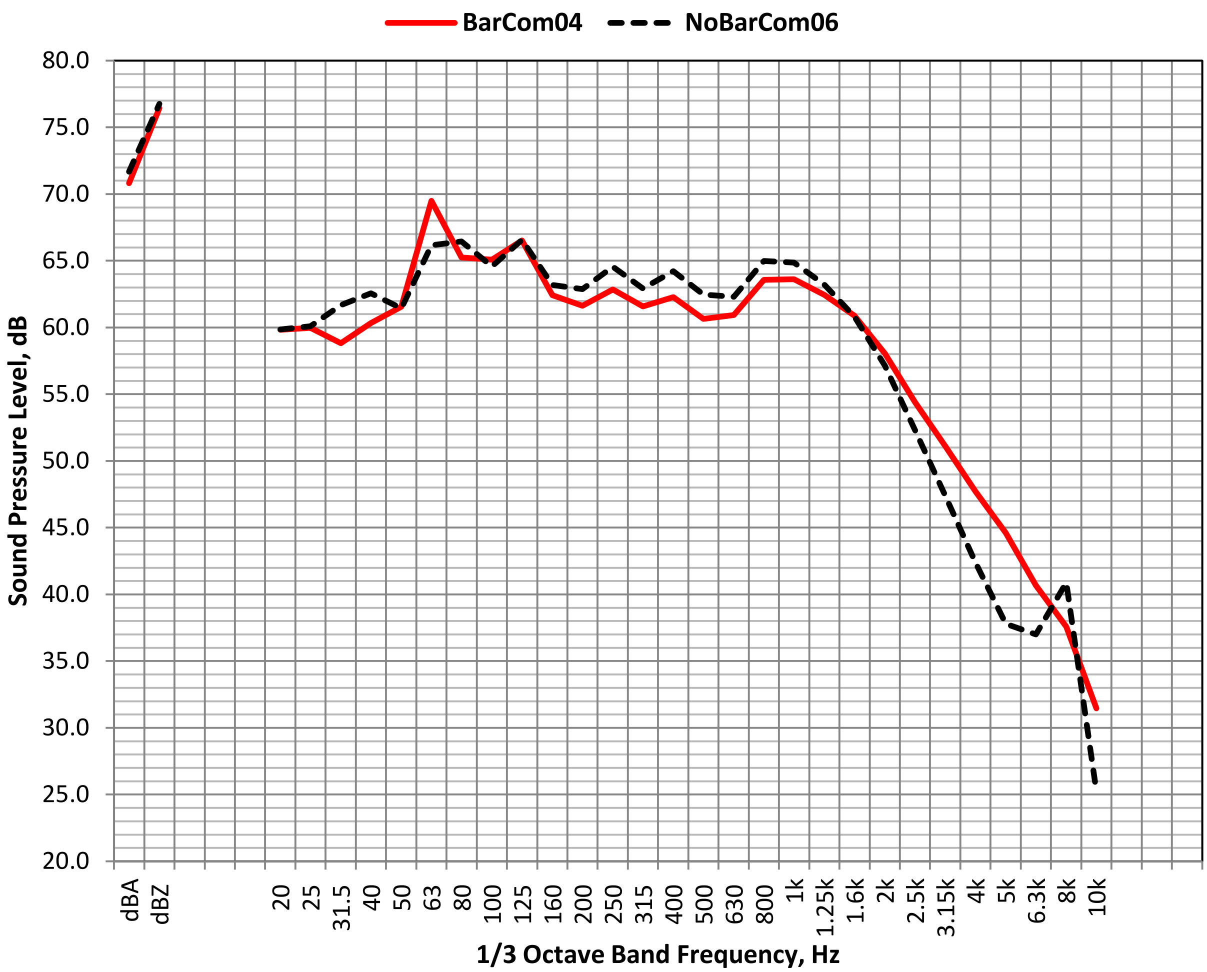


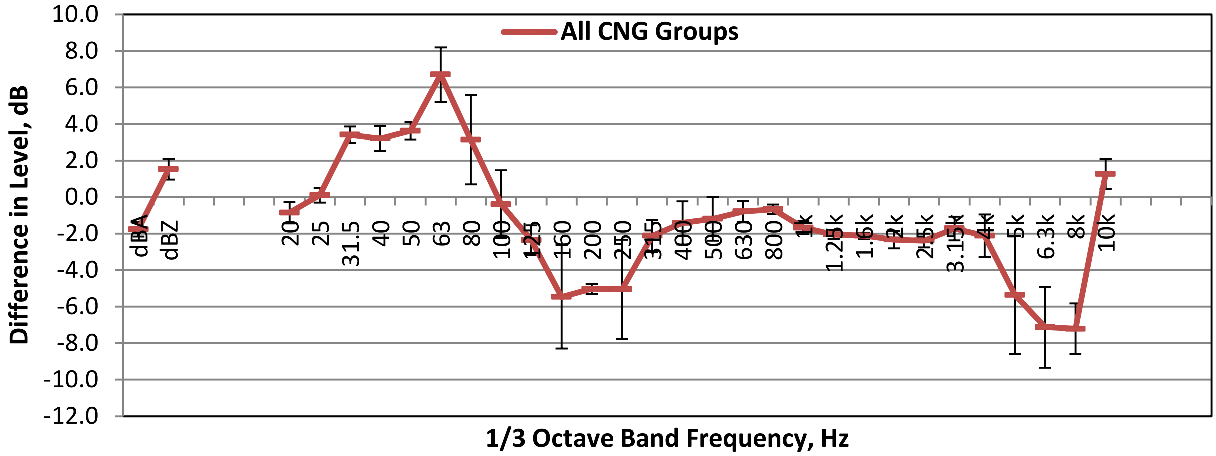
Figure 64. Sample sound pressure level spectra for BarCom04 and NoBarCom06, I-24, Calm Neutral group CNG-1-4, 17:25-17:30 (L_{eq}(5min), dBZ).

Figure 65 presents the averages of the sound level differences for all of the Calm Neutral groups. For the Calm Neutral meteorological class, the patterns of the differences for the lower microphones and upper microphones were similar to those for the Calm Lapse groups, with some differences.

For the Calm Neutral class, the levels at the BarCom04 upper microphone were higher than the NoBarCom06 upper microphone levels in the 63 Hz band and the bands from 1.6 kHz through 6.3 kHz – similar to the Calm Lapse class – with the increases being slightly higher in the 63 Hz band (2.5 dB vs. 1.5 dB). The BarCom04 levels were lower than the NoBarCom06 levels in the 31.5 Hz and 40 Hz bands, in the range of 160 Hz to 1.25 kHz (by 0.5 dB to 2 dB), and at 8 kHz (again due to insect noise at the No Barrier site). The BarCom04 levels were also 6 dB higher in the 10 kHz band.

The upper graph is for the lower microphone heights for the Calm Neutral class. As with the Calm Lapse class, the BarCom03 levels were higher than those at NoBarCom05 in the bands from 31.5 Hz through 80 Hz, by as much as 6.5 dB at 63 Hz. With the exception of a slight difference at the 10 kHz band, the levels in the rest of the bands were lower at BarCom03 compared to NoBarCom05, ranging from as little as less than a decibel at 800 Hz to approximately 5 dB at 160 Hz, 200 Hz and 250 Hz (as well as by 7 dB at 8 kHz, which was due to the insect noise at the No Barrier site).

Noise from vehicles hitting the bridge expansion joint at the Oak View Drive overpass several hundred feet east of the No Barrier site was audible at this site. However, this noise was very short in duration and not excessively loud such that the noise from the immediate passbys of vehicles dominated. It was initially speculated that the reason for the higher levels at NoBarCom05 and NoBarCom06 in the 160 Hz to 250 Hz bands might have been caused by tires striking the expansion joint. However, further examination of the 1-second sound level data and listening to the audio files demonstrated that this expansion joint noise was not a significant contributor to the 1-minute or 5-minute L_{eq} values.



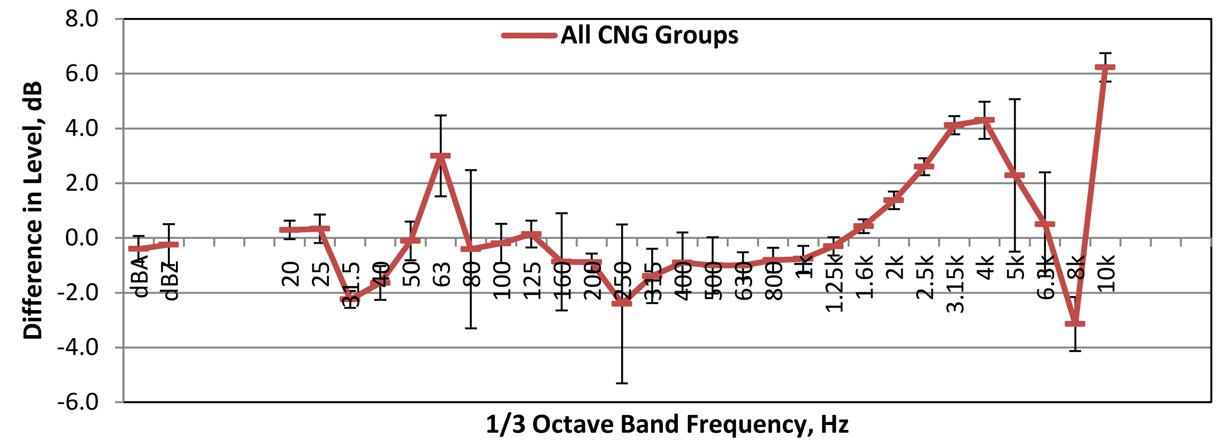


Figure 65. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Neutral groups, Briley Parkway.

Calm Inversion Class

The last set of results for Briley is for a sample from the Calm Inversion group. Figure 66 and Figure 67 show the spectral plots for BarCom03 and NoBarCom05 and then BarCom04 and NoBarCom06.

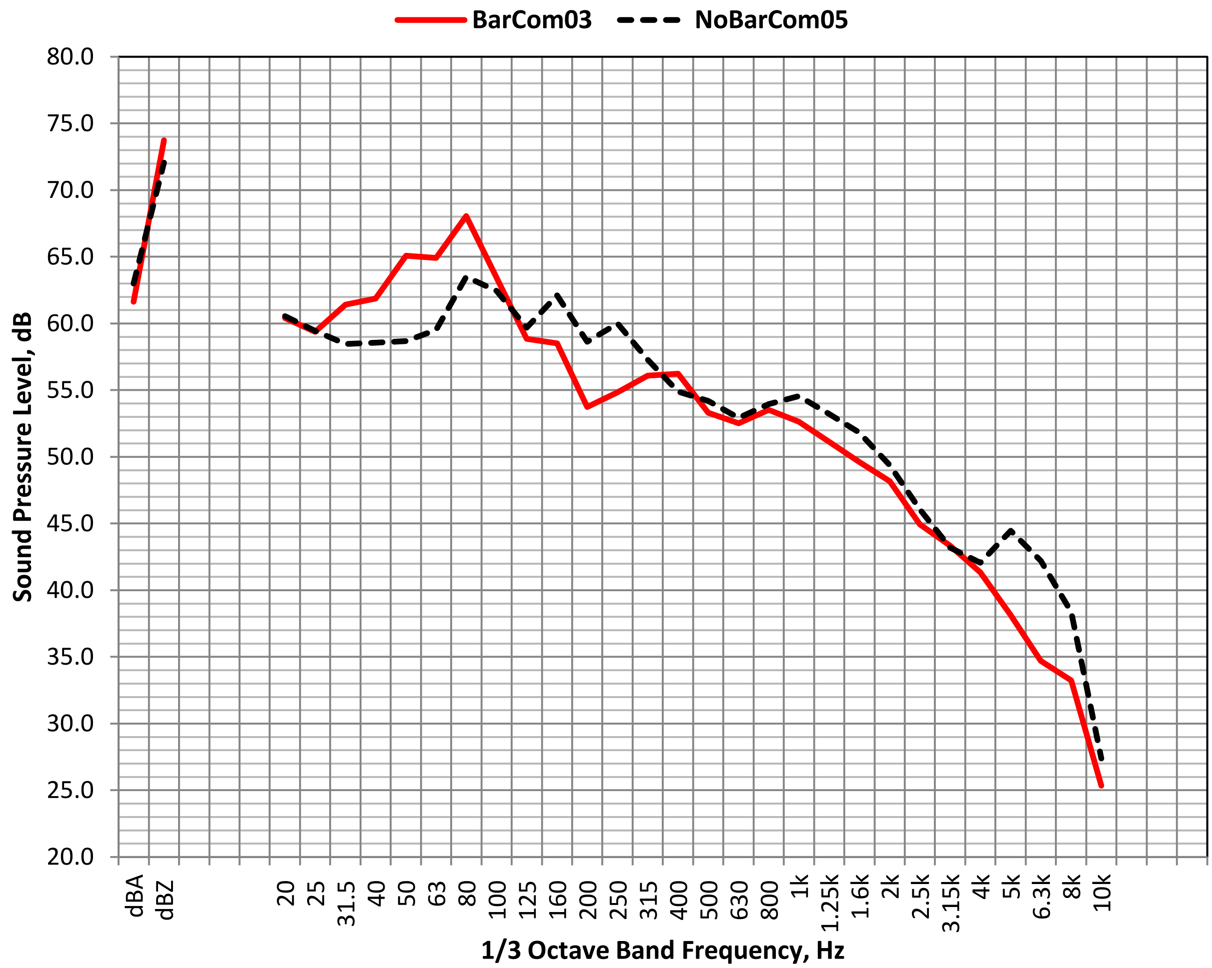


Figure 66. Sample Sound Pressure Level Spectra for BarCom03 and NoBarCom05, Briley, Calm Inversion Group CIG-6-1, 18:58-19:03 (L_{eq}(5min), dBZ)

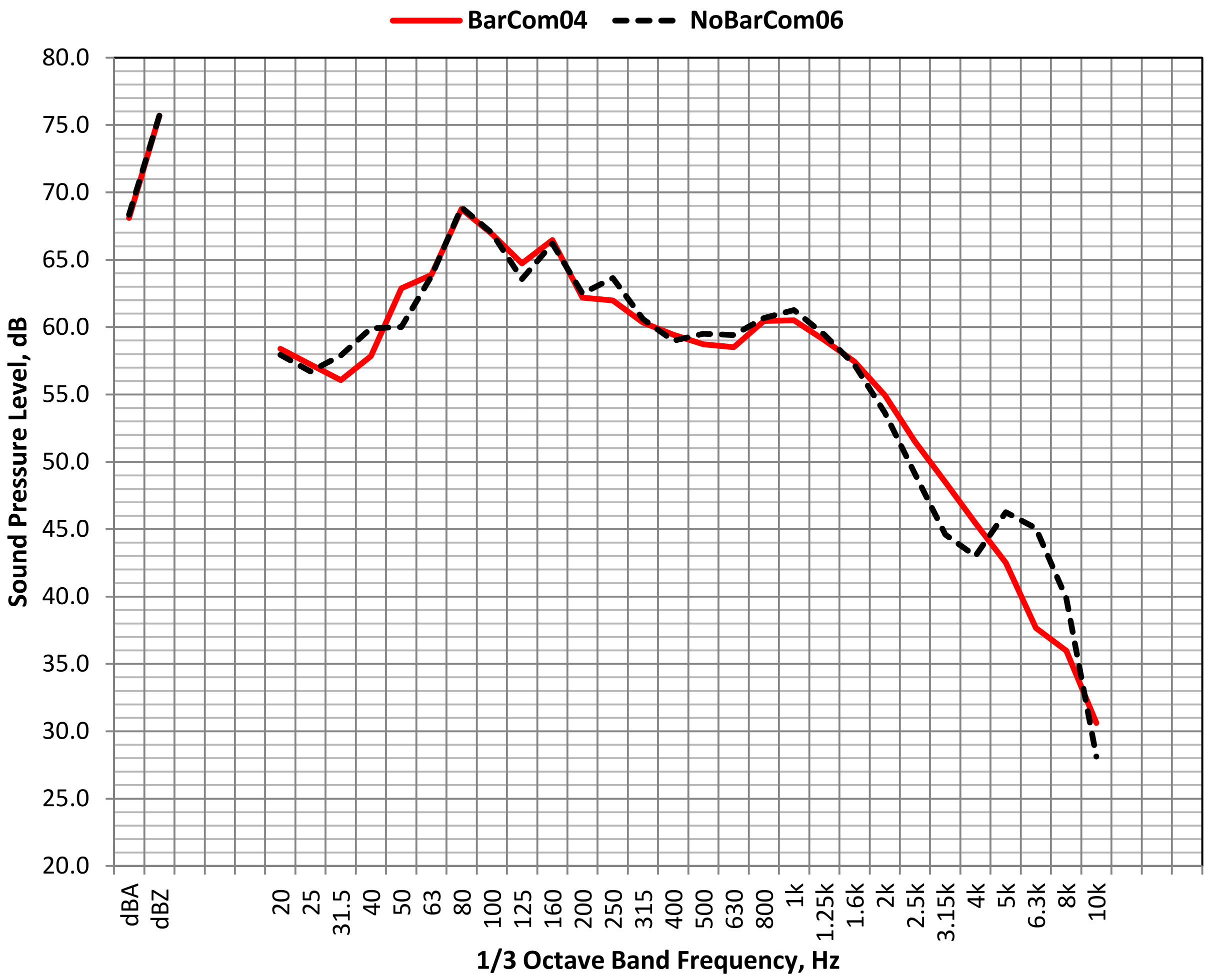
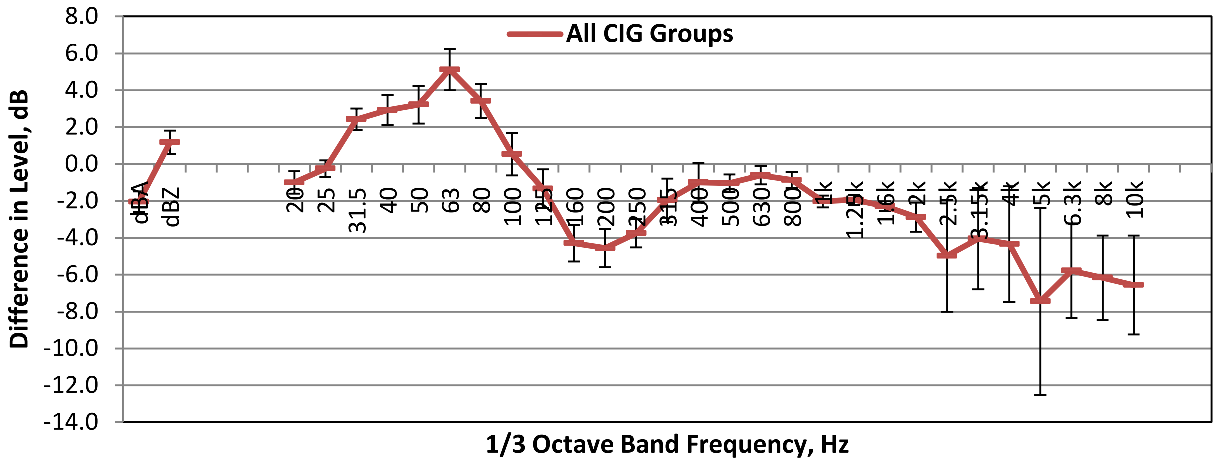


Figure 67. Sample Sound Pressure Level Spectra for BarCom04 and NoBarCom06, Briley, Calm Inversion Group CIG-6-1, 18:58-19:03 (L_{eq}(5min), dBZ)

Figure 68 compares the levels at the Barrier and No Barrier sites for the averages of all of the differences for the Calm Inversion groups. As with the other figures, the upper graph is for the upper microphones in BarCom04 and NoBarCom06 and the lower graph is for the lower microphone in BarCom03 and NoBarCom05. The average sound level difference line and error bars represent the averages of the differences in five equivalent 5-minute periods.

For this Calm Inversion group, the patterns of the differences for the upper microphones (the lower graph) are similar to those for the Calm Neutral Group, with some differences: (1) at 63 Hz, BarCom04 is only 1 dB higher than NoBarCom06 (2.5 dB for the Calm Neutral example); (2) in the 2 kHz to 4 kHz range, the BarCom04 levels are not as much higher than NoBarCom06 as they were in the Calm Neutral example – for example, only 1.5 dB higher at 4 kHz, compared to just over 4 dB in the Calm Neutral example; (3) in the 5 kHz and 6.3 kHz bands, the NoBarCom06 levels are slightly higher than at BarCom04, whereas in the Calm Neutral example the BarCom04 levels were 3 dB and 1 dB higher, respectively, than NoBarCom06; and (4) at 10 kHz, the NoBarCom06 level was 5 dB higher than BarCom04, compared to being 6 dB lower in the Calm Neutral example.

The upper graph in Figure 68 is for the lower microphones for the Calm Inversion example. The BarCom03 levels are 2 dB to 5 dB higher than the NoBarCom05 levels in the bands from 31.5 Hz to 80 Hz, which is roughly a decibel less than in the Calm Neutral example. The NoBarCom05 levels are up to 5 dB higher than the BarCom03 levels in the bands at and above 125 Hz, being 5 dB higher at 200 Hz and 2 dB to 3 dB higher from 1 kHz to 2 kHz, similar to the Calm Neutral example. At 2.5 kHz, the NoBarCom05 level is 5 dB greater than BarCom03, compared to 2.5 dB in the Calm Neutral example. Above 4 kHz, NoBarCom05 levels are 6 dB to 7.5 dB greater than those for BarCom03, largely attributable to insect and tree frog noise at the No Barrier site.



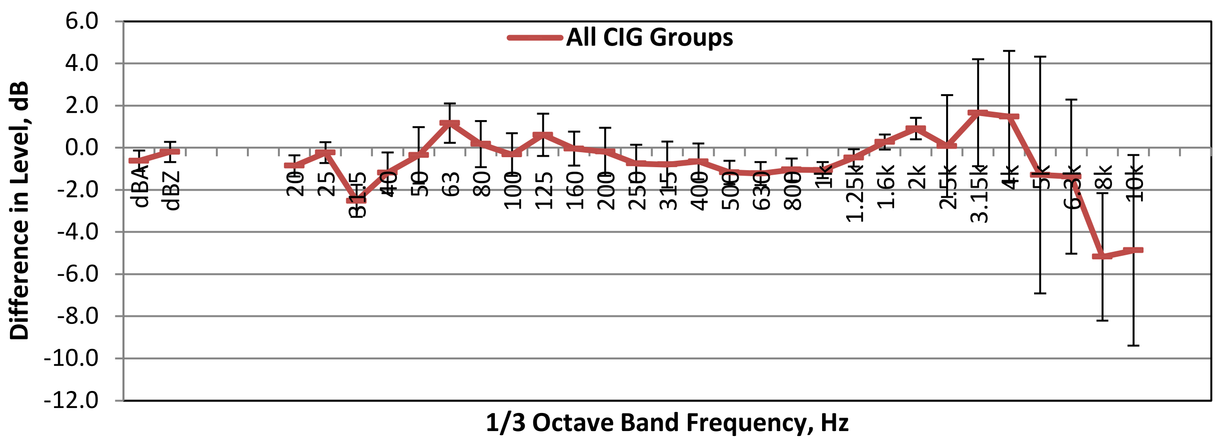


Figure 68. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Inversion groups, Briley Parkway.

Additional Sound Level Analysis for Briley Parkway – L_n Descriptors

Because of issues with loud insect noise at the No Barrier site, the L_n analysis was not done at the Briley site.

Data Analysis for Briley Parkway - Spectrograms

Spectrograms show the frequency content of sound as a function of time. This section presents results of the spectrogram analysis. As with the FHWA Method data analysis, for the spectrogram analysis, data were examined in the Calm Lapse group, Calm Neutral group, and the Calm Inversion Group, the prevalent meteorological conditions at the Briley site. Data were examined in 5-minute time blocks as well as vehicle pass-by events.

Shown in this section are two example pass-by events. Figure 69 shows a heavy truck traveling eastbound, and Figure 70 also shows a heavy truck traveling eastbound. Note that spectrograms are shown only for those on the community side of the highway, since there were not comparable reference positions.

Examination of the vehicle pass-by events reveals that the No Barrier site has amplified sound levels as compared to the Barrier site. This can be seen as an increase in sound levels over many frequencies. Several 5-minute data blocks were examined and support this finding. Since the amplification is at the No Barrier site, no conclusions can be drawn as to the effect of the barrier when comparing sites.

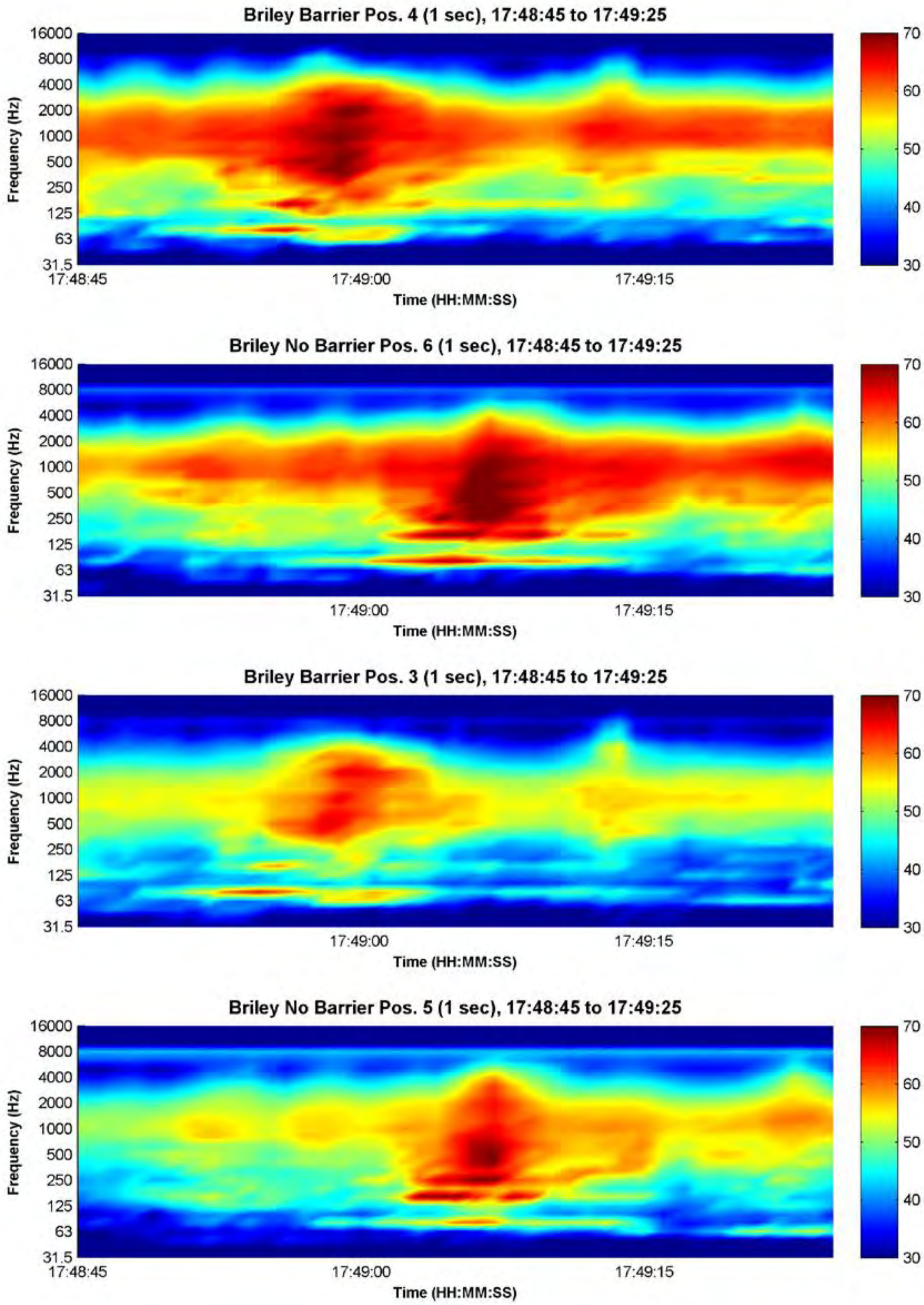


Figure 69. Spectrogram for a heavy truck eastbound (example 1); top to bottom: high mics (BarCom04 and NoBarCom06), low mics (BarCom03 and NoBarCom05); Briley.

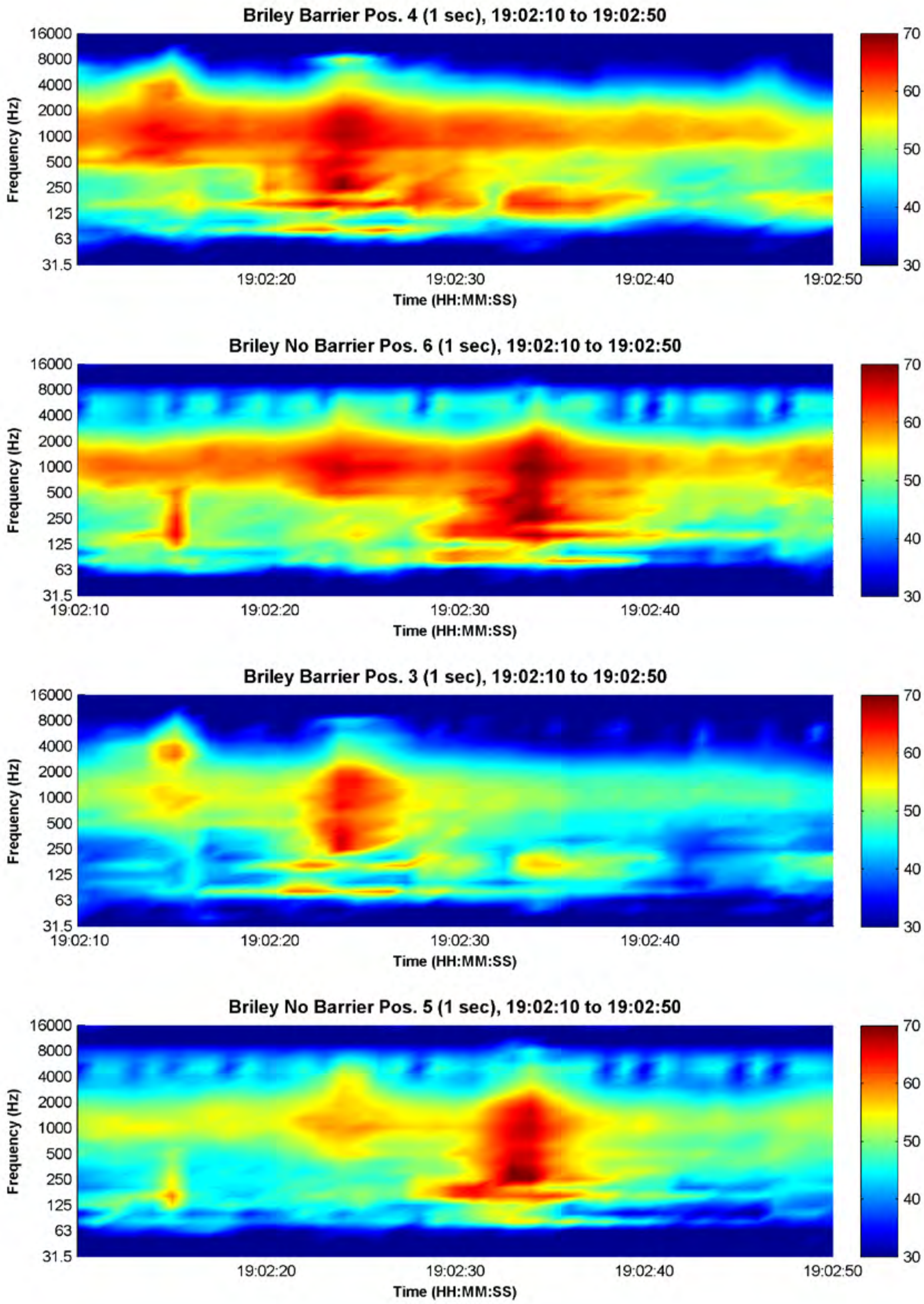


Figure 70. Spectrogram for a heavy truck eastbound (example 2); top to bottom: high mics (BarCom04 and NoBarCom06), low mics (BarCom03 and NoBarCom05); Briley.

Data Analysis for Briley Parkway – Psychoacoustics

The audio recordings for the monitoring period at Briley Parkway were too contaminated with electronic noise to perform meaningful psychoacoustical analyses. Therefore, they are omitted from this report.

CHAPTER B-5

Results - I-90, Rockford, IL (Location SID-1)

The measurements on I-90 in Rockford, IL took place on Dec. 26, 2014. Setup started at 7:00 am and data collection was done from 13:00 to 17:30. An aerial photo of the location and the microphone positions is shown in Figure 71. Figure 72 shows cross-sections at the Barrier and No Barrier sites. The microphone positions were as follows:

Table 8: Microphone positions for I-90 site

Mic name	Side of road	Distance from Center of Near Travel lane (ft)	Height above roadway plane (ft)
BarRef01	SB	20	20 (5 ft above barrier)
NoBarRef02	SB	20	20 (21 ft above ground)
BarCom03	NB	69	10.4 (6 ft 11 in above ground)
BarCom04	NB	93	17 (15.5 ft above ground)
NoBarCom05	NB	69	10.4 (5 ft above ground)
NoBarCom06	NB	93	17 (23.5 ft above ground)

The video camera and radar gun were located on the overpass located between the Barrier and No Barrier sites.

Appendix C of the Final Report includes site photographs.

Figure 71. I-90 microphone positions. (Source: Google Earth).

Figure 72. ***Cross-sections at the I-90 Barrier (top) and No Barrier (bottom) sites.***

Measurement Observations

Winds were very low during the measurement period. There was also very little noise contamination, with only an airplane overflight and a police siren.

Data collection went well and the audio recorders required change of AA batteries 2.5 hours into the measurements. The AA battery change was done to minimize the use of external power supplies that could introduce electronic noise into the recordings. The batteries were changed in sequential order and for future sites we will do the AA battery change as fast as possible to minimize data collection interruption (similar to what was done at the Chino Hills location in CA).

During these measurements, it was determined that the cause of the audio noise experienced at the first two study locations was from interference between the two microphone channels. This was resolved by using one audio recorder per microphone. Review of the audio files indicated that this approach was successful. The recordings appeared to be clean.

Measured Broadband Levels and Level Differences for I-90

The running L_{eq}(5min) for each site are presented in the following figures to give an overall picture of the measured levels, both in terms of unweighted sound pressure levels and A-weighted sound levels:

- BarRef01 and NoBarRef02 - Figure 73 (unweighted) and Figure 74 (A-weighted), with Figure 75 showing the differences in the unweighted and A-weighted levels for this microphone pair,
- BarCom03 and NoBarCom05 - Figure 76 (unweighted) and Figure 77 (A-weighted) , with Figure 78 showing the differences in the unweighted and A-weighted levels for this microphone pair; and
- BarCom04 and NoBarCom06 - Figure 79 (unweighted) and Figure 80 (A-weighted), with Figure 81 showing the differences in the unweighted and A-weighted levels for this microphone pair.

The following observations are prior to any attempt to group data into equivalent periods. In general, both the unweighted sound pressure levels and A-weighted sound levels are higher at the Barrier microphones than at the No Barrier microphones.

For the reference microphones, both the unweighted and A-weighted levels at BarRef01 are on the order of 0 dB to 0.5 dB above the NoBarRef02 levels for the first two hours of measurement (13:00 to 15:00). For the second half of the measurements 15:00 to 17:20), this difference increased to a range of 0.5 dB to 1.0 dB. The BarRef01 microphone was located atop the barrier and the barrier was just off the shoulder. The slightly higher levels at BarRef01 could be due to sound reflections off the barrier and then off the sides of the vehicles and back to the microphone, especially for heavy truck trailers.

For all of the running 5-minute L_{eq} periods, the BarCom03 unweighted sound pressure levels are on the order of 0 dB to 1.5 dB higher than the NoBarCom05 levels. For the A-weighted sound levels, the BarCom03 levels are on the order of 0.4 dB to 1.3 dB higher than the NoBarCom05 levels.

For most of the running 5-minute L_{eq} periods, the BarCom04 levels, both unweighted and A-weighted, are higher than the NoBarCom06 levels. The unweighted levels range from 0.7 dB lower than NoBarCom06 to 1.5 dB higher. The A-weighted levels range from 0.2 dB to 1 dB higher.

At all of the microphones, as time passed the L_{eq}(5min) dropped slowly, on the order of 1 dB to 2 dB, over the 4-hour period. In this same time period the differences in levels between the Barrier and No Barrier microphone pairs increased on the order of a half decibel.

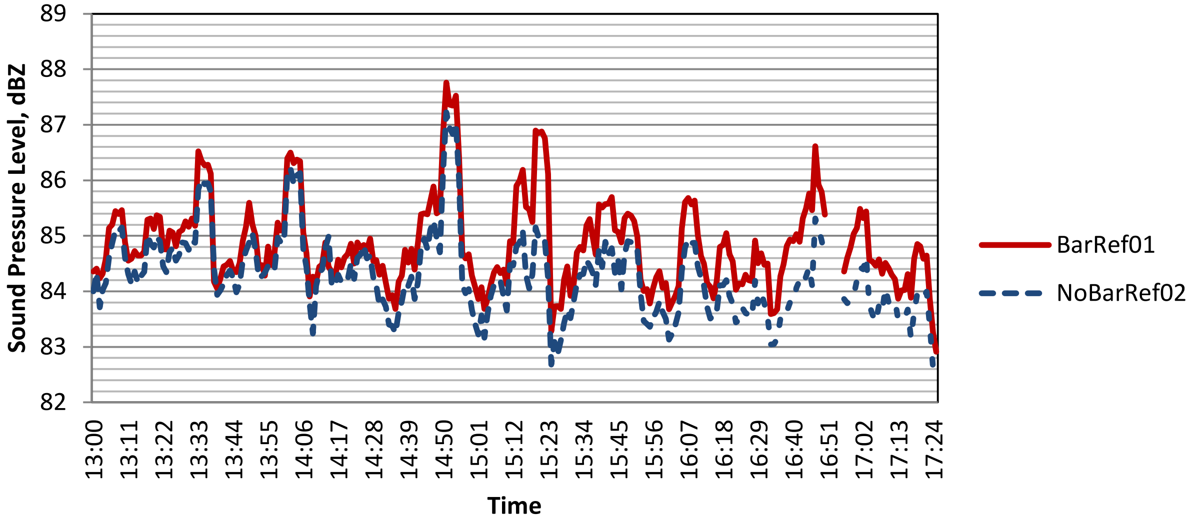


Figure 73. Running L_{eq}(5min), I-90, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

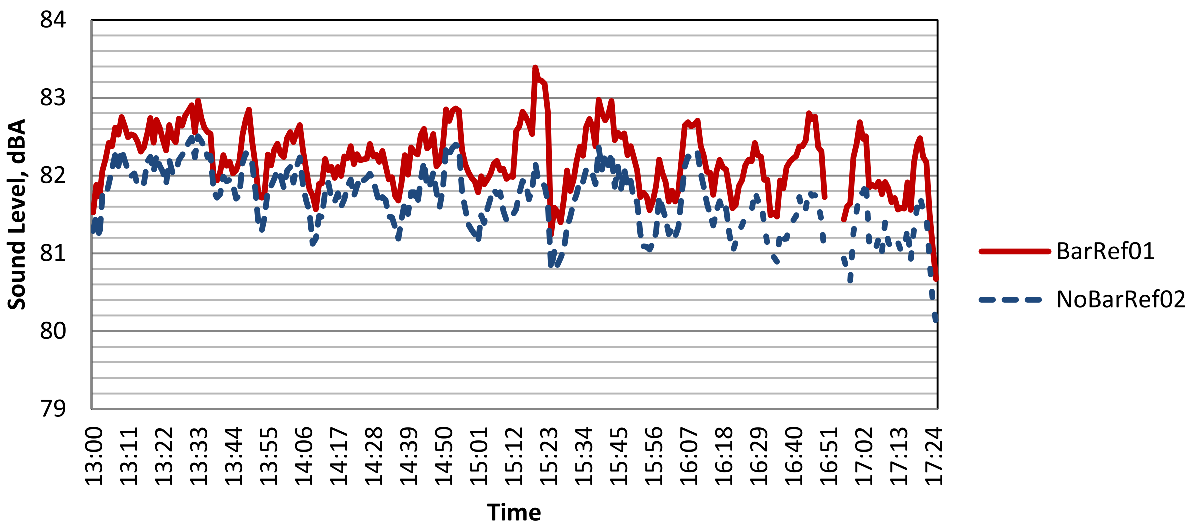


Figure 74. Running L_{eq}(5min), I-90, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

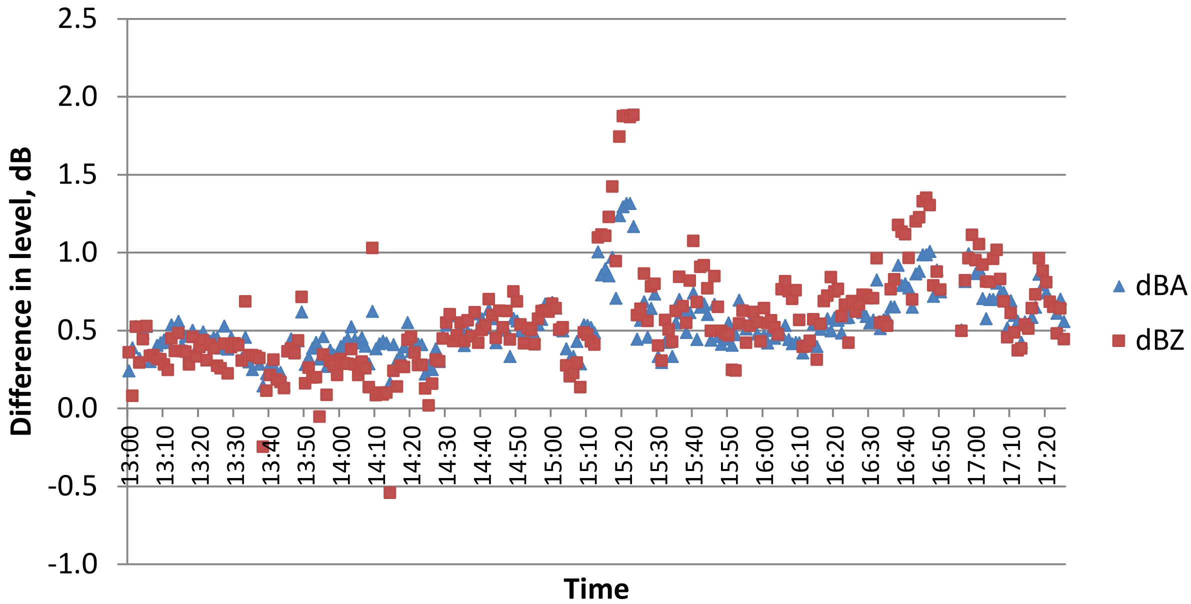


Figure 75. Differences in running L_{eq}(5min), I-90, BarRef01 minus NoBarRef02

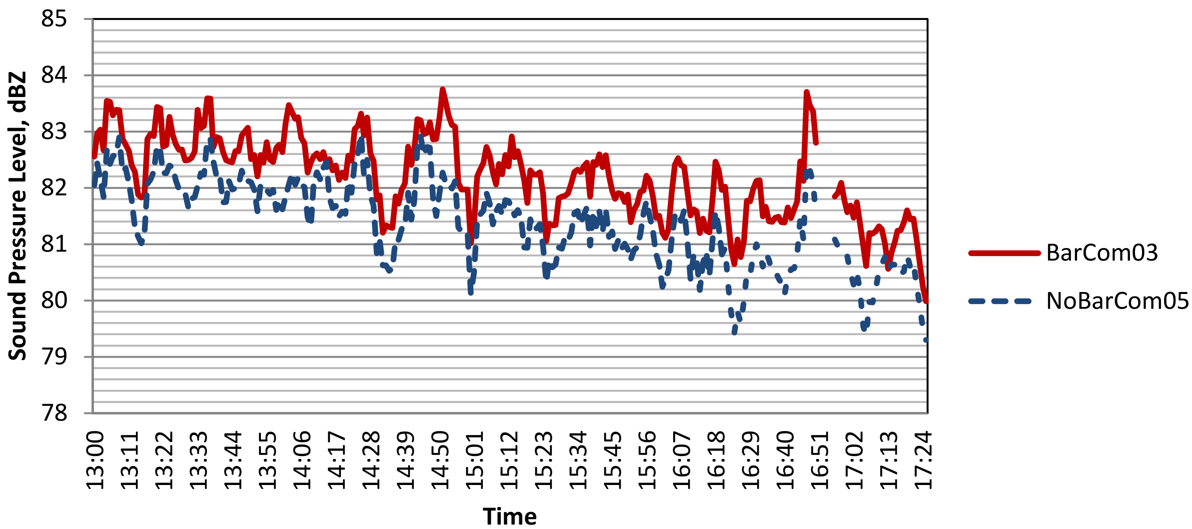


Figure 76. Running L_{eq}(5min), I-90, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

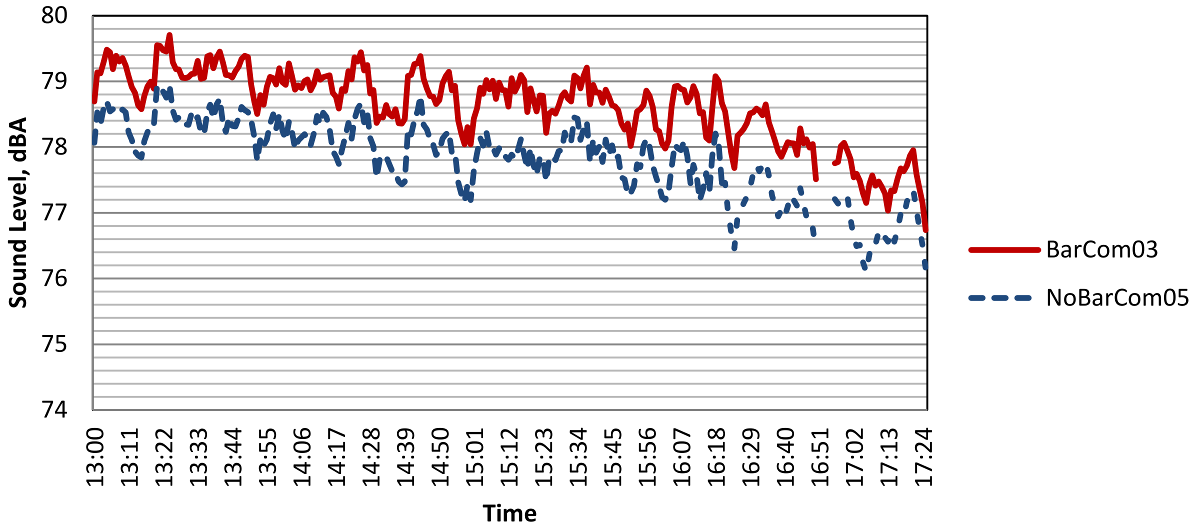


Figure 77. Running L_{eq}(5min), I-90, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

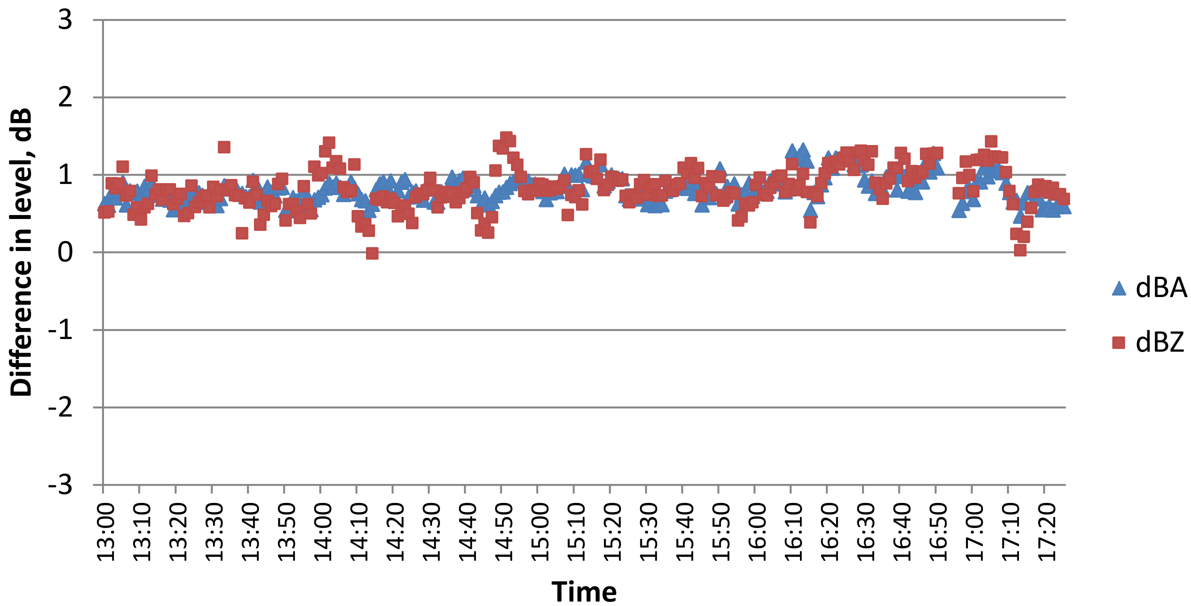


Figure 78. Differences in running L_{eq}(5min), I-90, BarCom03 minus NoBarCom05

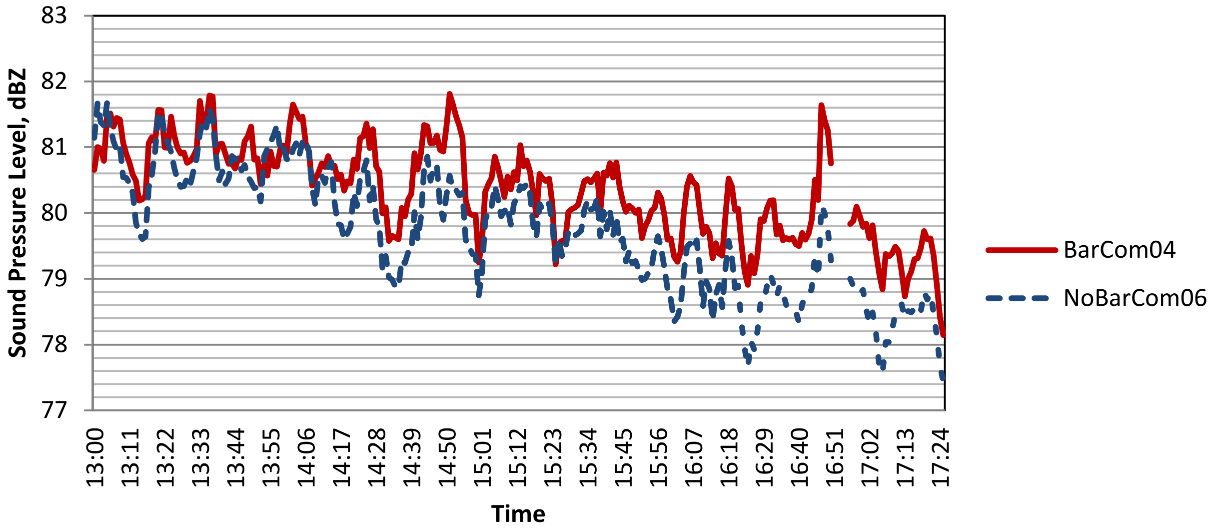


Figure 79. Running L_{eq}(5min), I-90, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

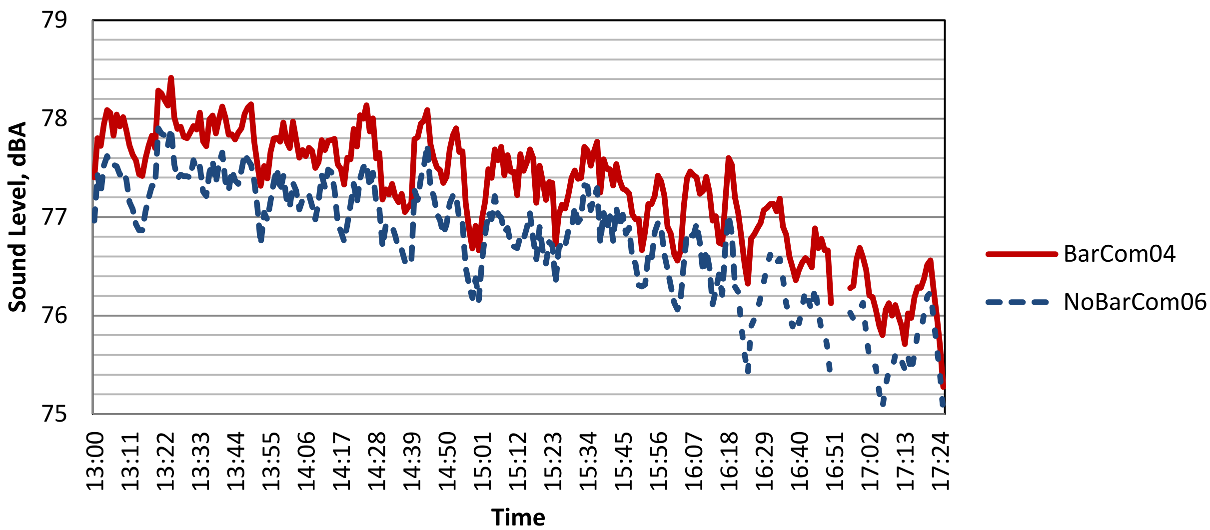


Figure 80. Running L_{eq}(5min), I-90, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

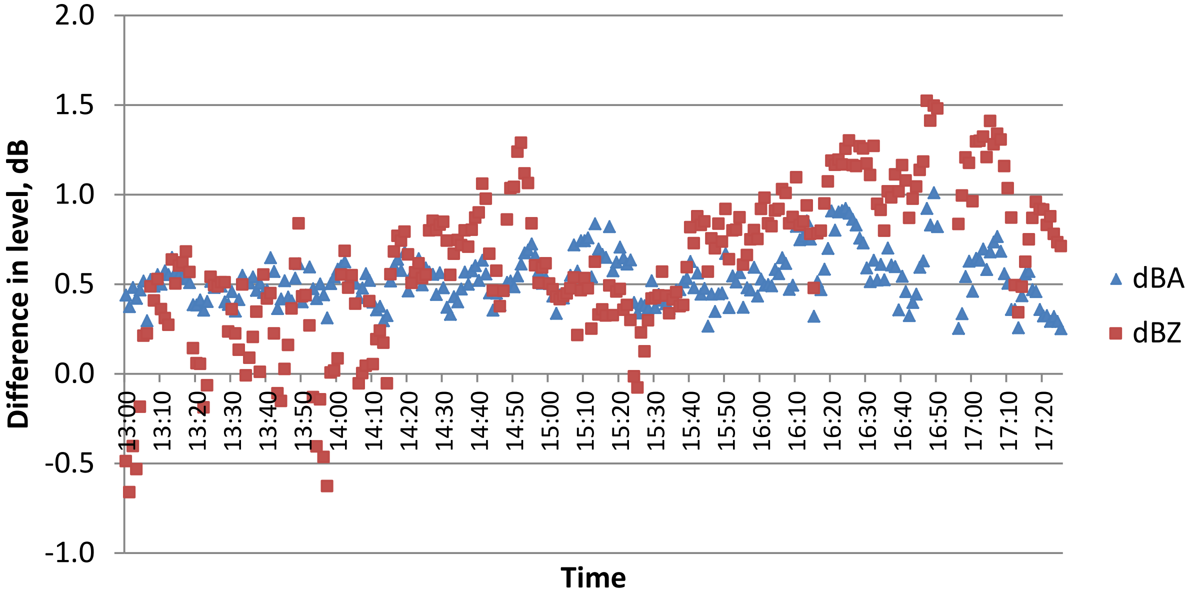


Figure 81. Differences in running L_{eq}(5min), I-90, BarCom04 minus NoBarCom06

Data Analysis for I-90- FHWA Method

Equivalent Groups

All of the groupings of 5-minute periods that were judged equivalent for traffic parameters at the I-90 location fell into two meteorological classes: Downwind Lapse and Calm Neutral. There were twelve groupings in the Downwind Lapse class, each with three to five 5-minute equivalent periods, and four groupings in the Calm Neutral class, each with three 5-minute equivalent periods.

Figure 82 shows these groupings graphically for the Downwind Lapse class. The times along the top represent the starting minute of each 5-minute period. Figure 83 shows the same for the Calm Neutral groups. Each group has a unique name, starting with “DLG-” or “CNG-”. Note that while all of the 5-minute periods in a group are non-overlapping in time, the same 5-minute periods often appear in multiple equivalent groups.

These periods had varying traffic volumes, as show in Table 9, which ranks first the Downwind Lapse groups and then the Calm Neutral groups by total two-way volume averaged across the periods in that group. For the Downwind Lapse class, the volumes of the highest group were roughly 15% greater than the volumes of the lowest group. For the Calm Neutral class, the highest group was only about 2% greater than the lowest group. In terms of equivalent hourly volumes, the overall range was from 4,779 vph to 5,488 vph.

Speeds were much more consistent, ranging from averages of 66 mph to 71 mph for the Downwind Lapse groups and 68 mph to 70 mph for the Calm Neutral groups.

Group ID	Starting Time of 5-minute Periods																				
	13:07	13:09	13:10	13:20	13:24	13:27	13:29	13:36	13:42	13:43	13:44	13:45	13:50	14:07	14:14	14:15	14:16	14:38	14:43	14:44	14:46
DLG-1-1												■		■		■		■			
DLG-1-2												■		■			■	■			
DLG-2-1									■						■				■		
DLG-2-2									■						■						■
DLG-2-3										■					■				■		
DLG-2-4										■					■						■
DLG-2-5											■				■				■		
DLG-2-6											■				■						■
DLG-3-1			■		■			■					■							■	
DLG-3-2			■			■		■					■							■	
DLG-4-1	■			■			■														
DLG-4-2		■		■			■														

Figure 82. Equivalent 5-minute periods for Downwind Lapse groups at I-90.

Group ID	Starting Time of 5-minute Periods				
	15:22	15:37	15:38	16:11	16:12
CNG-1-1	■	■		■	
CNG-1-2	■	■			■
CNG-1-3	■		■	■	
CNG-1-4	■		■		■

Figure 83. Equivalent 5-minute periods for Calm Neutral groups at I-90.

Table 9. Two-way traffic volumes in 5-minute periods, by equivalent group for Downwind Lapse and Calm Neutral conditions, sorted by factored hourly volume, I-90.

Group	Two-Way Traffic Volumes (5 minutes)					Factored Hourly Volume (vph)
	Period 1	Period 2	Period 3	Period 4	Period 5	
Downwind Lapse						
DLG-4-2	456	457	459			5,488
DLG-4-1	441	457	459			5,428
DLG-2-3	440	413	461			5,256
DLG-3-2	460	464	404	396	462	5,246
DLG-3-1	460	460	404	396	462	5,237
DLG-2-1	430	413	461			5,216
DLG-2-5	421	413	461			5,180
DLG-2-4	440	413	402			5,020
DLG-2-2	430	413	402			4,980

DLG-2-6	421	413	402			4,944
DLG-1-1	410	412	408	387		4,851
DLG-1-2	410	412	384	387		4,779
Calm Neutral						
CNG-1-1	389	436	464			5,156
CNG-1-2	389	436	458			5,132
CNG-1-3	389	415	464			5,072
CNG-1-4	389	415	458			5,048

Sound Pressure Level Spectra

Before discussing the differences in levels between the Barrier and No Barrier sites, typical sound pressure level spectra are shown to give some perspective on the data on which the differences are based. One of the 5-minute periods in the one of the Calm Neutral Groups was chosen as typical. Figure 84, Figure 85 and Figure 86 present the sound pressure level spectra for, respectively, BarRef01/NoBarRef02 (atop the barrier), BarCom03/NoBarCom05 (lower and closer microphones across from the barrier) and BarCom04/NoBarCom06 (higher and more distant microphones across from the barrier).

The reference microphones show slightly higher levels up through 1.6 kHz, by as much as 1 dB at 400 Hz, as can be seen in the difference graphs that are shown after the spectra. For BarCom03/NoBarCom05 and BarCom04/NoBarCom06, the levels across from the barrier are higher in the 250-500 Hz bands.

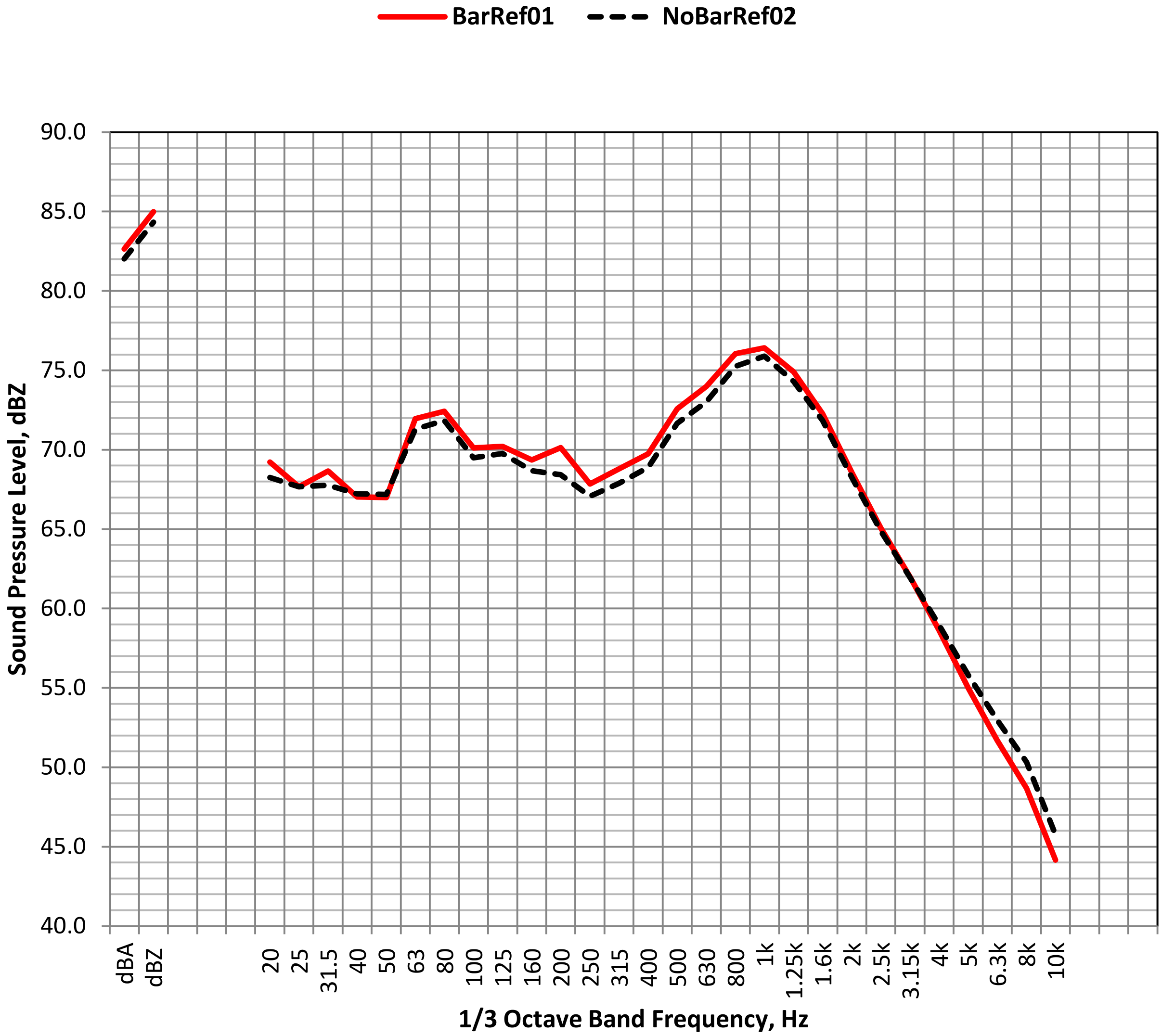


Figure 84. Sample sound pressure level spectra for BarRef01 and NoBarRef02, I-90, Calm Neutral class, CNG-1-1, Period 15:37 (L_{eq}(5min), dBZ)

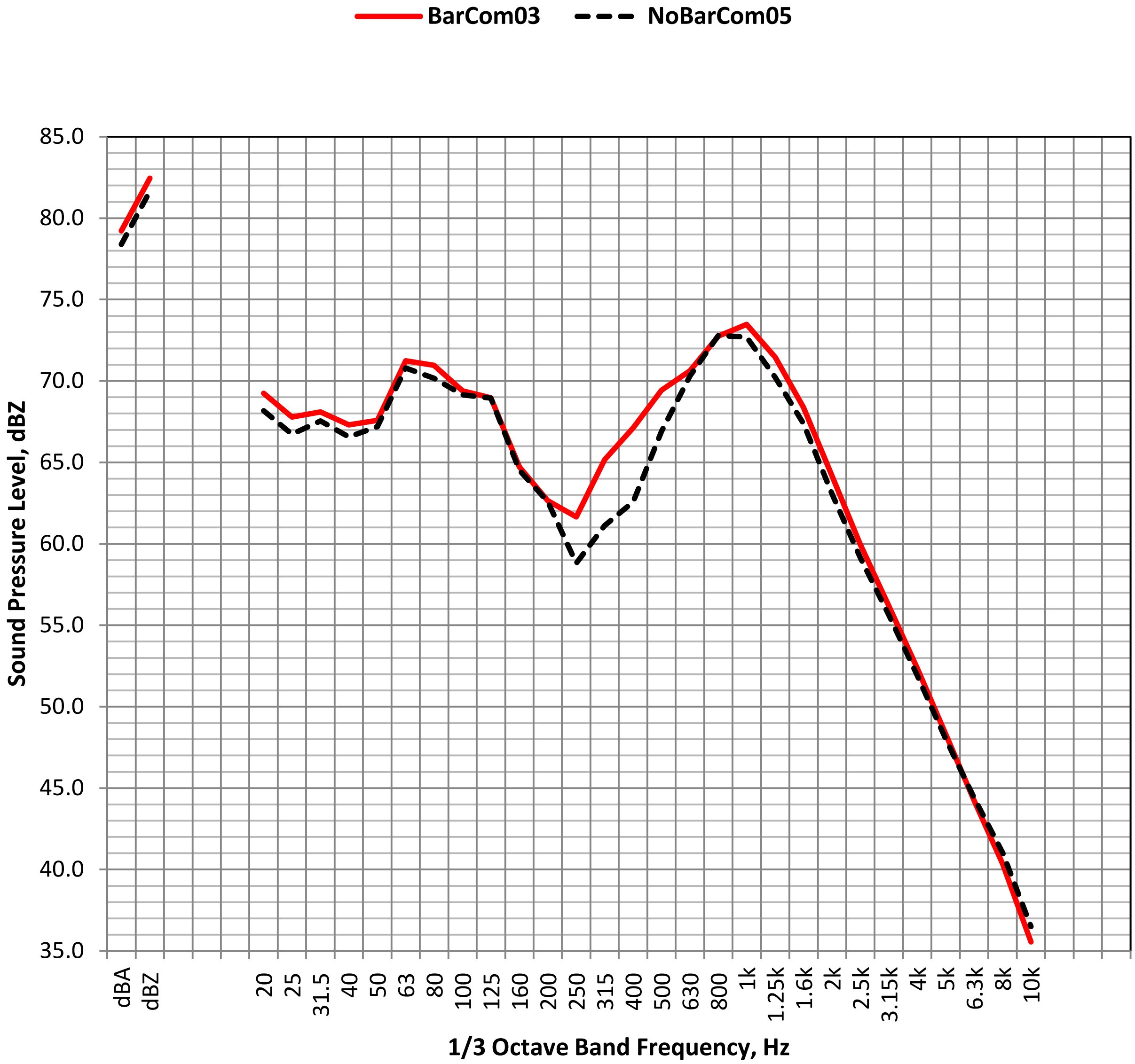


Figure 85. Sample sound pressure level spectra for BarCom03 and NoBarCom05, I-90, Calm Neutral class, CNG-1-1, Period 15:37 (L_{eq}(5min), dBZ)

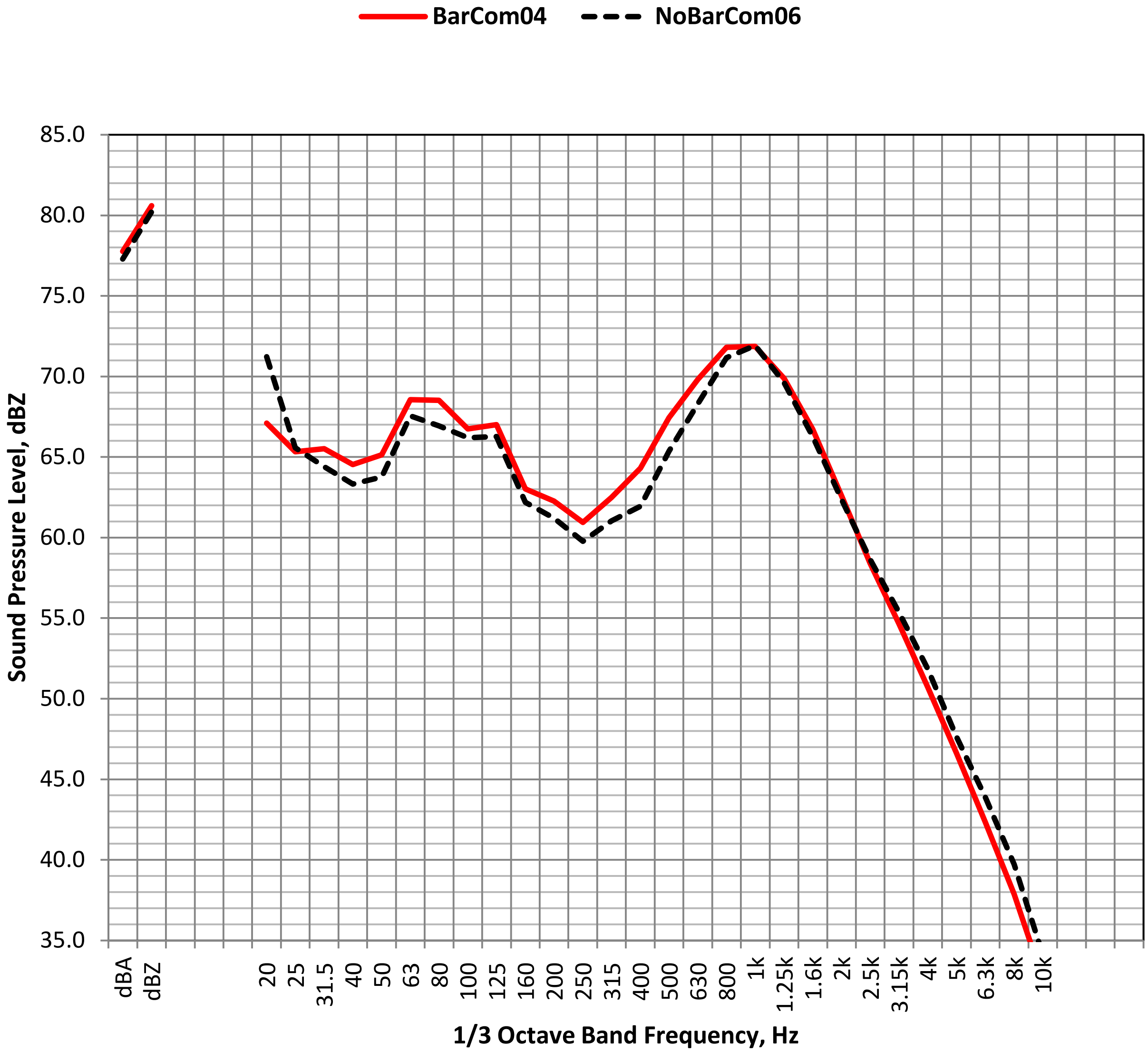


Figure 86. Sample sound pressure level spectra for BarCom04 and NoBarCom06, I-90, Calm Neutral class, CNG-1-1, Period 15:37 (L_{eq}(5min), dBZ).

Calm Neutral Class

Figure 87 shows the averages of the differences in the Barrier and No Barrier microphones' levels for all of the Calm Neutral groups, with their error bars. The error bars are +/- one standard deviation for each average value. This figure compares the following:

- BarRef01 and NoBarRef02 in the upper graph;
- BarCom03 and NoBarCom05 in the middle graph; and
- BarCom04 and NoBarCom06 in the lower graph.

Each graph shows the averages of the average level differences for the A-weighted sound level, the unweighted sound pressure level and the 1/3 octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all of the individual Calm Neutral groups are in spreadsheet files in the project record. The trends across the 1/3 octave band frequencies, described below, are generally similar in these individual groups of equivalent periods, with some differences likely related to background noise and the uniqueness of vehicle noise sources in each period.

Figure 87 shows in the upper graph that, in general, the BarRef01 levels are 0 dB to 1 dB higher than the NoBarRef02 levels at 400 Hz and below. Above 400 Hz up through 3.15 kHz, these levels are 0.5 dB to 1 dB higher than the NoBarRef02 levels. Above 4 kHz, the No Barrier levels are higher, likely due to localized insect noise.

The lower graph compares the levels at BarCom04 and NoBarCom06, both of which were 93 feet from the center of the near travel lane and 17 feet above the roadway surface. The levels in the frequency bands from 31.5 Hz up through 250 Hz were 0.5 dB to 1 dB higher at BarCom04. From 1.25 kHz to 3.15 kHz, the BarCom04 levels were approximately 0.5 dB higher. The most noticeable differences were in the 315 Hz to 630 Hz bands, where the levels were 1.5 dB to 3 dB (at 400 Hz) higher.

The middle graph compares the levels at BarCom03 and NoBarCom05, the lower-height microphones, both of which were 69 feet from the center of the near travel lane and 10.4 feet above the roadway surface. The levels in the frequency bands from 20 Hz up through 80 Hz were 0.5 dB to 1 dB higher at BarCom03. For 1 kHz and higher, the BarCom04 levels were approximately 1 dB to 2 dB than those at NoBarCom05. The most noticeable differences were in the 250 Hz to 500 Hz bands, where the levels were 2.5 dB to 5 dB (at 400 Hz) higher.

A possible explanation for the barrier effect being prominent in the low frequency range (250 to 500 Hz) for BarCom03 at I-90 is that direct and reflected sound take different propagation paths. The direct sound at both the Barrier and No Barrier sites is likely experiencing ground effects/wave interference that cause a dip in sound level in that frequency range, as is illustrated in the sample spectra in Figure 85. The reflected sound at the barrier site is experiencing a different propagation path than the direct sound, with different ground effects and wave interference with ground reflections; the dip in the 250 to 500 Hz range is non-existent or diminished. As a result, the barrier effect is pronounced in the 250 to 500 Hz range.

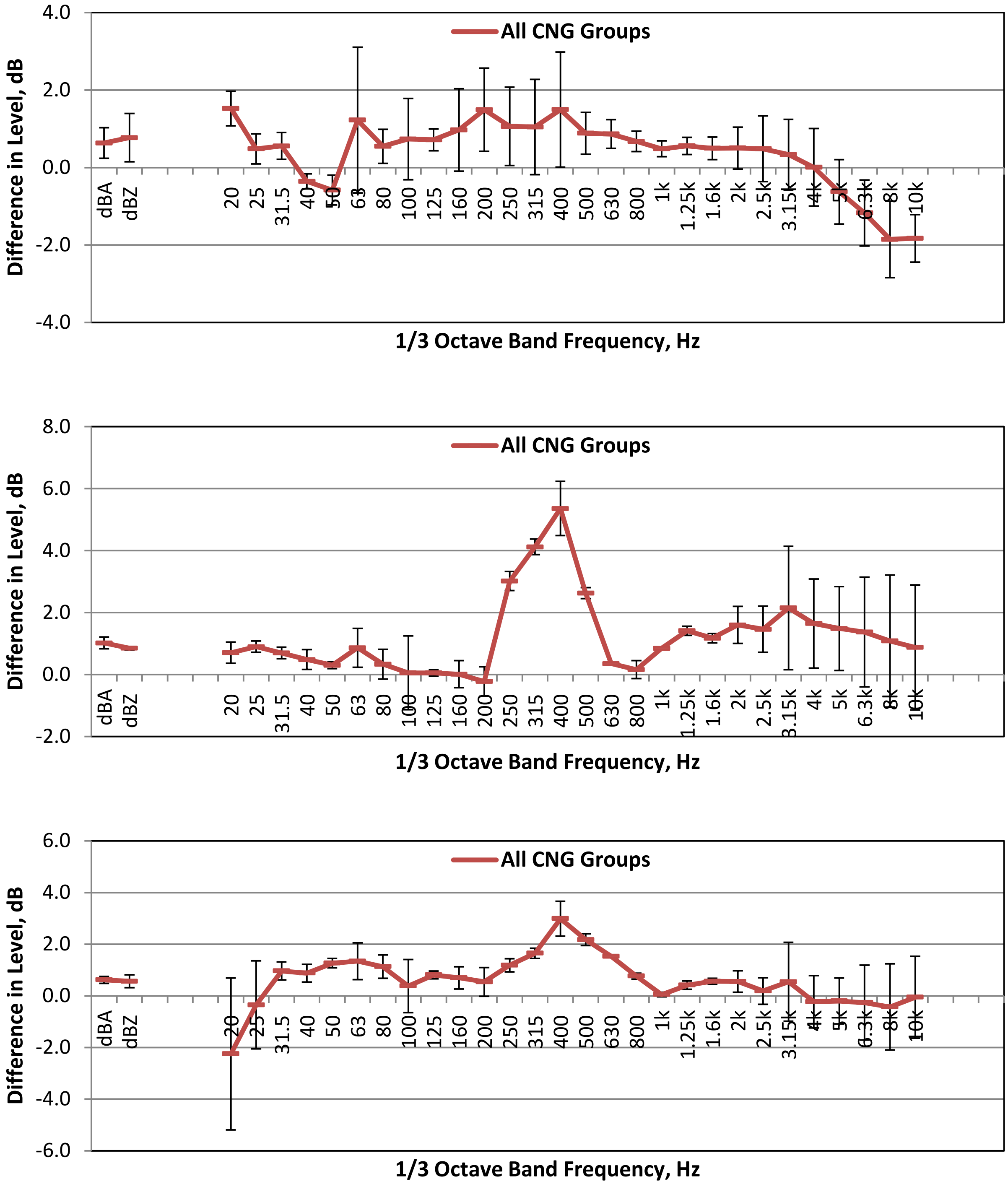


Figure 87. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), BarCom03 minus NoBarCom05, for all Calm Neutral groups, I-90.

Downwind Lapse Class

Figure 88 shows the averages of the differences in the Barrier and No Barrier microphones' levels for all of the Downwind Lapse groups, with their error bars, in the same manner as the Calm Neutral groups.

Each graph shows the averages of the average level differences for the A-weighted sound level, the unweighted sound pressure level and the 1/3 octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all of the individual Downwind Lapse groups are in spreadsheet files in the project record. Once again, the trends across the 1/3 octave band frequencies below, are generally similar in these individual groups of equivalent periods.

The upper graph shows that, in general, the BarRef01 levels are 0 dB to approximately 0.8 dB higher than the NoBarRef02 levels from 63 Hz up through 2.5 kHz. Above 400 Hz up through 3.15 kHz, the BarRef01 levels are 0.5 dB to 1 dB higher than the NoBarRef02 levels. Above 2.5 kHz, the No Barrier levels are higher, likely due to localized insect noise.

The middle graph compares the levels at BarCom03 and NoBarCom05, the lower-height microphones. The patterns are similar to the Calm Neutral class up through 2 kHz, except that the increase at 400 Hz is only 4 dB instead of 5 dB. Above 2 kHz, the level difference change from being slightly higher at BarCom03 up to 5 kHz and slightly higher at NoBarCom05 above 5 kHz. It is likely that the lower height of NoBarCom05 compared to NoBarCom06 allowed the former to pick up more ground-level insect noise.

The lower graph compares the levels at the higher BarCom04 and NoBarCom06 positions. The patterns are similar to the Calm Neutral class, with the increase at 400 Hz being 2 dB compared to 3 dB for the Calm Neutral class.

While all of the 5-minute periods in all of the groups were not equivalent in traffic volume and speed across all of the groups, these average differences show consistency with the results in the individual groups.

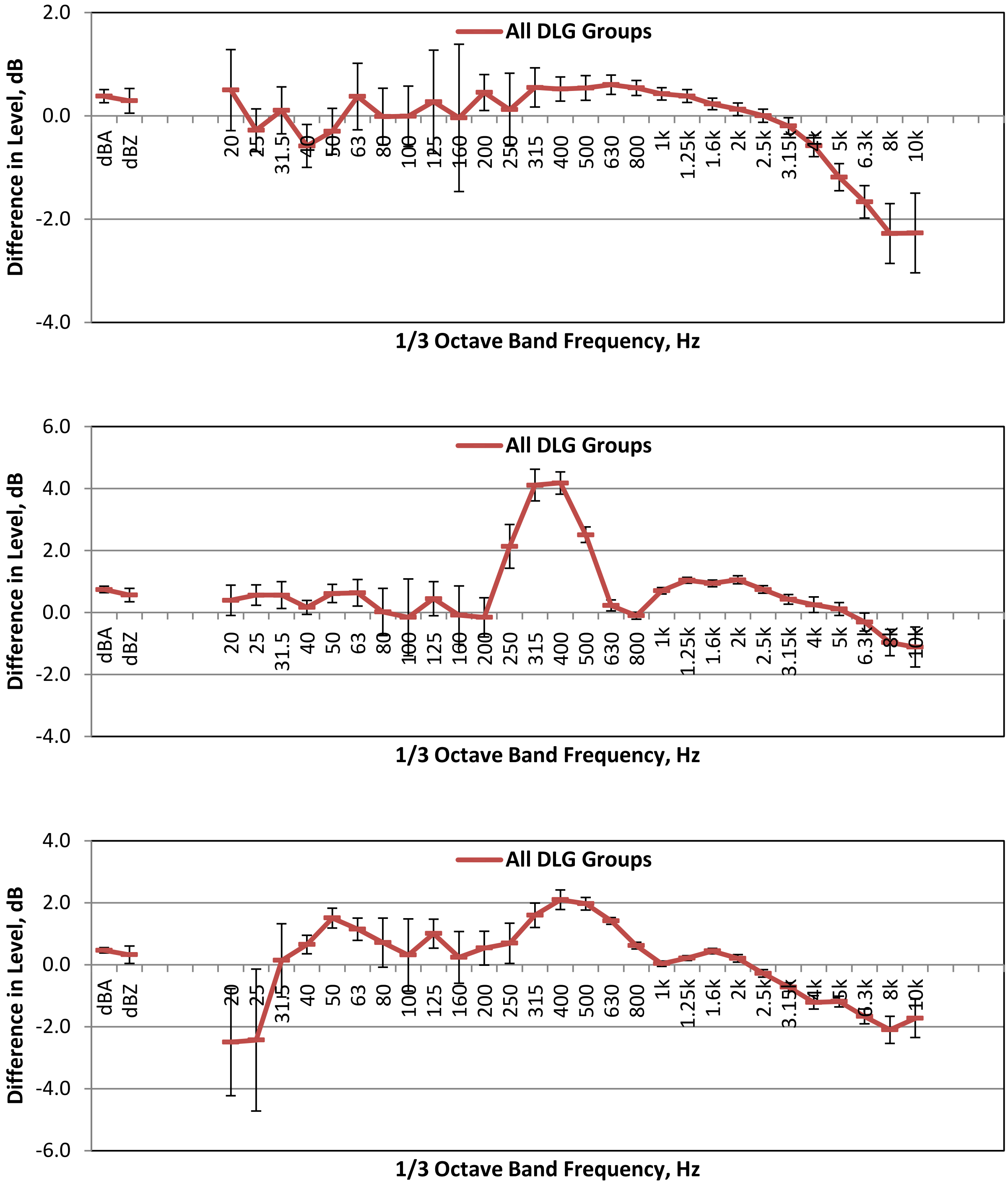


Figure 88. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Downwind Lapse groups, I-90.

Comparison of Downwind Lapse (community microphones) and Calm Neutral Results and Upwind Lapse (reference microphones) and Calm Neutral Results

At I-90, there were slightly higher levels at BarRef01 atop the barrier than at NoBarRef02, described earlier as possibly due to reflections off the barrier that was just of the edge of shoulder and then back off the vehicle bodies.

Figure 88 shows the average differences for all of the Downwind Lapse equivalent groups. In this case "Downwind" refers to the microphones *across* the road. The reference microphones are actually *upwind* from the road in the downwind case.

In Figure 89, the top graph compares the differences in level for the *Upwind Lapse (*for the *reference* microphones) *and Calm Neutral classes,* and the bottom two graphs compare the Downwind Lapse and Calm Neutral classes for the community microphone pairs (BarCom03 vs. NoBarCom05 and BarCom04 vs. NoBarCom06). The data values for each frequency band are the average Calm Neutral differences minus the average Upwind Lapse differences (in the top graph) and the Calm Neutral differences minus the average Downwind Lapse differences (bottom two graphs).

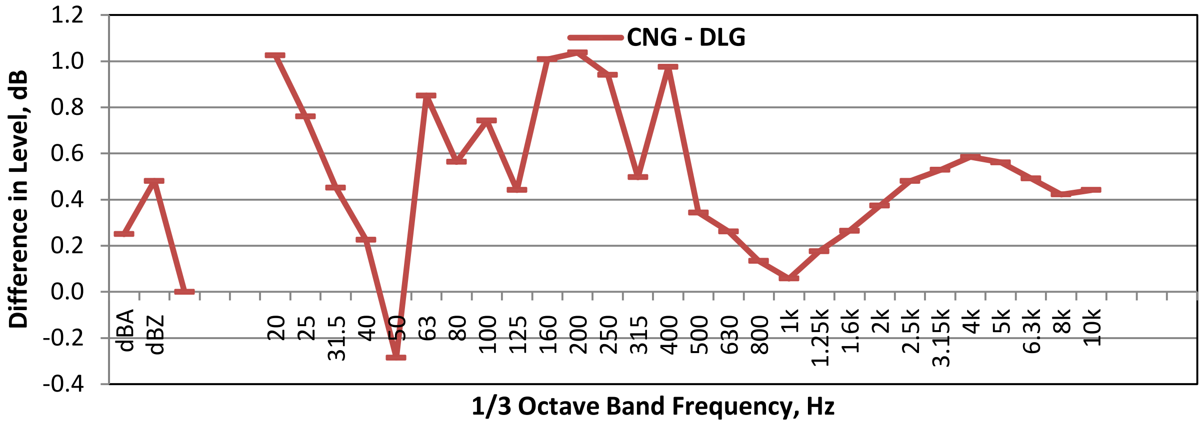
For the reference microphones, the differences are a decibel or less. In other words, the difference in the BarRef01 and NoBarRef02 levels were slightly less for the Upwind Lapse class than for the Calm Neutral class. The data show that the Calm Neutral average differences tend to be slightly greater than the Downwind Lapse average differences across the frequency spectrum.

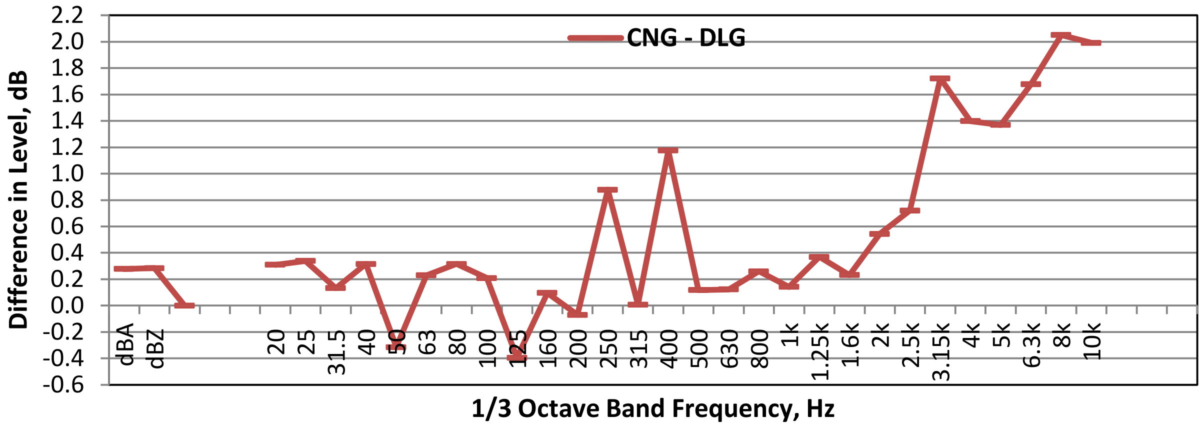
For both microphone pairs, the Calm Neutral differences are greater than the Downwind Lapse differences by a decibel or less up though 2.5 kHz. (with the exception at 25 Hz, where the difference is 2 dB). At 3.15 kHz and above, the Calm Neutral differences range from 0.5 dB to 2.0 dB higher.

Taken together, the Calm Neutral differences were greater than the *Upwind* Lapse differences at the reference microphones and greater than the *Downwind* Lapse differences at the community microphones.

Effects of Traffic Volume and Speed

No trends were evident when considering the differences in sound level as a function of two-way traffic volume, both for the Calm Neutral and Downwind Lapse classes. Also, the range in speeds for each class was too small (5 mph) to address any relationship between speed sound level difference.





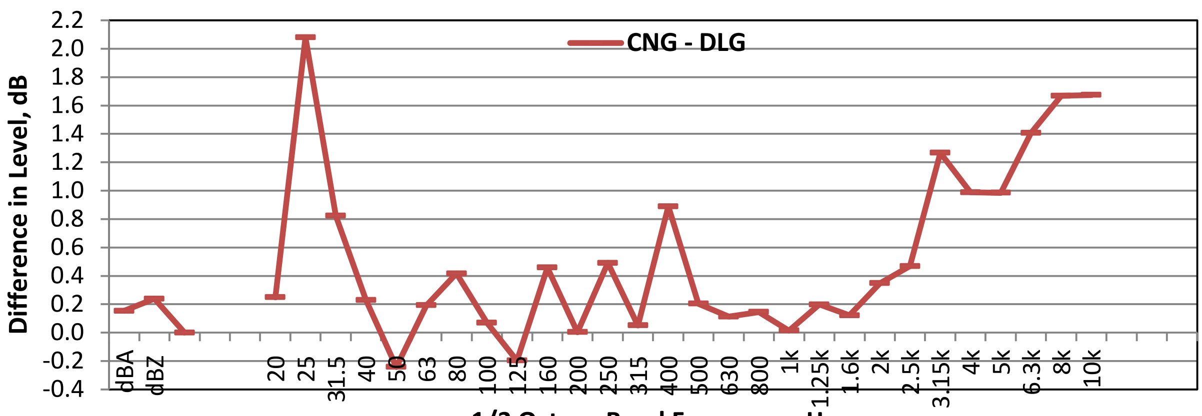


Figure 89. Differences in the Calm Neutral average differences and the Downwind Lapse average differences (L_{eq}(5min), all microphone pairs, I-90.

Additional Sound Level Analysis for I-90 – L_n Descriptors

Figure 90 presents the L_{90}(5min) and L_{99}(5min) for BarRef01 and NoBarRef02, in terms of overall A-weighted sound levels and unweighted sound pressure level. The upper graphs are L_{90} (A-weighted on the left and unweighted on the right). The lower graphs are L_{99} (A-weighted on the left and unweighted on the right).

Then, Figure 91 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min),computed as BarRef1 minus NoBarRef2 for the A-weighted sound levels.

The results show that while the L_{eq}(5min) averages about 0.5 dB higher at BarRef01 than at NoBarRef02, the L_{90} and L_{99} at BarRef01 tend on average to be lower than at NoBarRef02, with approximately 40% of the points higher and 60% lower. With the BarRef01 microphone atop the barrier, no increase due to reflections was expected. The periods of higher L90 and L99 at NoBarRef02 could be due to localized background noise such as insects.

Figure 92 then presents the L_{90}(5min) and L_{99}(5min) for BarCom03 and NoBarCom05 (the lower microphones across from the barrier), again for overall A-weighted sound levels and unweighted sound pressure level, in the same layout as for the reference microphones. Figure 93 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05.

There is strong evidence of the elevated background level at BarCom03. While the L_{eq}(5min) averages about 0.5 dB to 1 dB higher than NoBarCom05, the L_{90} at BarCom03 are 1 dB to 2 dB higher and the L_{99} at BarCom03 are 1 dB to 4 dB higher.

Then, Figure 94 presents the L_{90}(5min) and L_{99}(5min) for BarCom04 and NoBarCom06 (the upper microphones across from the barrier) for overall A-weighted sound levels and unweighted sound pressure level. Figure 95 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06.

There is strong evidence of the elevated background level at BarCom04 compared to NoBarCom06, with the differences very similar to the BarCom03 comparison to NoBarCom05.

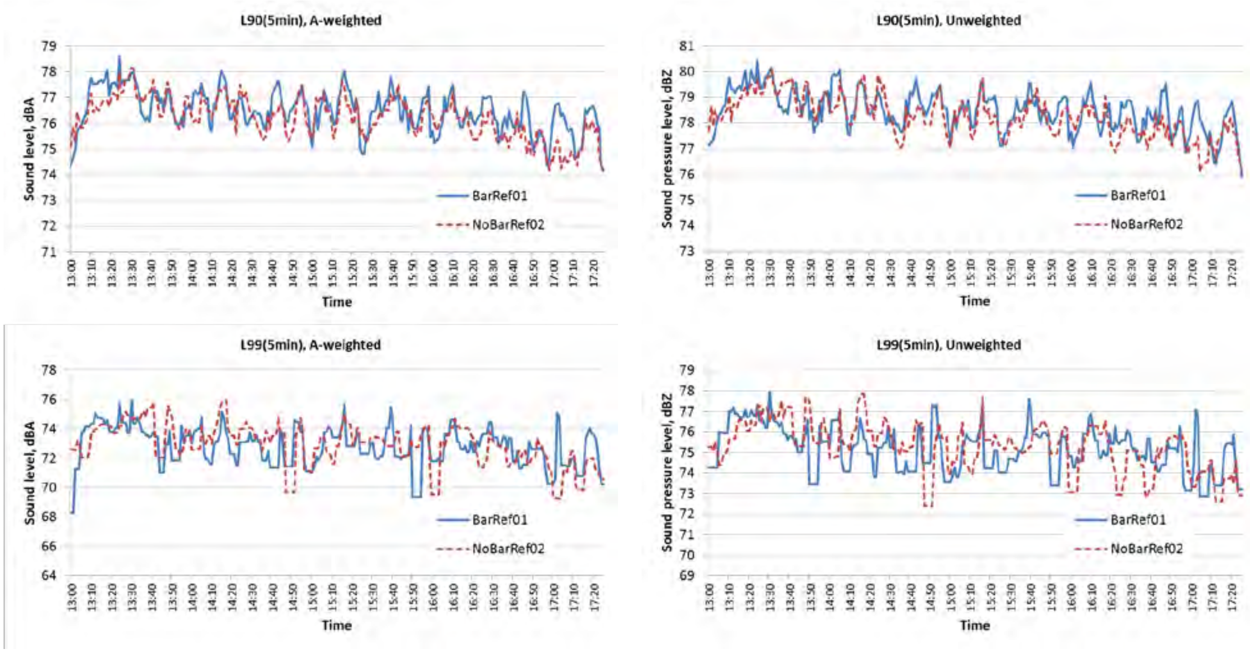


Figure 90. L_{90}(5min) and L_{99}(5min), I-90, BarRef01 and NoBarRef02 – broadband A-weighted sound level (left) and sound pressure level (right).

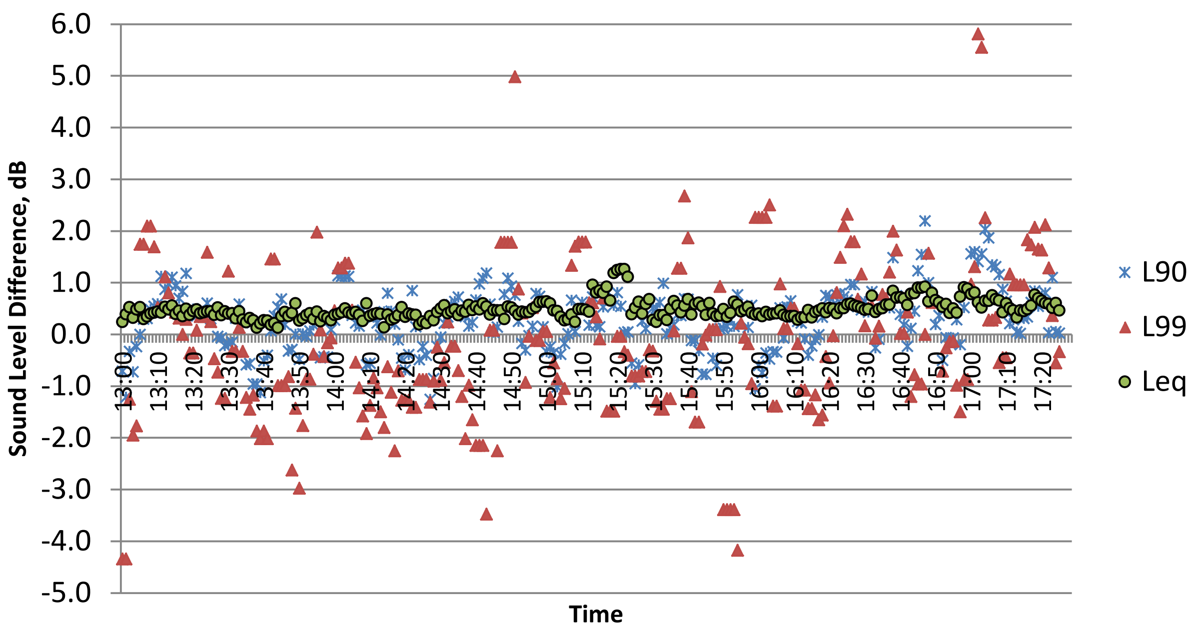


Figure 91. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-90, BarRef01 and NoBarRef02

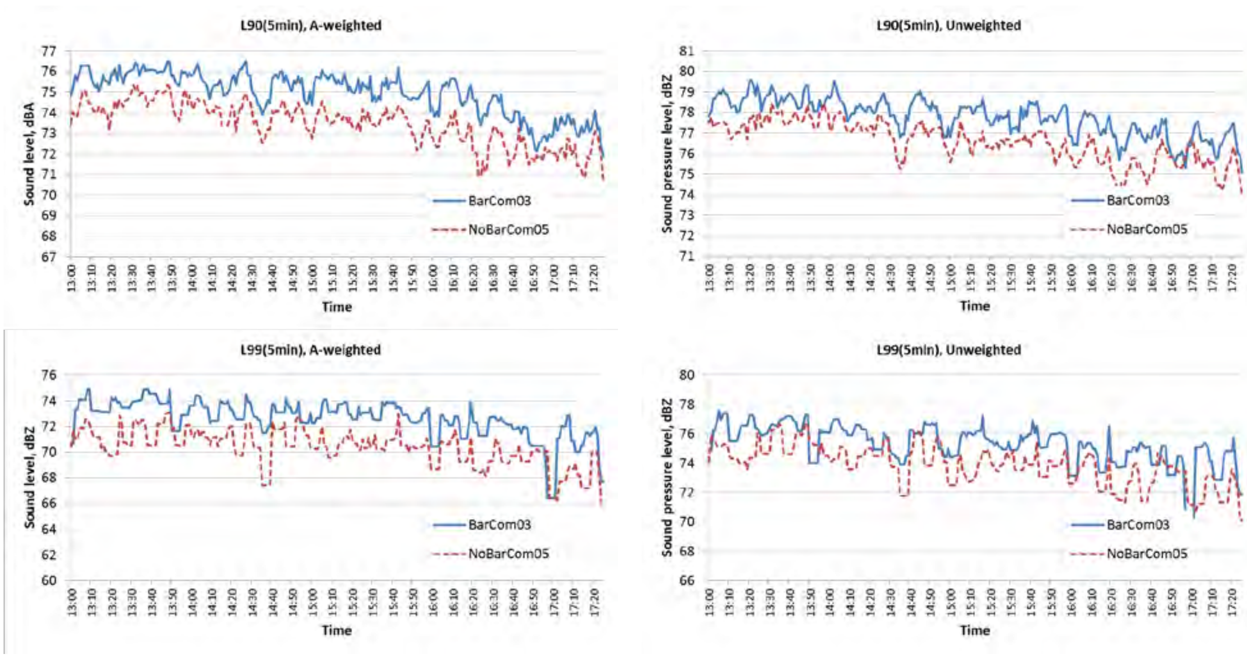


Figure 92. L_{90}(5min) and L_{99}(5min), I-90, BarCom03 and NoBarCom05 – broadband A-weighted sound level (left) and sound pressure level (right)

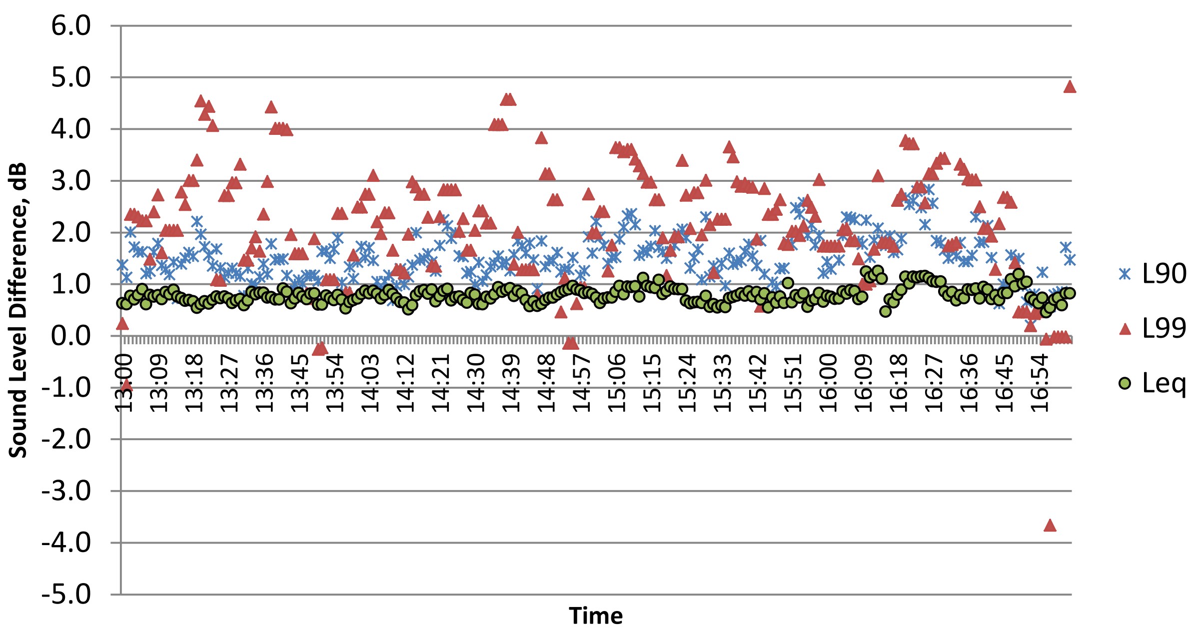


Figure 93. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-90, BarCom03 and NoBarCom05

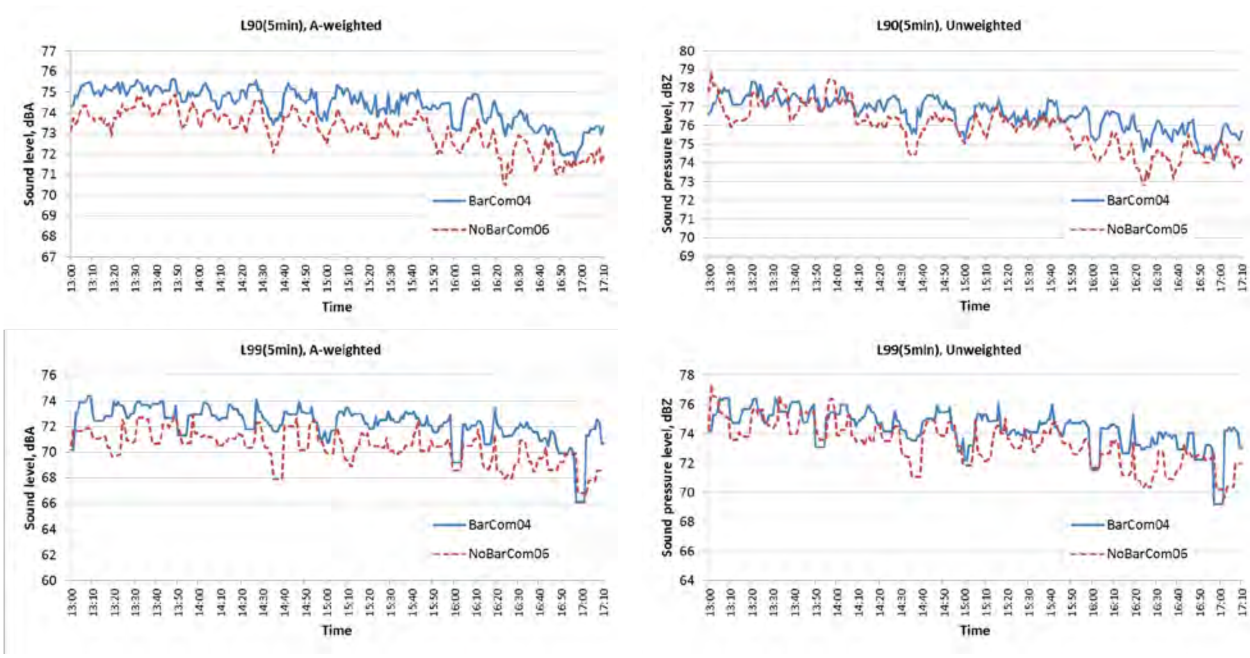


Figure 94. L_{90}(5min) and L_{99}(5min), I-90, BarCom04 and NoBarCom06 – broadband A-weighted sound level (left) and sound pressure level (right)

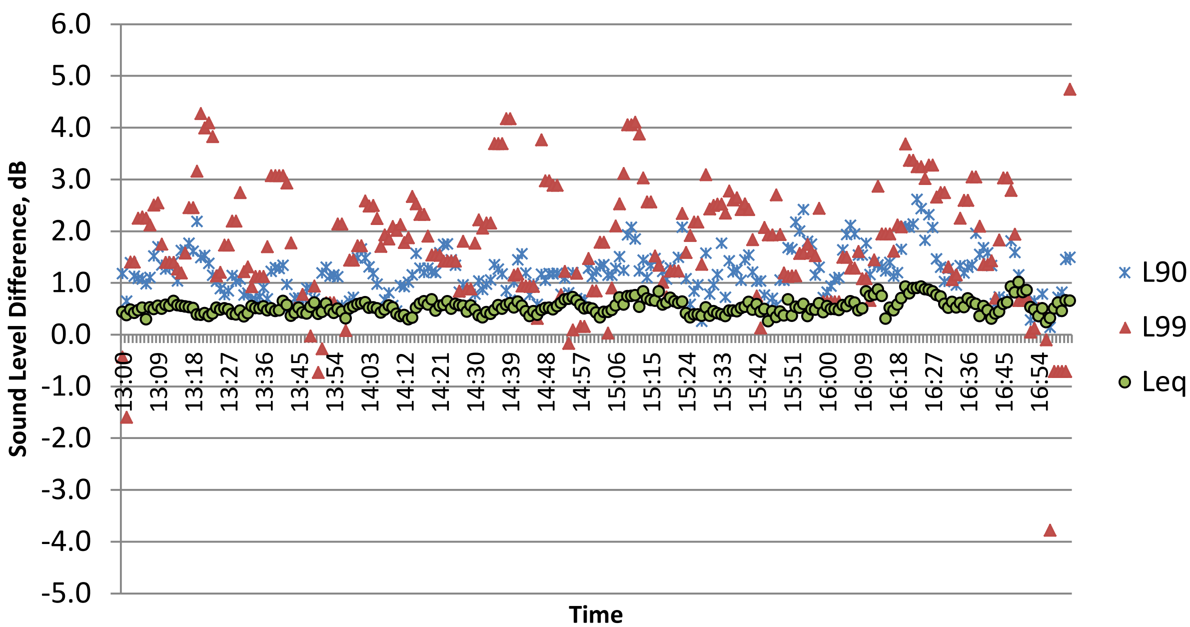


Figure 95. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, I-90, BarCom04 and NoBarCom06

The above graphs were for the broadband A-weighted sound levels and unweighted sound pressure levels only. Figure 96, shown below, broadens the analysis to include the individual 1/3 octave bands by use of color shading. The brown color means that the BarRef01 levels are higher than the NoBarRef02 levels and blue means that NoBarRef02 is higher. In the graph, time runs from top to bottom (increasing as one moves down each figure, with each row representing the starting minute of a running five-minute period) and the total block representing approximately four hours. The 1/3 octave bands run across from left to right, with the broadband A-weighted sound levels and unweighted sound pressure levels on the far left. Within each band's column of data are the differences for seven Ln sound pressure level Ln values (L_1, L_5, L_{10}, L_{33}, L_{50}, L_{90} and L_{99}) and L_{eq}.

There is little evidence of elevated background levels due to sound reflections at BarRef01 compared to NoBarRef02, again, not unexpected because the BarRef01 microphone was atop the barrier. The blue color in the bands at and above 4 kHz are evidence of elevated high frequency levels at the NoBarRef02, typically attributed to insect noise.

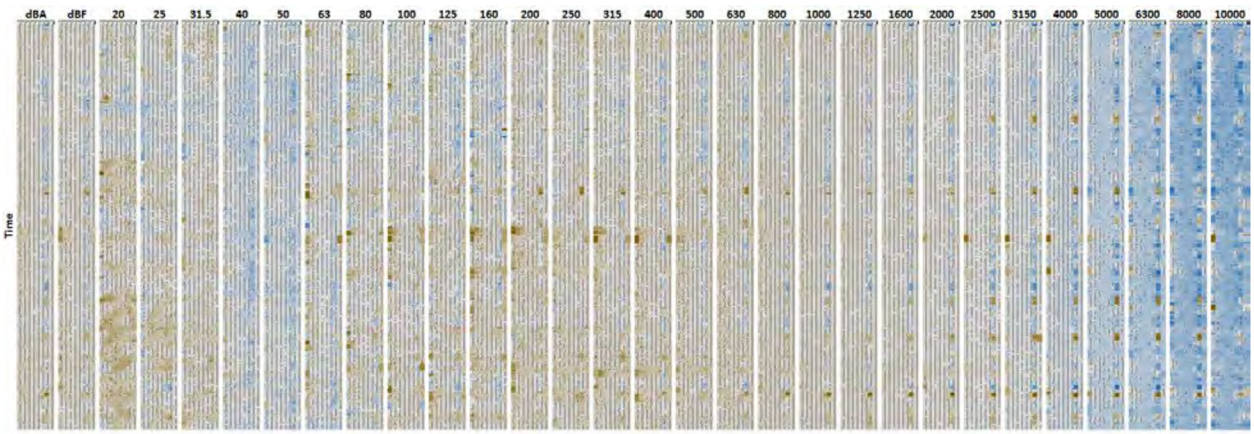


Figure 96. I-90 Differences in L_n(5min) by 1/3 octave frequency bands: BarRef01 and NoBarRef02

Figure 97 presents the L_n differences for BarCom03 and NoBarCom05, while Figure 98 presents the L_n differences for BarCom04 and NoBarCom06.

The brown color in the 250-500 Hz bands in Figure 96 indicates an increase in all of the L_n descriptors meaning the BarCom03 levels are higher than the NoBarCom05 levels. Blue means the No Barrier levels are higher. Vertical brown streaks on the right sides of the data columns in the frequency bands from 630 Hz up through 3.15 kHz mean that the BarCom03 background levels are higher than the NoBarCom05 background levels.

There is much less brown in Figure 98, showing that the BarCom04 upper microphone levels are not that much higher than the NoBarCom06 levels. The blue color in the 20 Hz to 31.5 Hz bands and the bands at and above 4 kHz band show the NoBarCom06 levels to be higher than at BarCom04.

NoBarCom05 brown color in the 250-500 Hz bands in Figure 96 indicate an increase in all of the L_n descriptors means the BarCom03 levels are higher than the NoBarCom05 levels and blue means the No Barrier levels are higher. Vertical brown streaks on the right sides of the data columns in the frequency bands from 630 Hz up through 3.15 kHz mean that the BarCom03 background levels are higher than the NoBarCom05 background levels.

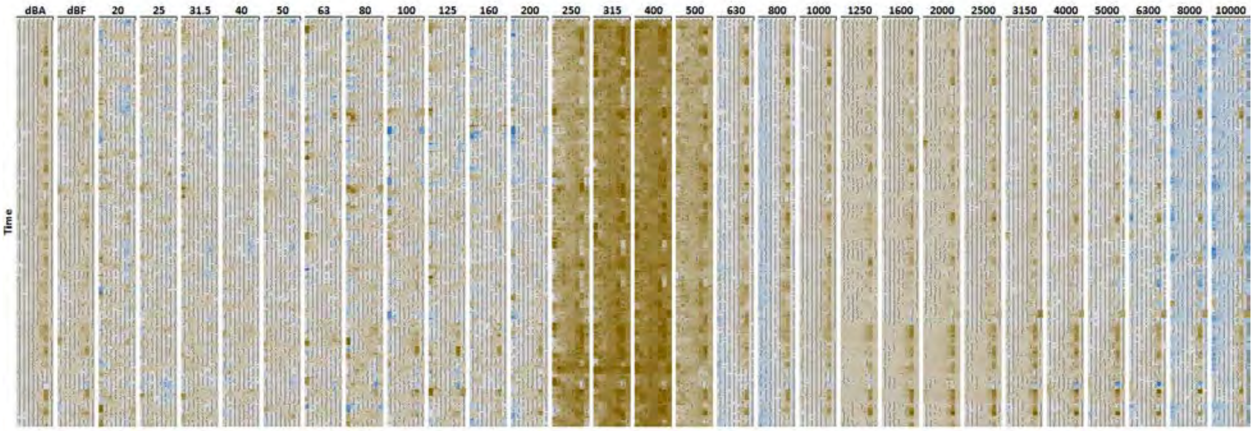


Figure 97. I-90 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom03 and NoBarCom05

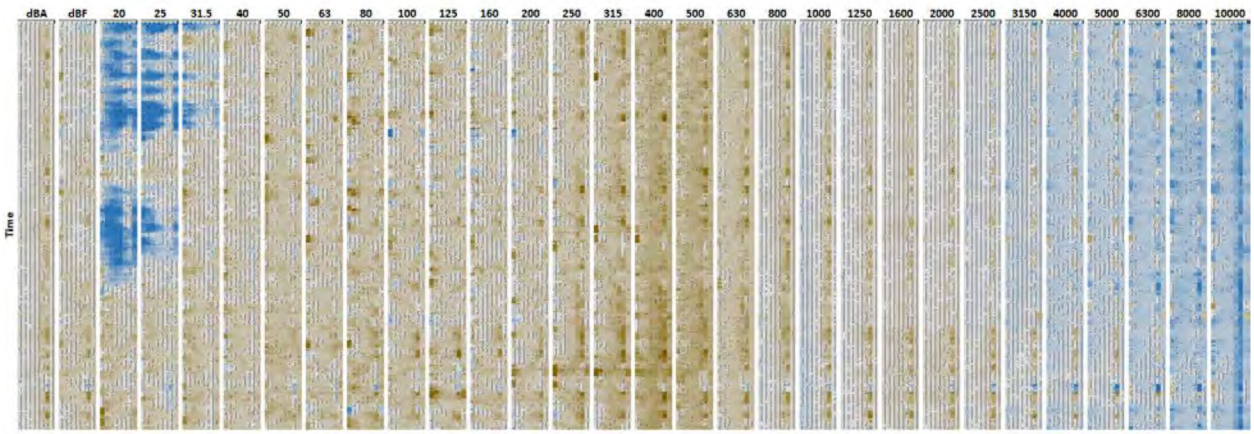


Figure 98. I-90 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom04 and NoBarCom06

Data Analysis for I-90 - Spectrograms

Spectrograms show the frequency content of sound as a function of time. Refer to Table 8 for the I-90 location microphone positions.

There are two equivalent microphones comparing a site with a barrier and one without: BarCom03/NoBarCom05 and BarCom04/NoBarCom06. Each set is directly comparable. The reference microphones BarRef01/NoBarRef02 are not intended to be compared for purposes of determining barrier effect for this site and so are not discussed further in the analysis.

Spectrograms from I-90 Rockford vehicle pass-by events are shown in the figures below. These compare only the near microphones on the community side of the highway, BarCom03 and NoBarCom05 (69 ft from the center of the near travel lane). For the farther microphones (BarCom04/NoBarCom06), the results are similar to the BarCom03/NoBarCom05 pair, just with lower sound levels.

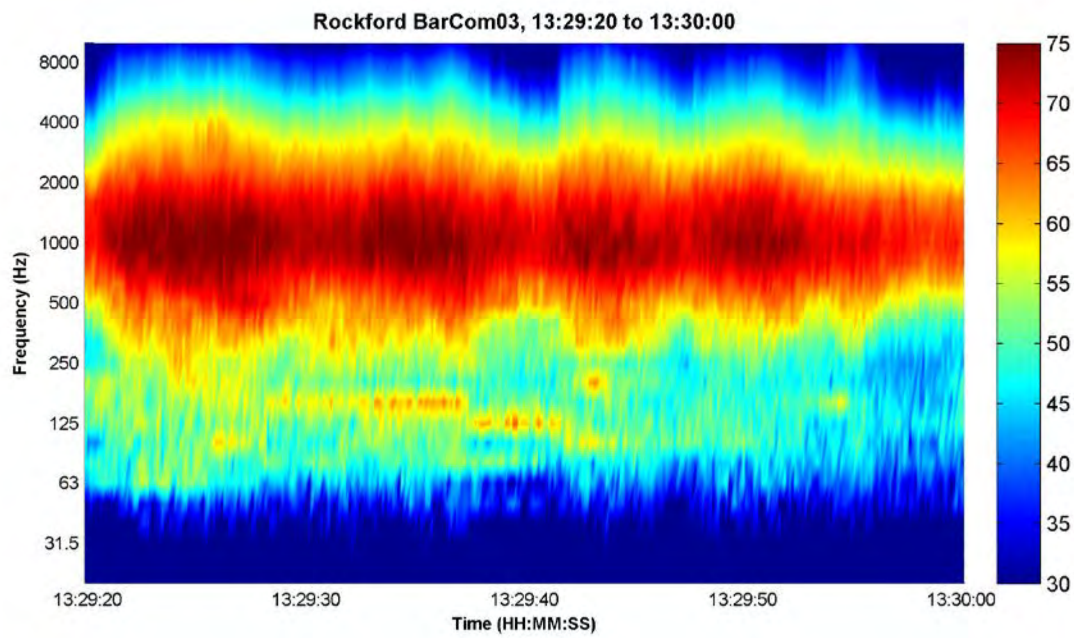
Figure 99 shows two plots of a heavy truck traveling southbound. The pass-by event is around 13:29:36 at the barrier site and around 13:29:43 at the No Barrier site. The event can be identified by Doppler Effect, with a distinct band yellow/orange band (around 62 dBA) along time shifting from 160 Hz to 125 Hz.

Figure 100 shows two plots of another heavy truck traveling southbound. The pass-by event is around 14:12:34 at the Barrier site and around 14:12:40 at the No Barrier site.

Figure 101 shows two plots of a third heavy truck, this time traveling northbound. The pass-by event is around 14:41:36 at the barrier site and around 14:41:27 at the No Barrier site.

The barrier reflection effect can be seen in the spectrograms for the heavy trucks traveling in either the northbound or southbound direction. For the Barrier site, the hot spots are wider and taller than for the No Barrier site for a broad range of frequencies. It can be seen that the tallest darkest red band (highest sound level band) centered around 1000 Hz is both wider and taller, with the same effect occurring in the surrounding frequency bands, stepping through various colors of the spectrum.

This difference indicates that the barrier is causing higher sound levels at frequencies which contribute most to the overall sound level and causing these levels to be sustained for a longer period for each vehicle pass-by event. The same effect can be seen where there are distinct red lower frequency bands. Such is the case for the northbound heavy truck at 500 Hz in Figure 101.



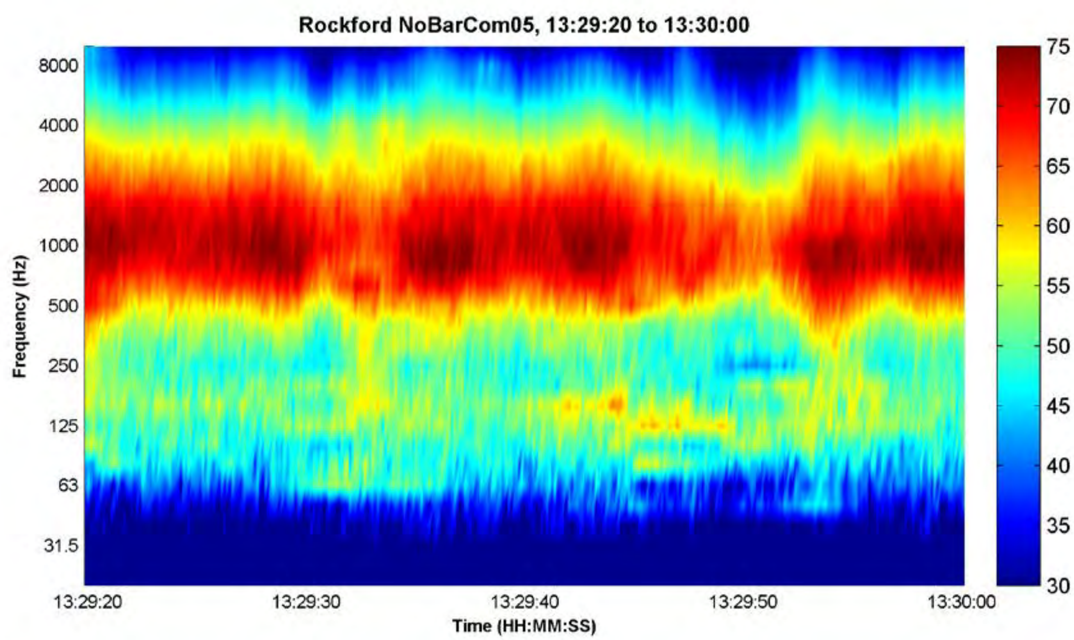


Figure 99. I-90 spectrograms for a heavy truck on southbound (community) side: top is BarCom03; bottom is NoBarCom05 (approximate event times: Barrier site 13:29:36, No Barrier site 13:29:43).

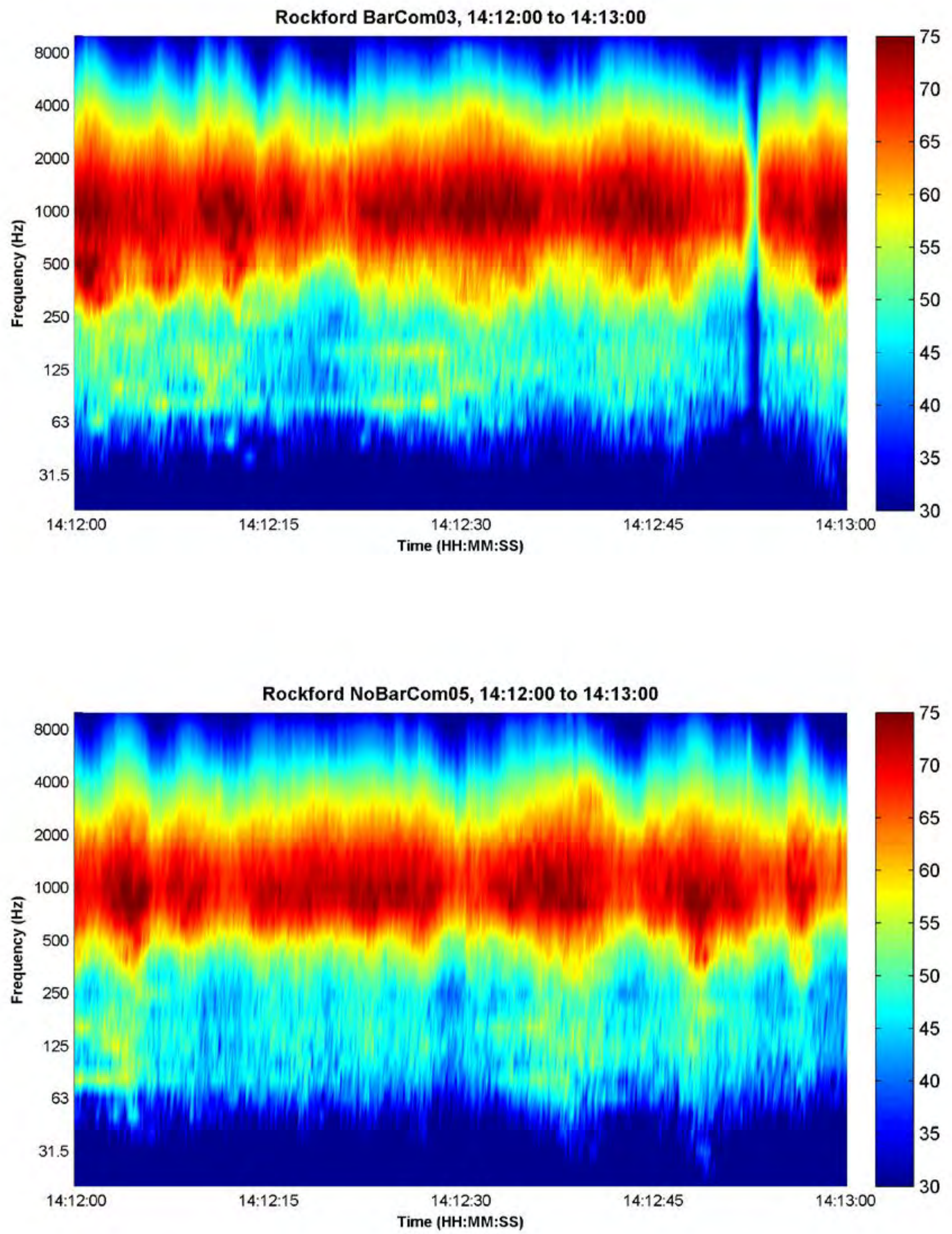


Figure 100. ***I-90 spectrograms for a second heavy truck on southbound (community) side: top is BarCom03; bottom is NoBarCom05 (approximate event times: Barrier site 14:12:34, No Barrier site 14:12:40).***

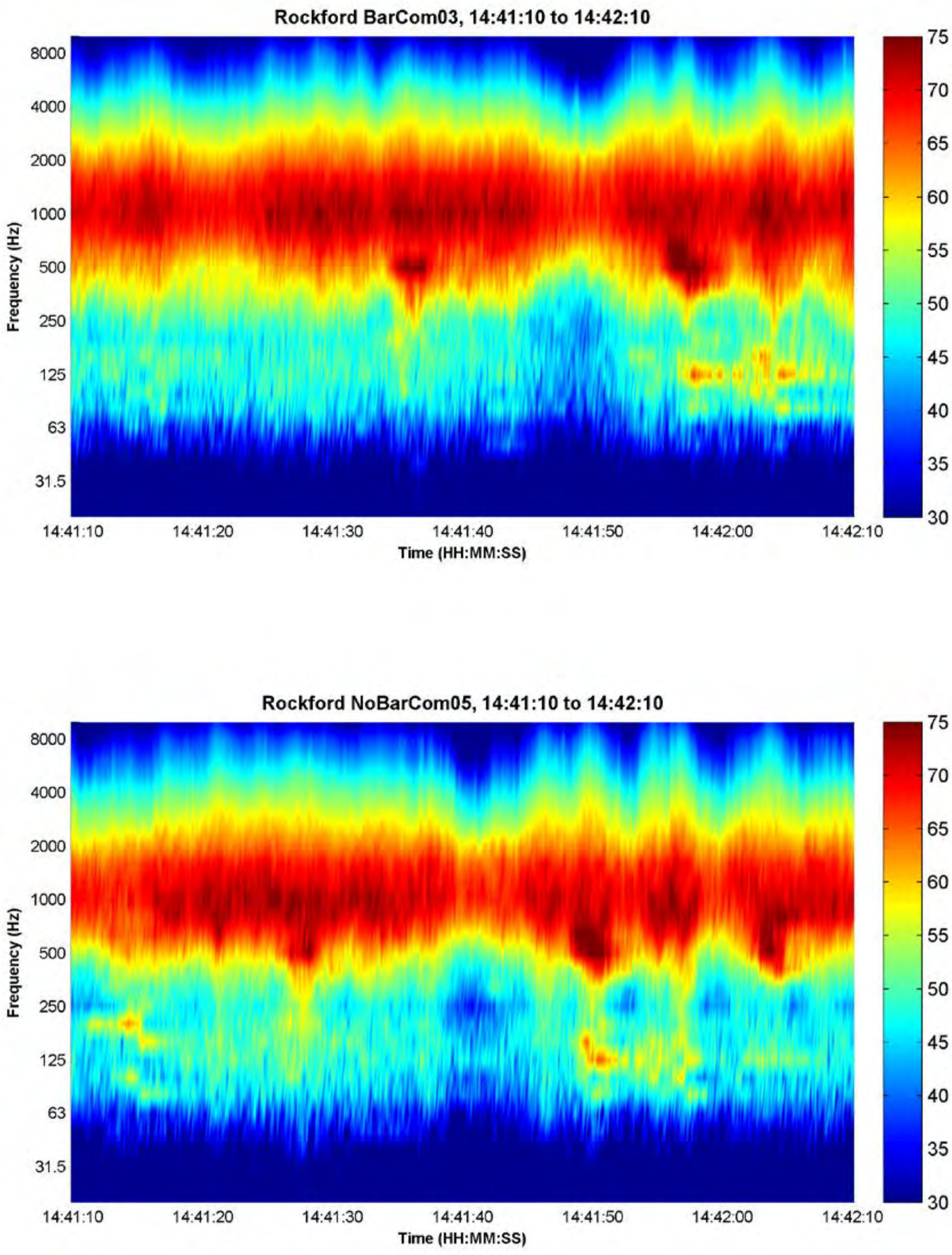


Figure 101. I-90 spectrograms for a third heavy truck on northbound (barrier) side: top is BarCom03; bottom is NoBarCom05 (approximate event times: Barrier site 14:41:36, No Barrier site 14:41:27).

In addition to examining vehicle pass-by events, spectrograms for larger blocks of data were also examined. An example is provided in Figure 102 for the near microphones at 52.5 ft (BarCom03/NoBarCom05) for an hour-long data block starting at 15:30. Other blocks of data showed similar results. The farther microphones (BarCom04 and NoBarCom06) also showed similar results, just with lower sound levels.

The spectrogram data show a clear difference between the Barrier and the No Barrier sites. As with the pass-by data, the clean data blocks show that hot spots are both wider and taller for a broad range of frequencies. Again, it can be seen that the tallest darkest red band (highest sound level band) centered around 1000 Hz is both wider and taller at the barrier site, with the same effect occurring in the surrounding frequency bands, stepping through various colors of the spectrum. Again, this indicates that the barrier is causing higher sound levels at frequencies which contribute most to the overall sound level and causing these levels to be sustained for a longer period for each vehicle pass-by event.

Another item to note about the spectrogram data is a dip in sound level at the 250 Hz band at the No Barrier site (examining across time as compared to the Barrier site). Examination of 1-minute A-weighted L_{eq} values shows that the overall sound level was about 1 dB higher at the Barrier site compared to the No Barrier site. In the 250-500 Hz range, the differences span from 2-5 dB. The spectrogram data show a clear indication of differences between the two sites at 250 Hz. These larger differences in the 250-500 Hz range are likely attributable, at least in part, to the height-above-ground differences between microphones BarCom03 and NoBarCom05. Although they are the same height above the roadway plane, the NoBarCom05 microphone is closer to the ground, allowing greater ground effects. Ground effects can cause a dip in the spectrum in that frequency range.

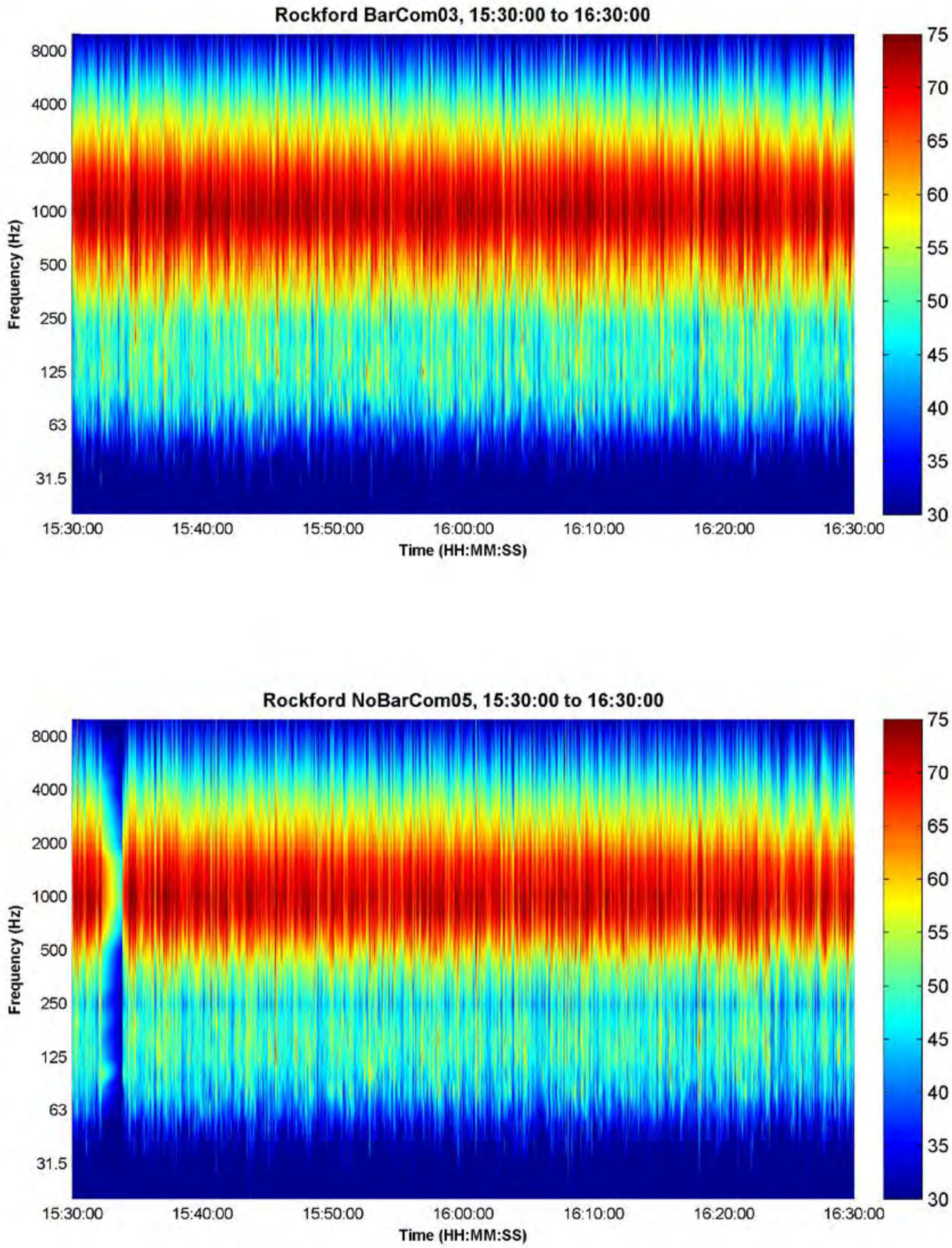


Figure 102. I-90 spectrograms for an hour-long block of data from 15:30 to 16:30: top is BarCom03; bottom is NoBarCom05.

Data Analysis for I-90 - Psychoacoustics

Descriptive statistics for the computed annoyance metrics at I-90 are summarized in Table 10. The associated histograms in each of the subsequent Figures relate the distribution of magnitudes for each metric at each microphone to the descriptive statistics in the Table.

The Unbiased Annoyance (UBA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 104. The Psychoacoustic Annoyance (PA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 105. The Category Scale of Annoyance (CSA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 106.

There is a clear difference in the means of the Unbiased Annoyance between the Barrier and No Barrier locations for both the higher and lower microphones; the metrics at the higher microphones differ by more than two standard deviations. A similar difference is seen in the Psychoacoustic Annoyance. Since the higher microphones at this site are further from the roadway, this increase in deviation of the means may be related to the additional propagation distance. In this configuration the lower Barrier microphone has higher mean annoyance, while the higher Barrier microphone has lower mean annoyance. That the higher level of annoyance flips from the closer, lower microphones to the higher, farther microphones appears to be a function of the height and distance. The acoustical signals have clearly different levels and frequency content at the two locations, and the UBA and PA both depend strongly on Loudness (distance) and Sharpness (high-frequency content). It is not clear whether the UBA or the PA substantiate an assumption of increased annoyance due to the presence of the barrier at this site.

There is no significant difference in the means of the Category Scale of Annoyance for either pair of microphones. The simple linear regression that forms CSA, and its derivation from product noise, do not apply well to highway traffic noise.

Table 10. Descriptive statistics of annoyance metrics, I-90.

Metric	Location	Mean	Std. Dev.	Skewness	Kurtosis
UBA	BarCom03	49.4	4.5	-0.022	0.270
	NoBarCom05	44.8	5.3	0.127	-0.098
	BarCom04	35.8	3.6	0.122	0.008
	NoBarCom06	45.1	4.4	0.276	0.221
PA	BarCom03	13.6	1.4	0.360	0.555
	NoBarCom05	11.7	1.6	0.244	0.139
	BarCom04	9.34	1.08	0.355	0.050
	NoBarCom06	12.1	1.3	0.525	0.893
CSA	BarCom03	41.7	1.9	0.098	0.855
	NoBarCom05	40.3	2.0	0.337	0.549
	BarCom04	38.3	1.6	0.608	0.486
	NoBarCom06	38.4	1.7	0.807	1.872

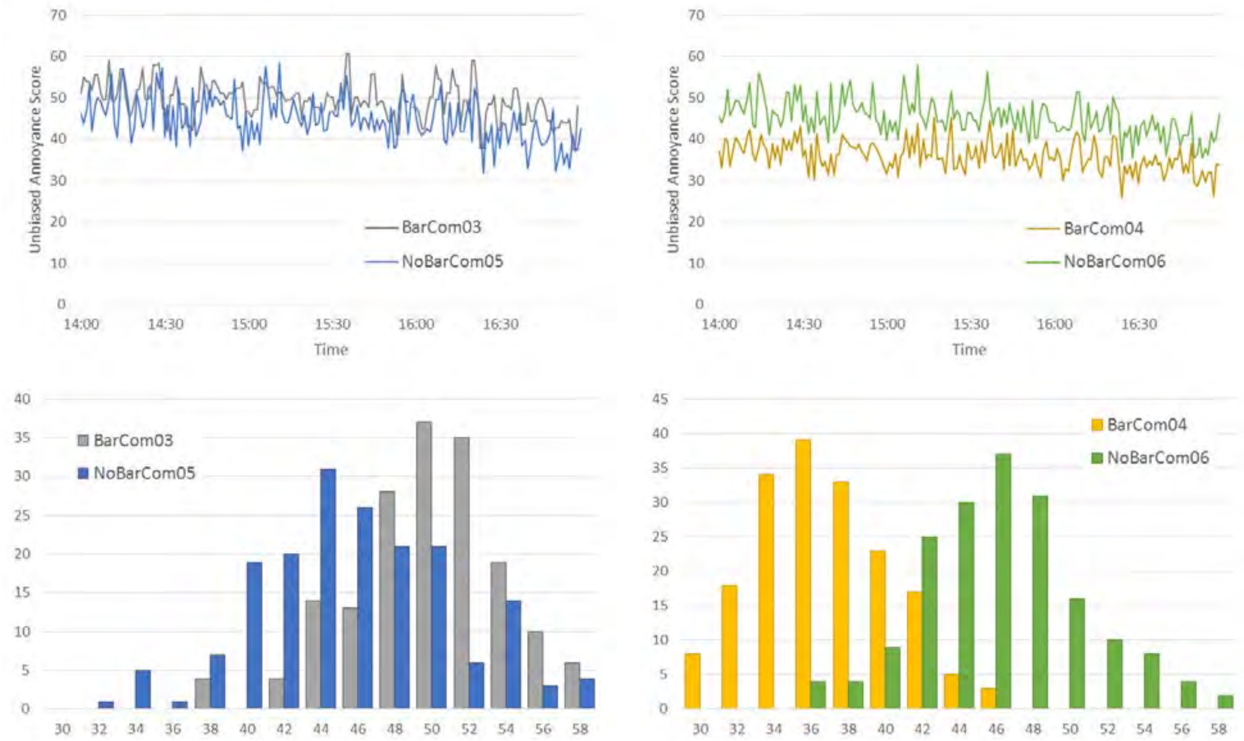


Figure 104. Unbiased annoyance vs. time and histograms, I-90.

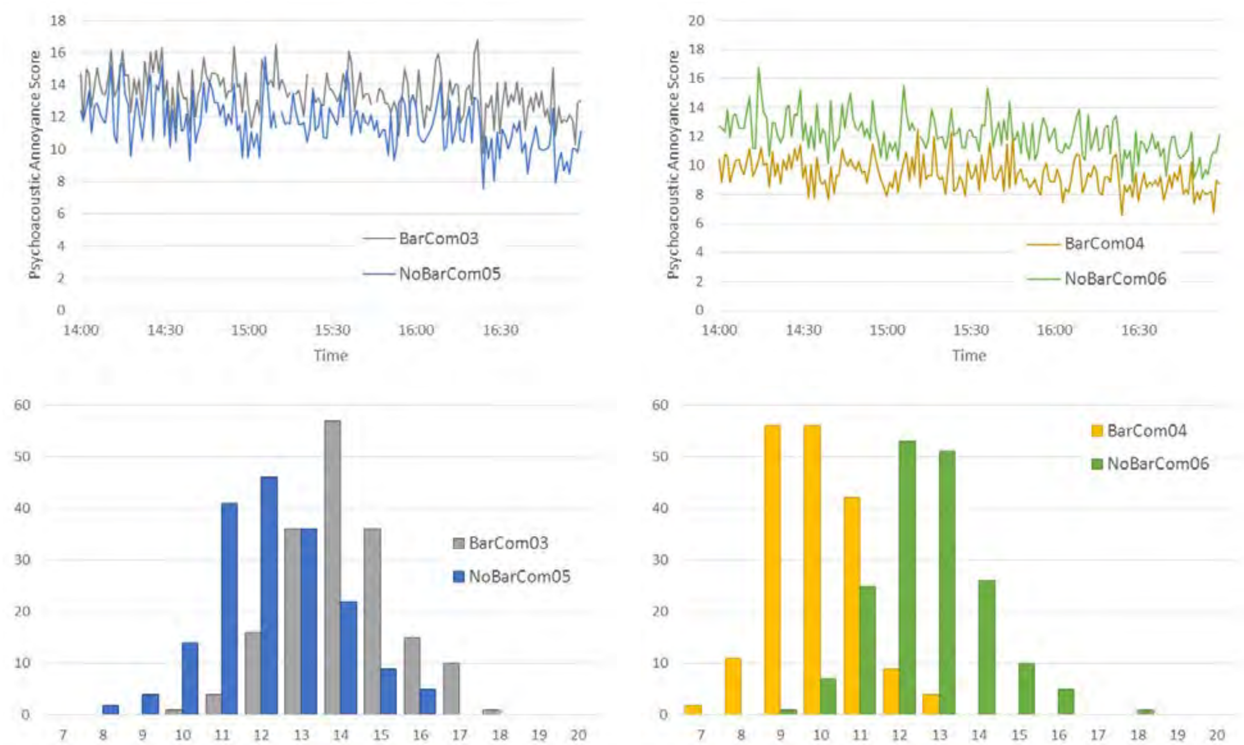


Figure 105. Psychoacoustic annoyance vs. time and histograms, I-90.

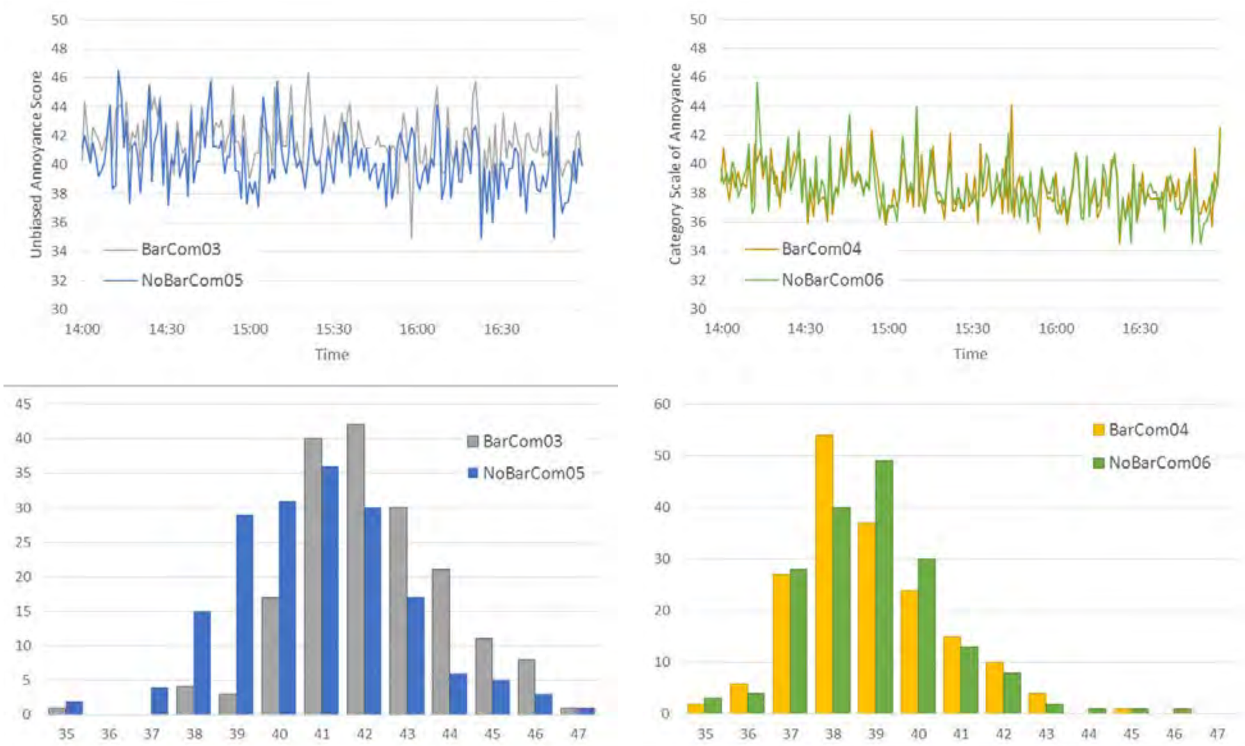


Figure 106. Category scale of annoyance vs. time and histograms, I-90.

CHAPTER B-6

Results – SR-71, Chino Hills, CA (Location ATS-3)

On January 28, 2015, data was successfully collected at the fourth location, SR-71, in Chino Hills, California. Data were collected from about 9 am to 1:30 pm, with a 15 to 20 minute break in the middle for battery changes. There were calm winds in the morning and some stronger winds toward the end.

The microphone layout is shown in Figure 107. Figure 108 shows cross-sections at the Barrier and No Barrier sites. The barrier is 13-ft tall, consisting of a 7-ft concrete block wall atop a 6-ft high berm and located 50 ft from the center of the near travel lane. Appendix C of the Final Report includes site photographs.

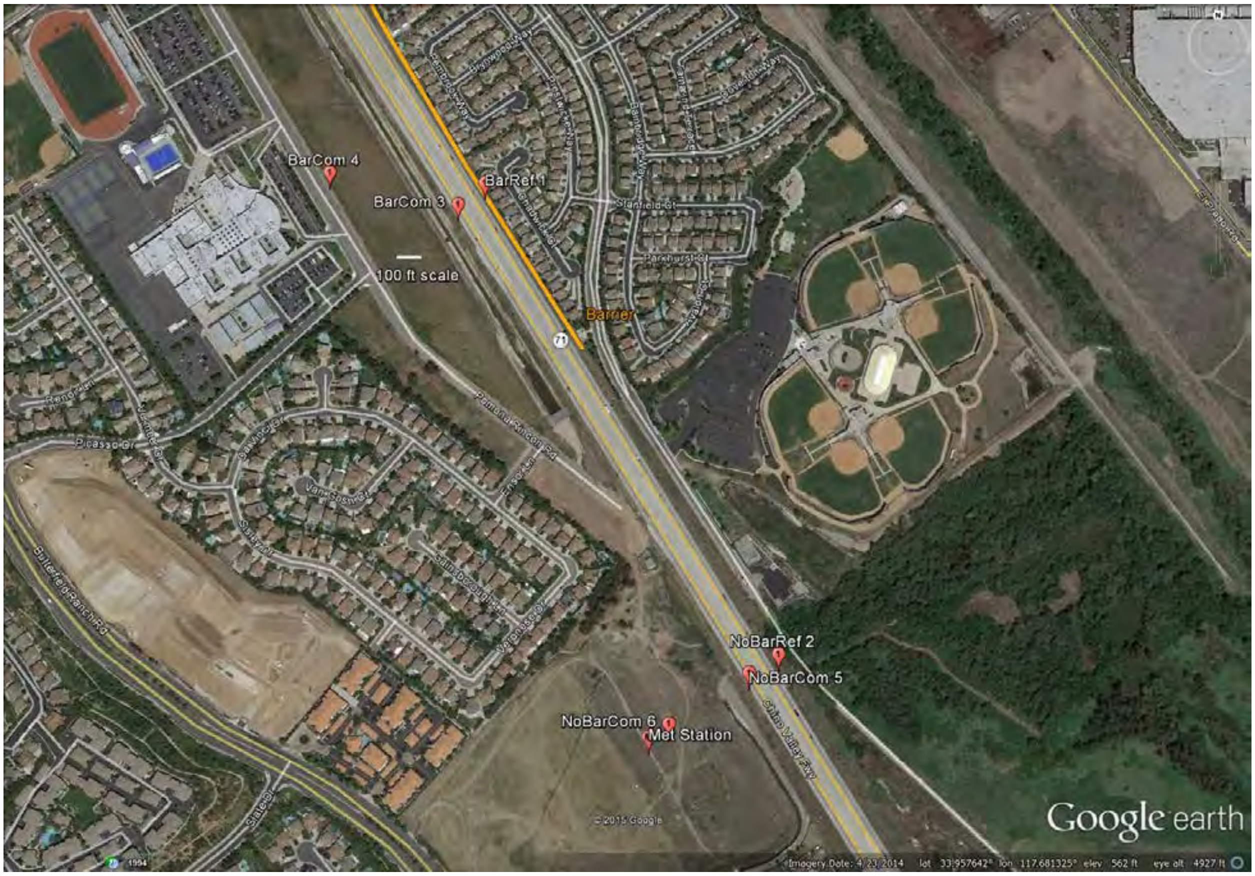


Figure 107. SR-71 microphone positions. (Source: Google Earth.)

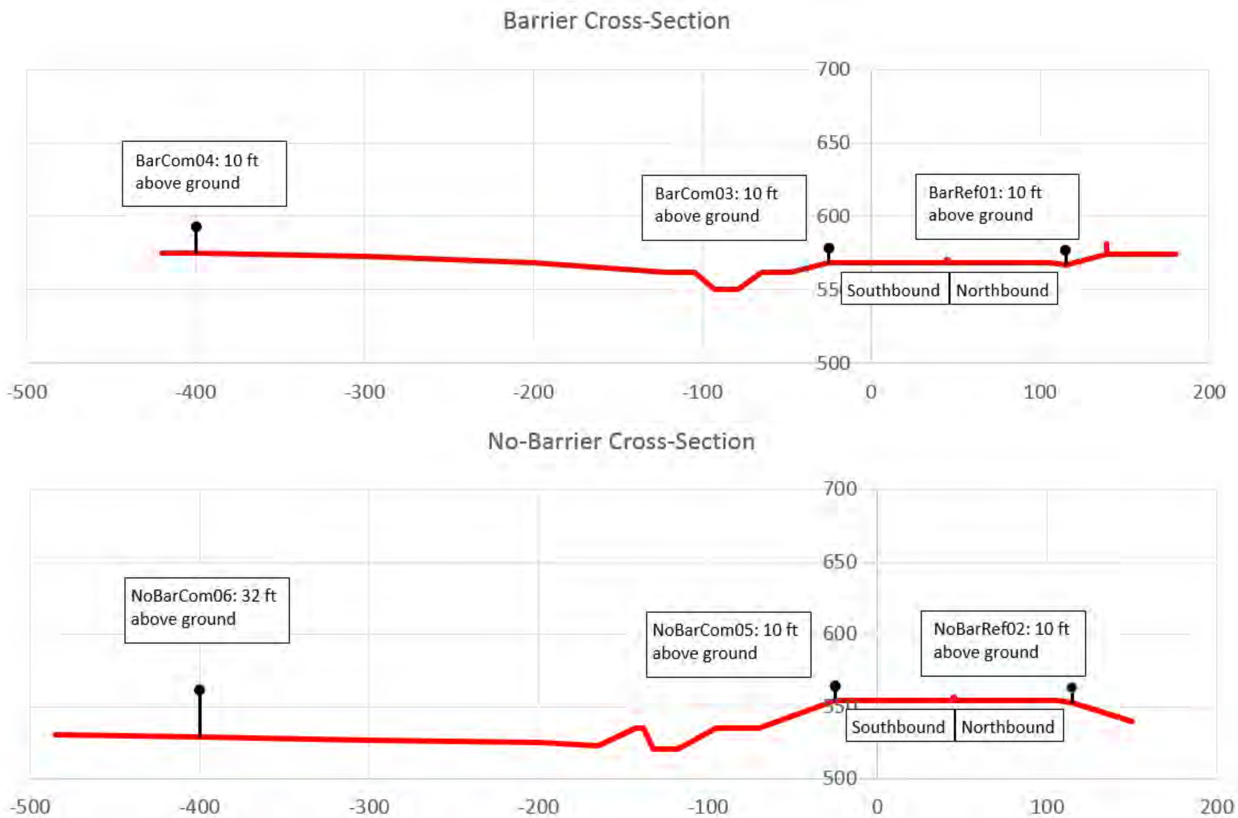


Figure 108. Cross-sections at the SR-71 Barrier (top) and No Barrier (bottom) sites.

The SR-71 location consisted of six microphone locations:

Table 11: Microphone positions for SR-71 site

Mic Name	Side of Road	Distance from Center of Near Travel lane (ft)	Height Above Roadway Plane (ft)
BarRef01	NB	25	10 (10 ft above ground)
NoBarRef02	NB	25	10 (10 ft above ground)
BarCom03	SB	25	10 (10 ft above ground)
BarCom04	SB	400	~17 (10 ft above ground)
NoBarCom05	SB	25	10 (10 ft above ground)
NoBarCom06	SB	400	At least 5 ft (32 ft above ground)

The exact height of NoBarCom06 above the roadway plane was not known, since elevation data for the ground could not be obtained. By observation in the field looking from the road, the microphone was at least 5 ft above the roadway plane. While having identical heights above the road would be ideal, simplified TNM modeling described in the spectrogram section gave an indication that any effect of the height difference would be minimal in the main frequencies of interest for traffic noise.

It should be noted that the far microphone at the barrier site (BarCom04) was offset from the near-roadway microphone line. Both the near roadway microphones and far microphone were strategically placed for the most meaningful comparisons to the No Barrier data. The parameters considered in the placement were: region of barrier influence (consideration of the end of the barrier for the far microphone position) and intervening ground (e.g., if the close microphones were placed in line with the far microphone, the ground between the highway noise source and BarCom03 would have included more pavement than for NoBarCom05 due to a merge lane; the close microphones were shifted south of where the merge lane ends).

Measurement Observations

As observed at the traffic count and speed site in the center of an overpass about a half a mile southeast of the No Barrier site, traffic was free-flowing with brief lulls in each direction throughout the measurement period. There was slightly greater volume on the northbound side. Some occasional platooning was observed. Heavy trucks were mostly in the outer lane on each side (average 6% of the traffic volume on each side).

During the measurement period, speeds were generally easier to acquire for receding vehicles than oncoming vehicles. Speeds were measured in all lanes, primarily for automobiles, medium trucks, and heavy trucks, since these were the dominant vehicle types. Speeds typically ranged from 55-75 mph, with the lower end of the range representing heavy trucks. Inside lane speeds were generally higher than outside lane speeds, and heavy trucks were mostly in the outer lane on each side of the highway, and only occasionally in the middle lane.

Observers were positioned at BarCom04 and NoBarCom06, the far microphones at each site; there was also a roving observer who experienced both sites. The main source of noise at both sites (Barrier and No Barrier) was the SR-71 traffic. At the Barrier site, however, there was also occasional noise from single vehicles on an adjacent road. Also, observers at both sites noted an intermittent “banging” sound throughout the measurement period. The roving observer noted the sound at both sites, and while at the traffic video site, observed that the sound seemed to be coming from a distant location to the south of both sites and south of the traffic video site. The observer at the No Barrier site noted that the source of some of the banging sounds could have been nearby home construction.

During set-up and time of battery change-over, sound observations were possible at the near microphones, on both the reference and community sides of the road. It was observed that the No Barrier site had a more “open” feel than the Barrier site; in other words, the presence of the barrier was “felt” at the Barrier site. At the far locations, direct comparison of observations of the highway traffic noise is complicated by the difference in elevation of the observer (although the microphones at the Barrier and No Barrier sites and the observer at the Barrier site were above the roadway plane, the observer at the No Barrier site was well below the roadway plane). The roving observer noticed that it seemed to be easier to audibly distinguish single vehicle pass-by events at the No Barrier site.

The measurement problems encountered at this location were minor. There was an issue with the data card from the radar gun. As a result, the speeds were recorded manually. In addition, throughout the measurement period, there was intermittent distant banging, at times sounding like a pile driver and at other times sounding like fireworks. This sound likely affected all microphones, although the four near the road were experiencing fairly high sound levels, so the banging may not be apparent in the data. To help with later data processing, the team logged when the banging was heard and when not and also collected data for a little more than four hours to have some extra data.

Measured Broadband Levels and Level Differences for SR-71

The running L_{eq}(5min) for each site are presented in the following figures to give an overall picture of the measured levels, both in terms of unweighted sound pressure levels and A-weighted sound levels:

- BarRef01 and NoBarRef02 - Figure 109 (unweighted) and Figure 110 (A-weighted); then Figure 111 shows the differences in the unweighted and A-weighted levels for this mic pair
- BarCom03 and NoBarCom05 - Figure 112 (unweighted) and Figure 113 (A-weighted); then Figure 114 shows the differences in the unweighted and A-weighted levels for this mic pair; and
- BarCom04 and NoBarCom06 - Figure 115 (unweighted) and Figure 116 (A-weighted); then Figure 117 shows the differences in the unweighted and A-weighted levels for this mic pair.

The following observations are prior to any attempt to group data into equivalent periods. In general, both the unweighted sound pressure levels and A-weighted sound levels are higher at the Barrier microphones than at the No Barrier microphones.

For the reference microphones, the unweighted levels at BarRef01 are on the order of 0 dB to 1.8 dB higher than the NoBarRef02 levels, averaging roughly 1 dB higher. The A-weighted levels at BarRef01 are on the order of 0 dB to 1 dB higher than NoBarRef02, averaging roughly 0.5 dB. Higher levels at BarRef01 were expected because the microphone was positioned between the barrier and the road.

For the microphones just off the shoulder on the opposite side from the barrier, little evidence of reflection is seen. The unweighted levels at BarCom03 range from 0.9 dB *lower* to 1 dB higher than those at NoBarCom05. The A-weighted levels at BarCom03 range from 0.7 dB lower to 0.5 dB higher than those at NoBarCom05. With these microphones so close the far lanes of traffic, relative to the distance from BarCom03 to the barrier, little increase in level due to reflections was expected.

For virtually all of the running 5-minute L_{eq} periods, the BarCom04 levels, both unweighted and A-weighted, are higher than the NoBarCom06 levels. The unweighted levels ranged mostly from 0 dB to 4 dB higher than NoBarCom06. The A-weighted levels ranged from 1 dB to nearly 4 dB higher. For both unweighted and A-weighted cases, the average difference was 2.1 dB higher at BarCom04.

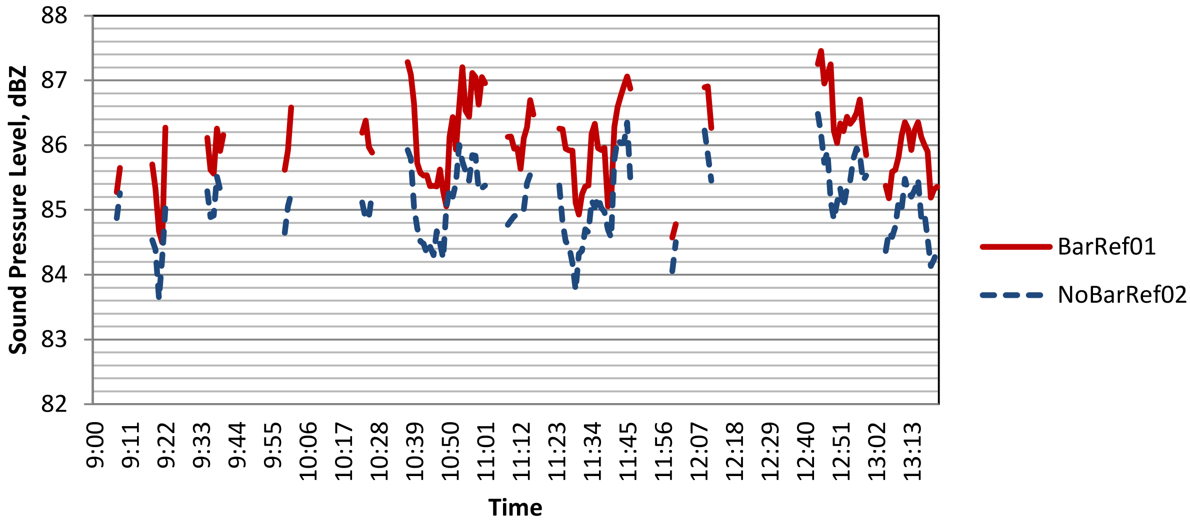


Figure 109. Running L_{eq}(5min), SR-71, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

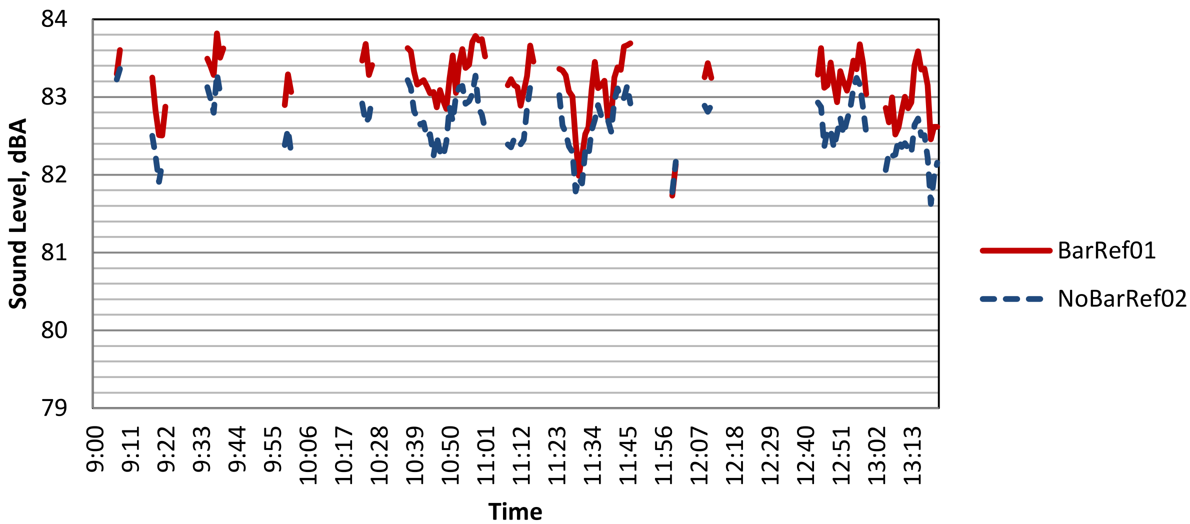


Figure 110. Running L_{eq}(5min), SR-71, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

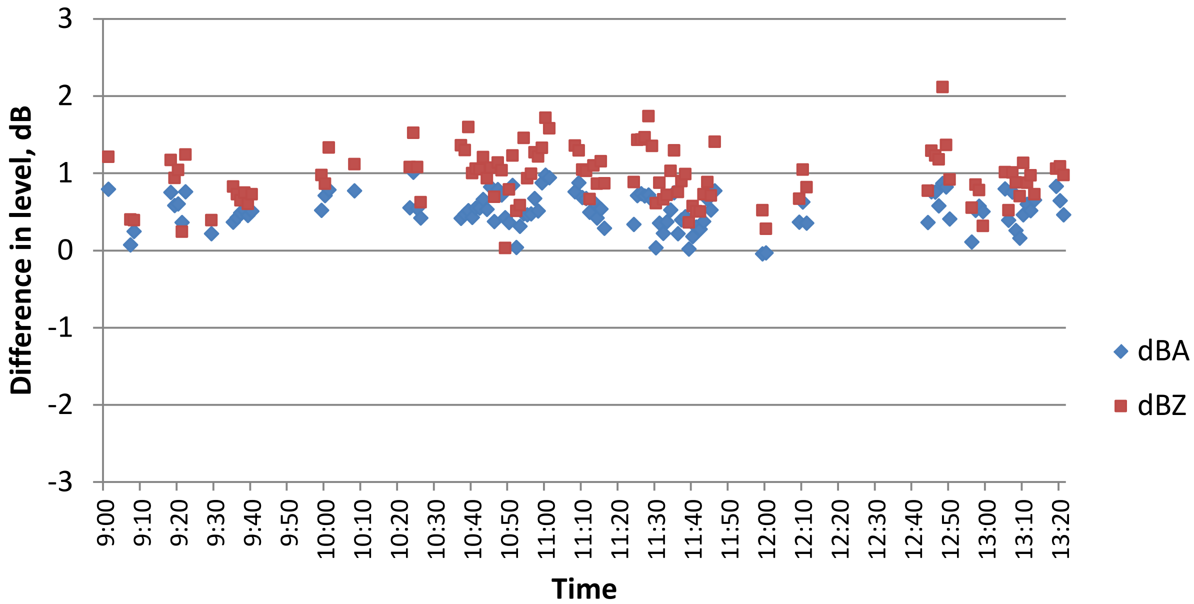


Figure 111. Differences in running L_{eq}(5min), SR-71, BarRef01 minus NoBarRef02

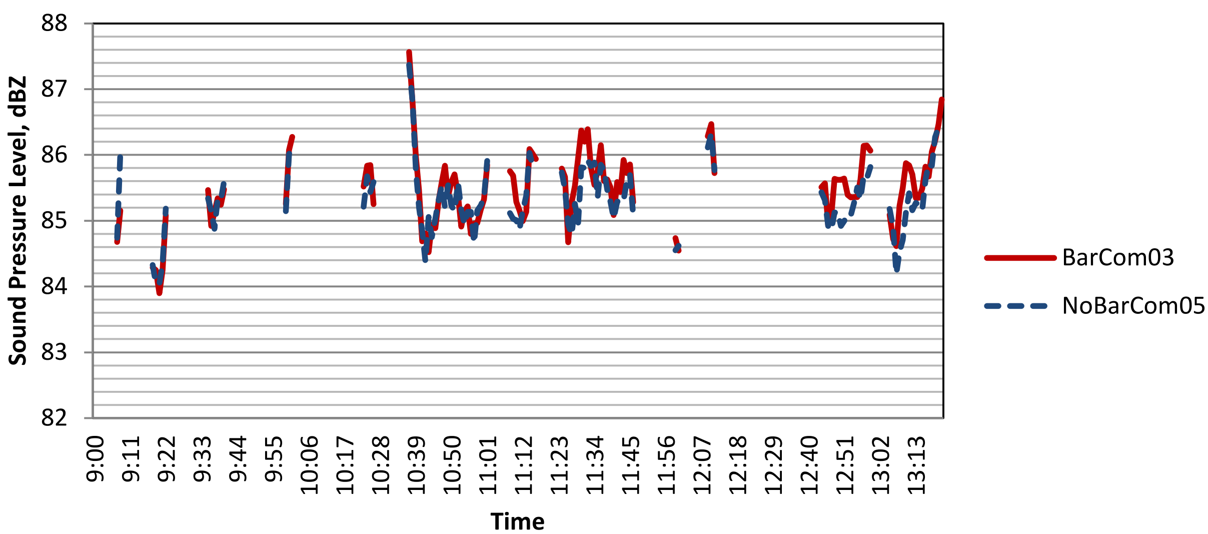


Figure 112. Running L_{eq}(5min), SR-71, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

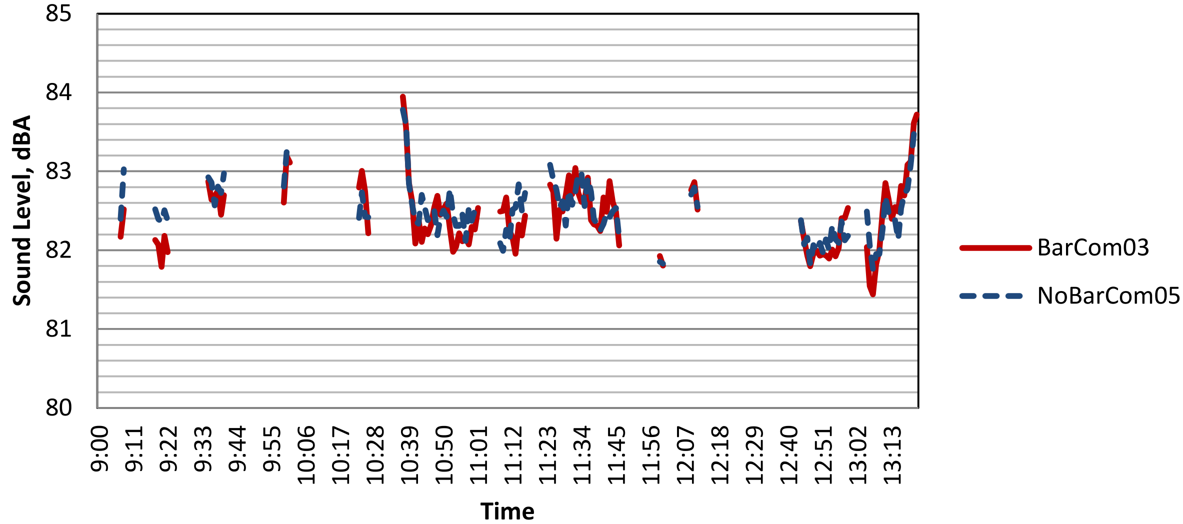


Figure 113. Running L_{eq}(5min), SR-71, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

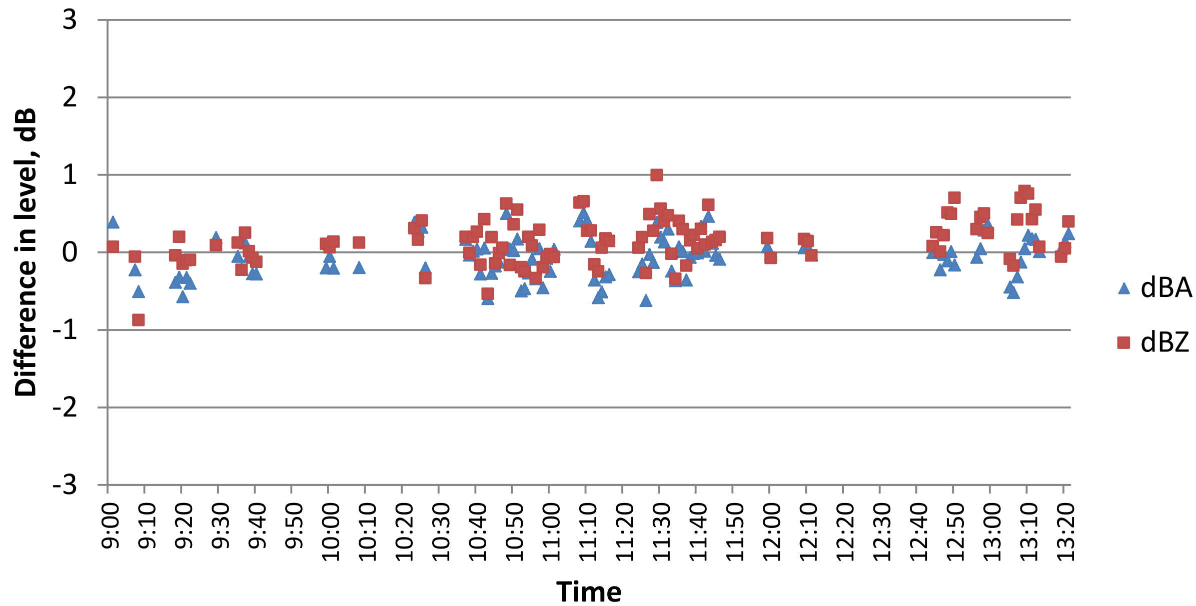


Figure 114. Differences in running L_{eq}(5min), SR-71, BarCom03 minus NoBarCom05

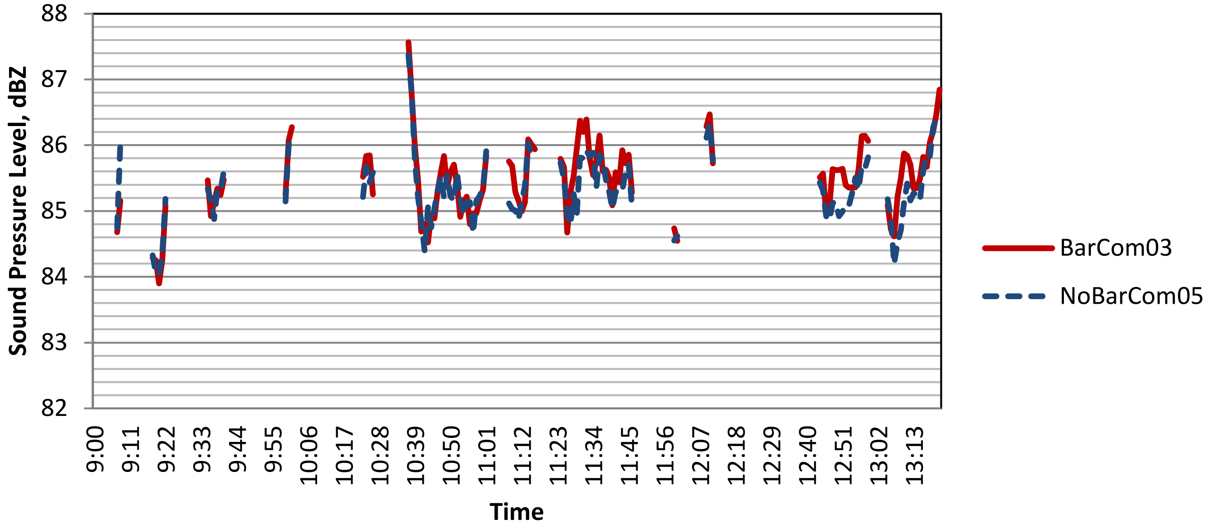


Figure 115. Running L_{eq}(5min), SR-71, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

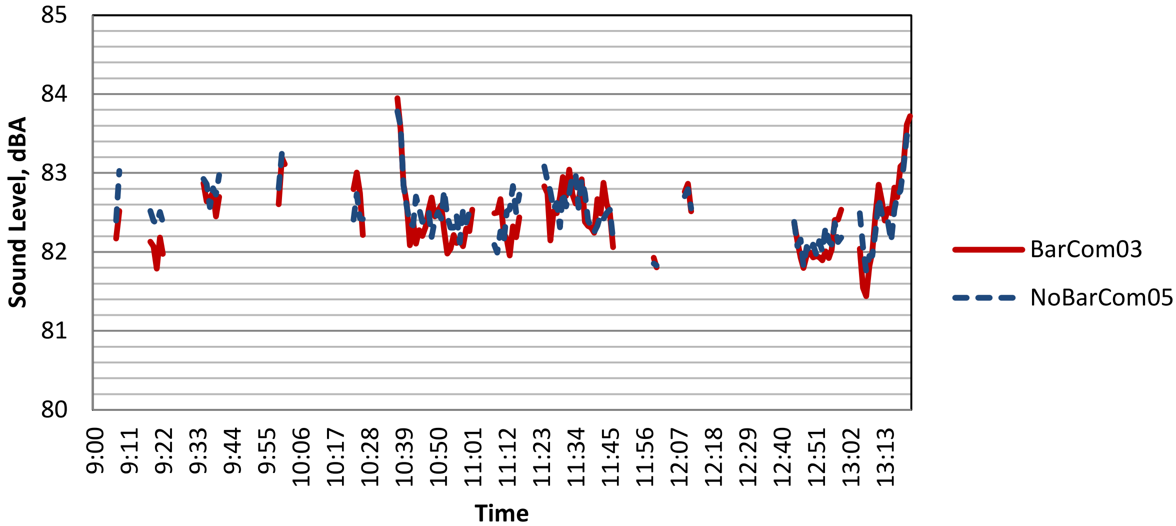


Figure 116. Running L_{eq}(5min), SR-71, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

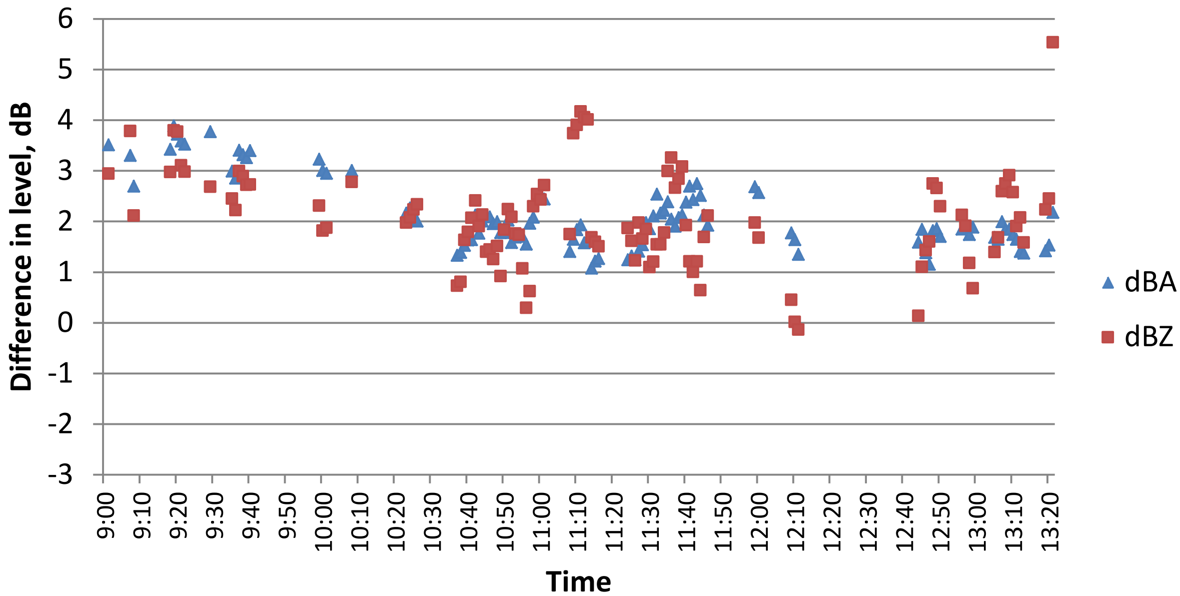


Figure 117. Differences in running L_{eq}(5min), SR-71, BarCom04 minus NoBarCom06

Data Analysis for SR-71 - FHWA Method

Equivalent Groups

All of the groupings of 5-minute periods that were judged equivalent for the reference L_{eq} and average speeds at the SR-71 location fell into one meteorological class: Downwind Neutral. There were six groupings in this class, each with three or four 5-minute equivalent periods, as shown in Figure 118. Each group has a unique name, starting with “DNG”. Note that while all of the 5-minute periods in a group are non-overlapping in time, the same 5-minute periods often appear in multiple equivalent groups.

These periods had very consistent traffic volumes, as show in Table 12 . In terms of equivalent hourly volumes, the overall range was only from 3,628 to 3,764 vph.

Speeds ranged from averages of 66 mph to 76 mph.

Group ID	Starting Time of 5-minute Periods																		
	10:23	10:26	10:39	10:44	10:51	10:55	11:35	11:38	11:40	11:44	11:46	12:11	12:45	12:46	12:48	12:58	13:09	13:10	13:21
DNG-1-1														■				■	■
DNG-2-1				■	■		■												
DNG-2-2									■						■		■		
DNG-3-1	■									■		■	■						
DNG-3-2		■						■			■								
DNG-3-3			■			■										■			

Figure 118. Equivalent 5-minute periods for Downwind Neutral groups at SR-71.

Table 12. Two-way traffic volumes in 5-minute periods, by equivalent group for Downwind Neutral conditions, sorted by factored hourly volume, SR-71.

Group	Two-Way Traffic Volumes (5 minutes)				Factored Hourly Volume (vph)
	Period 1	Period 2	Period 3	Period 4	
Downwind Neutral					
DNG-1-1	277	348	316		3,764
DNG-2-1	309	328	299		3,744
DNG-2-2	303	289	336		3,712
DNG-3-3	310	296	320		3,704
DNG-3-1	322	300	311	282	3,645
DNG-3-2	306	310	291		3,628

Sound Pressure Level Spectra

Before discussing the differences in levels between the Barrier and No Barrier sites, typical sound pressure level spectra are shown to give some perspective on the data on which the differences are based. One of the 5-minute periods in the one of the Downwind Neutral groups was chosen as typical. Figure 119, Figure 120, and Figure 121 present the sound pressure level spectra for, respectively, BarRef01/NoBarRef02, BarCom03/NoBarCom05 and BarCom04/NoBarCom06.

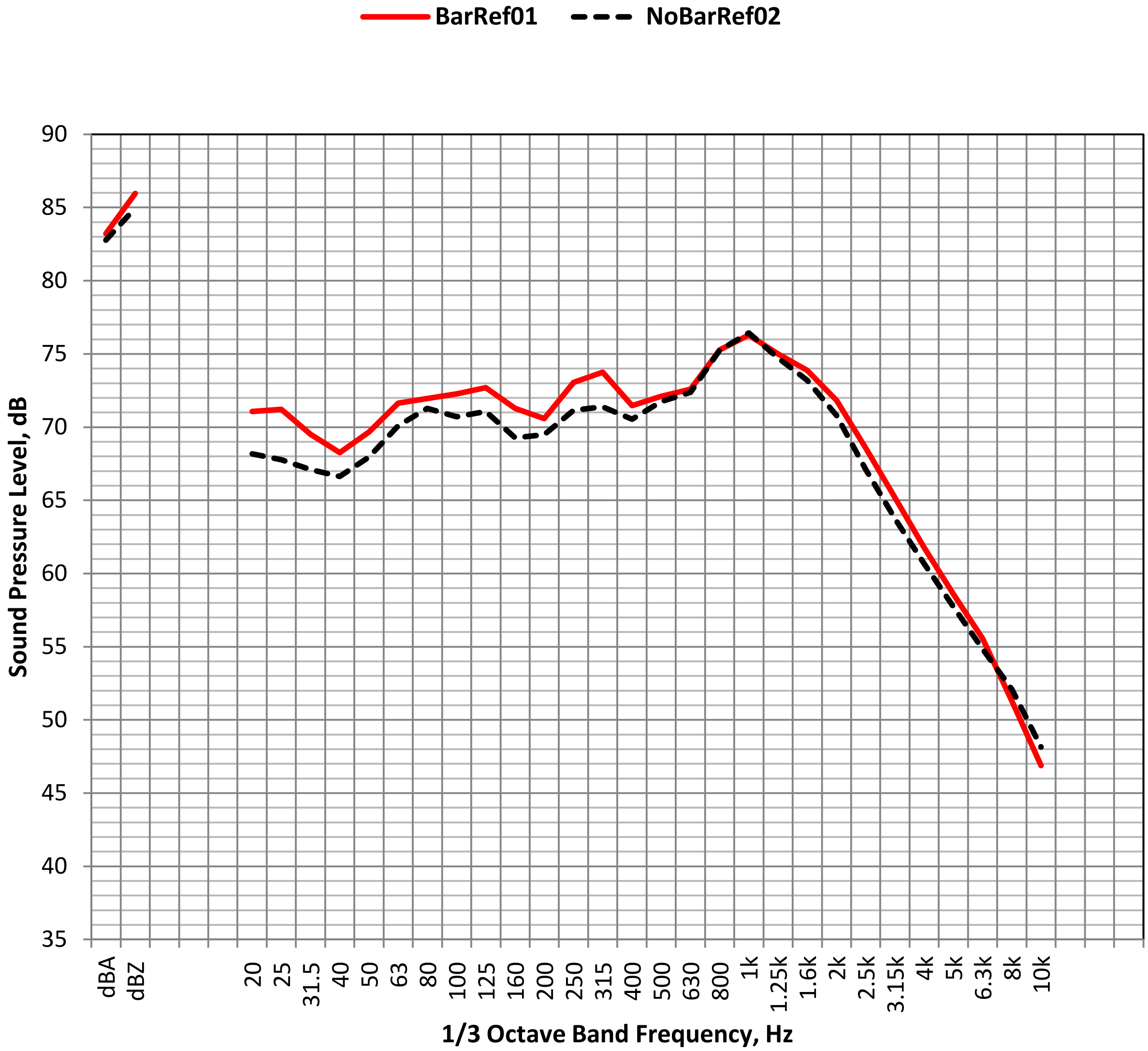


Figure 119. Sample sound pressure level spectra for BarRef01 and NoBarRef02, SR-71, Downwind Neutral group DNG-3-2, 11:38-11:43 (L_{eq}(5min), dBZ)

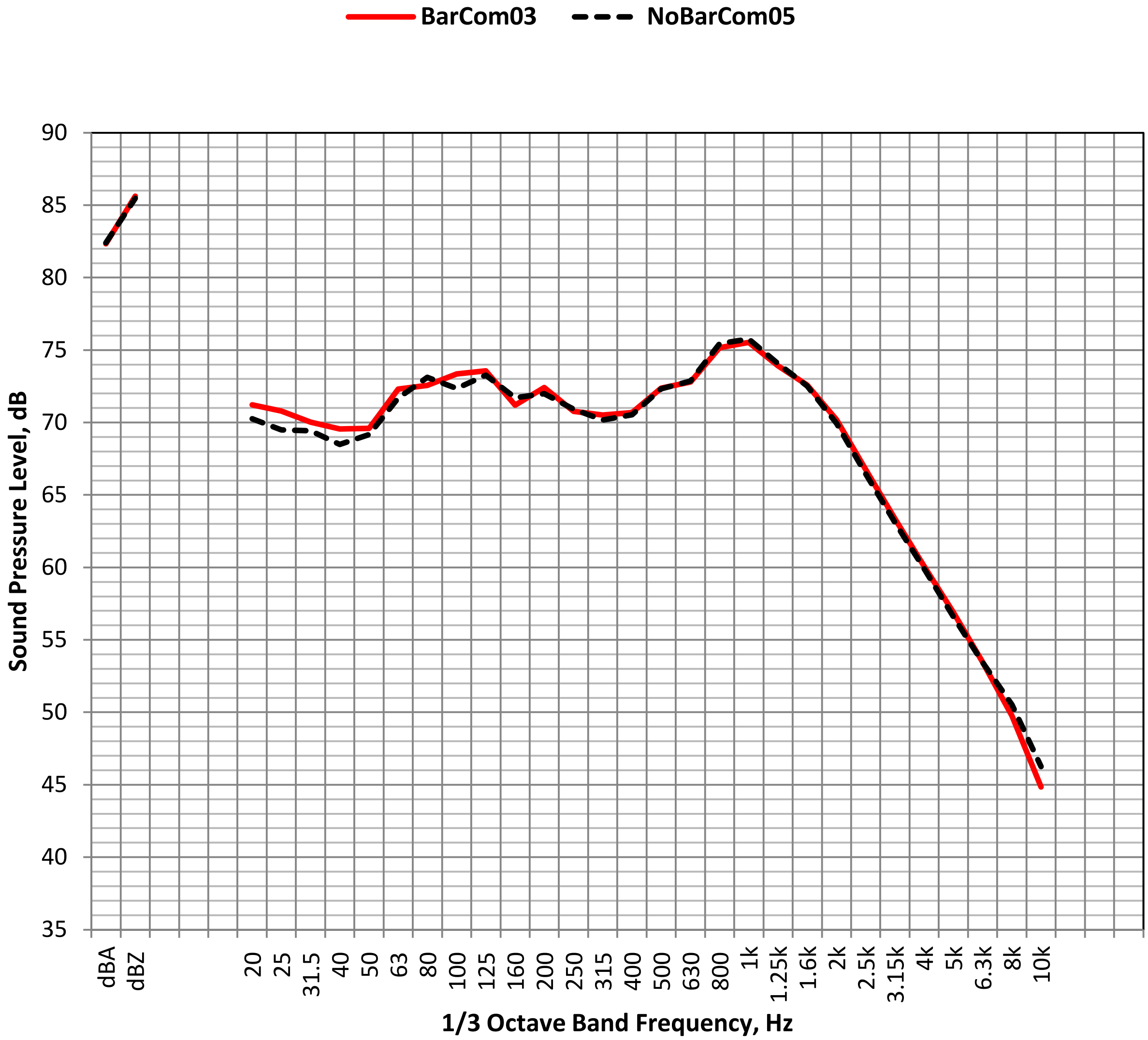


Figure 120. Sample sound pressure level spectra for BarCom03 and NoBarCom05, SR-71, Downwind Neutral group DNG-3-2, 11:38-11:43 (L_{eq}(5min), dBZ)

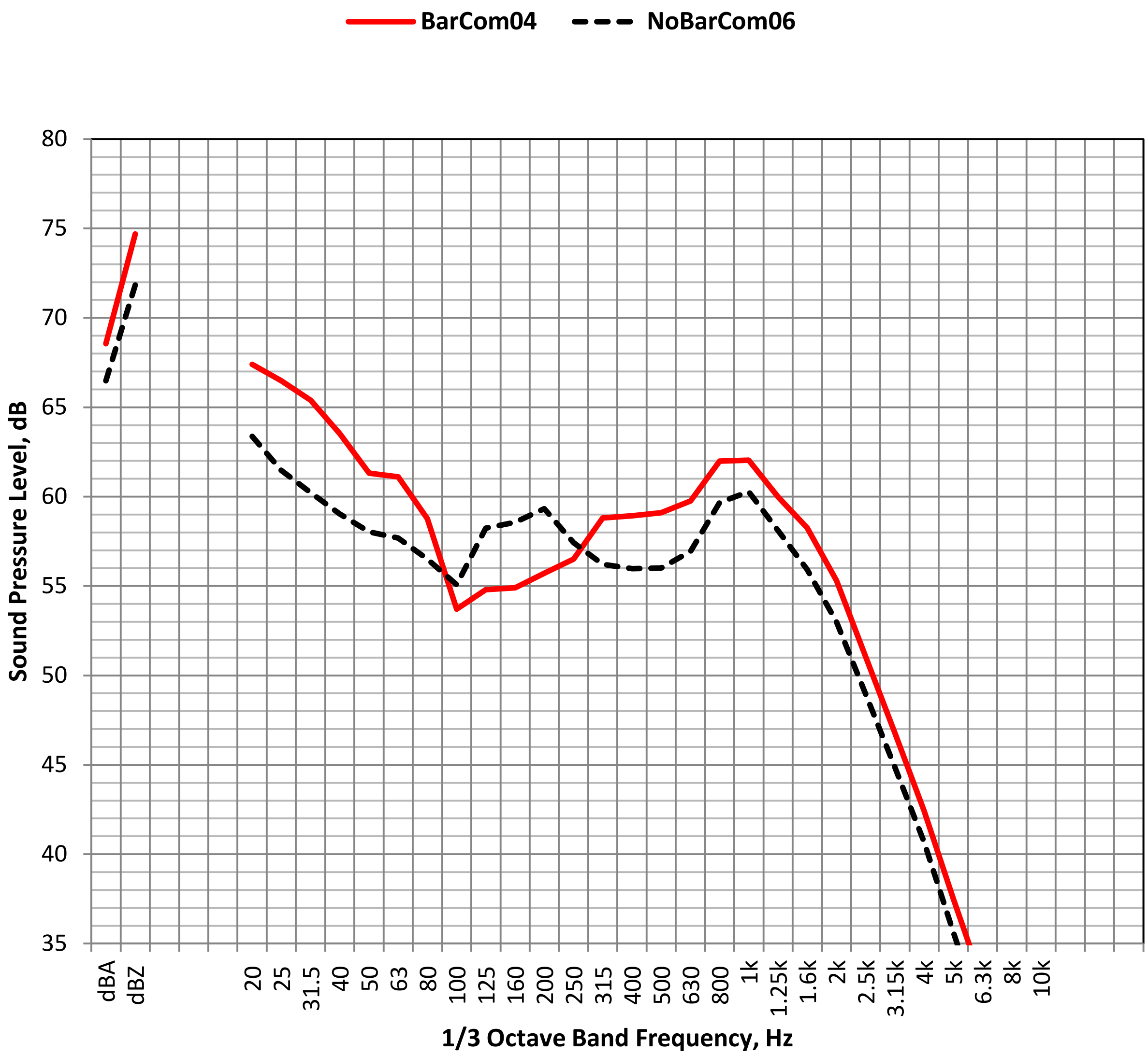


Figure 121. Sample sound pressure level spectra for BarCom04 and NoBarCom06, SR-71, Downwind Neutral group DNG-3-2, 11:38-11:43 (L_{eq}(5min), dBZ).

Downwind Neutral Class

Figure 122 shows the averages of the differences in the Barrier and No Barrier microphones' levels for all of the Downwind Neutral groups, with their error bars. The error bars are +/- one standard deviation for each average value. This figure compares the following:

- BarRef01 and NoBarRef02 in the upper graph;
- BarCom03 and NoBarCom05 in the middle graph; and
- BarCom04 and NoBarCom06 in the lower graph.

Each graph shows the averages of the average level differences for the A-weighted sound level, the unweighted sound pressure level and the 1/3 octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all of the individual Downwind Neutral groups are in spreadsheet files in the project record. The trends across the 1/3 octave band frequencies, described below, are generally similar in these individual groups of equivalent periods, with some differences likely related to background noise and the uniqueness of vehicle noise sources in each period.

Figure 122 shows in the upper graph that the BarRef01 levels are higher than the NoBarRef02 levels at across virtually the entire spectrum, with exception of 8 kHz and 10 kHz. The BarRef01 levels are higher by 3 dB at 31.5 Hz, 2.5 dB at 125 Hz and 1.5 dB at 2.5 kHz. In the range from 400 Hz to 1.25 kHz, the differences are less than 0.5 dB. Because the BarRef01 microphone was in front of the barrier, higher levels were expected than at NoBarRef02.

The middle graph compares the levels at BarCom03 and NoBarCom05, the microphones close to SR-71 on the opposite side from the barrier. The levels at BarCom03 are generally higher than or the same as those at NoBarCom05. The levels in the frequency bands from 20 Hz up through 125 Hz are 0.5 dB to 1.5 dB higher at BarCom03. From 160 Hz up through 1.6 kHz, the levels are different by only 0.5 dB or less. From 2 kHz through 5 kHz, the BarCom03 level are a half decibel higher than NoBarCom05 The NoBarCom05 levels are less than 1.5 dB higher than BarCom03 at and above 6.3 kHz.

The lower graph compares the levels at the distant BarCom04 and NoBarCom06 positions. The levels in the frequency bands from 20 Hz up through 80 Hz were 2 dB to 4 dB higher at BarCom04 compared to NoBarCom06. Then, from 315 Hz through 8 kHz, the BarCom04 levels are 1.5 dB to 3 dB higher than NoBarCom06. In the range of 100 Hz through 250 Hz, the NoBarCom06 levels range from 0 dB to 3 dB (at 200 Hz) higher than the BarCom04 levels.

Effects of Traffic Volume and Speed

No trends were evident when considering the differences in sound level as a function of two-way traffic volume for the Downwind Neutral class. Also, the range in speeds was too small to address any relationship between speed sound level difference.

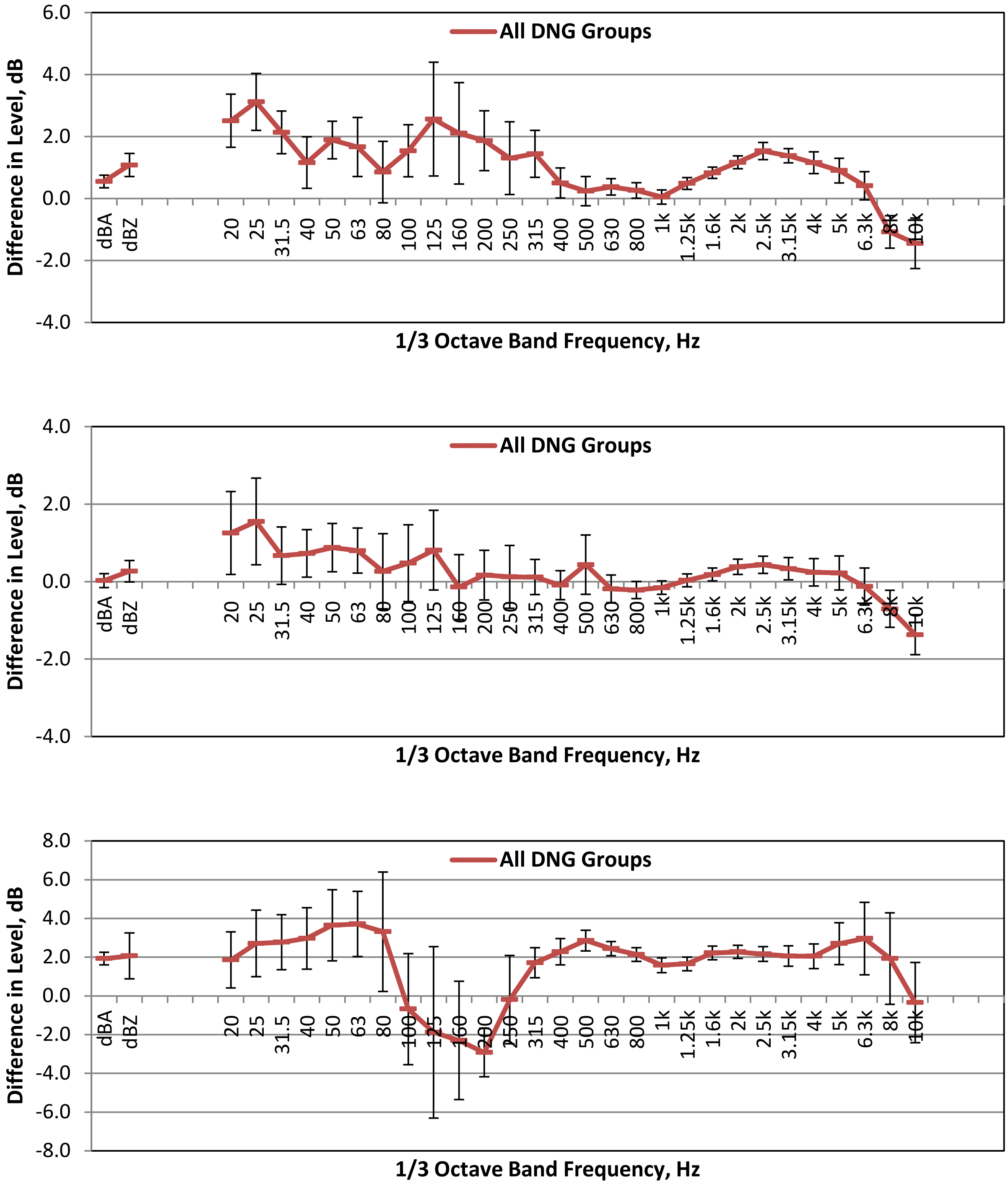


Figure 122. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Downwind Neutral groups, SR-71.

Additional Sound Level Analysis for SR-71 – L_n Descriptors

Figure 123 presents the L_{90}(5min) and L_{99}(5min) for BarRef01 and NoBarRef02, in terms of overall A-weighted sound levels and unweighted sound pressure level. The upper graphs are L_{90} (A-weighted on the left and unweighted on the right). The lower graphs are L_{99} (A-weighted on the left and unweighted on the right).

Then, Figure 124 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min), computed as BarRef1 minus NoBarRef2 for the A-weighted sound levels.

Much like the I-24 data, the results show that while the L_{eq}(5min) averages about 0 dB to 1 dB higher at BarRef01 than at NoBarRef02, the L_{90}(5min) and L_{99}(5min) at BarRef01 are much higher than at NoBarRef02: L_{90} by as much as 4 dB and L_{99} by as much as 7 dB. These differences are strong evidence of an increase in the background level in front of the barrier that could be attributed to the presence of reflected sound rays from the passing vehicles reaching the microphone in addition to the direct rays, producing a sustained sound that keeps the background level from dropping off during gaps between vehicles.

Figure 125 then presents the L_{90}(5min) and L_{99}(5min) for BarCom03 and NoBarCom05 (the lower microphones across from the barrier), again for overall A-weighted sound levels and unweighted sound pressure levels, in the same layout as for the reference microphones. Figure 126 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05.

There is some evidence of the elevated background level at BarCom03 compared to NoBarCom05 even though these two microphones are very close to the edge of the shoulder for the far-lane traffic across from the barrier. While the L_{eq}(5min) at BarCom03 ranges about 0.5 dB higher to 1 dB lower than NoBarCom05, the L_{90} at BarCom03 are, on average, about a decibel higher than NoBarCom05 and the L_{99} at BarCom03 average approximately 1.5 dB higher.

For both descriptors, there are also many times when the NoBarCom05 levels are higher than the BarCom03 levels. This variation in level differences is likely related to the 50-ft setback of the barrier from the center of the near travel lane on the opposite side of the highway and differences in traffic from one data block to the next. Regarding the barrier setback, the near-lane traffic would tend to cause the highest levels at the nearby BarCom03 and NoBarCom05 microphones, followed by the far lane traffic and then any far-lane reflections, followed by any near-lane reflections. Regarding traffic, because there is some difference in distance between the Barrier and No Barrier sites, the exact same vehicles are not passing each mic in each 5-minute period. Also, there could be operational differences of the vehicles at the two sites, such as speed and lane changes Nonetheless, it is interesting that, on average, the trend is for the L90 and L99 to be higher at the Barrier microphone. As observed when listening to the audio recordings, one senses the “presence” of the barrier at the Barrier microphone.”

Then, Figure 127 presents the L_{90}(5min) and L_{99}(5min) for BarCom04 and NoBarCom06 (the upper microphones across from the barrier) for overall A-weighted sound levels and unweighted sound pressure level. Figure 128 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06. Both of these figures start 45 minutes into the measurement period. The was a great deal of what turned out to be roofing nail gun noise that was audible at NoBarCom06 during this period, Rather than trying to edit it all out of the data, this period was just deleted from this L_n analysis.

The results are different for this microphone pair than most of the other pairs across the various study locations because these microphones are the farthest from the road. The BarCom04 L_{eq}(5min) ranged from 2.5 dB to 3.8 dB higher than the NoBarCom06 level for the first 23 minutes of the period shown on the figures. During this time, the L_{90}(5min) and L_{99}(5min) differences ranged from 2 dB to 5 dB higher at BarCom04 than at NoBarCom06. During this period, the meteorological class was Calm Neutral. During the last three hours, the L_{eq}(5min) difference became more variable, from 0.5 dB to 2.5 dB higher at BarCom04. During this period, L_{90}(5min) differences also became more variable, being 0 to 3.5 dB higher at BarCom04. The L_{99}(5min) became even more variable, with the BarCom04 values ranging from 1 dB lower than those at NoBarCom06 to 5.4 dB higher. During this time period, the meteorological class was Downwind Neutral. On average over the full measurement period, the BarCom04 L_{eq}(5min), L_{90}(5min) and L_{99}(5min) were 1.7 dB, 2.0 dB and 2.1 dB higher than at NoBarCom06.

These results, taken together, suggest that the overall levels from the traffic noise are higher at the Barrier site, but because the traffic 400 ft away, there is less overall rise and fall to the levels compared to being in close to the road. As a result, there is little chance for lulls in the noise under the studied traffic flows. Perhaps nighttime measurements when the flow is much lower might show that elevating of the background level at a distant site across from a barrier.

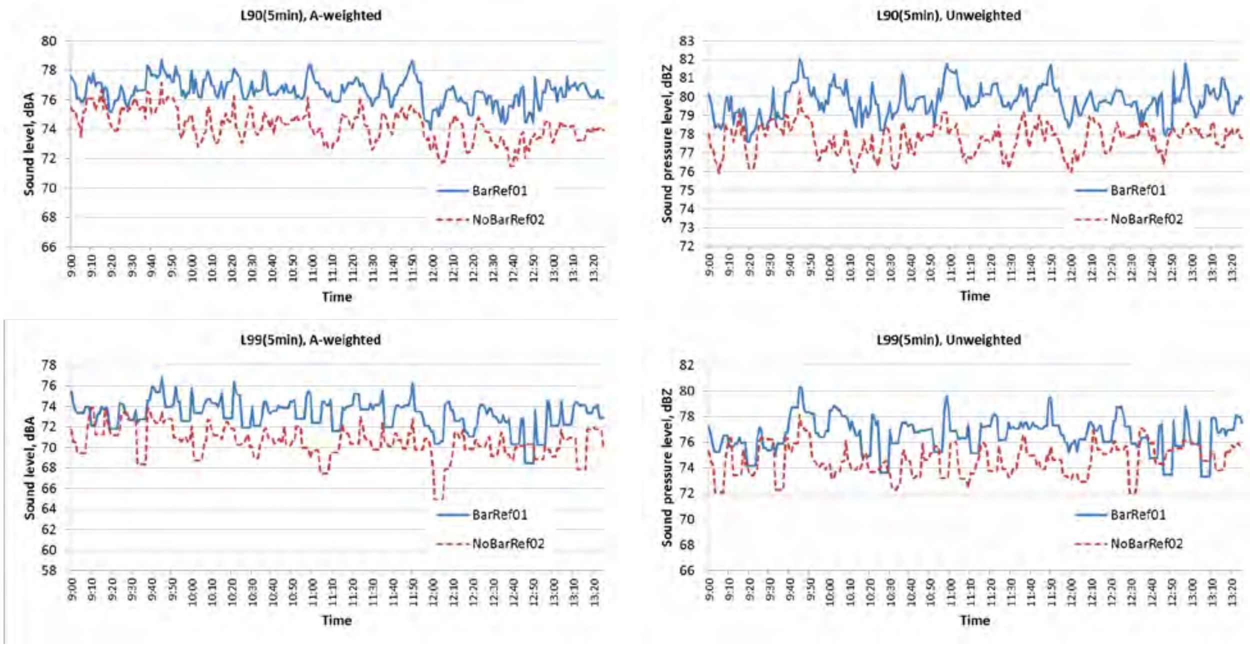


Figure 123. L_{90}(5min) and L_{99}(5min), SR-71, BarRef01 and NoBarRef02 – broadband A-weighted sound level (left) and sound pressure level (right).

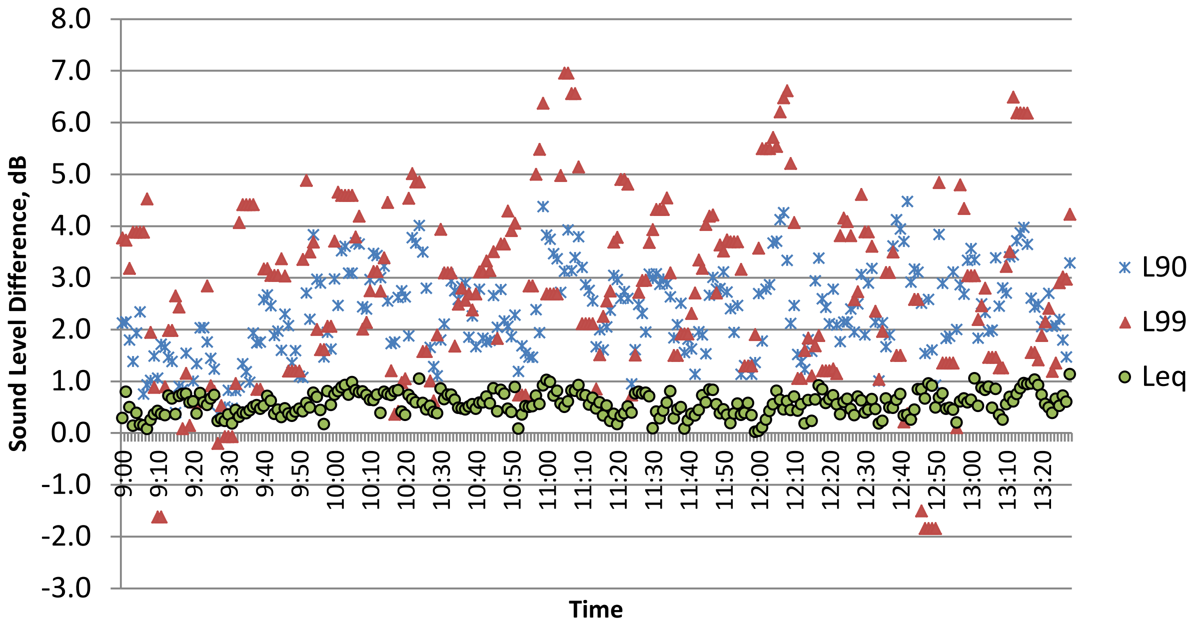


Figure 124. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, SR-71, BarRef01 and NoBarRef02.

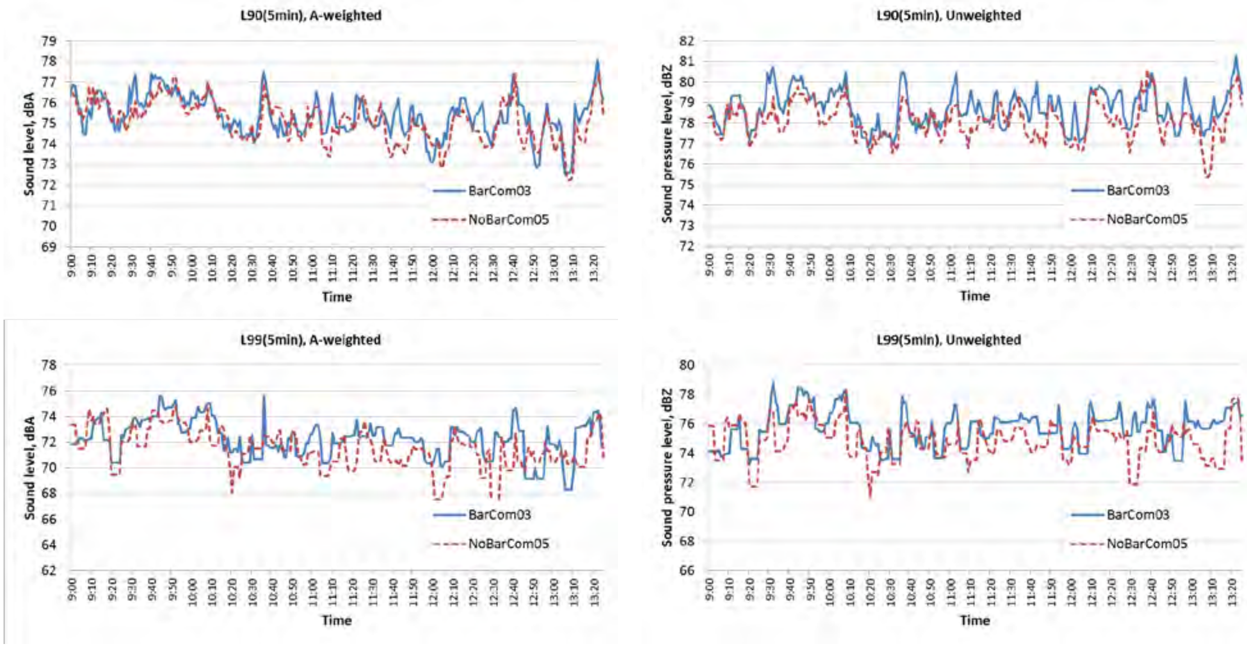


Figure 125. L_{90}(5min) and L_{99}(5min), SR-71, BarCom03 and NoBarCom05 – broadband A-weighted sound level (left) and sound pressure level (right).

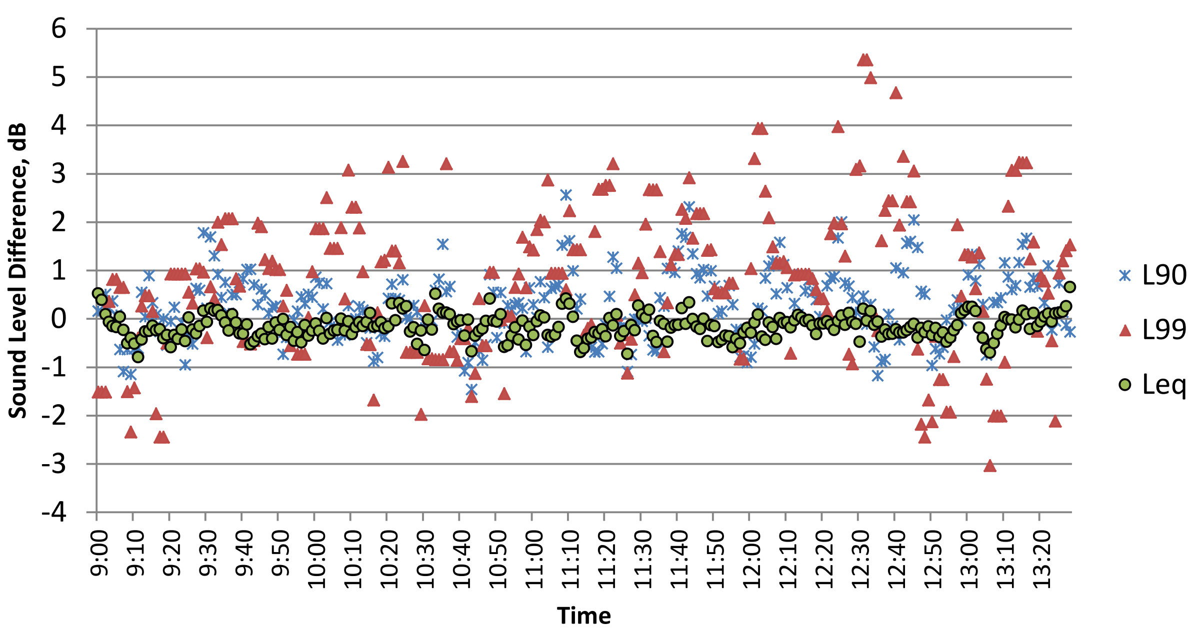


Figure 126. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, SR-71, BarCom03 and NoBarCom05.

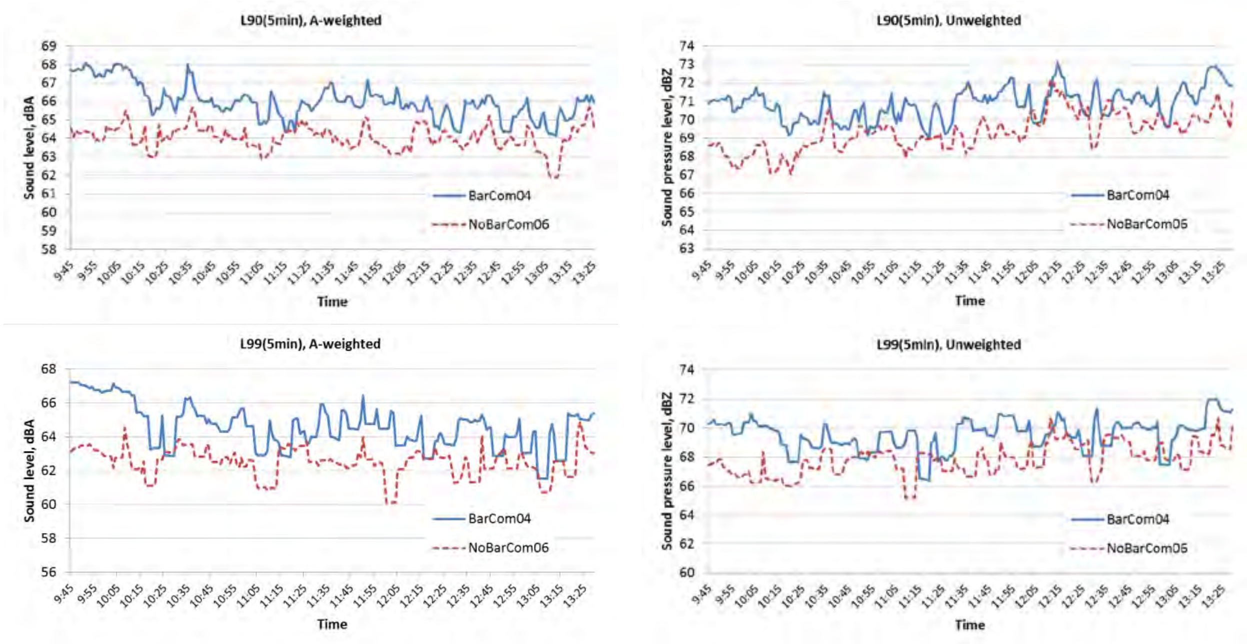


Figure 127. L_{90}(5min) and L_{99}(5min), SR-71, BarCom04 and NoBarCom06 – broadband A-weighted sound level (left) and sound pressure level (right).

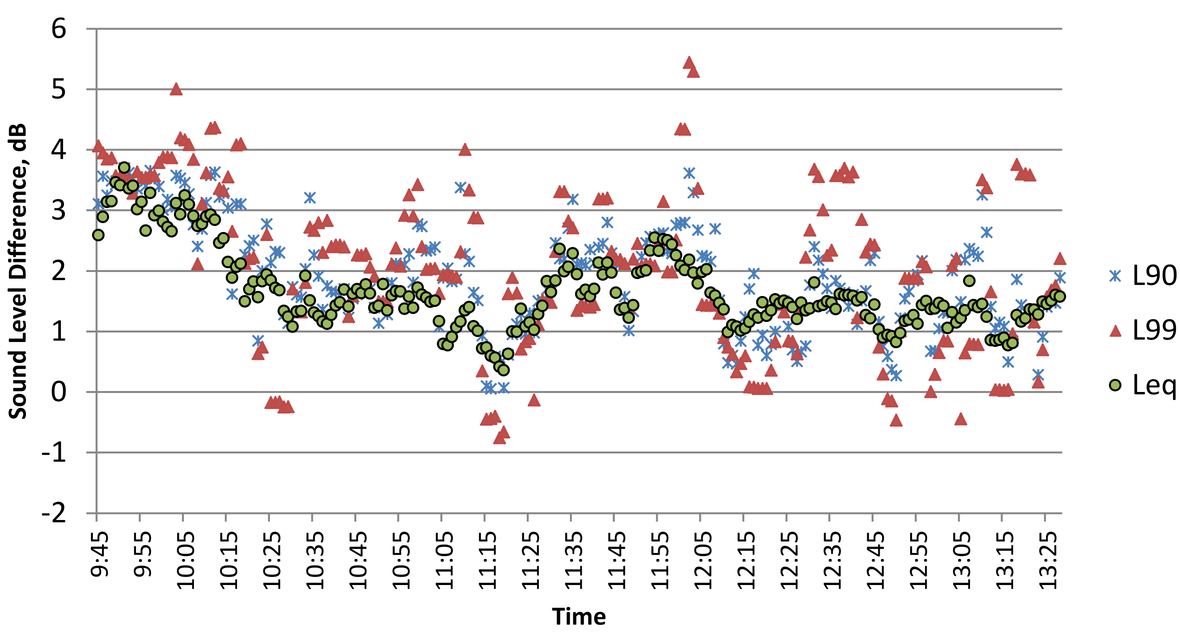


Figure 128. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, SR-71, BarCom04 and NoBarCom06.

The above graphs were for the broadband A-weighted sound levels and unweighted sound pressure levels only. Figure 129 broadens the analysis to include the individual 1/3 octave bands by use of color shading, where brown means that the BarRef01 levels are higher than the NoBarRef02 levels and blue means that NoBarRef02 is higher. In the graph, time runs from top to bottom (increasing as you move down each figure, with each row representing the starting minute of a running five-minute period). The 1/3 octave bands run across from left to right with the broadband A-weighted sound levels and unweighted sound pressure levels on the far left. Within each band's data are the differences for seven Ln sound pressure level Ln values (L_1, L_5, L_{10}, L_{33}, L_{50}, L_{90} and L_{99}) and L_{eq}.

Vertical brown streaks are on the right sides of the data columns (representing L_{90}(5min) and L_{99}(5min)) in the frequency bands from 500 Hz up through 4 kHz for nearly all of the sample period, and up through 5 kHz for the first half of the sample period. These brown streaks mean that the BarRef01 background levels are higher than the NoBarRef02 background levels, evidence of a sustaining of a vehicle's passby noise due to the creation of an image source for each vehicle as the sound reflects off the barrier. This result is similar to the I-24 result, where that location's BarRef01 microphone was also between the barrier and the road. The BarRef01 levels were also higher in the 20 Hz to 31.5 Hz bands across most of the descriptors for most of the measurement period. The reason for that difference in those very low frequency bands is not apparent.

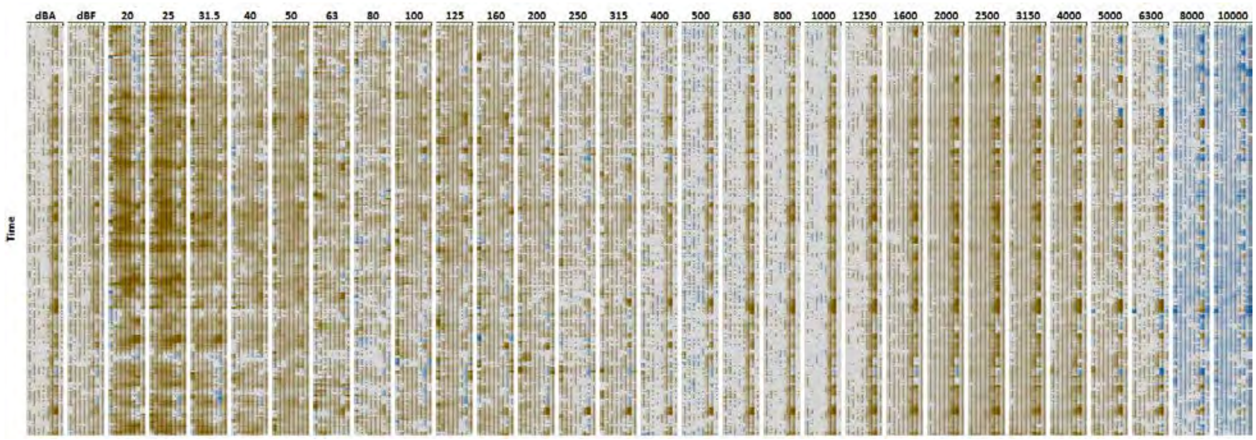


Figure 129. SR-71 Differences in L_n(5min) by 1/3 octave frequency bands: BarRef01 and NoBarRef02.

Figure 130 presents the spectral L_n differences for BarCom03 and NoBarCom05. Not a great deal of difference is seen between the descriptors for the two microphones, which is consistent with A-weighted sound level graphs. An exception is the L_{90} and L_{99} background levels in the 1 kHz to 4 kHz bands, where there appears to be a general trend for the BarCom03 values to be higher than NoBarCom05 values, evidence of an elevated background in these bands.

Figure 131 presents the spectral L_n differences for BarCom04 and NoBarCom06. A pattern can be seen of higher broadband A-weighted levels at BarCom04 in the low and mid-to-upper bands, with higher NoBarCom06 levels in the 100 Hz to 250 Hz bands as well as the highest frequency bands. This pattern applies across most of the Ln descriptors, not just L_{90}(5min) and L_{99}(5min).

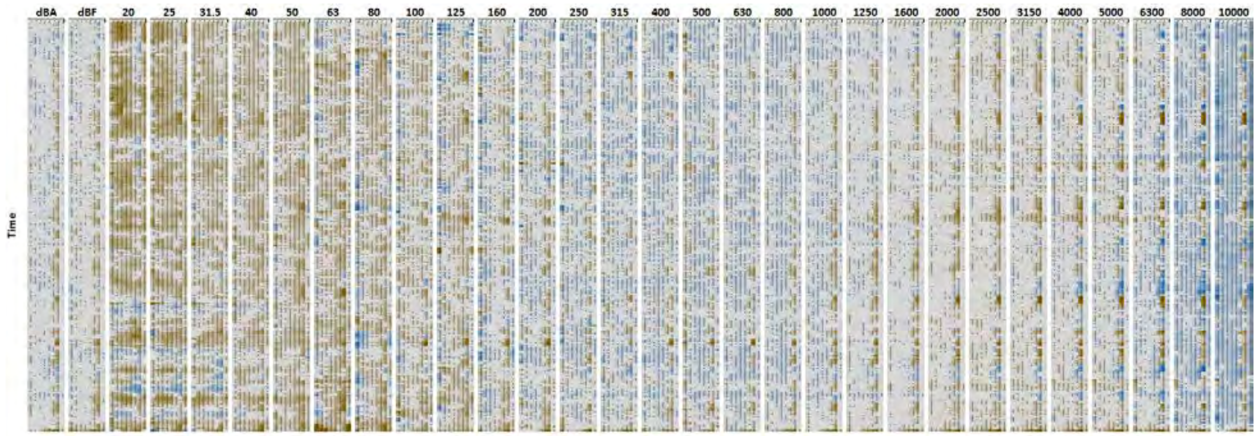


Figure 130. SR-71 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom03 and NoBarCom05.

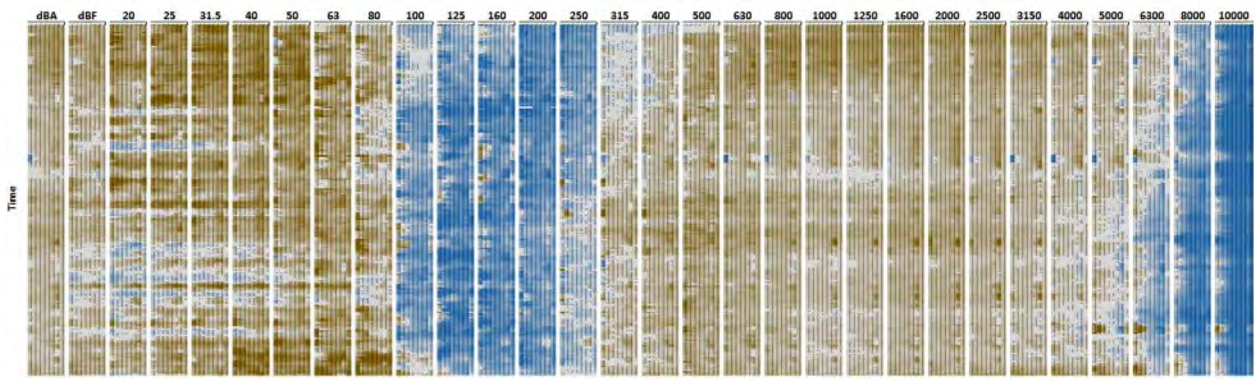


Figure 131. SR-71 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom04 and NoBarCom06.

Data Analysis for SR-71 - Spectrograms

Refer to Table 11 for the SR-71 location microphone positions.

Analysis of Possible Ground Effects

While the three sets of equivalent microphones at the Barrier and No Barrier sites (BarRef01/NoBarRef02, BarCom03/NoBarCom05, and BarCom04/NoBarCom06) are directly comparable, there was some question as to the influence of the differences in terrain between BarCom04 and NoBarCom06, the far distance microphones.

To help address this question, a simple FHWA Traffic Noise Model (TNM) v2.5 analysis was conducted to determine the 1/3-octave band differences in sound levels that could be attributable to the terrain. For the TNM analysis, the cross sections for BarCom04 and NoBarCom06 were each modeled as shown in Figure 132 (BarCom03 and NoBarCom05 were also included in the model). These are approximations of the actual terrain, with enough detail to provide a good acoustic representation.

The traffic is the same at both sites and is based on traffic data measured at SR-71. For ground type, calculations were done with both hard and soft ground to determine the possible influence from either one. (Note that the ground type was dirt and weeds, and it had recently rained, so it was difficult to determine which ground type was most appropriate; the ground also included a concrete trench that made up a portion of the terrain.)

Results of the TNM analysis shown in Figure 133 indicate that, for soft ground, the sound levels at BarCom04 should be lower than at NoBarCom06. For hard ground, the sound levels at BarCom04 should be lower than at NoBarCom06 in the range of 630 Hz and up and higher in the range 400 Hz and down (and approximately the same at 500 Hz).

These results indicate that from 500 Hz and up, any levels that are higher at BarCom04 as compared to NoBarCom06 are likely due to barrier reflections. Below 500 Hz, any differences could be a combination of terrain differences and barrier reflections. Note that the figures also include results for BarCom03 and NoBarCom05 for reference and to demonstrate that those results are nearly identical to each other, as is expected right near the road. This was not technically rigorous modeling, since it was not in the work scope, but was conducted to help determine in what frequency ranges differences between the sites to the barrier reflections could be attributed.

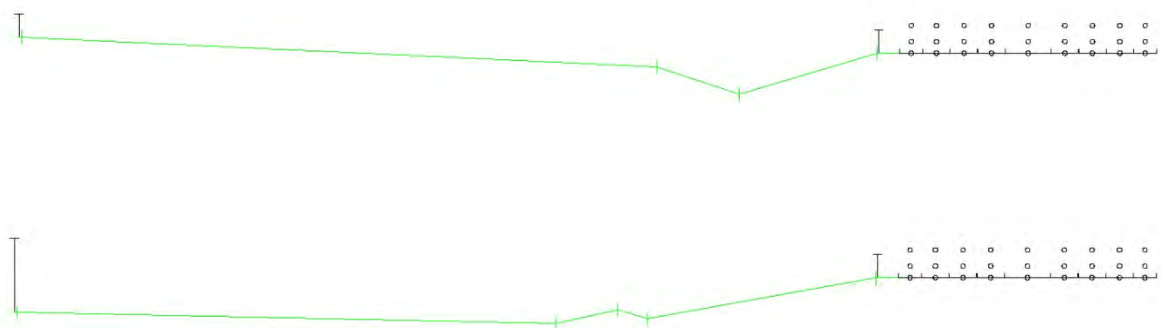
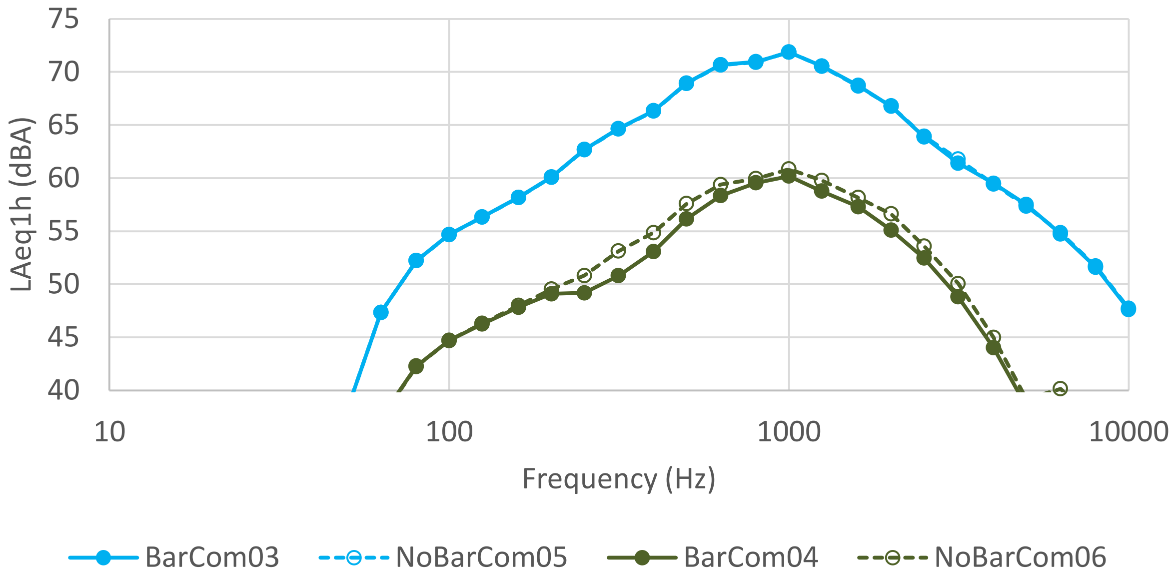


Figure 132. TNM modeling cross-sections: Barrier site (top) and No Barrier site (bottom), SR-71.



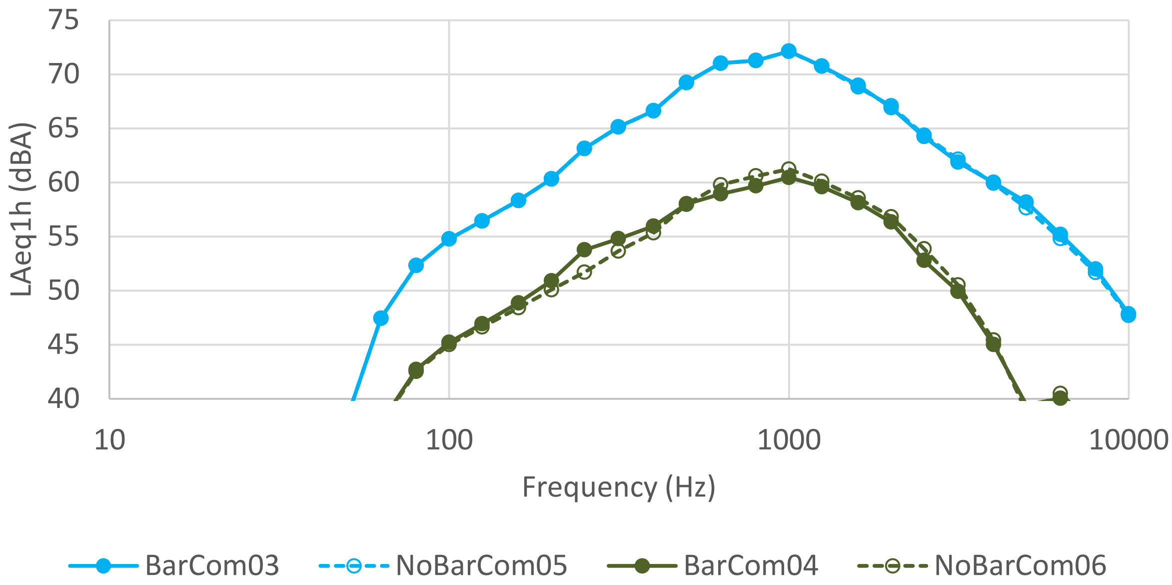


Figure 133. TNM modeling results: TNM soft ground (top) and TNM hard ground (bottom), SR-71.

Spectrograms

Spectrograms from SR-71 vehicle pass-by events are shown below. These compare just the far microphones BarCom04 and NoBarCom06 (400 ft from the center of the near travel lane). For the closer microphones, the events are hard to distinguish from other events and/or it is difficult to distinguish differences in levels, since the differences are fairly small near the road.

Figure 134 shows a group of trucks traveling southbound. The pass-by event is around 10:43:50 at the barrier site and around 10:44:20 at the No Barrier site.

Figure 135 shows a motorcycle traveling southbound. The pass-by event is around 12:10:25 at the barrier site and around 12:10:50 at the No Barrier site.

The barrier effect for both the heavy trucks and motorcycle can be seen in the spectrograms for the far microphones. For the barrier site, the hot spots are wider and taller for a broad range of frequencies. It is particularly noticeable for frequencies from 400 Hz to 2.5 kHz for the heavy trucks and from 250 Hz to 2.5 kHz for motorcycles. Based on the TNM analysis conclusions, the differences seen from 500 Hz to 2.5 kHz can be attributed to the barrier. Below 500 Hz the differences may or may not be attributed to the barrier.

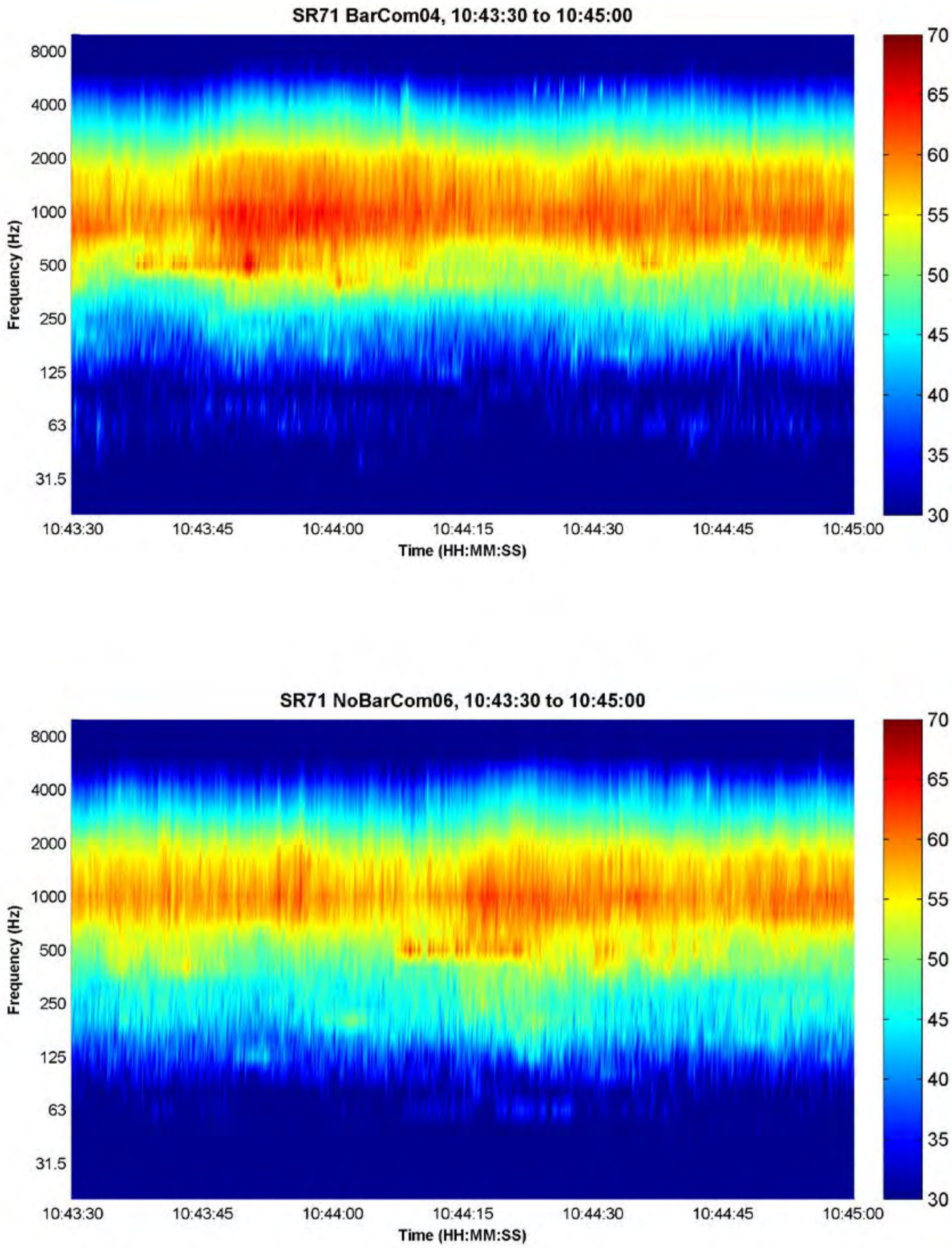
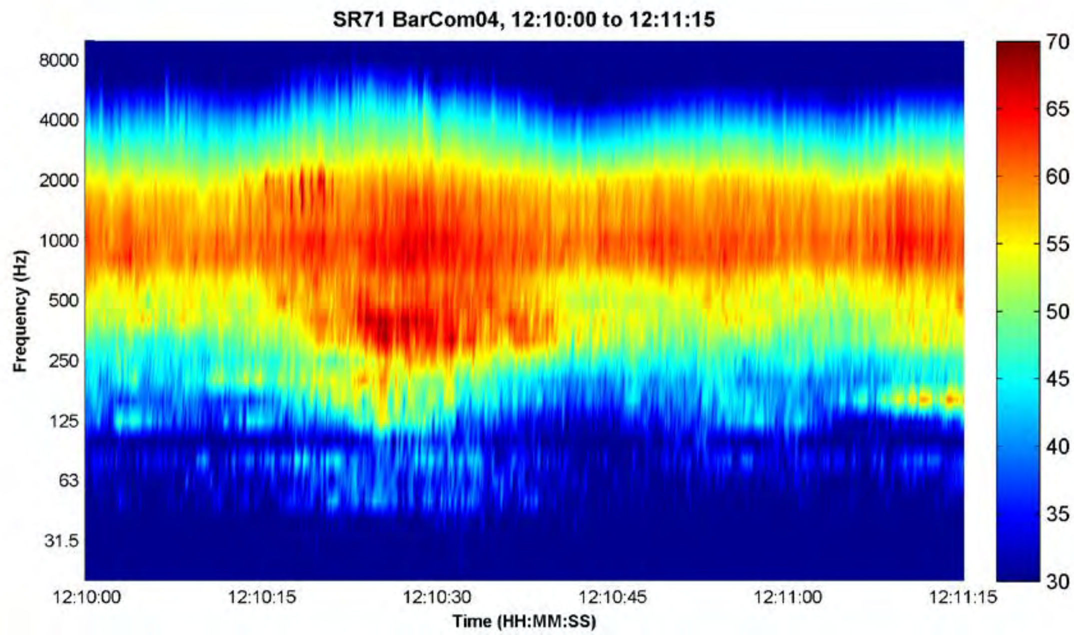


Figure 134. SR-71 spectrograms for heavy trucks on southbound (community) side: top is BarCom04; bottom is NoBarCom06.



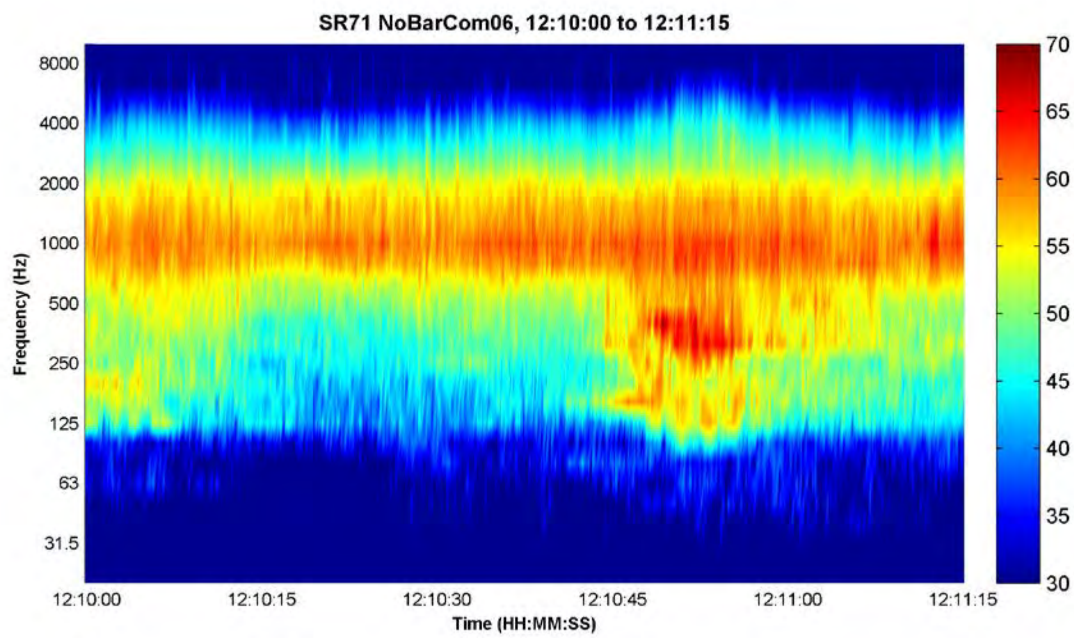
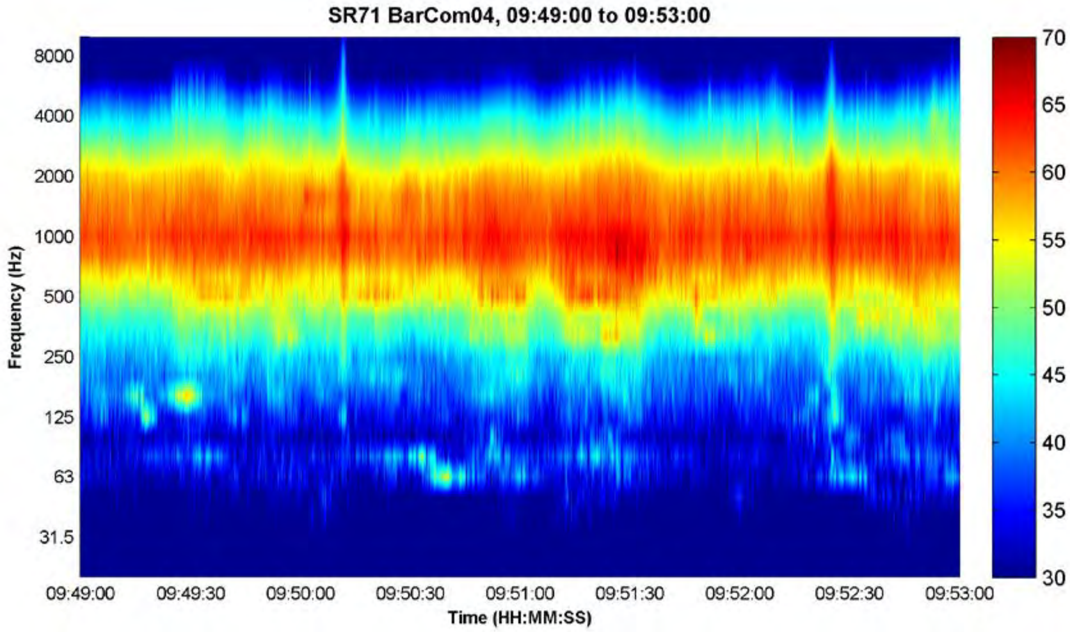


Figure 135. SR-71 spectrograms for motorcycle on southbound (community) side: top is BarCom04; bottom is NoBarCom06.

In addition to examining vehicle pass-by events, spectrograms for blocks of data were also examined. Two examples are provided below for the far-distance microphones (400 ft). The first, Figure 136 shows a 4-minute block of clean data in the morning at 9:49 am, and the second, Figure 137, shows a 5-minute block of clean data in the afternoon at 12:45 pm.

Both blocks of data show a clear difference between the Barrier and No Barrier sites at the far microphones. As with the pass-by data, the clean data blocks show that hot spots are both wider and taller for a broad range of frequencies, particularly for 500 Hz and up, the range to which barrier effects can be attributed. For the overall A-weighted equivalent sound level, several clean data blocks were examined, and it was found that the difference between Barrier and No Barrier A-weighted equivalent sound levels ranged from 1.3 to 3.3 dB. The 4-minute block at 9:49 shown in the spectrogram is the case where there was a 3.3 dB difference.

The spectrogram analysis for the far microphones for both vehicle pass-by events and time blocks of data are indicating a clear effect due to barrier reflections. For the other microphones, the differences are small and cannot be readily perceived with the spectrograms. It is assumed that the barrier effect is greater for the far distance since the path length difference between direct and reflected sound is fairly small, allowing both the direct and reflected sound to contribute to the overall sound level. With larger path length differences, as is the case near the highway, the direct sound would be more dominant than the reflected, and therefore contribute more to the overall sound level, with the reflected sound contributing very little (since it has to travel so much farther than the direct sound).



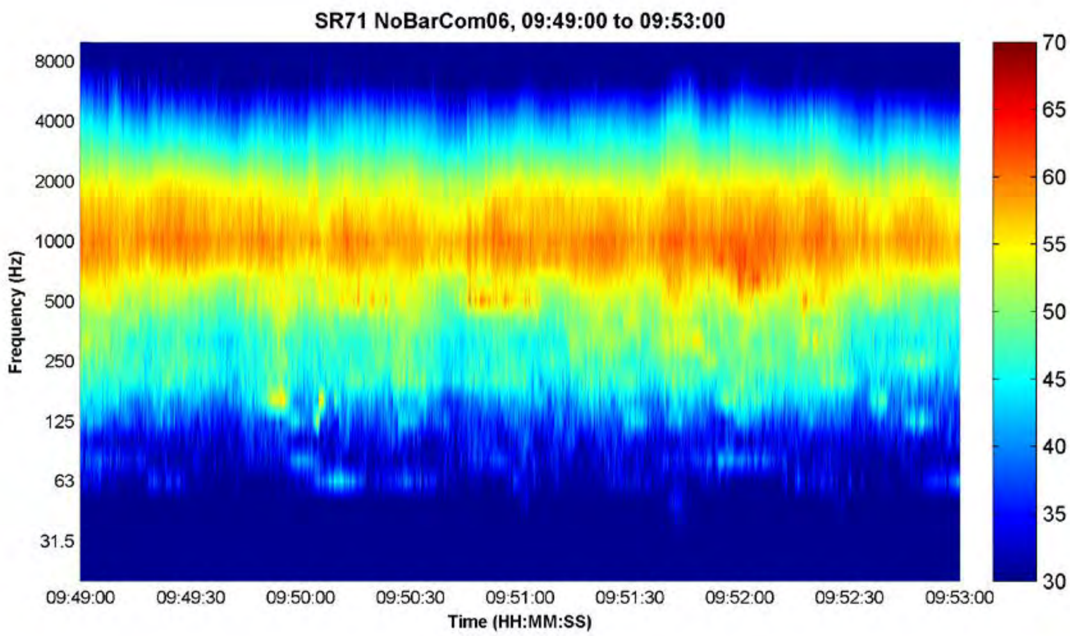
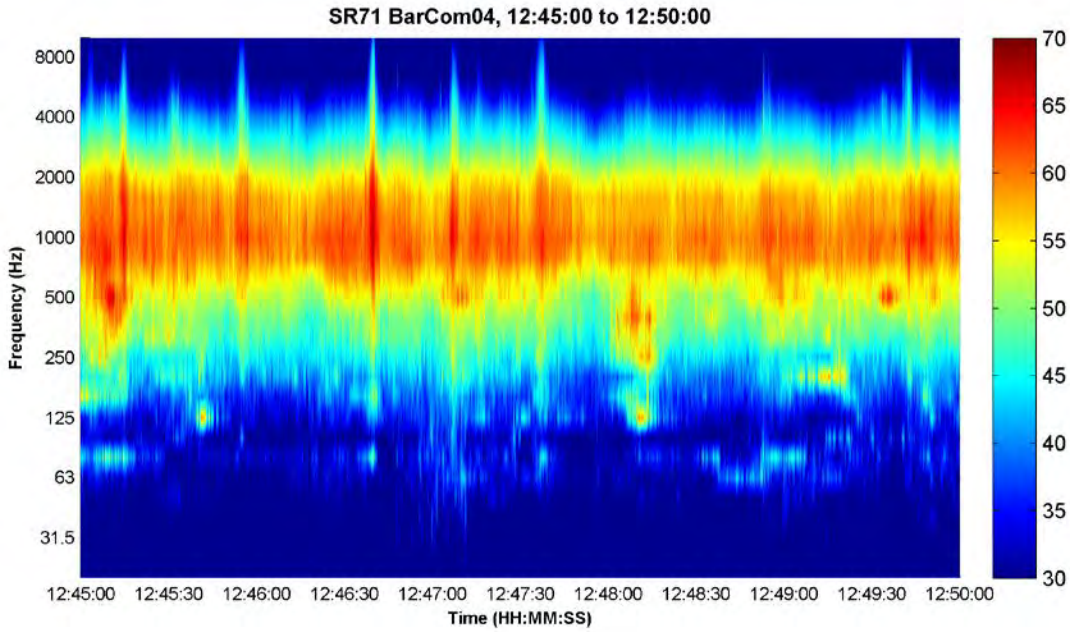


Figure 136. SR-71 spectrograms for 4-minute block of data in the morning at 09:49: top is BarCom04; bottom is NoBarCom06.



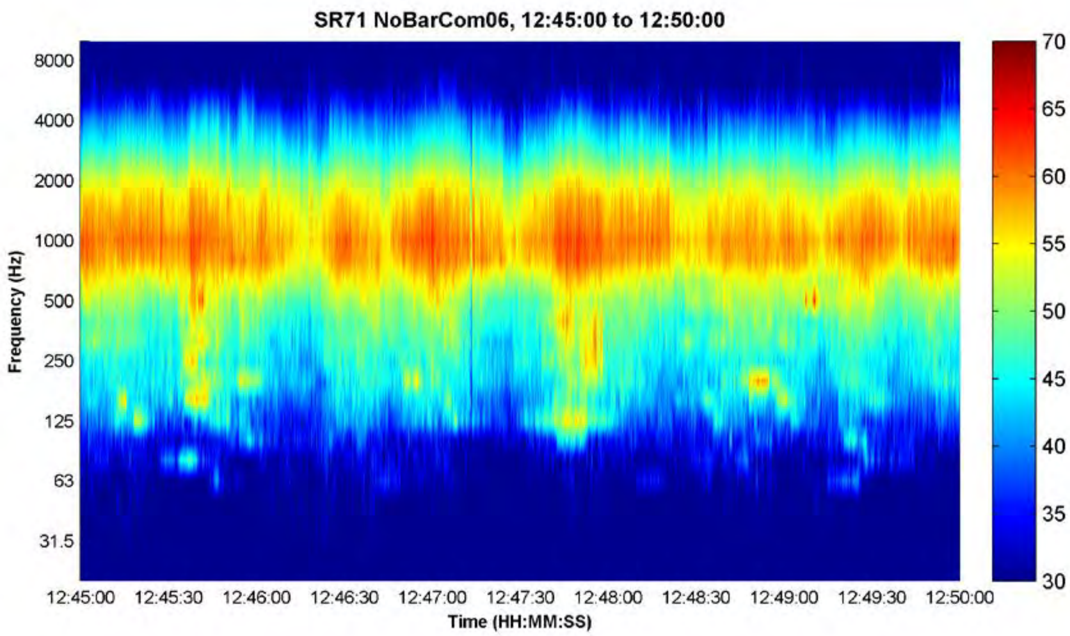


Figure 137. S SR-71 spectrograms for 5-minute block of data in the morning at 12:45: top is BarCom04; bottom is NoBarCom06.

Data Analysis for SR-71 - Psychoacoustics

Descriptive statistics for the computed annoyance metrics at SR-71 are summarized in Table 13. The associated histograms in each of the subsequent Figures relate the distribution of magnitudes for each metric at each microphone to the descriptive statistics in the table.

The Unbiased Annoyance (UBA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 139. The Psychoacoustic Annoyance (PA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 140. The Category Scale of Annoyance (CSA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 141.

There is no significant difference in the means of the Unbiased Annoyance between the Barrier and No Barrier locations for lower microphones. The same is true of the Psychoacoustic Annoyance. There is a clear difference in the means of the Unbiased Annoyance and the Psychoacoustic Annoyance between the Barrier and No Barrier locations for the higher microphones; they differ by more than two standard deviations. The higher microphones at this site were a great deal further from the roadway than were the lower microphones. The close proximity to the highway of the lower microphones seems to account for the lack of difference in means: the same behavior is seen at the Reference microphones, which were placed relatively close to the traffic lanes. As with the I-24 and I-90 results, the higher Barrier microphones have lower mean annoyance than do the No Barrier microphones; therefore, neither the UBA nor the PA substantiate an assumption of increased annoyance due to the presence of the barrier at this site.

There is no significant difference in the means of the Category Scale of Annoyance for either pair of microphones. The simple linear regression that forms CSA, and its derivation from product noise, do not apply well to highway traffic noise.

Table 13. Descriptive statistics of annoyance metrics, SR-71.

Metric	Location	Mean	Std. Dev.	Skewness	Kurtosis
UBA	BarCom03	126	15.7	0.562	0.181
	NoBarCom05	130	16.7	0.376	-0.101
	BarCom04	14.9	1.76	0.435	0.149
	NoBarCom06	18.7	1.25	1.183	2.505
PA	BarCom03	34.4	4.80	0.338	-0.349
	NoBarCom05	34.7	4.71	0.321	-0.153
	BarCom04	3.72	0.46	0.942	1.524
	NoBarCom06	4.39	0.34	1.330	3.082
CSA	BarCom03	54.0	3.19	0.349	-0.361
	NoBarCom05	54.8	2.97	0.390	0.643
	BarCom04	27.8	1.26	0.865	1.708
	NoBarCom06	27.3	0.98	1.772	5.612

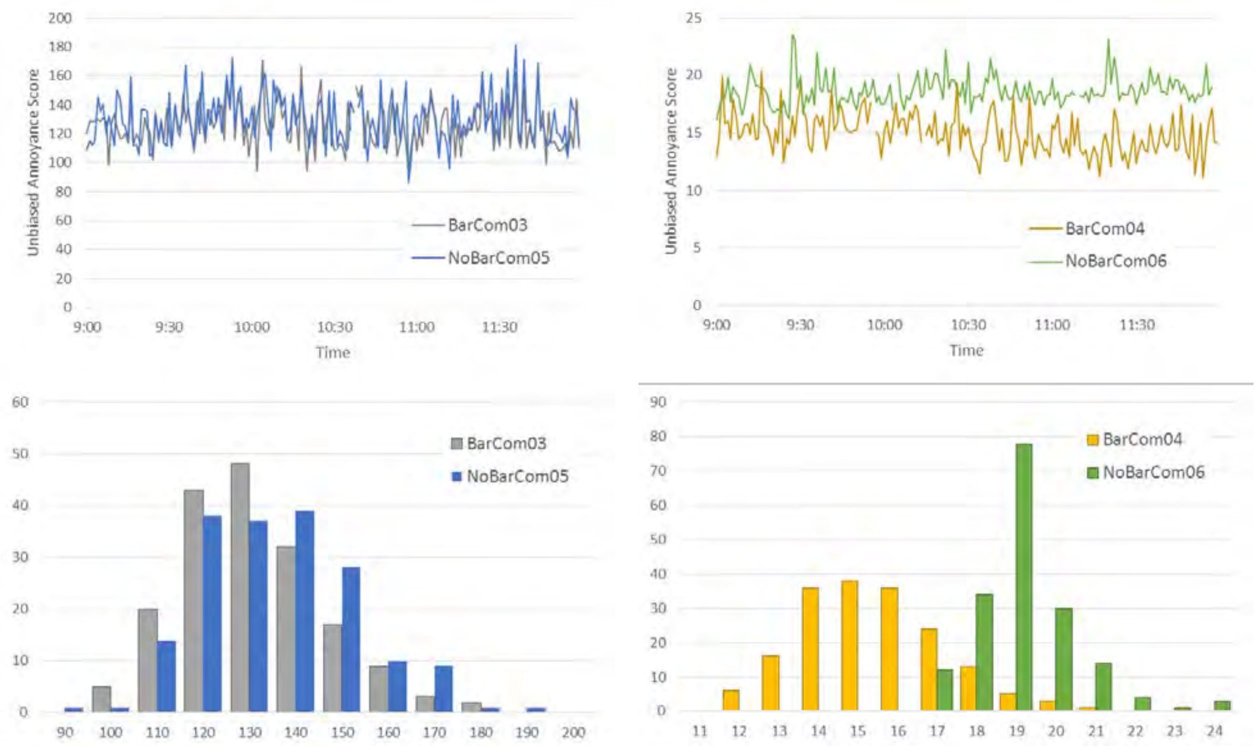


Figure 139. Unbiased Annoyance vs. time and histograms, SR-71.

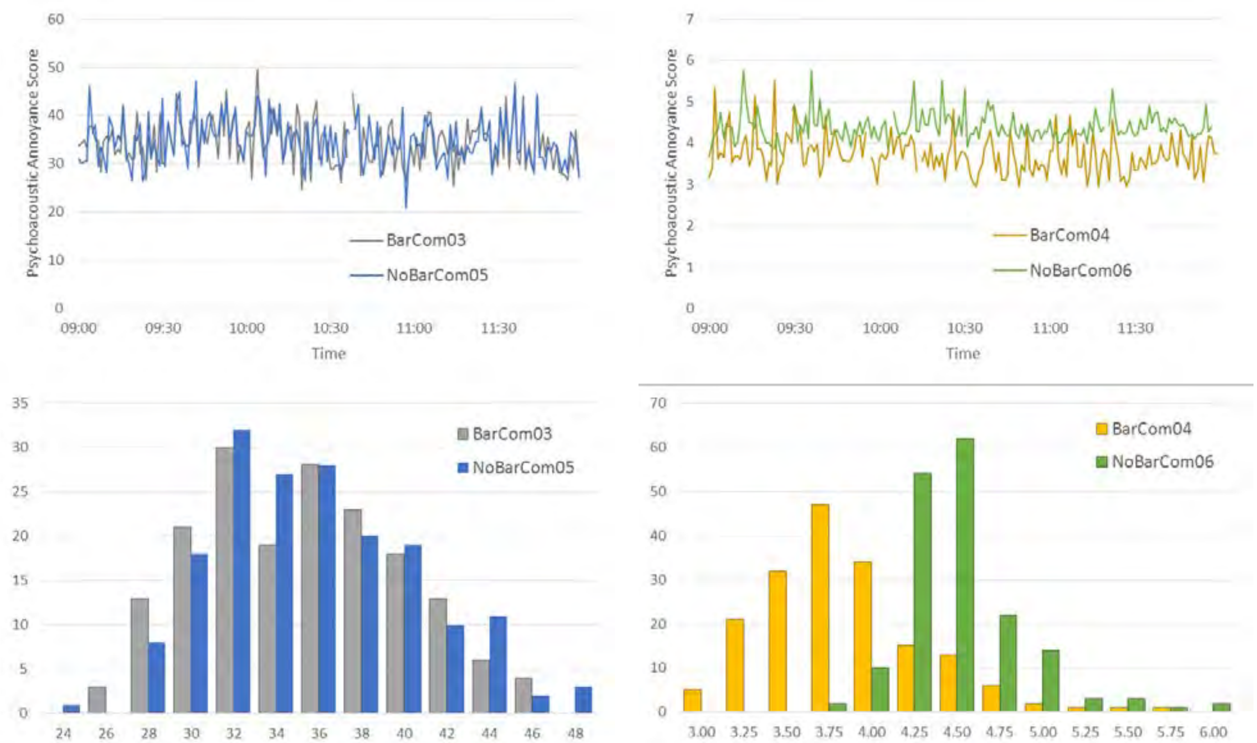


Figure 140. Psychoacoustic annoyance vs. time and histograms, SR-71.

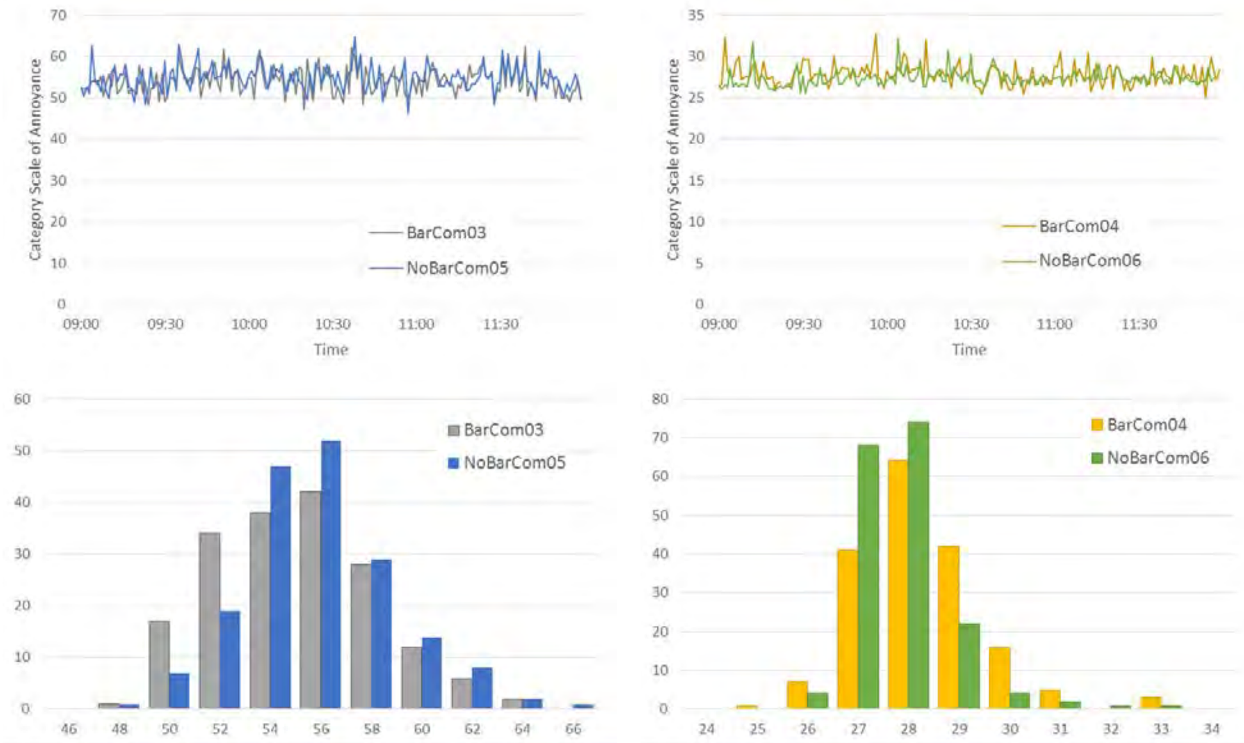


Figure 141. Category scale of annoyance vs. time and histograms, SR-71.

CHAPTER B-7

Results – MD-5, Hughesville, MD (Location EA-5)

The noise measurements at the last field site, MD-5 in Hughesville, Maryland were conducted on June 9, 2015. Hughesville, MD, southeast of Washington D.C. MD-5 is a bypass and curves into the project area from the north where southbound local traffic on Old Leonardtown Road merges onto it and northbound local traffic exits off it.

At the location, the project team set up six microphone positions:

- BarRef01 – A reference microphone placed 17.5 feet above the road and 15 feet from the center of the near travel lane
- NoBarRef02 – A reference microphone placed 17.5 feet above the road and 18 feet from the center of the near travel lane
- BarCom03 and 04 – The community microphones placed on the side of the road opposite the barrier and 80 feet from the center of the near travel lane. BarCom03 is at a height of 5.0 feet and BarCom04 is at a height of 15 feet above the road
- NoBarCom05 and 06 – The community microphones placed on the same side of the road as BarCom03 and 04, but with no barrier on the opposite side

In addition to the microphones, a 10-ft meteorological tower was set up, vehicle speed was measured by laser, and traffic was video recorded so that vehicle volume and mix could be later analyzed.

Figure 142 shows the microphone positions at the MD-5 location. Figure 143 shows cross-sections at the Barrier and No Barrier sites. The microphone positions are summarized below:

Table 14: Microphone positions for MD-5 site

Mic Name	Side of Road	Distance from Center of Near Travel lane (ft)	Height Above Roadway Plane (ft)
BarRef01	SB	15	17.5 (5 ft above barrier)
NoBarRef02	SB	18	17.5 (18 ft above ground)
BarCom03	NB	80	5 (9 ft 3 in above ground)
BarCom04	NB	80	15 (19 ft 3 in above ground)
NoBarCom05	NB	69	7 (5 ft above ground)
NoBarCom06	NB	69	17 (15 ft above ground)

Appendix C of the Final Report includes site photographs.

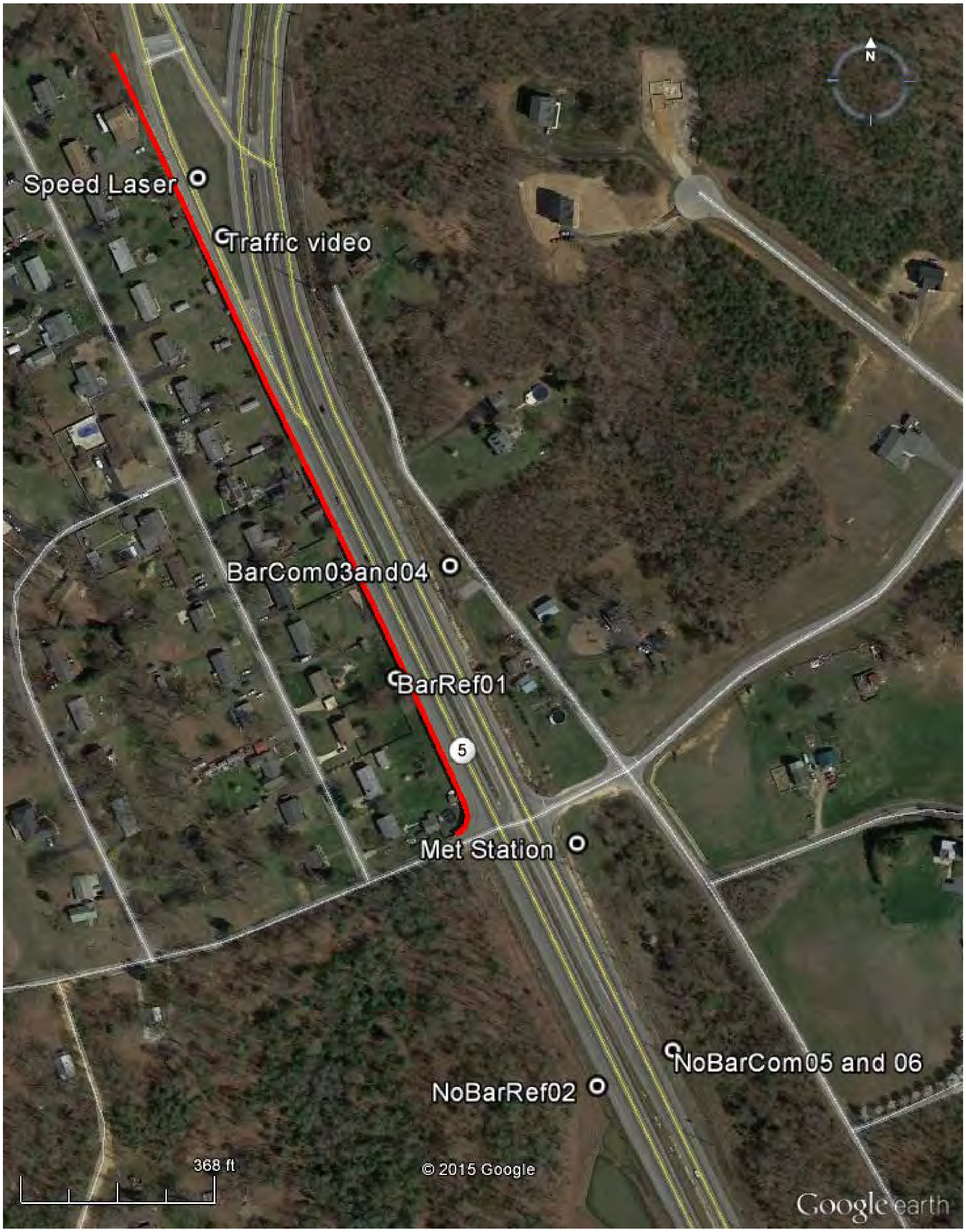


Figure 142. MD-5 microphone positions. (Source: Google Earth.)

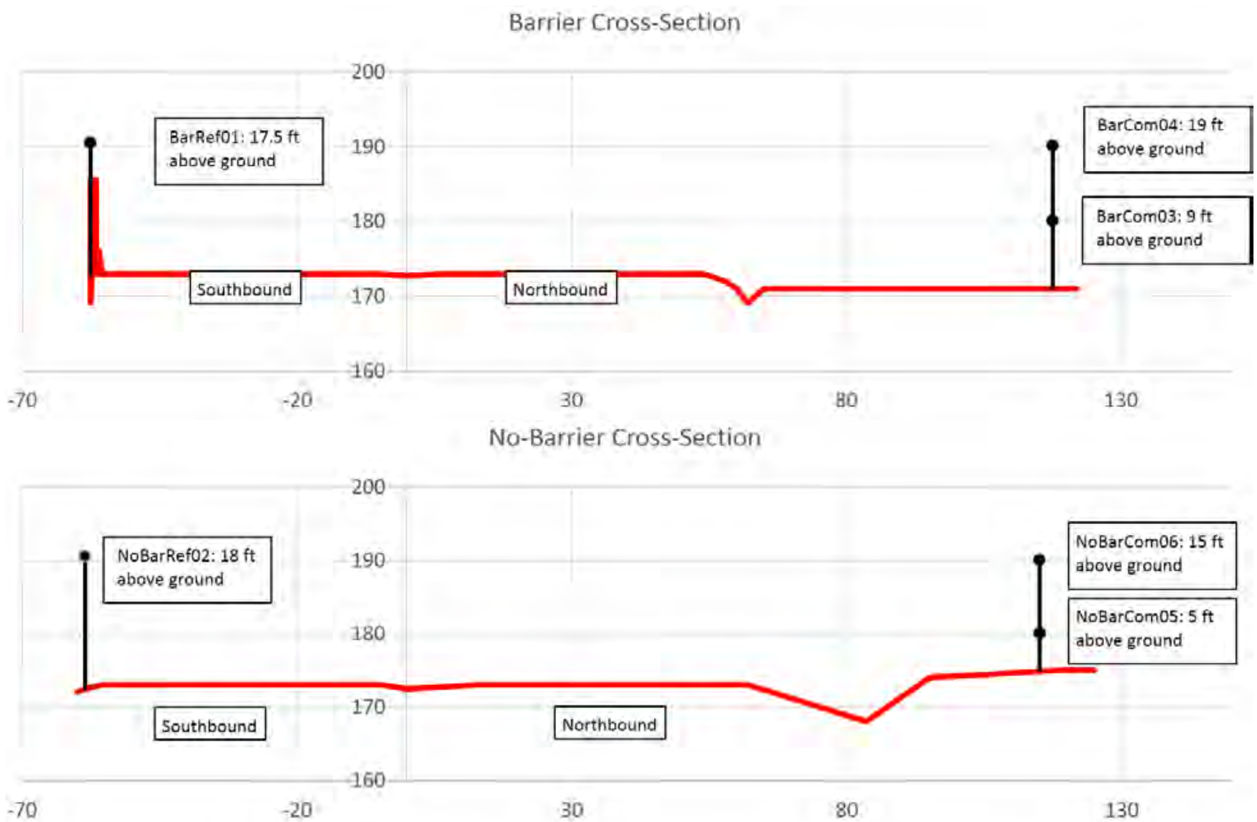


Figure 143. Cross-sections at the MD-5 Barrier (top) and No Barrier (bottom) sites.

Measurement Observations

Data were collected during the daytime (nominally 12:00 to 16:10) and nighttime (nominally 19:40 - 23:50). Daytime measurements were intended to capture a more continuous traffic stream, while nighttime measurements were intended to capture more individual vehicle passbys.

During the first hour of measurements of the daytime session, the winds were generally 4 to 5 mph with gusts up to 9 mph. At BarRef01, wind conditions were still with partly cloudy skies. At NoBarCom05 and NoBarCom06, temperature conditions were reported as hot and humid, with an observation that there may have been a strong lapse rate during the daytime measurements. Ground-level winds were low but observations of tree tops indicated a fairly strong wind gradient during the day with variable wind direction. By 13:30, the clouds had mostly cleared and conditions were sunny with light winds from the west and northwest.

During the daytime session, traffic was fairly consistent, with few breaks in the traffic flow. Heavy truck traffic was a noticeable but not sizeable portion of the traffic mix in both directions. Speeds were consistently maintained throughout the session with the exception of 1 to 2 minutes where there was a brief southbound slowdown.

Southbound traffic from Old Leonardtown Road onto MD-5 was frequent with those vehicles typically accelerating past the speed observation area and merging into MD-5 in front of the barrier. That same lane was also used by southbound MD-5 traffic to turn right onto Carrico Mill Road at the south end of the barrier. The conflicting moves of merging onto MD-5 from southbound Old Leonardtown Road and moving over from southbound MD-5 to turn onto Carrico Mill Road were the likely cause of reduced speeds that were generally observed in the right lane of southbound MD-5.

Left-hand turns out of the neighborhood from Carrico Mill Road onto northbound MD-5 occurred but were not a major traffic movement. The movement from northbound MD-5 into the left-hand turn lane to access Old Leonardtown Road was common; however, that movement was past the northernmost measurement site. The outside/right lane of southbound MD-5 was typically slower than the left lane. The outside/right lane of northbound MD-5 was typically slower than the left lane.

As expected, the traffic and speed monitoring team were not able to identify many single vehicle pass-bys during the daytime session.

At BarRef01, traffic was discernible from the observer location approximately 30 feet behind the noise barrier. It seemed that traffic traveled in platoons and was perhaps grouped due to upstream and downstream traffic signals. It was easy to hear heavy trucks and some motorcycles with direction difficult to detect at times due to traffic volumes. There were noticeable instances of engine compression brake use and what sounded like rumble strip/stripe crossovers north of the measurement site. During traffic lulls, birds became the most noticeable noise source. This continued throughout the measurement period with the birds seeming much louder at some times than at others.

At BarCom03 and BarCom04, birds were audible during slower traffic periods. Heavy truck traffic was noticeable. During instrument checks, it was observed that sound levels varied but were 65-75 dB during times with traffic. The background levels were in the 50 dB range.

At NoBarCom05 and NoBarCom06, traffic was also variable between light and heavy with groups of vehicles related to signalized roadways. Traffic as a source of sound was strong and at least 15 dB above background during much of the test. Some frog and insect noise was noted at this location but signal to noise ratio was probably 15 dB or greater. Single-vehicle events were observed at this site although background traffic sounds may have been too high to obtain a “clean passby” event. There were very few “interference” events at this site such as aircraft or other sources that could interfere with the ability to measure the target source.

During the nighttime measurement session, darkness fell between 20:45 and 21:00. The winds were relatively calm dying down to nearly a no-wind condition for much of the test, and the skies were partly cloudy. It was observed that there was most likely an inversion time period as the sun went down, with the temperature changing from daytime in the mid-80° F range to probably mid or low 60° F in the evening. The meteorological data confirmed the inversion.

Traffic in the first hour of the nighttime session was consistent but much lighter than the daytime session. Heavy truck traffic was noticeably less and likely under 2% of the total volume. After 9:00 pm traffic volumes decreased even more and the traffic and speed monitoring team identified 20 to 30 single vehicle pass-by events. Those events were judged to be candidates for further study.

At BarRef01, wind conditions were as before. Darkness fell between 20:45 and 21:00. Traffic was easily discernible, but it was difficult to differentiate vehicle type among loud vehicles with low frequency exhaust. It sounded like there may be a quantity of large pickup trucks with modified exhausts, which later discussion confirmed. Natural environmental noise consisted of birds until approximately 21:00 when bird sounds stopped. These sounds were replaced later in the evening by insect noises from the south. Occasional dog barking occurred in response to loud vehicles within the neighborhood and to a vehicle with high frequency engine noise starting at around 22:00 that sounded like a sport motorcycle.

At BarCom03 and BarCom04, more single vehicle passbys were captured during this time period. There was still a noticeable amount of heavy truck traffic but lighter traffic occurred overall for this measurement period. Insect noise was audible from the east away from the road. Sound levels varied, being 65-75 dB during times with traffic, with background levels in the 60 dB range.

At NoBarCom05 and NoBarCom06, traffic was much lighter in the evening but again had the pattern of groups of vehicles that are often present on signalized roadways. Single vehicle passbys were now able to be measured. Frogs and insects were much louder, especially at NoBarRef02 which was near a pond and forested area. However traffic signal-to-noise was still sufficient for adjacent traffic lanes for solo events (i.e., southbound vehicles at NoBarRef02 and northbound vehicles for near NoBarCom05 and NoBarCom06). Louder solo events and platoons of traffic were most likely strongly present in the acoustic record for all microphones regardless of traffic lane designation. The frog/insect noise will be present in the record as a slowly increasing background level, which at some point reached a constant value. The dew point was crossed during the evening test as evidenced by the amount of moisture on equipment cases at the tear down stage of the test.

Measured Broadband Levels and Level Differences for MD-5

The running L_{eq}(5min) for each site are presented in the following figures to give an overall picture of the measured levels, both in terms of unweighted sound pressure levels and A-weighted sound levels:

- BarRef01 and NoBarRef02 - Figure 144 (unweighted) and Figure 145 (A-weighted); then Figure 146 shows the differences in the unweighted and A-weighted levels for this mic pair ;
- BarCom03 and NoBarCom05 - Figure 147 (unweighted) and Figure 148 (A-weighted); then Figure 149 shows the differences in the unweighted and A-weighted levels for this mic pair; and
- BarCom04 and NoBarCom06 - Figure 150 (unweighted) and Figure 151 (A-weighted); then Figure 152 shows the differences in the unweighted and A-weighted levels for this mic pair.

The following observations are prior to any attempt to group data into equivalent periods. In general, both the unweighted sound pressure levels and A-weighted sound levels were higher at the Barrier community microphones than at the No Barrier community microphones, although evening frog and insect noise affected the results.

For the reference microphones, the levels at BarRef01 and NoBarRef02 are roughly comparable. Unweighted levels at BarRef01 ranged mostly from 2 dB *below* NoBarRef02 levels to 2.2 dB above them. A-weighted levels were within ±0.5 dB of each other during the afternoon session. However, due to frog noise near NoBarRef02, its evening A-weighted levels were generally *higher* than the BarRef01 levels. Little difference in the levels was expected because the BarRef01 microphone was positioned atop the barrier, although reflections off the vehicle bodies might increase its levels, as was discussed for the I-90 location.

For the lower community microphones opposite the barrier, the daytime unweighted running L_{eq}(5min) at BarCom03 ranged from 1.0 dB *lower* to 2 dB higher than those at NoBarCom05. The daytime A-weighted levels at BarCom03 generally ranged from 0.5 dB to 2.4 dB higher than those at NoBarCom05. In the evening, the unweighted levels at the two microphones were roughly within -2 dB to 1.5 dB of each other. The BarCom03 A-weighted levels ranged mostly from 0 dB to 1.5 dB higher than the NoBarCom05 levels.

For most of the running L_{eq}(5min) periods during both the afternoon and evening, the BarCom04 levels were higher than the NoBarCom06 levels. The unweighted L_{eq}(5min) generally ranged from 0.5 dB lower to 1.5 dB higher during the day and -1 dB lower to 2 dB higher during the evening. The A-weighted levels ranged from 0.5 dB lower to 1 dB higher than NoBarCom06 during both daytime and nighttime.

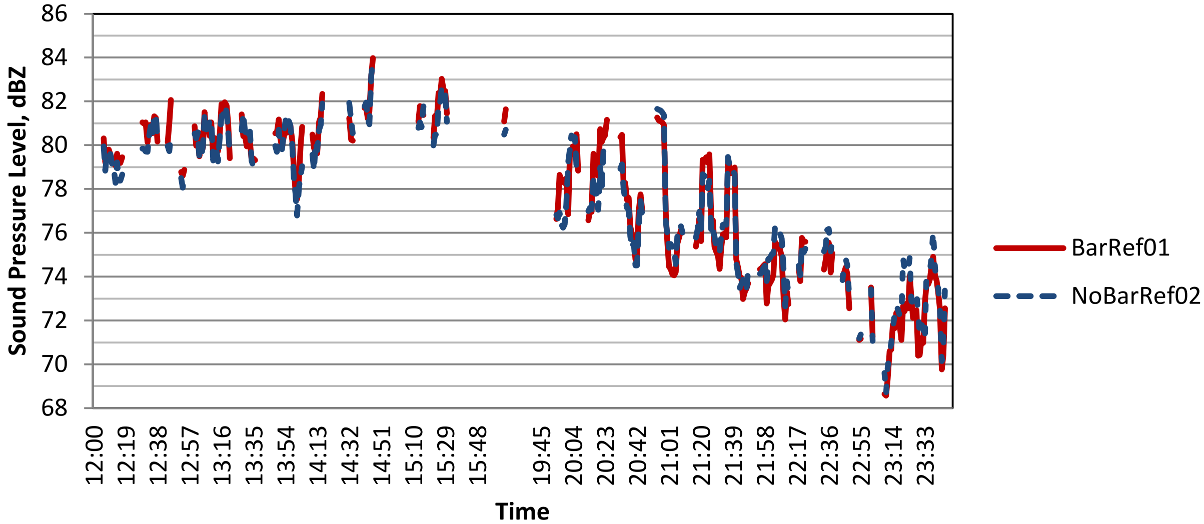


Figure 144. Running L_{eq}(5min), MD-5, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

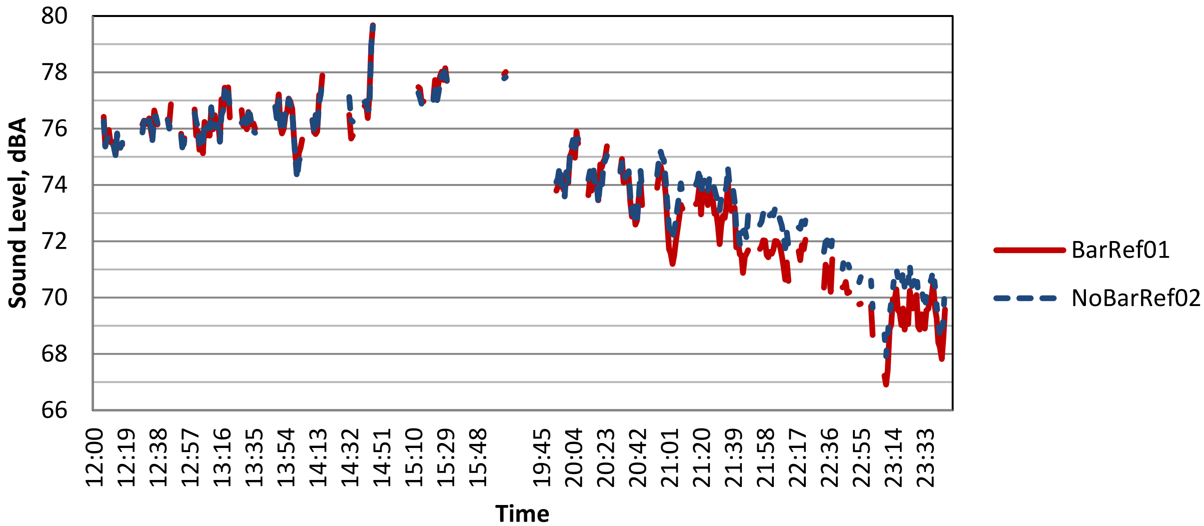


Figure 145. Running L_{eq}(5min), MD-5, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

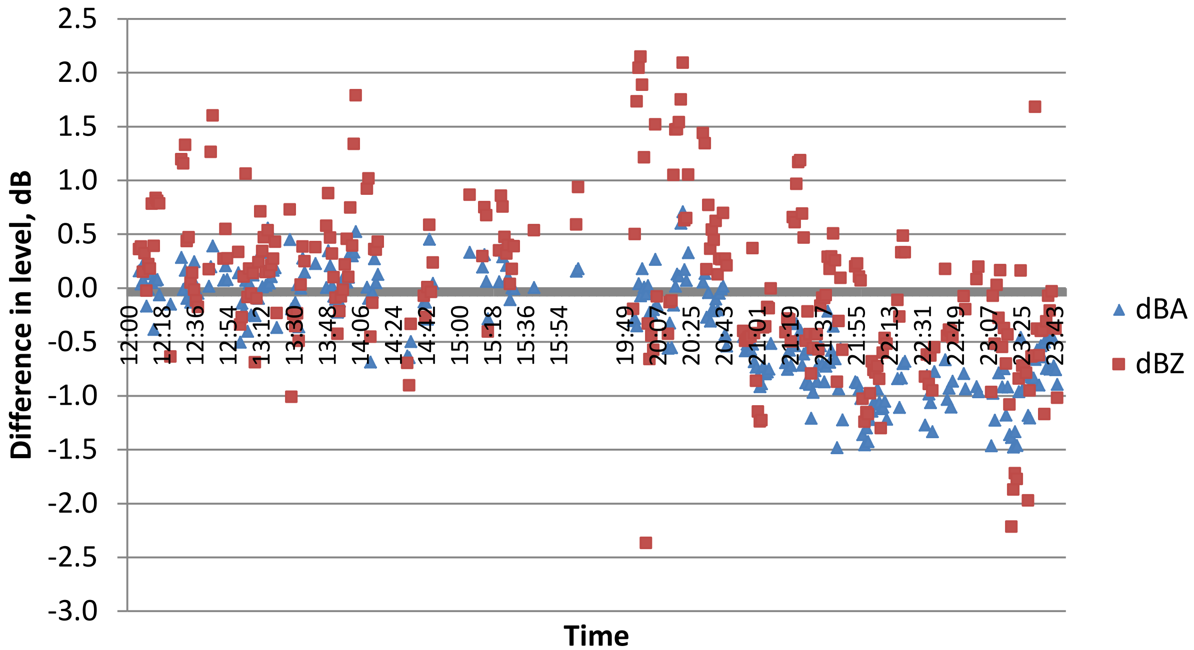


Figure 146. Differences in running L_{eq}(5min), MD-5, BarRef01 minus NoBarRef02

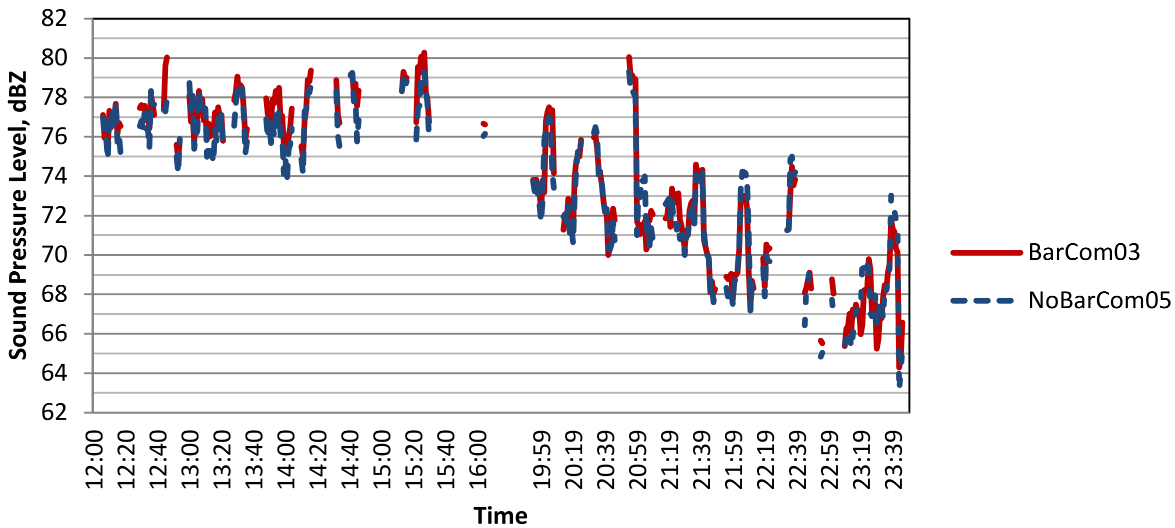


Figure 147. Running L_{eq}(5min), MD-5, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

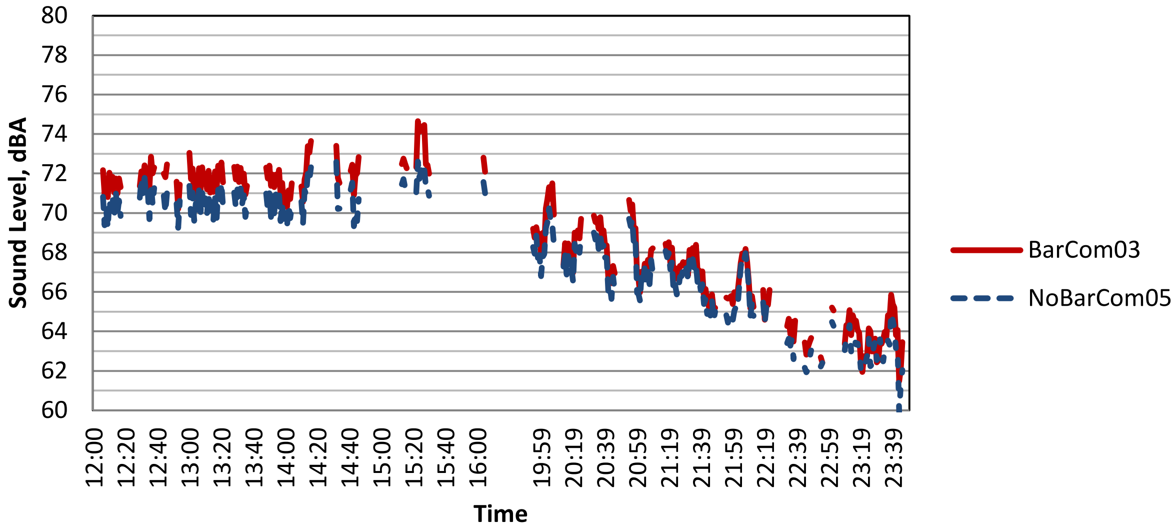


Figure 148. Running L_{eq}(5min), MD-5, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

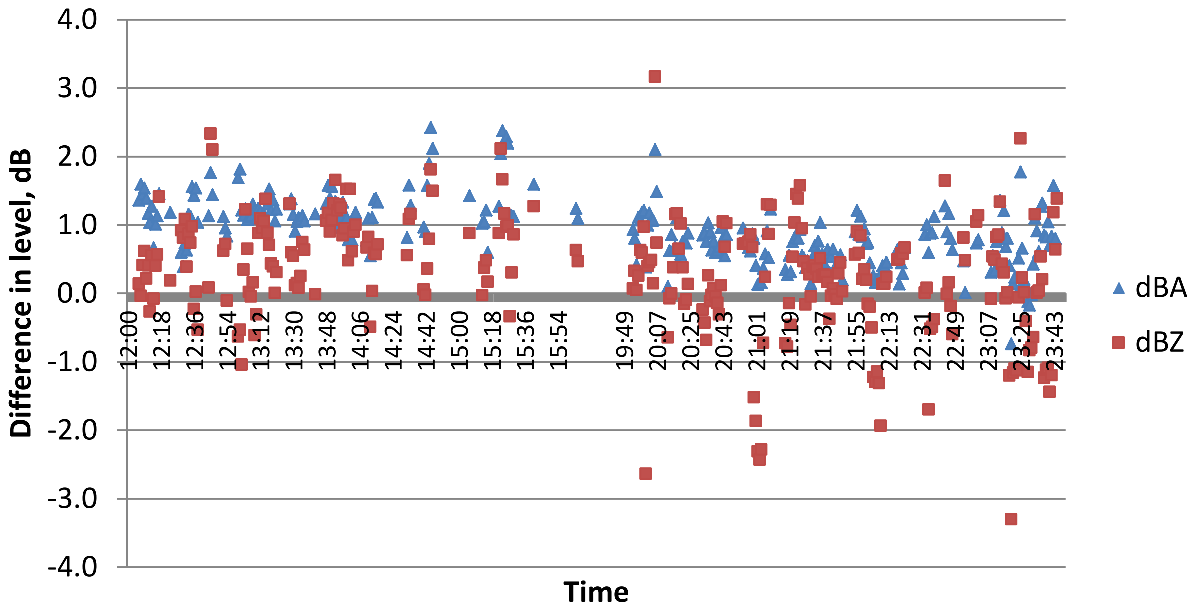


Figure 149. Differences in running L_{eq}(5min), MD-5, BarCom03 minus NoBarCom05

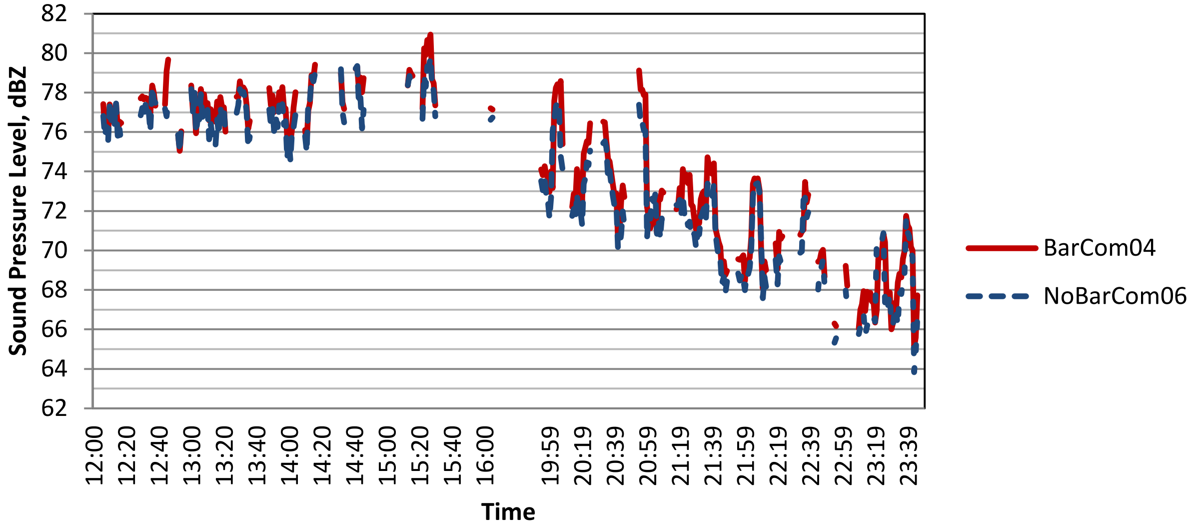


Figure 150. Running L_{eq}(5min), MD-5, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

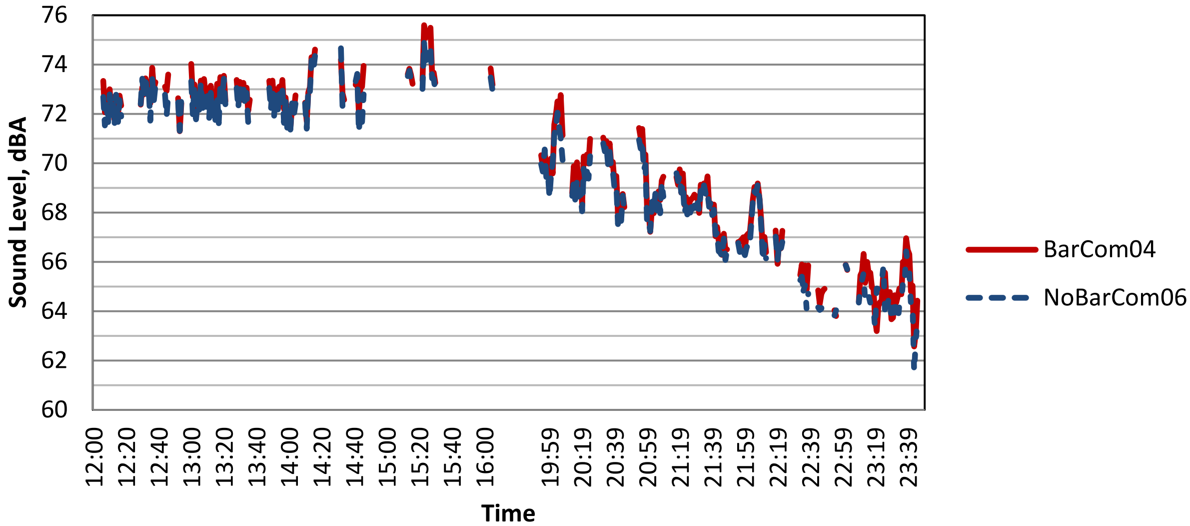


Figure 151. Running L_{eq}(5min), MD-5, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

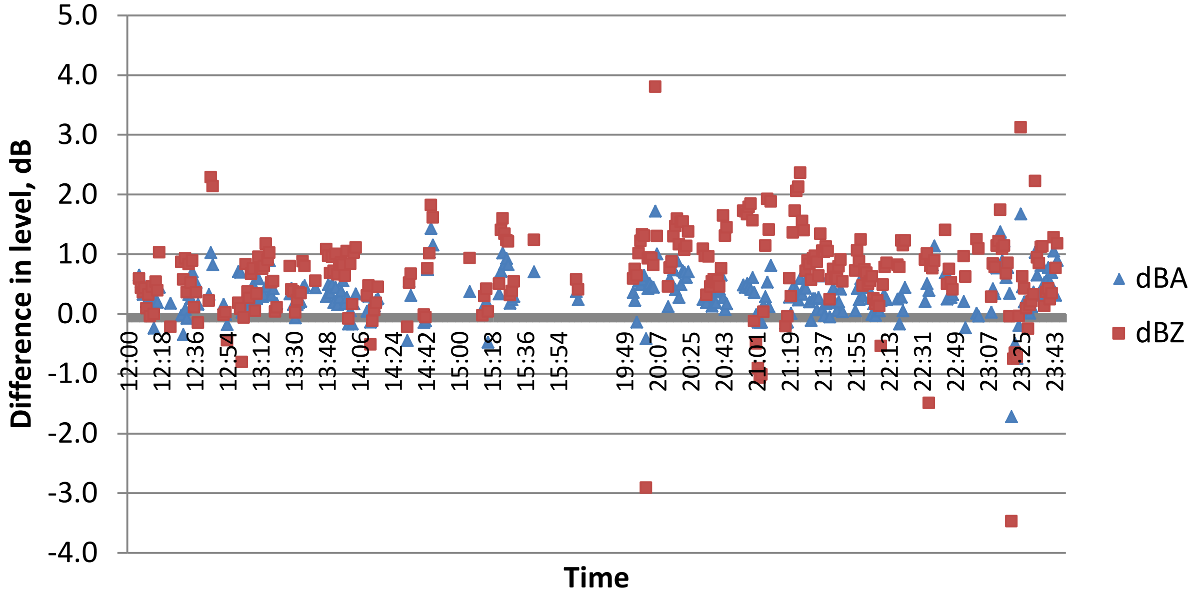


Figure 152. Differences in running L_{eq}(5min), MD-5, BarCom04 minus NoBarCom06

Data Analysis for MD-5 - FHWA Method

Equivalent Groups

All of the groupings of 5-minute periods that were judged equivalent for traffic parameters at the MD-5 location fell into four meteorological classes:

- Calm Neutral: 10 groupings each with three to four 5-minute equivalent periods ("CNG-"), with the starting times shown graphically in Figure 153.
- Downwind Neutral: 7 groupings each with three to five 5-minute equivalent periods ("DNG-"), with the starting times shown graphically in Figure 154
- Downwind Lapse: 15 groupings each with three to five 5-minute equivalent periods ("DLG-"), with the starting times shown graphically in Figure 155
- Calm Inversion: 15 groupings each with three to five 5-minute equivalent periods ("CIG-"), with the starting times shown graphically in Figure 156

Note that while all of the 5-minute periods in a group are non-overlapping in time, the same 5-minute periods often appear in multiple equivalent groups.

These periods had varying traffic volumes, as show in Table 15, which ranks the Calm Inversion, Calm Neutral, Downwind Lapse, and Downwind Neutral groups by total two-way volume averaged across the periods in that group. For the Calm Inversion class, the volumes of the highest group were roughly 315% greater than the volumes of the lowest group. For the Calm Neutral class, the highest group was 30% greater than the lowest group. For the Downwind Lapse class, the highest group was 64% greater than the lowest group. For the Downwind Neutral class, the highest group was 25% greater than the lowest group. In terms of equivalent hourly volumes, the overall range was from 400 vph to 2,936 vph.

Speeds were much more consistent, ranging from averages of 56 mph to 63 mph for the Calm Inversion groups, 58 mph to 63 mph for both the Calm Neutral and Downwind Lapse groups, and 58 mph to 64 mph for the Downwind Neutral groups.

Group ID	Starting Time of 5-minute Periods																		
	19:55	19:56	19:57	19:58	20:00	20:01	20:16	20:17	20:19	20:32	20:34	20:36	20:37	20:40	20:43	20:44	20:45	21:27	21:28
CNG-1-1														■			■		■
CNG-2-1									■						■			■	
CNG-3-1						■		■			■					■			
CNG-3-2	■					■		■				■				■			
CNG-3-3			■					■			■					■			
CNG-3-4				■				■				■				■			
CNG-4-1		■								■			■						
CNG-4-2		■					■			■			■						
CNG-4-3					■					■			■						
CNG-4-4					■		■			■			■						

Figure 153. Equivalent 5-minute periods for Calm Neutral groups at MD-5.

Group ID	Starting Time of 5-minute Periods																		
	12:09	12:30	12:31	12:32	13:14	13:16	13:18	13:20	13:29	13:50	13:51	13:53	13:54	14:10	14:43	15:22	15:23	15:25	15:30
DNG-1-1	■			■					■		■								
DNG-1-2	■			■					■			■							
DNG-2-1		■			■								■	■	■				
DNG-2-2			■		■									■	■				
DNG-3-1						■				■						■			
DNG-4-1							■										■		■
DNG-4-2								■										■	■

Figure 154. Equivalent 5-minute periods for Downwind Neutral groups at MD-5.

Group ID	Starting Time of 5-minute Periods																																					
	12:06	12:07	12:08	12:12	12:13	12:14	12:16	12:17	12:29	12:33	12:36	12:44	12:45	12:46	13:05	13:06	13:07	13:08	13:10	13:11	13:12	13:13	13:33	13:34	13:36	13:48	13:56	13:57	13:58	14:00	14:11	14:13	14:14	14:15	14:32	14:33	14:34	15:15	15:16
DLG-1-1					■										■															■									
DLG-2-1		■		■				■									■																			■			
DLG-2-2		■					■										■																				■		
DLG-2-3			■					■									■																				■		
DLG-2-4			■			■											■																			■			
DLG-3-1									■											■					■						■								
DLG-3-2									■											■				■								■							
DLG-3-3									■													■	■									■							
DLG-3-4									■													■		■							■								
DLG-4-1	■									■		■				■																							
DLG-4-2	■									■			■					■																					
DLG-5-1											■										■														■				
DLG-6-1														■					■							■			■									■	
DLG-7-1																											■						■						■
DLG-7-2																												■						■					■

Figure 155. Equivalent 5-minute periods for Downwind Lapse groups at MD-5.

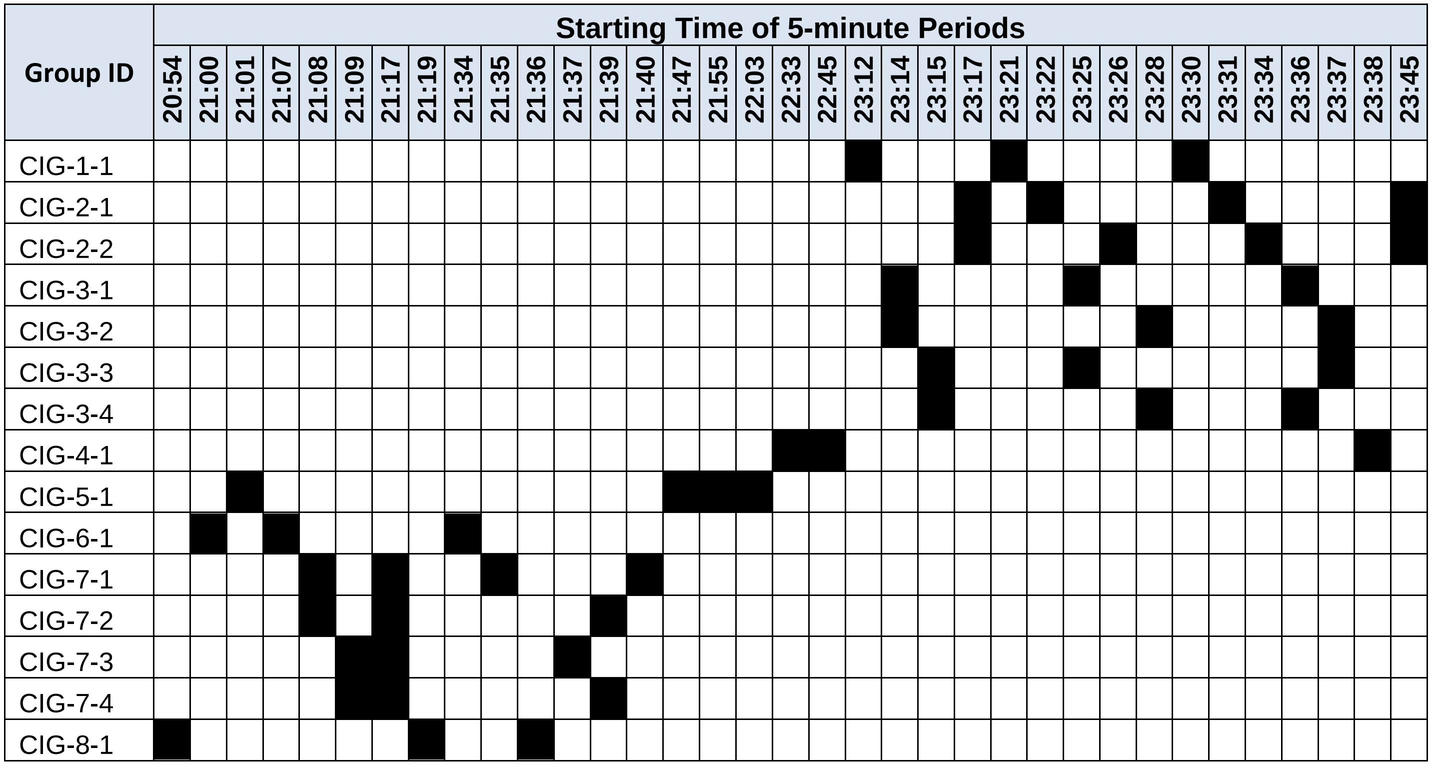


Figure 156. Equivalent 5-minute periods for Calm Inversion groups at MD-5.

Table 15. Two-way traffic volumes in 5-minute periods, by equivalent group for Calm Inversion, Calm Neutral, Downwind Lapse and Downwind Neutral conditions, sorted by factored hourly volume, MD-5.

Group	Two-Way Traffic Volumes (5 minutes)					Factored Hourly Volume (vph)
	Period 1	Period 2	Period 3	Period 4	Period 5	
Calm Inversion						
CIG-8-1	103	108	104			1,260
CIG-7-3	102	100	93			1,180
CIG-7-4	102	100	93			1,180
CIG-7-2	95	100	93			1,152
CIG-7-1	95	100	99	86		1,140
CIG-6-1	94	92	89			1,100
CIG-5-1	78	80	93	102		1,059
CIG-3-2	48	37	36			484
CIG-3-4	49	37	34			480
CIG-3-3	49	34	36			476
CIG-3-1	48	34	34			464
CIG-4-1	40	42	33			460
CIG-2-2	39	34	36	31		420
CIG-2-1	39	34	35	31		417
CIG-1-1	39	30	31			400
Calm Neutral						
CNG-4-3	142	124	116			1,528
CNG-4-4	142	118	124	116		1,500
CNG-4-1	132	124	116			1,488
CNG-4-2	132	118	124	116		1,470
CNG-3-1	142	105	134	108		1,467
CNG-3-2	125	142	105	126	108	1,454
CNG-3-3	132	105	134	108		1,437
CNG-3-4	120	105	126	108		1,377
CNG-2-1	100	107	105			1,248
CNG-1-1	103	89	102			1,176
Downwind Lapse						
DLG-7-2	200	303	231			2,936
DLG-7-1	207	283	231			2,884
DLG-5-1	185	182	224			2,364
DLG-6-1	117	199	205	187	234	2,261
DLG-3-2	170	152	187	223		2,196
DLG-4-1	181	179	164	197		2,163
DLG-3-3	170	170	157	223		2,160
DLG-4-2	181	179	151	189		2,100
DLG-3-4	170	170	187	165		2,076
DLG-3-1	170	152	178	165		1,995
DLG-2-2	150	152	175	185		1,986
DLG-2-3	151	151	175	185		1,986
DLG-2-4	151	140	175	186		1,956
DLG-2-1	150	140	151	175	186	1,925
DLG-1-1	130	149	169			1,792
Downwind Neutral						
DNG-4-1	173	264	231			2,672
DNG-4-2	175	238	231			2,576
DNG-3-1	172	213	255			2,560

DNG-2-1	181	187	249	178	178	2,335
DNG-1-2	156	188	167	233		2,232
DNG-1-1	156	188	167	217		2,184
DNG-2-2	172	187	178	178		2,145

Sound Pressure Level Spectra

Before discussing the differences in levels between the Barrier and No Barrier sites, typical sound pressure level spectra are shown to give some perspective on the data on which the differences are based. One of the 5-minute periods in each of the four meteorological classes was chosen as typical. These are:

- Calm Neutral
  - Figure 157: BarRef01/NoBarRef02
  - Figure 158: BarCom03/NoBarCom05
  - Figure 159: BarCom04/NoBarCom06
- Downwind Neutral
  - Figure 160: BarRef01/NoBarRef02
  - Figure 161: BarCom03/NoBarCom05
  - Figure 162: BarCom04/NoBarCom06
- Downwind Lapse
  - Figure 163: BarRef01/NoBarRef02
  - Figure 164: BarCom03/NoBarCom05
  - Figure 165: BarCom04/NoBarCom06
- Calm Inversion
  - Figure 166: BarRef01/NoBarRef02
  - Figure 167: BarCom03/NoBarCom05
  - Figure 168: BarCom04/NoBarCom06

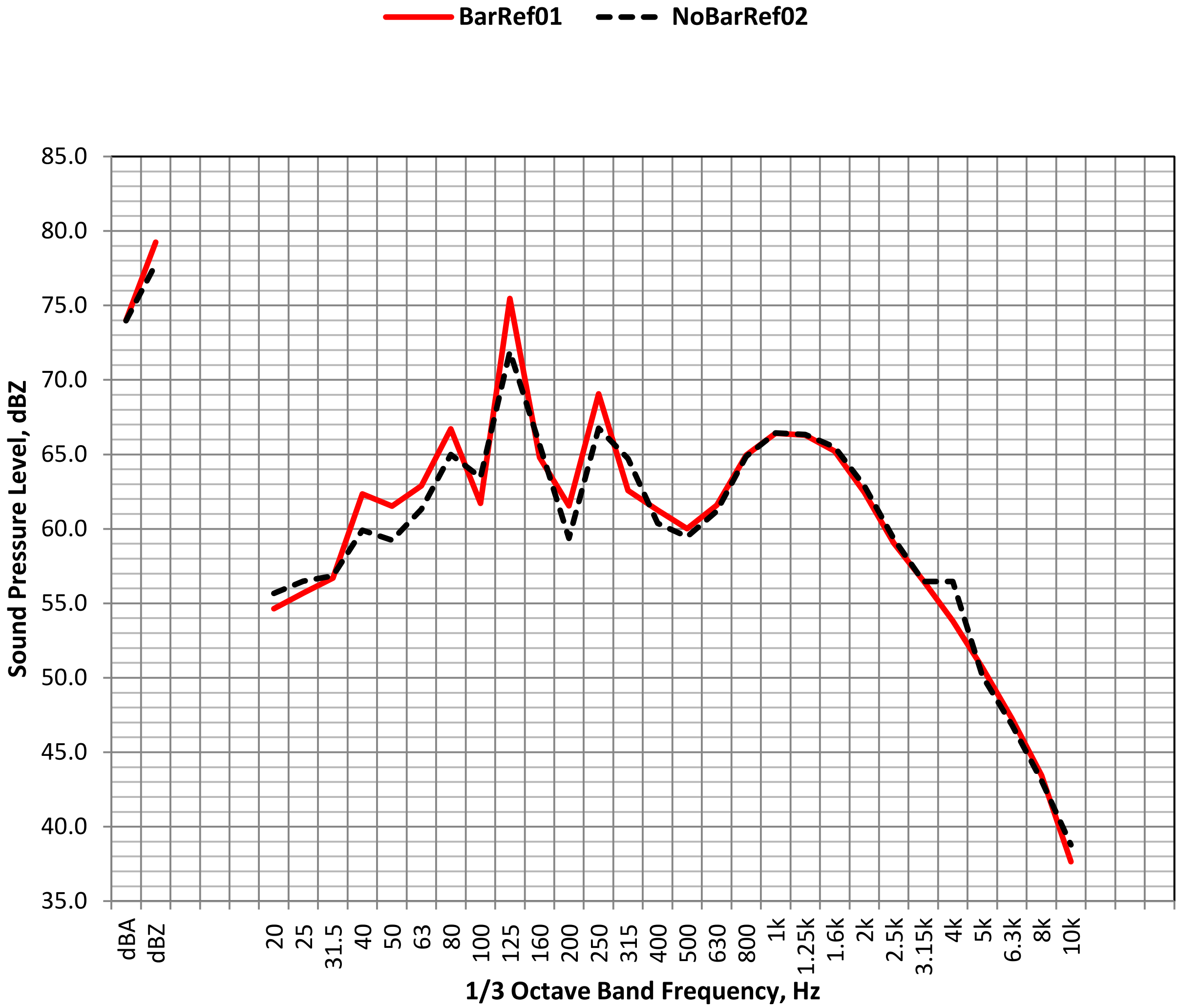


Figure 157. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Calm Neutral Group CNG-3-4, 20:17 (L_{eq}(5min), dBZ).

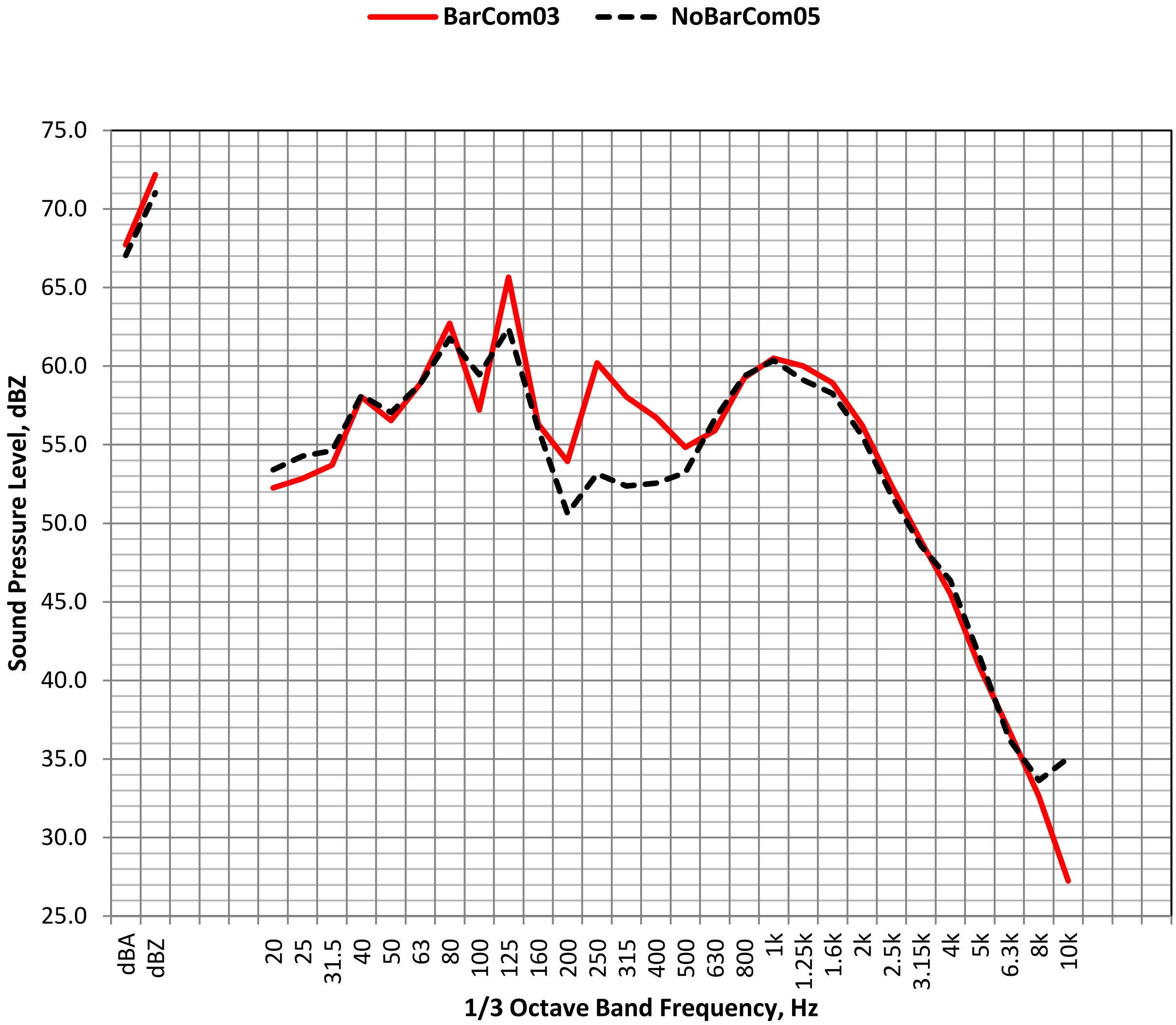


Figure 158. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Calm Neutral Group CNG-3-4, 20:17 (L_{eq}(5min), dBZ).

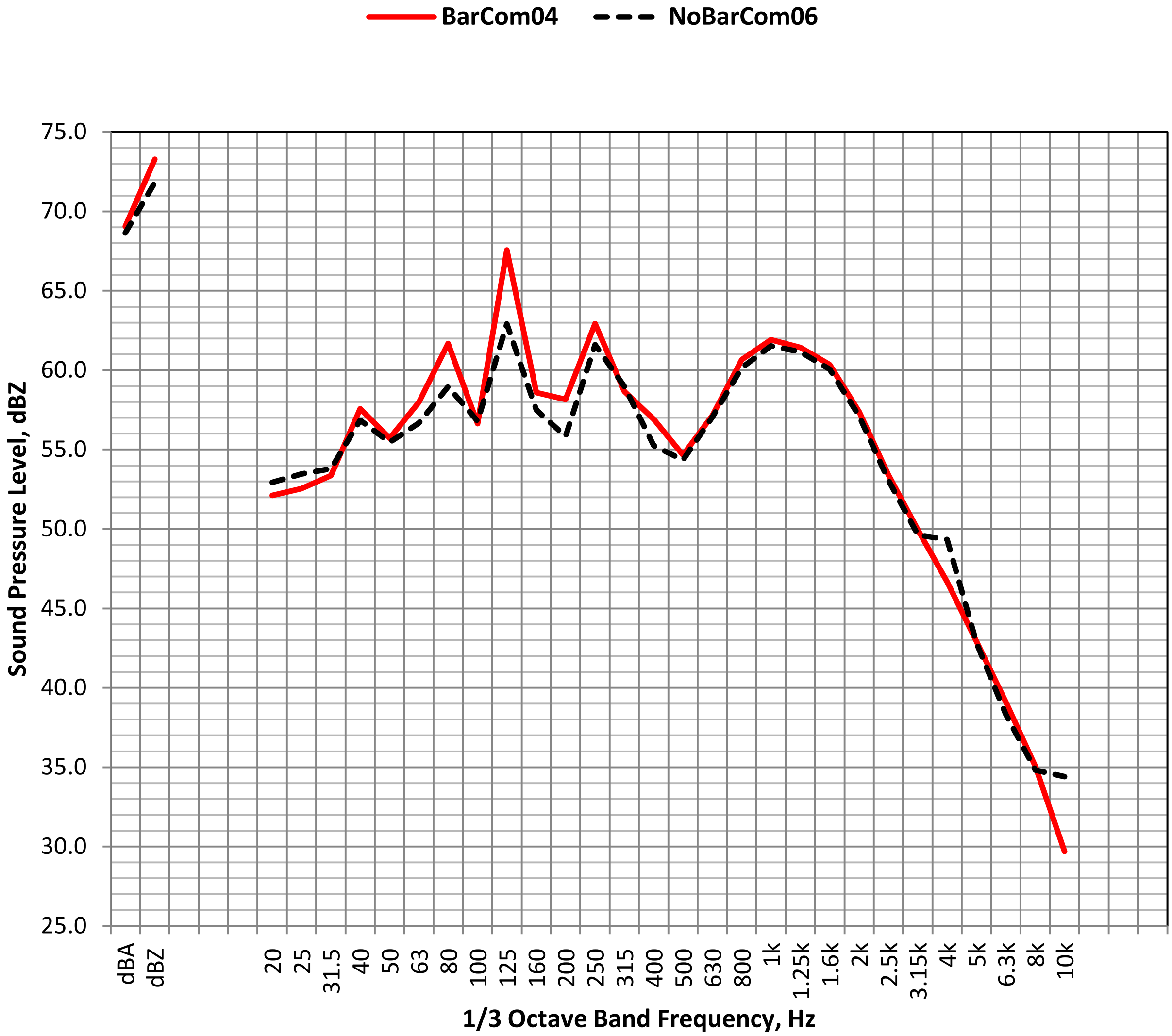


Figure 159. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Calm Neutral Group CNG-3-4, 20:17 (L_{eq}(5min), dBZ).

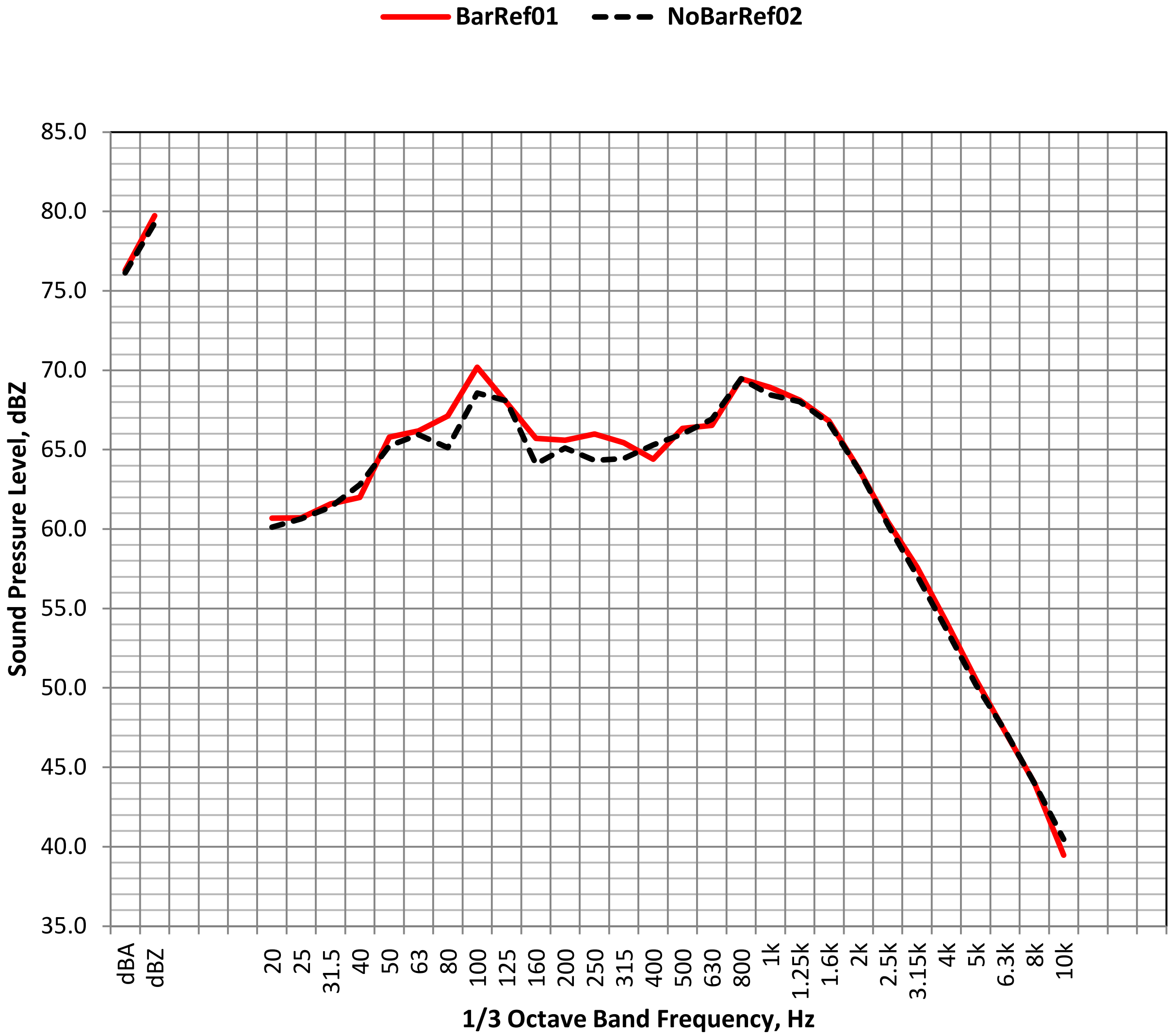


Figure 160. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Downwind Neutral Group DNG-2-2, 13:14 (L_{eq}(5min), dBZ).

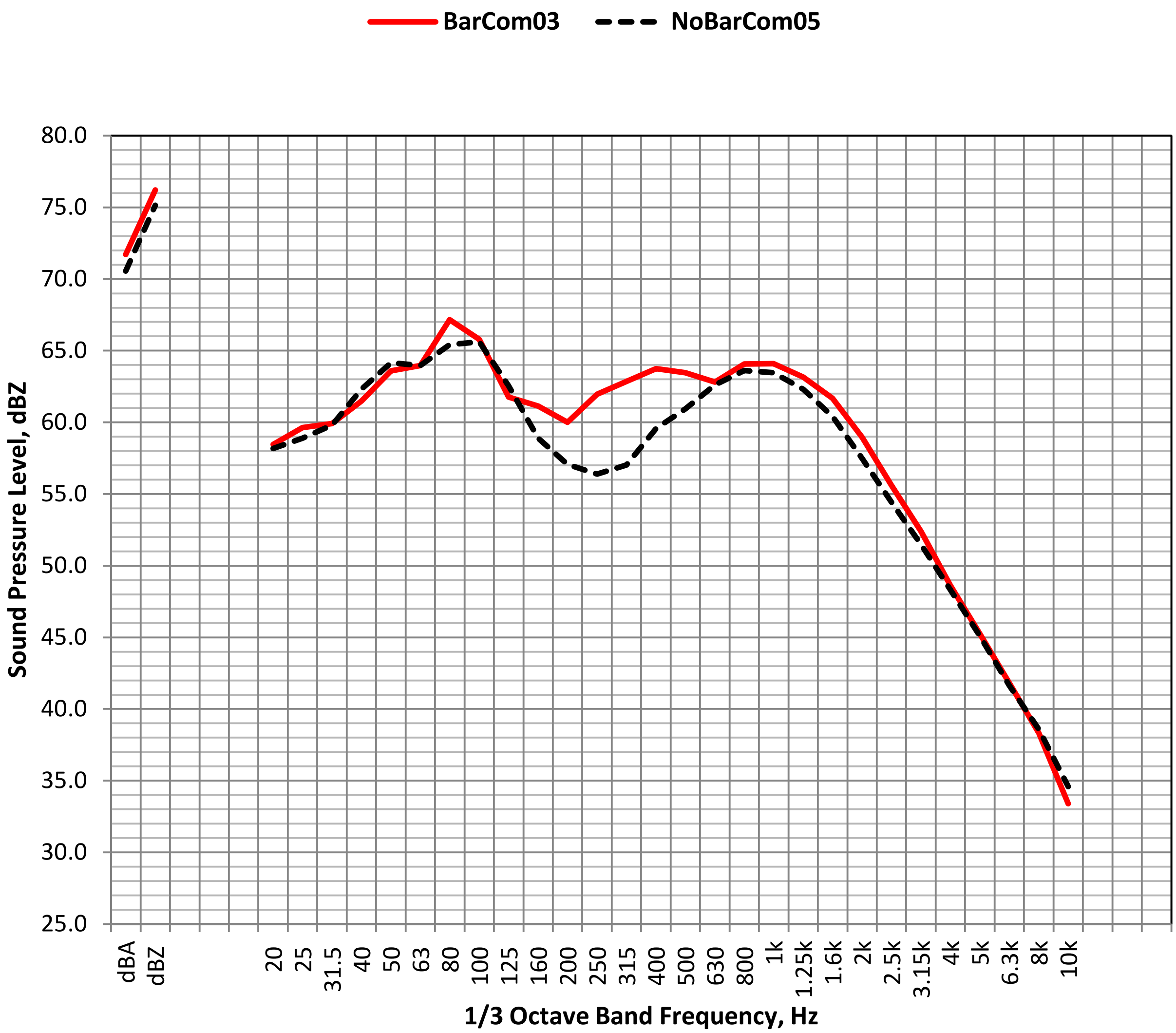


Figure 161. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Downwind Neutral Group DNG-2-2, 13:14 (L_{eq}(5min), dBZ).

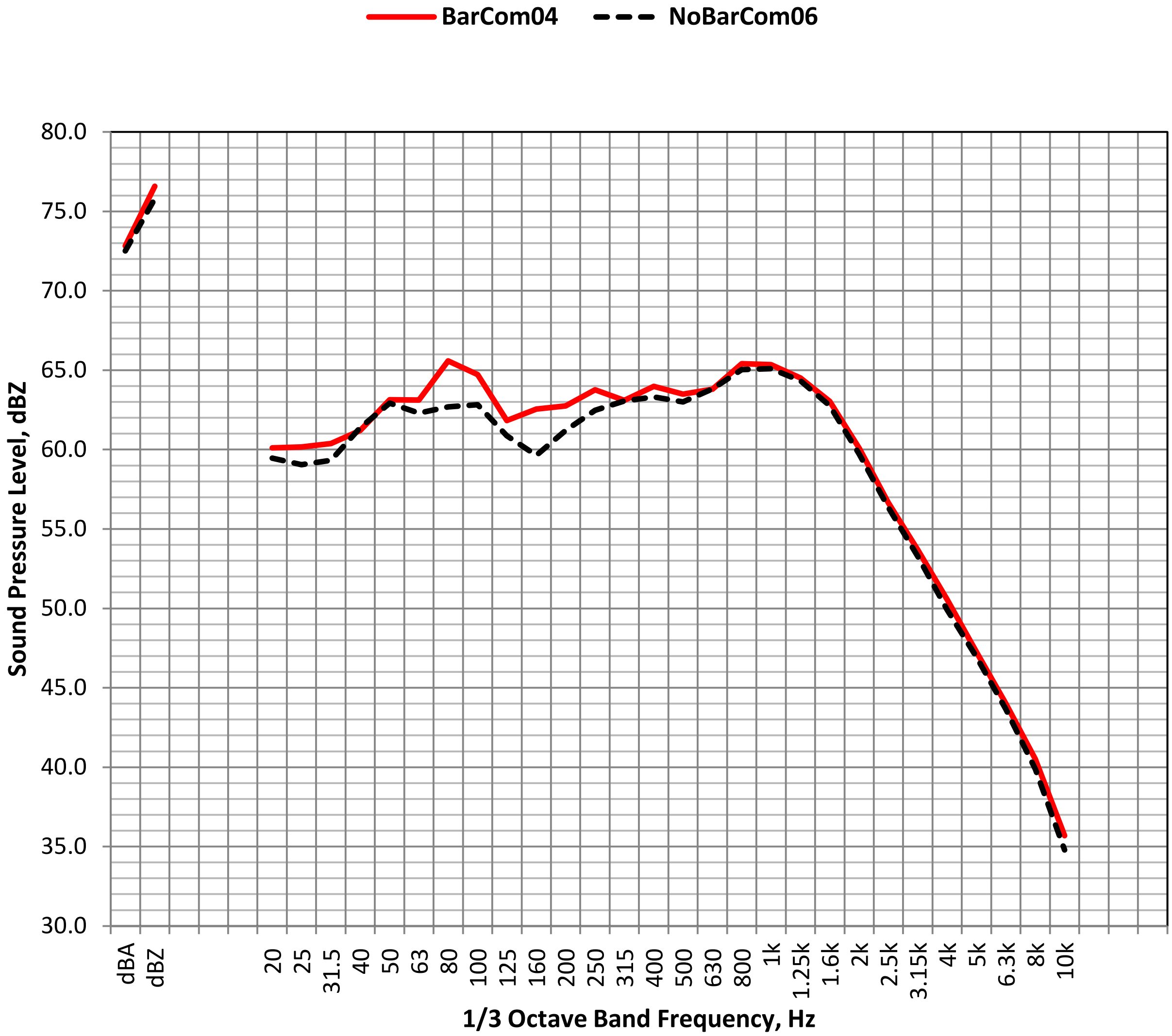


Figure 162. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Downwind Neutral Group DNG-2-2, 13:14 (L_{eq}(5min), dBZ).

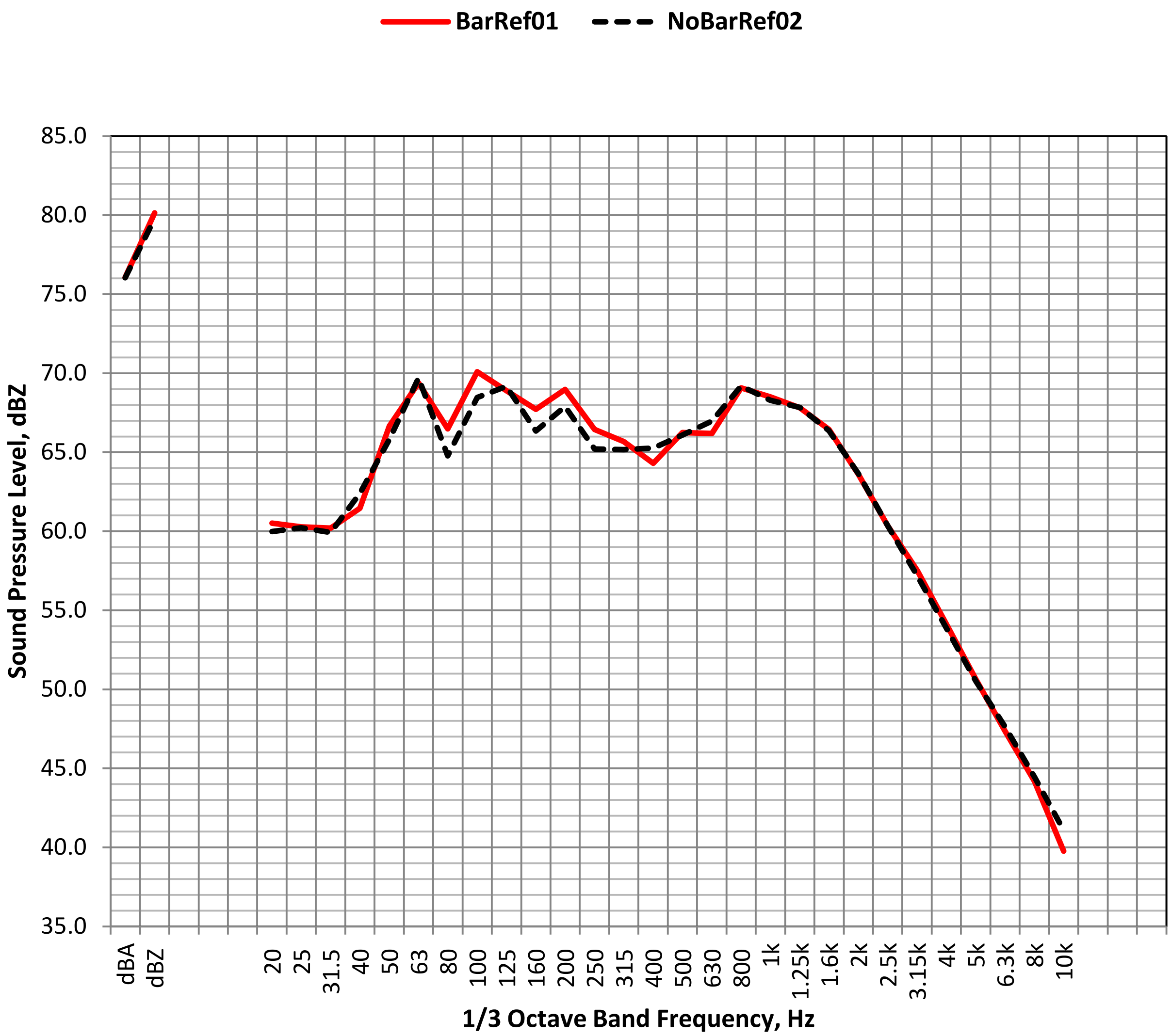


Figure 163. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Downwind Lapse Group DLG-3-4, 13:13 (L_{eq}(5min), dBZ).

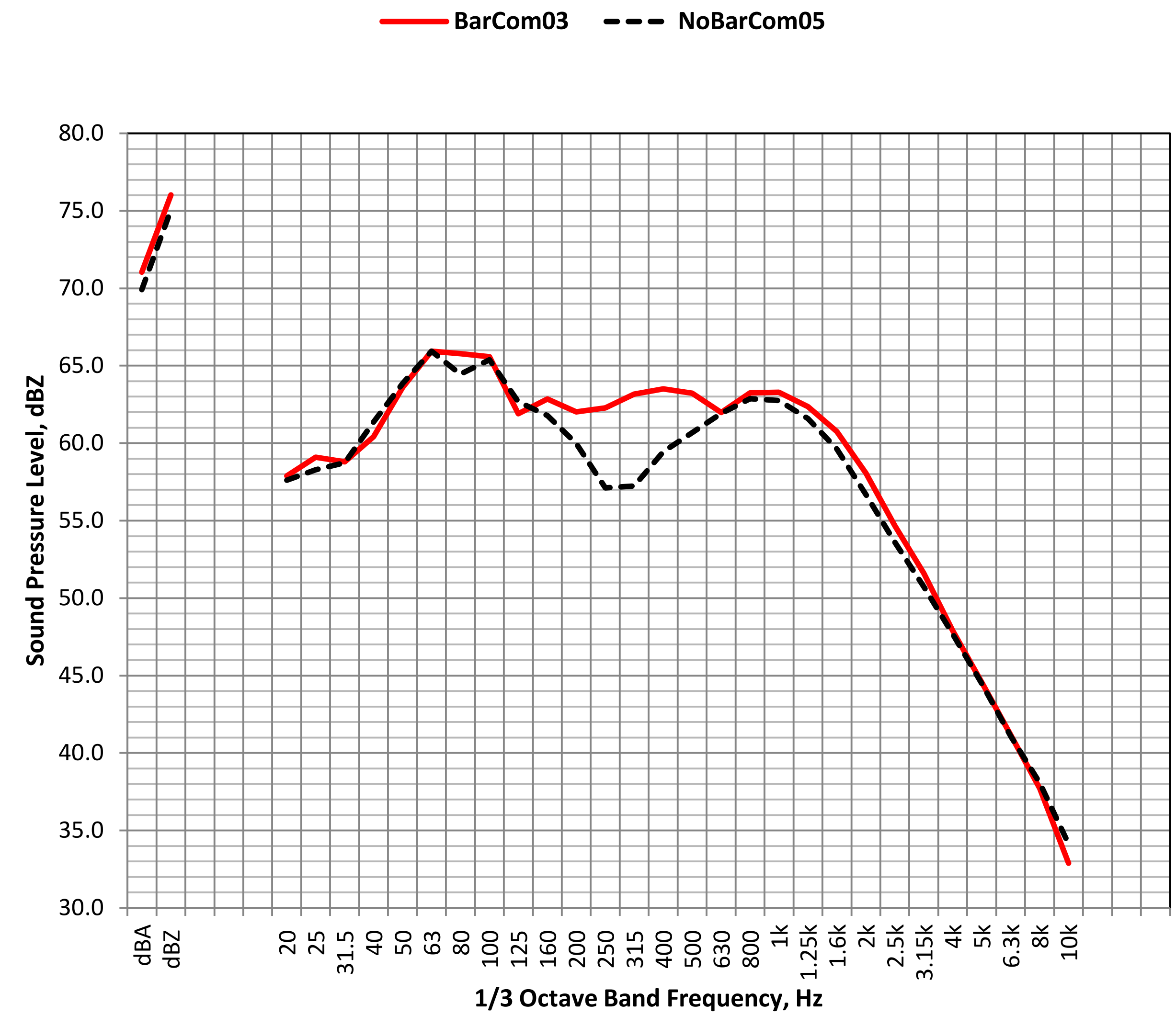


Figure 164. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Downwind Lapse Group DLG-3-4, 13:13 (L_{eq}(5min), dBZ).

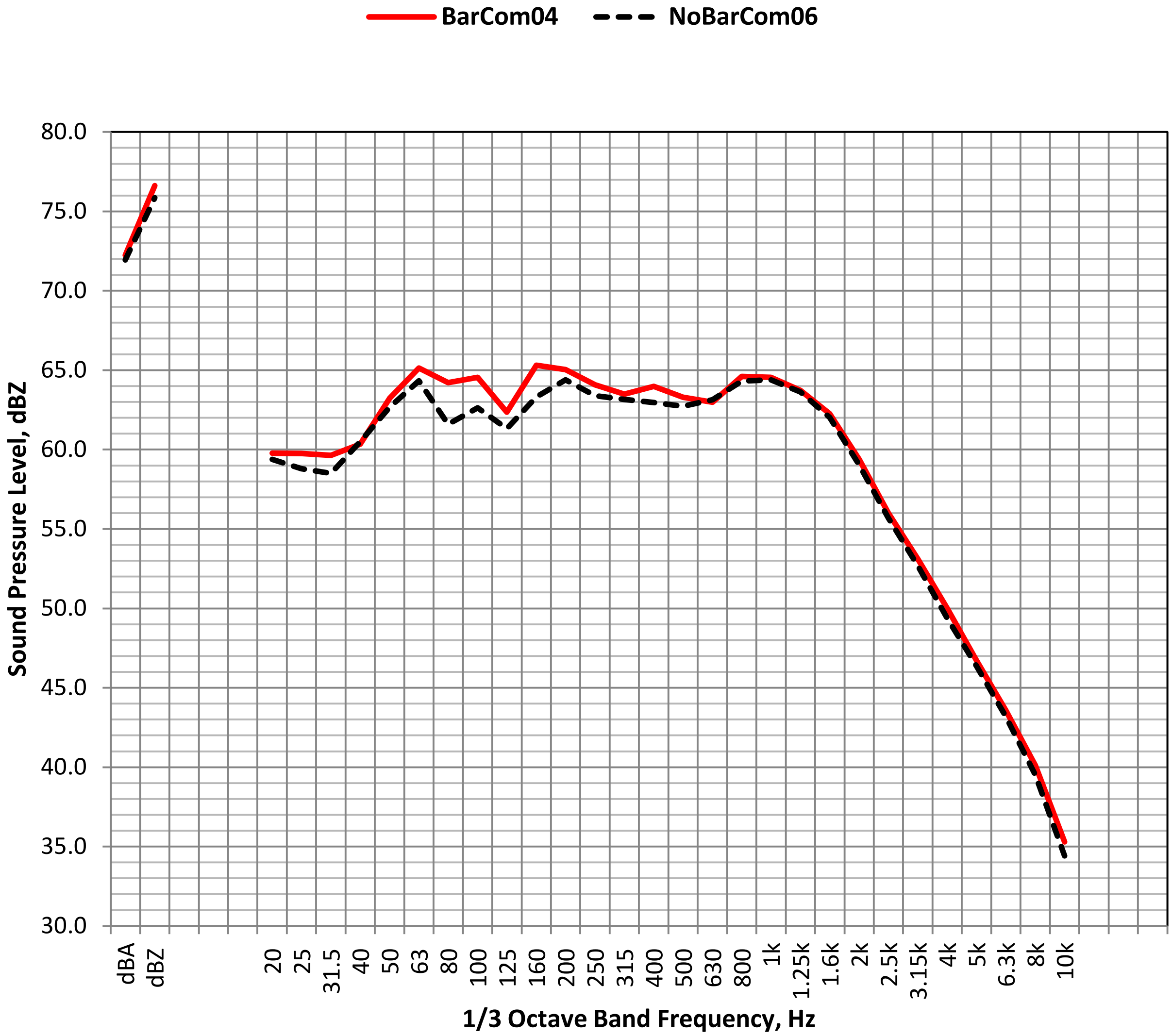


Figure 165. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Downwind Lapse Group DLG-3-4, 13:13 (L_{eq}(5min), dBZ).

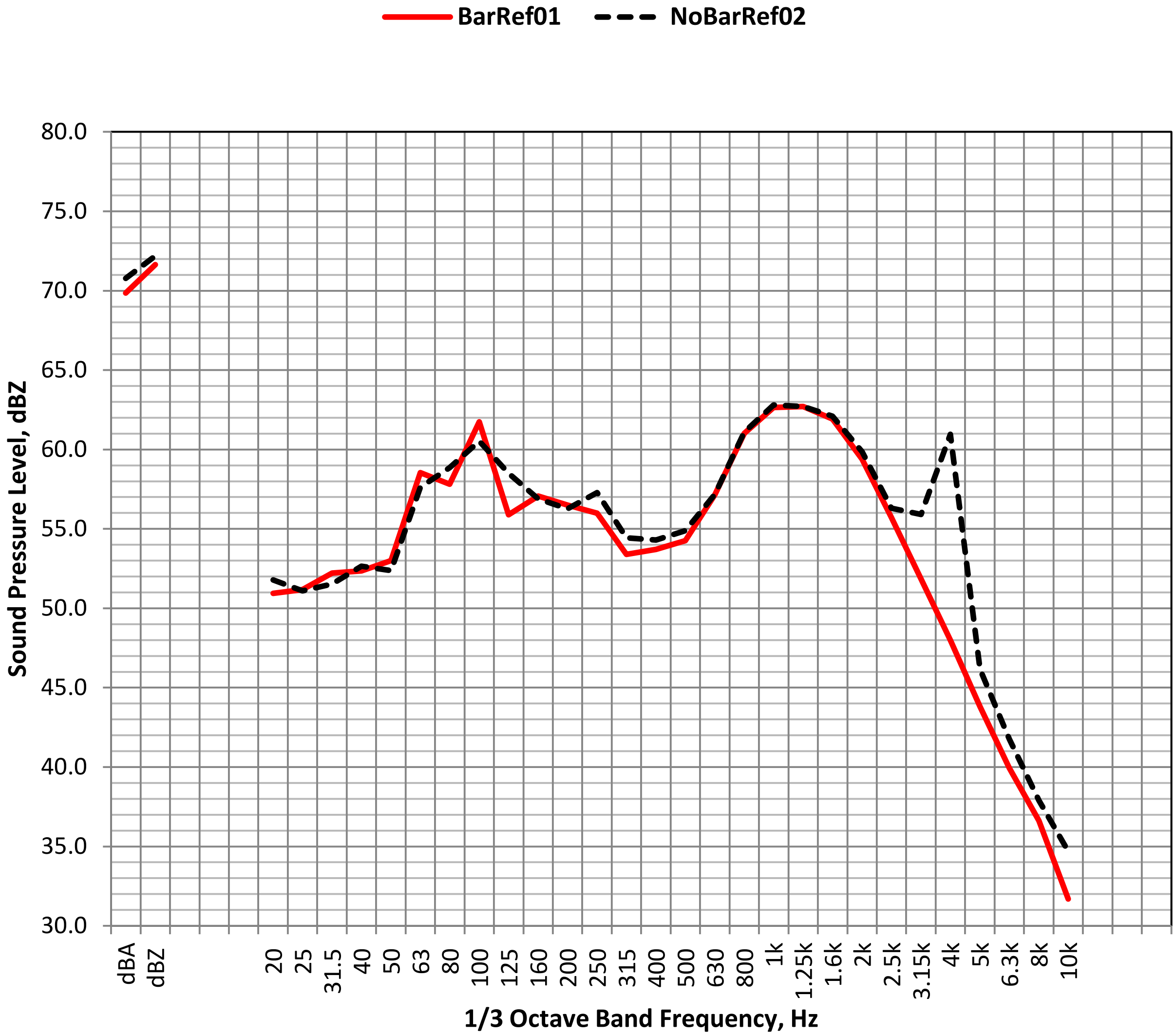


Figure 166. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Calm Inversion Group CIG-3-4, 23:15 L_{eq}(5min), dBZ).

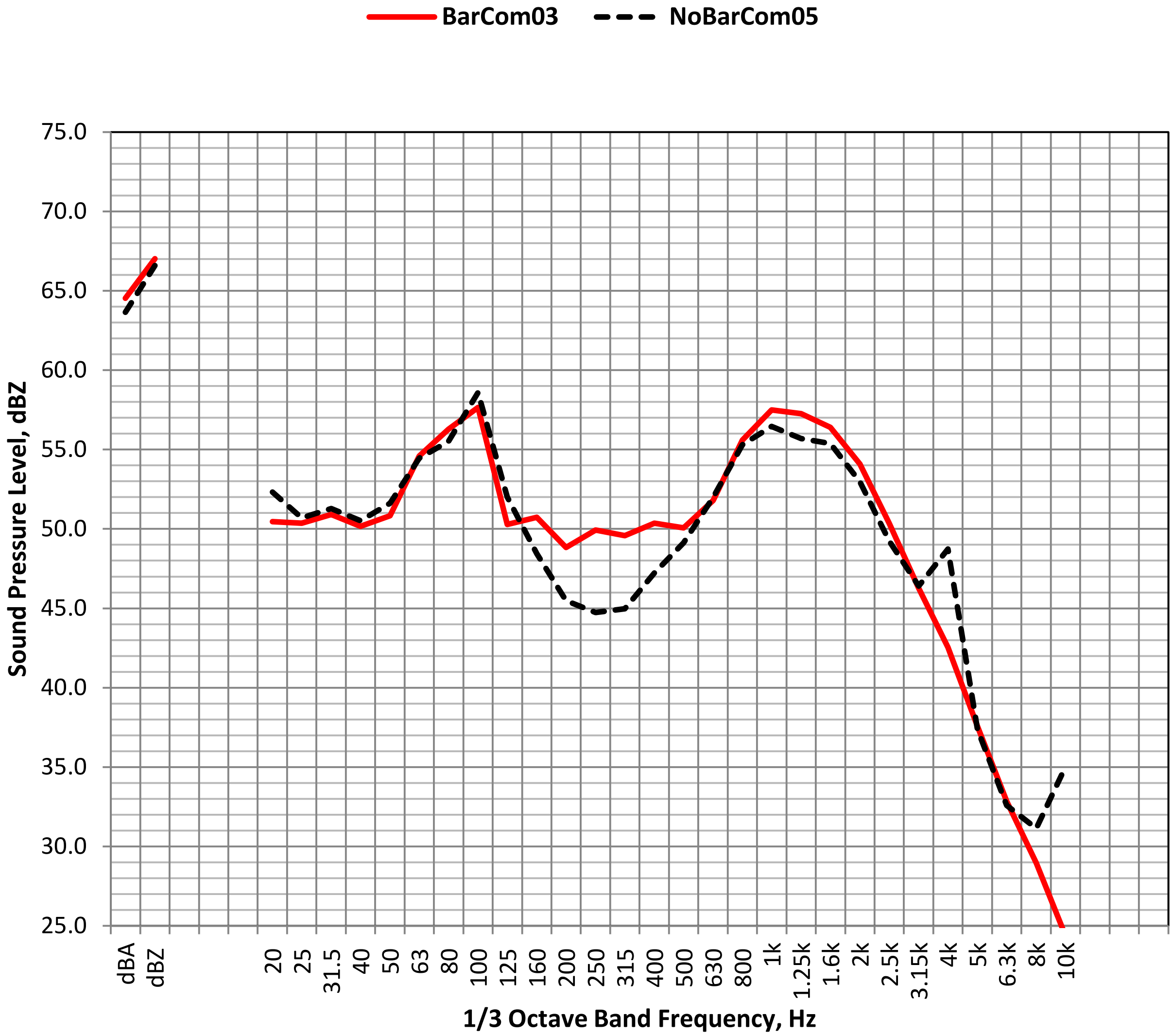


Figure 167. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Calm Inversion Group CIG-3-4, 23:15 (L_{eq}(5min), dBZ)

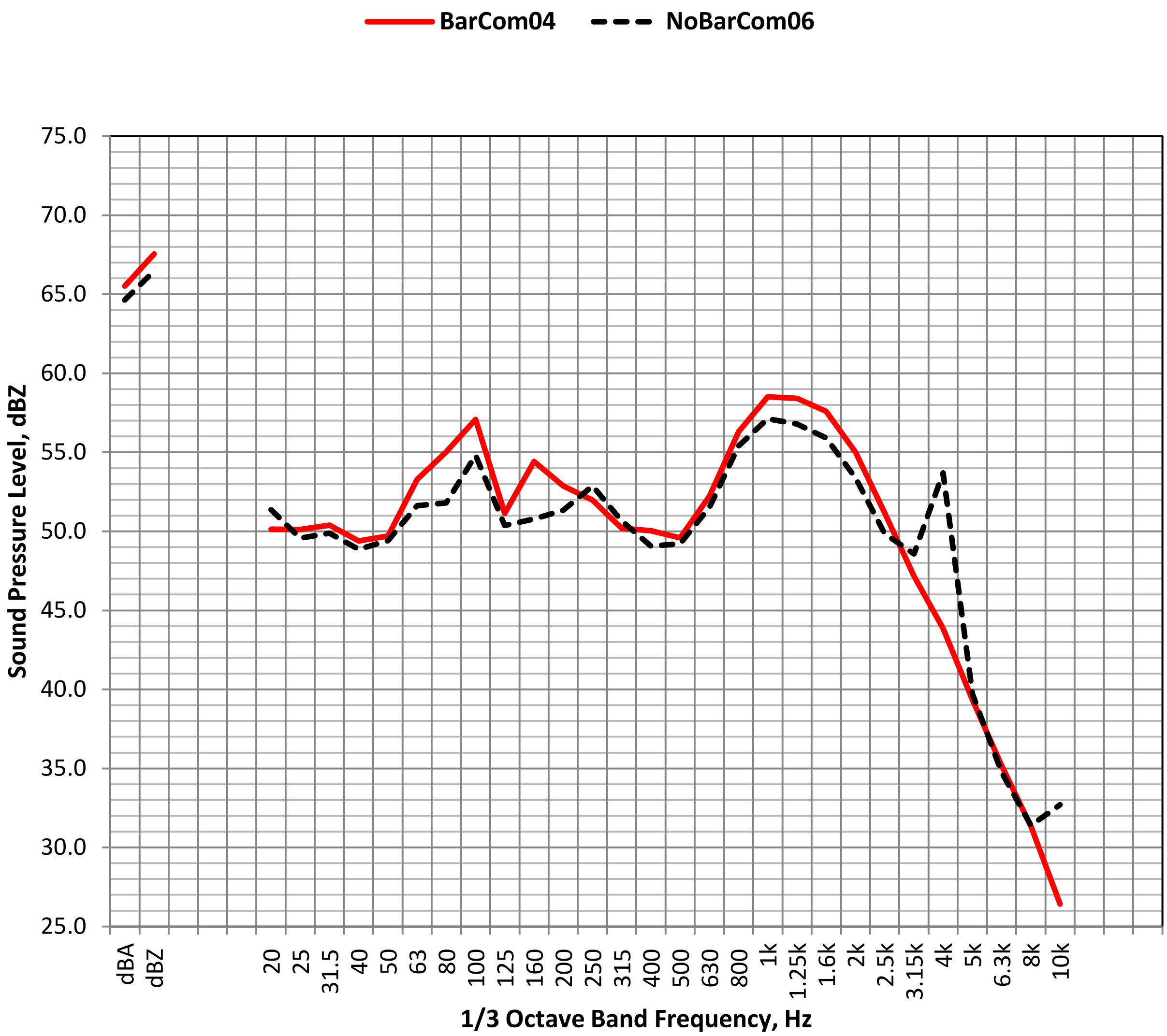


Figure 168. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Calm Inversion Group CIG-3-4, 23:15 L_{eq}(5min), dBZ).

The next four figures show the averages of the differences in the Barrier and No Barrier microphones' levels for each of the four studied meteorological classes, with their error bars. The error bars are +/- one standard deviation for each average value. Each figure compares the following:

- BarRef01 and NoBarRef02 in the upper graph;
- BarCom03 and NoBarCom05 in the middle graph; and
- BarCom04 and NoBarCom06 in the lower graph.

Each graph shows the averages of the average level differences for the A-weighted sound level, the unweighted sound pressure level and the 1/3 octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all of the groups in all of the meteorological classes are in spreadsheet files in the project record. The trends across the 1/3 octave band frequencies, described below, are generally similar in these individual groups of equivalent periods, with some differences likely related to background noise and the uniqueness of vehicle noise sources in each period.

In each figure, the middle graph comparing BarCom03 and NoBarCom05 shows the barrier reflection effect being prominent in the low frequency range (250-500 Hz), as was also seen for the same microphones for the I-90 location. As noted in the I-90 discussion, a possible explanation is that direct and reflected sound take different propagation paths. The direct sound at both the Barrier and No Barrier sites is likely experiencing ground effects/wave interference that cause a dip in sound level in that frequency range. The reflected sound at the barrier site is experiencing a different propagation path than the direct sound, with different ground effects and wave interference with ground reflections; a dip in the 250-500 Hz range would be non-existent or diminished. Exactly this effect is seen for all four of the meteorological classes in the sample spectra just presented in Figure 158, Figure 161, Figure 164 and Figure 167. As a result, the barrier effect is pronounced in the 250-500 Hz range.

Calm Neutral Class

Figure 169 shows the results for the Calm Neutral class. The upper graph that, in general, the BarRef01 levels vary little compared to NoBarRef02 across most of the frequency range from 20 Hz to 2.5 kHz, with the exception of 125 Hz, where the BarRef01 level averaged 2.5 dB higher than that at NoBarRef02. Above 2.5 kHz, the No Barrier levels are higher, likely due to localized frog noise at 4 kHz with most of the Calm Neutral periods being in the evening.

The middle graph compares the Calm Neutral levels at BarCom03 and NoBarCom05, the lower-height microphones. Up through 100 Hz, the NoBarCom05 level is about 1 dB higher than the BarCom03 level. From 125 Hz through 500 Hz, the BarCom03 level is higher, ranging from 0.5 dB up to a maximum of 6 dB at 250 Hz and 315 Hz. From 1 kHz through 3.15 kHz, the BarCom03 level is higher by up to 1 dB. Above 3.15 kHz, the No Barrier levels are generally higher, likely due to localized frog and insect noise centered around 4 kHz.

The lower graph compares the levels at the higher BarCom04 and NoBarCom06 positions for the Calm Neutral class. The patterns are similar to the middle graph: little difference in the lower bands; a 1 dB to 4 dB higher level at BarCom04 from 80 Hz to 200 Hz (as much as 3.5 dB higher at 125 Hz); a 0.5 dB higher level from 800 Hz up through 2.5 kHz; and a 4 dB higher level at NoBarCom06 due to frog and insect noise.

While all of the 5-minute periods in all of the Calm Neutral groups were not equivalent in traffic volume and speed across all of the groups, these averages of the average differences generally show consistency with the results in the individual groups.

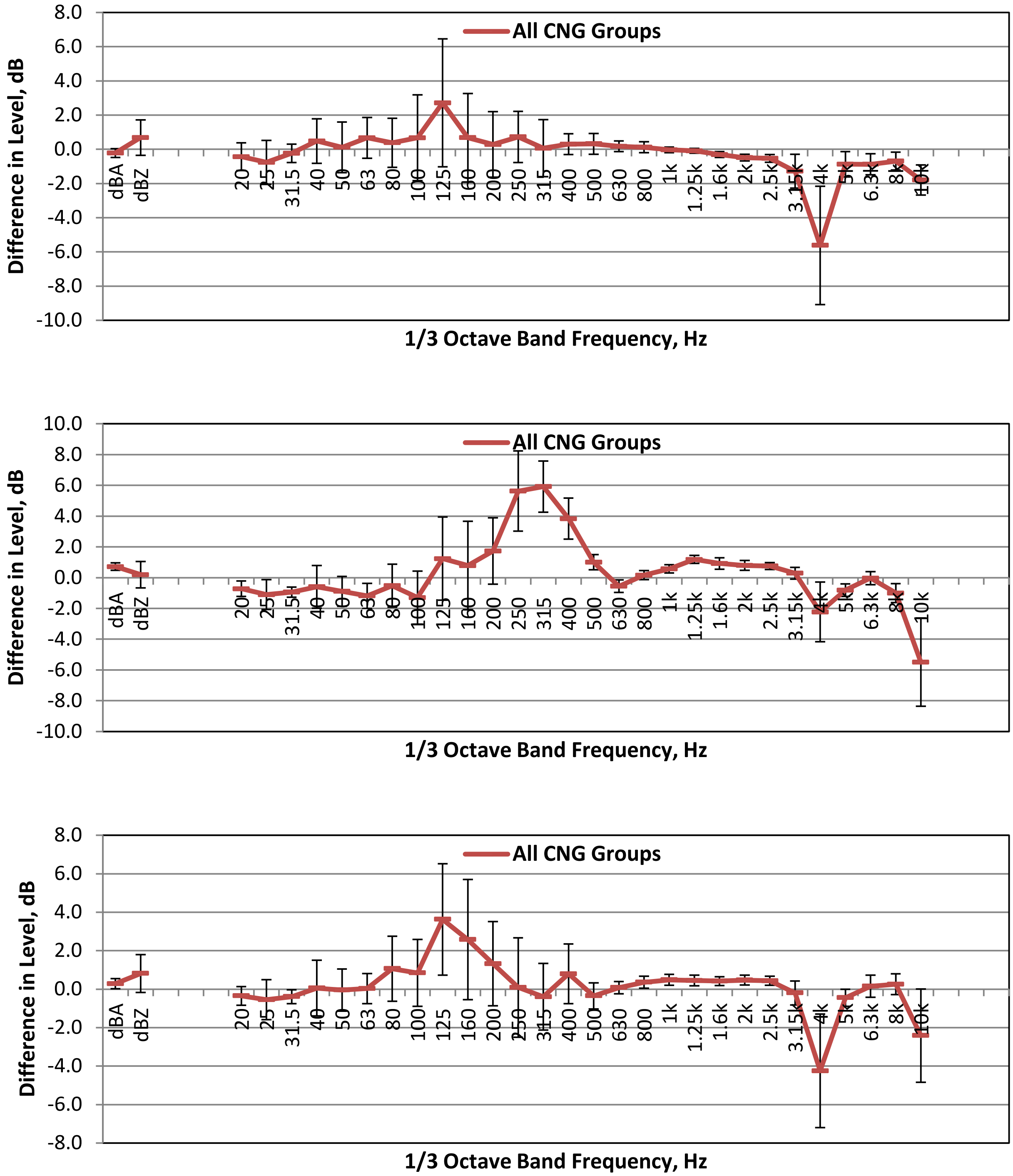


Figure 169. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Neutral groups, MD-5.

Downwind Neutral Class

Figure 170 shows the results for the Downwind Neutral class. The upper graph that, in general, the BarRef01 levels vary little compared to NoBarRef02 from 500 Hz through 6.3 kHz. Below 500 Hz, the BarRef01 levels were generally less than a decibel above those at NoBarRef02. The Downwind Neutral time periods were in the afternoon before the high frequency frog noise began.

The middle graph compares the Downwind Neutral levels at BarCom03 and NoBarCom05, the lower-height microphones. Up through 125 Hz, any differences are less than half a decibel. From 160 Hz through 500 Hz, the BarCom03 levels are higher, ranging from 1.0 at those ends of the range up to 6 dB at 315 Hz, the key band for the Calm Neutral class. From 630 Hz through 6.3 kHz, the BarCom03 level is higher by 0.5 dB to 1.5 dB (at 2 kHz). Again, no frog noise at 4 kHz is seen

The lower graph compares the levels at the higher BarCom04 and NoBarCom06 positions. The patterns are similar to the Calm Neutral class, with the low frequency levels being higher for BarCom04 , but only by a maximum of 2 dB at 160 Hz. The BarCom04 level is slightly higher than the NoBarCom06 level across the rest of the spectrum, but by no more than a decibel at 400 Hz and 6.3 kHz. The difference at 315 Hz is 0 dB compared to 6 dB at the lower height microphones.

While all of the 5-minute periods in all of the Downwind Neutral groups were not equivalent in traffic volume and speed across all of the equivalent groups, these averages of the average differences generally show consistency with the results in the individual groups.

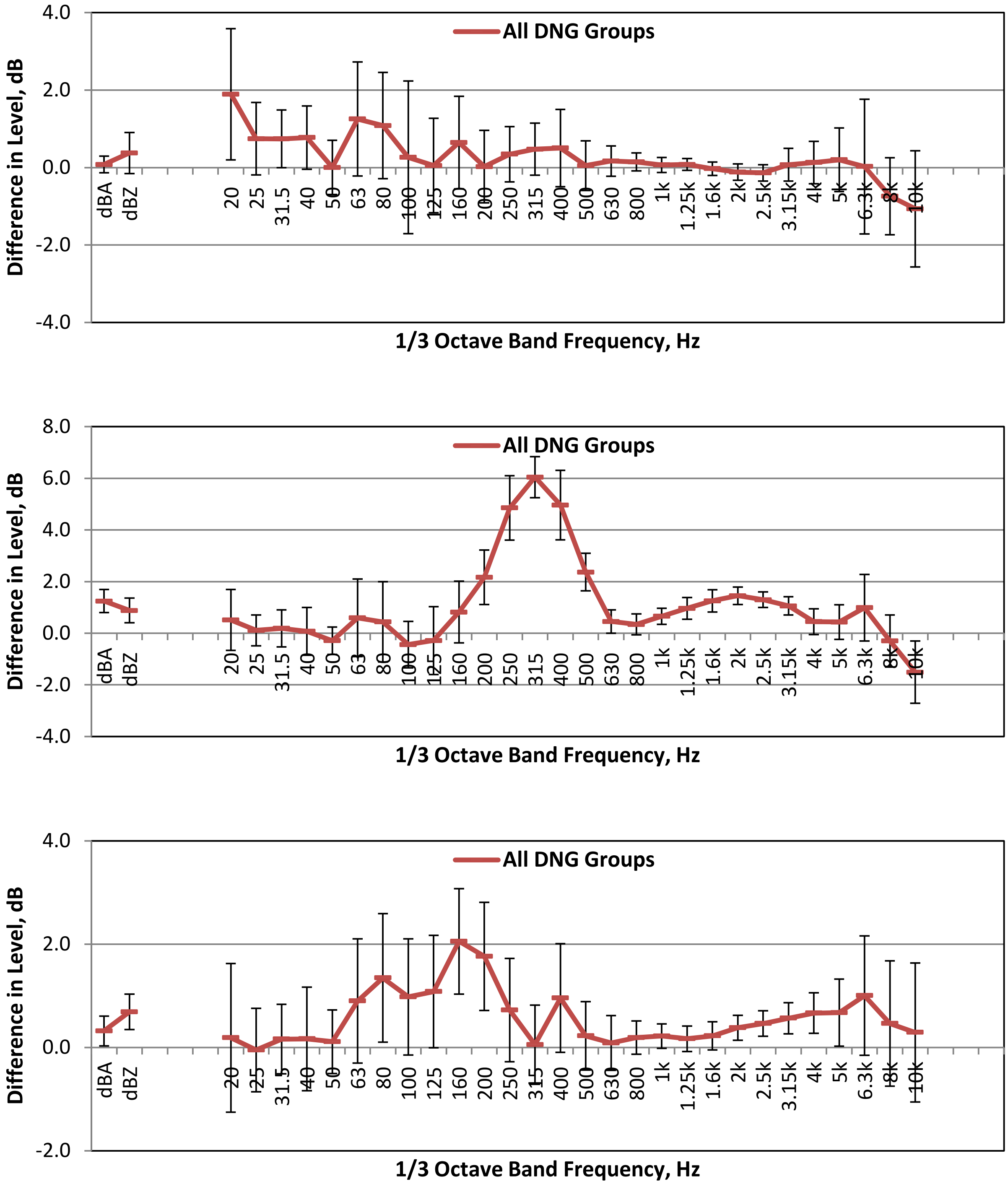


Figure 170. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Downwind Neutral groups, MD-5.

Downwind Lapse Class

Figure 171 shows the results for the Downwind Lapse class. The results for these daytime periods are similar to those for the daytime Downwind Neutral class. In the upper graph, there are little differences at the reference microphones above 160 Hz and minor differences of up to a decibel (BarRef01 being higher) below 160 Hz.

The middle graph compares the levels at the lower microphones, BarCom03 and NoBarCom05. The Downwind Lapse data show the same large differences between 200 Hz and 500 Hz with the maximum difference , again at 315 Hz, being 5 dB instead of the 6 dB value for the Downwind Neutral class

The lower graph compares the levels at the higher BarCom04 and NoBarCom06 positions. The patterns are similar to the Downwind Neutral class, with the low frequency levels being higher at BarCom04, but only by a maximum of just under 2 dB at 160 Hz. The difference at 315 Hz is -1 dB (NoBarCom06 being higher) compared to 5 dB (BarCom04 being higher) at the lower height microphones. This large difference at 315 Hz at the two heights is also in the Downwind Neutral data.

While all of the 5-minute periods in all of the Downwind Lapse groups were not equivalent in traffic volume and speed across all of the equivalent groups, these averages of the average differences generally show consistency with the results in the individual groups.

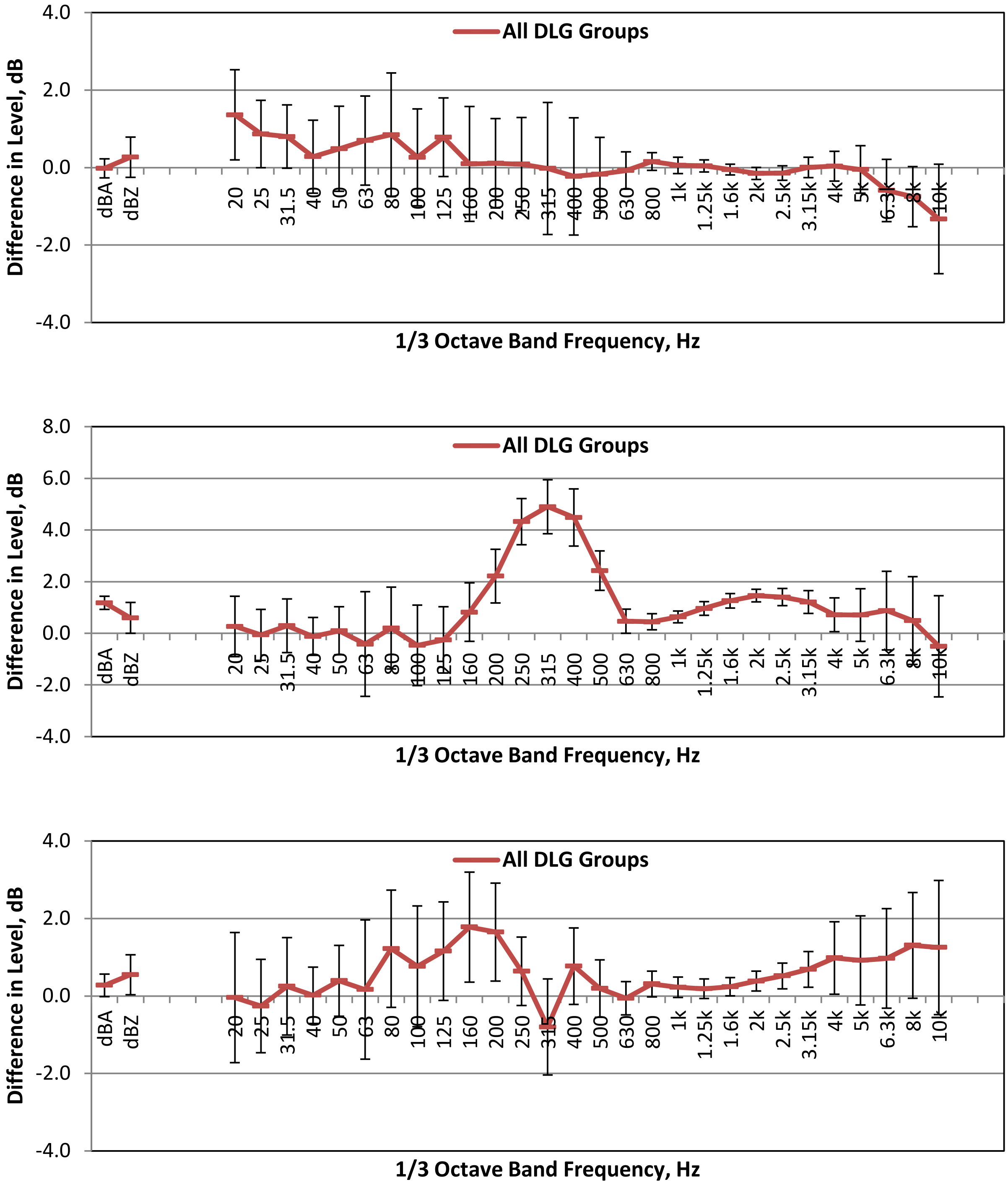


Figure 171. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Downwind Lapse groups, MD-5.

Calm Inversion Class

Figure 172 shows the results for the Calm Inversion class. The results for these later evening periods are similar to those for the Calm Neutral class. In the upper graph, there are little differences at the reference microphones across the entire spectrum, with the exception of the 4 kHz bands where the frogs near NoBarRef02 raised its level by 12 dB over that at BarRef01.

The middle graph compares the levels at the lower microphones, BarCom03 and NoBarCom05. The Calm Inversion data is again similar to the Calm Neutral data, with the higher levels at BarCom03 in the bands from 200 Hz to 500 Hz (peaking at 5 dB higher at 250 Hz and 315 Hz). The 4 kHz band is 6 dB higher at NoBarRef02 than BarRef01 due to localized frog noise.

The lower graph compares the levels at the higher BarCom04 and NoBarCom06 positions. The patterns are again to the Calm Neutral class. The low frequency levels are higher at BarCom04, but only by a maximum of 2 dB at 125 Hz. The difference at 315 Hz is 0 dB compared to 5 dB at the lower height microphones (BarCom04 being higher). The 4 kHz band due to frog noise is 10 dB higher at NoBarRef02 than BarRef01.

While all of the 5-minute periods in all of the Calm Inversion groups were not equivalent in traffic volume and speed across all of the equivalent groups, these averages of the average differences generally show consistency with the results in the individual groups. Although, the Calm Inversion group actually showed a roughly 300% change in Factored Hourly traffic volume across all of the equivalent groups, meaningful conclusions about any correlations between traffic volumes and the differences in L_{eq}(5min) could not be established.

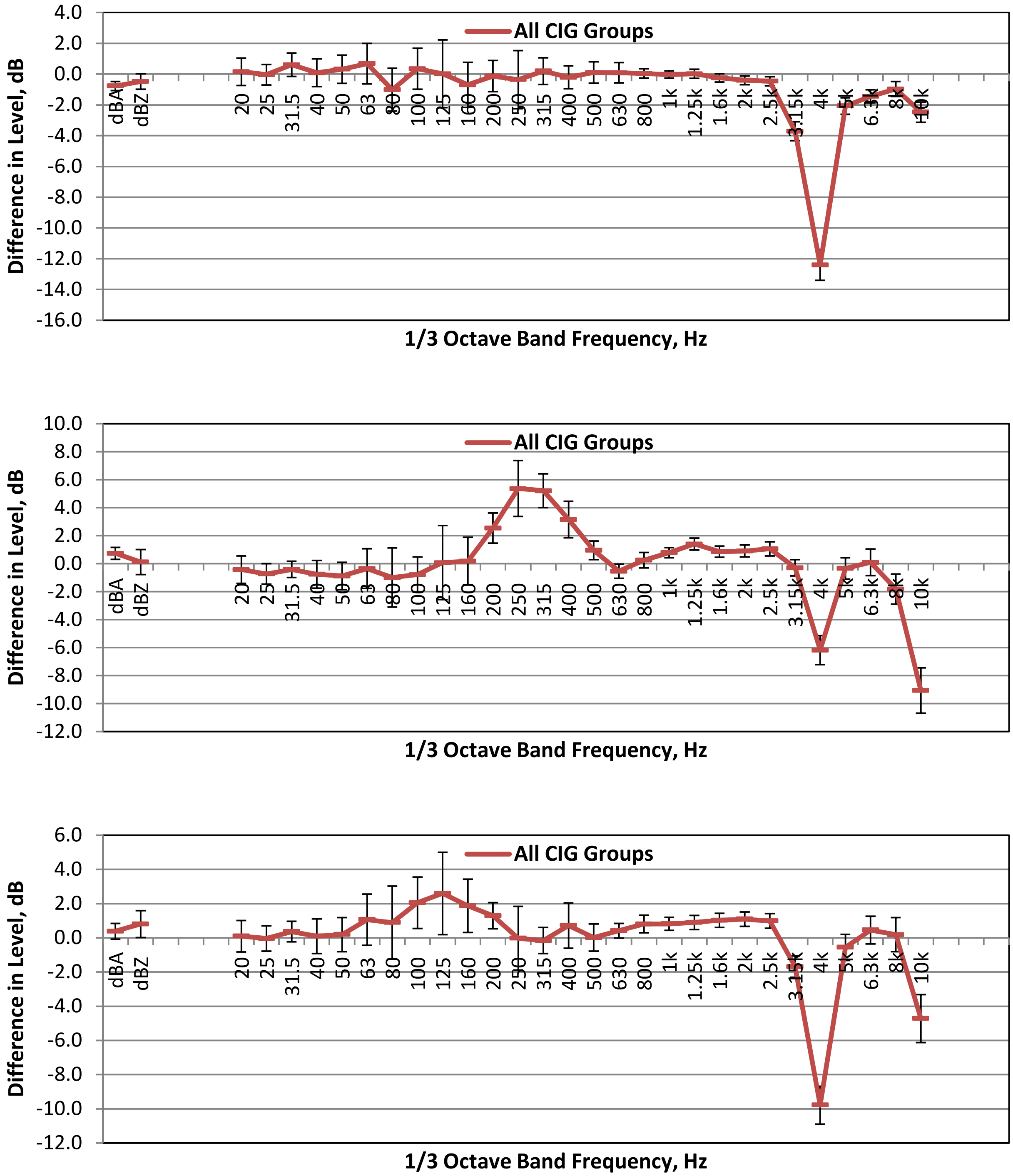


Figure 172. Averages of the differences in L_{eq}(5min) +/- one standard deviation (dB), all microphones, for all Calm Inversion groups, MD-5.

Comparison of Results for Downwind Lapse, Downwind Neutral, Calm Neutral and Calm Inversion at MD-5

For the MD-5 data, the results are shown by microphone pair. Keep in mind that the Downwind cases are in the afternoon measurement session and the Calm cases are in the evening session. In each figure, the top graph is for the differences in the Calm Neutral average differences and Downwind Lapse difference; the middle graph compares Calm Neutral to Downwind Neutral; and the bottom graph compare Calm Neutral to Calm Inversion. Figure 173 shows the difference for the reference microphones. Figure 174 is for BarCom03 minus NoBarCom05 (the lower microphones in the field). Figure 175 is for BarCom04 minus NoBarCom06 (the upper microphones in the field).

As with the I-90 data, for the reference microphones, Downwind refers to the community microphones and is therefore *Upwind* for the reference microphones on the opposite side of the road. With the exception of 4 kHz (frog noise at NoBarRef02) and 125 Hz (Calm Neutral is higher than all three of the other classes by 2 dB to 3 dB), the difference for most of the other bands is a half decibel or less.

For the lower community microphones (BarCom03 and NoBarCom05), ignoring the frog noise at 4 kHz, the Calm Neutral differences are:

- 1 dB to 1.5 dB greater than all three of other classes at 125 Hz ;
- 0.5 dB to 1.0 dB less than all three other classes at 200 Hz ;
- About 1 dB greater than the two Downwind cases at 250 Hz 1 dB to 1.5 dB less than the two Downwind cases at 400 Hz through 630 Hz;
- About a half decibel less than the two Downwind cases at 1 kHz through 3.15 kHz.

For the upper community microphones (BarCom04 and NoBarCom06), again ignoring the frog noise at 4 kHz, the Calm Neutral differences are:

- 1 dB to 2.5 dB greater than all three of other classes at 125 Hz ;
- 0.5 dB to 1.0 dB less than all three other classes at 200 Hz ;
- About 1 dB less than the Calm Inversion cases at 63 and 100 Hz ;
- A half decibel or less different at the rest of the frequency bands compared to all three other meteorological classes

Effects of Traffic Volume and Speed

No trends were evident when considering the differences in sound level as a function of two-way traffic volume for Calm Neutral, Downwind Neutral, Downwind Lapse, and Calm Inversion classes. Also, the range in speeds for each class was too small to address any relationship between speed sound level differences.

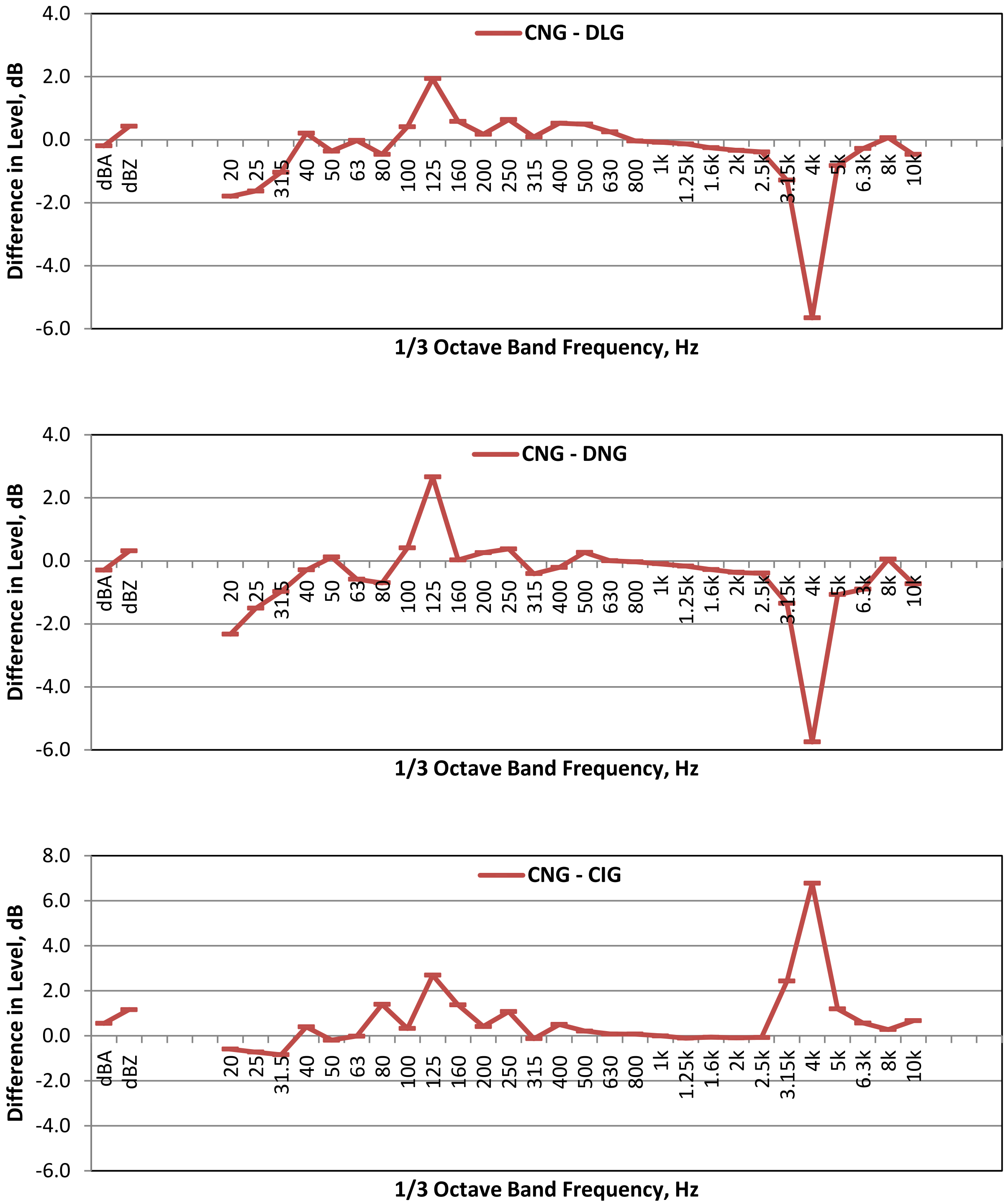


Figure 173. Differences in the Calm Neutral average differences and Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq}(5min), BarRef01 minus NoBarRef02, MD-5.

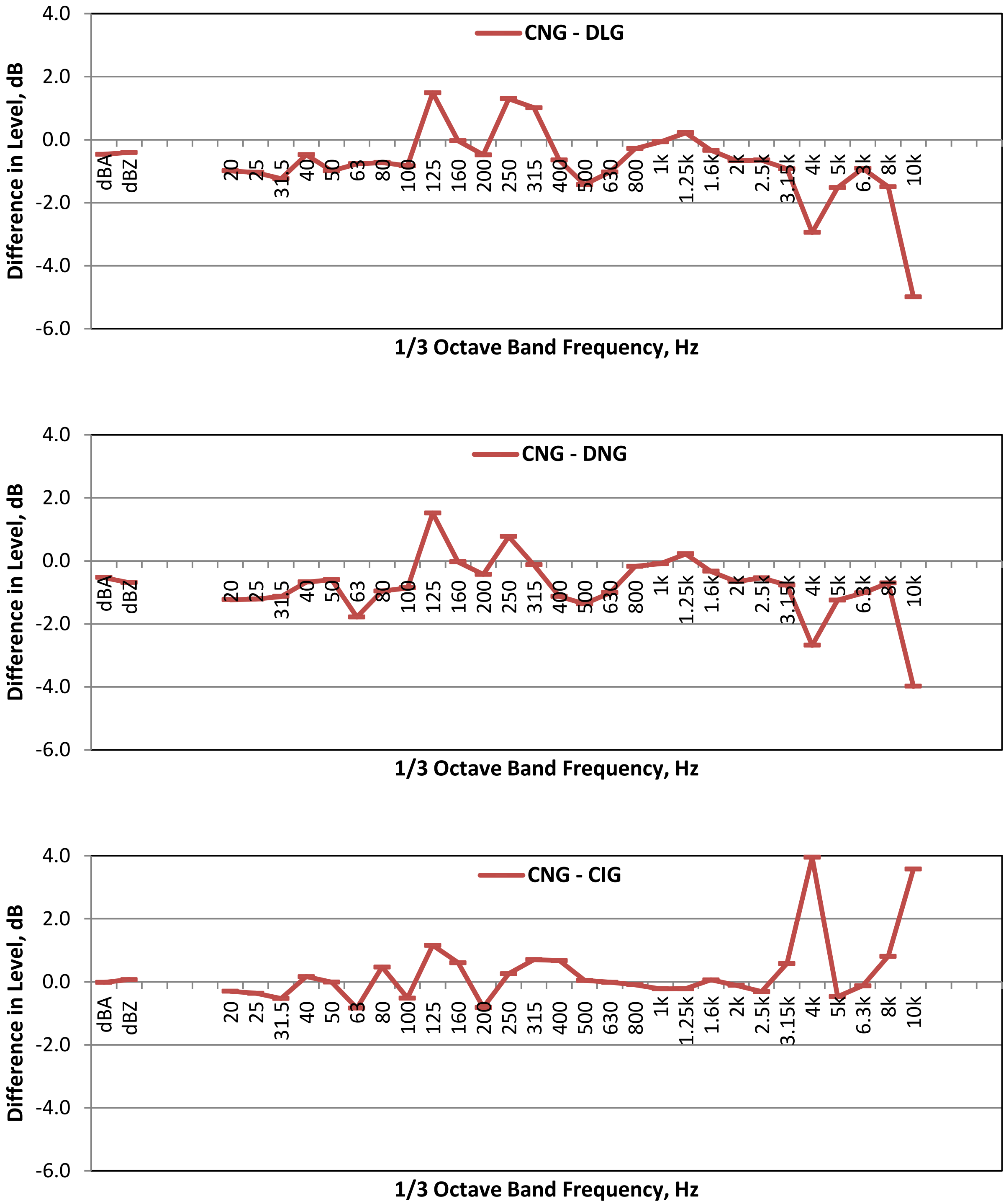


Figure 174. Differences in the Calm Neutral average differences and Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq}(5min), NoBarCom05 minus NoBarCom05, MD-5.

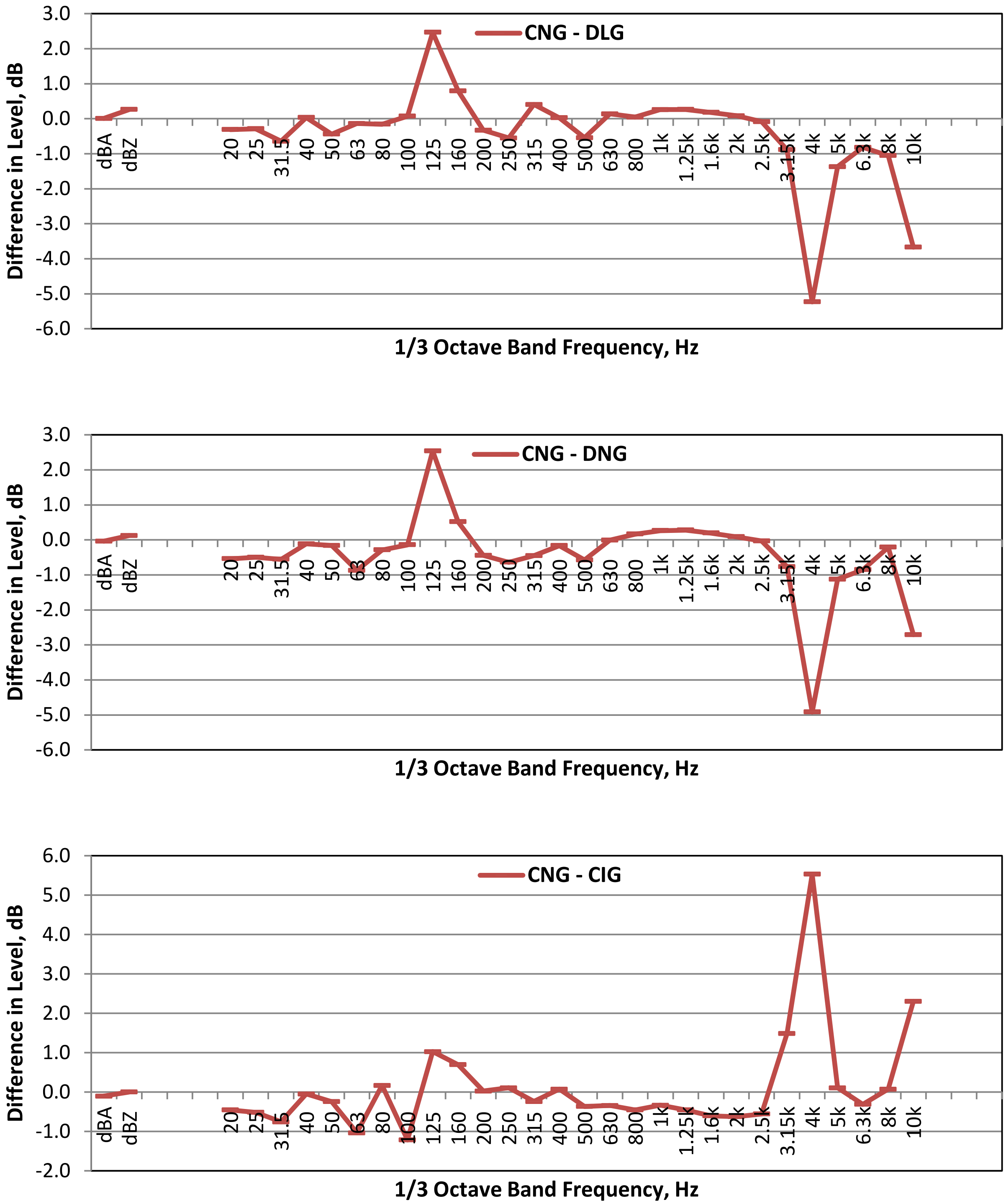


Figure 175. Differences in the Calm Neutral average differences and Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq}(5min), BarCom04 minus NoBarCom06, MD-5.

Additional Sound Level Analysis – L_n Descriptors

Figure 176 presents the L_{90}(5min) and $L_9$9(5min) for BarRef01 and NoBarRef02, in terms of overall A-weighted sound levels and unweighted sound pressure level. The upper graphs are L_{90} (A-weighted on the left and unweighted on the right). The lower graphs are L_{99} (A-weighted on the left and unweighted on the right).

Then, Figure 177 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min),computed as BarRef1 minus NoBarRef2 for the A-weighted sound levels.

The results show that while there is little difference in the L_{eq}(5min) averages for BarRef01 and NoBarRef02, the L_{90} and L_{99} at BarRef01 tend on average to be higher than at NoBarRef02 in the daytime (left side) and substantially lower during the evening (right side). The evening result demonstrates the sustained loudness of the frog noise in the evening near NoBarRef02. The daytime result suggest that the background level at BarRef01 was louder than at NoBarRef02 more often than not. With the BarRef01 microphone atop the barrier, no increase due to reflections was expected.

Figure 178 presents the L_{90}(5min) and L_{99}(5min) for BarCom03 and NoBarCom05 (the lower microphones across from the barrier), again for overall A-weighted sound levels and unweighted sound pressure level, in the same layout as for the reference microphones. Figure 179 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05.

There is evidence of the elevated background level at BarCom03 during the daytime hours. While the L_{eq}(5min) averages about 0.5 dB to 1 dB higher than NoBarCom05, the L_{90}(5min) at BarCom03 range from 9 dB lower to 10 dB higher than NoBarCom05, averaging approximately 2 dB higher. Almost all of the daytime L_{99}(5min) are higher at BarCom03 than NoBarCom05, evidence of an increase in the background level due to reflected sound off the barrier. As noted at the other locations, none of these levels have been edited for contaminating sounds. In the evening the clear trend was for the L_{90}(5min) and L_{99}(5min) at NoBarCom05 to grow louder relative to BarCom03 as the evening got later. This trend is a result of the increased level and constancy of frog and insect noise.

Then, Figure 180 presents the L_{90}(5min) and L_{99}(5min) for BarCom04 and NoBarCom06 (the upper microphones across from the barrier) for overall A-weighted sound levels and unweighted sound pressure level. Figure 181 presents the differences in L_{90}(5min) and L_{99}(5min) along with L_{eq}(5min) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06.

There is mixed evidence of the elevated background level at BarCom04 compared to NoBarCom06 during the daytime. For the first part of the afternoon measurements, the NoBarCom06 background level appears to be higher than that at BarCom04. For the second part of the afternoon measurements, the reverse appears to be true. In the evening, there is strong evidence of elevated background level at NoBarCom06 due to frog and insect noise in the No Barrier area.

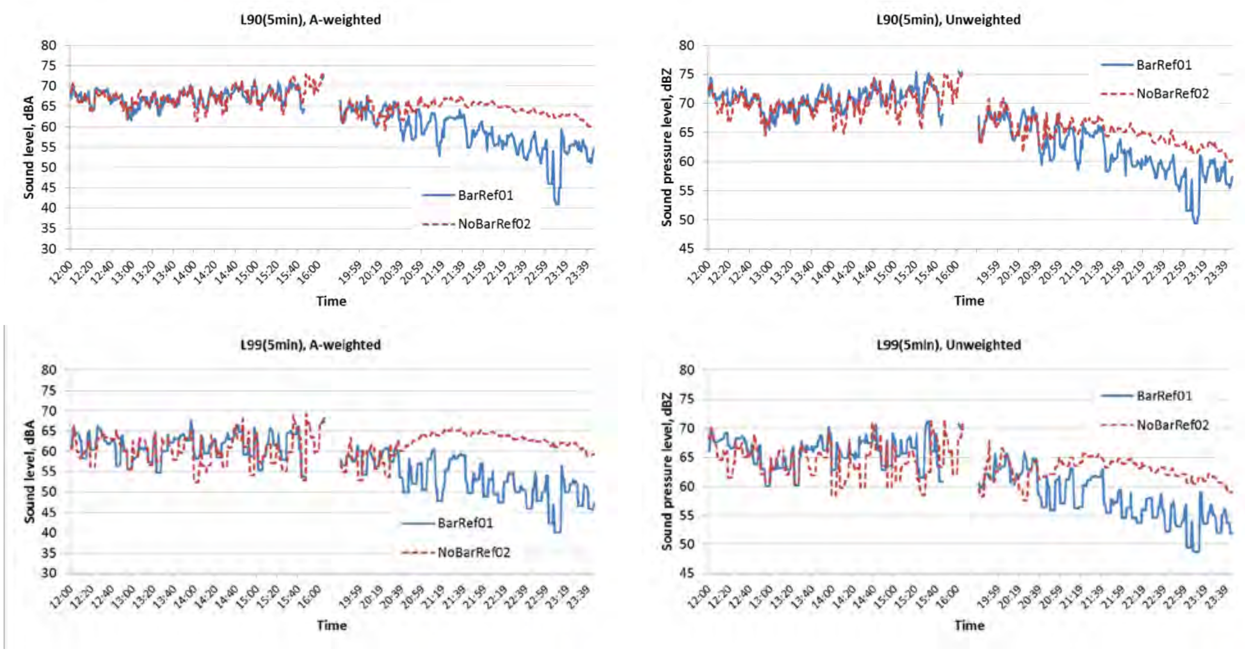


Figure 176. L_{90}(5min) and L_{99}(5min), MD-5, BarRef01 and NoBarRef02 – broadband A-weighted sound level (left) and sound pressure level (right).

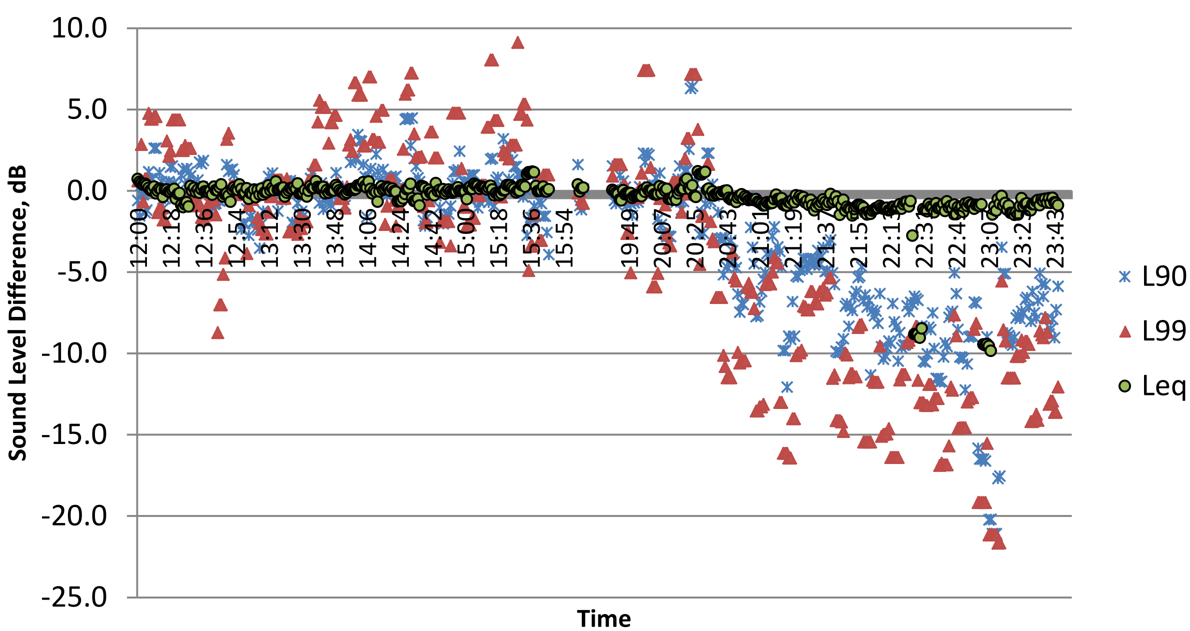


Figure 177. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, MD-5, BarRef01 and NoBarRef02.

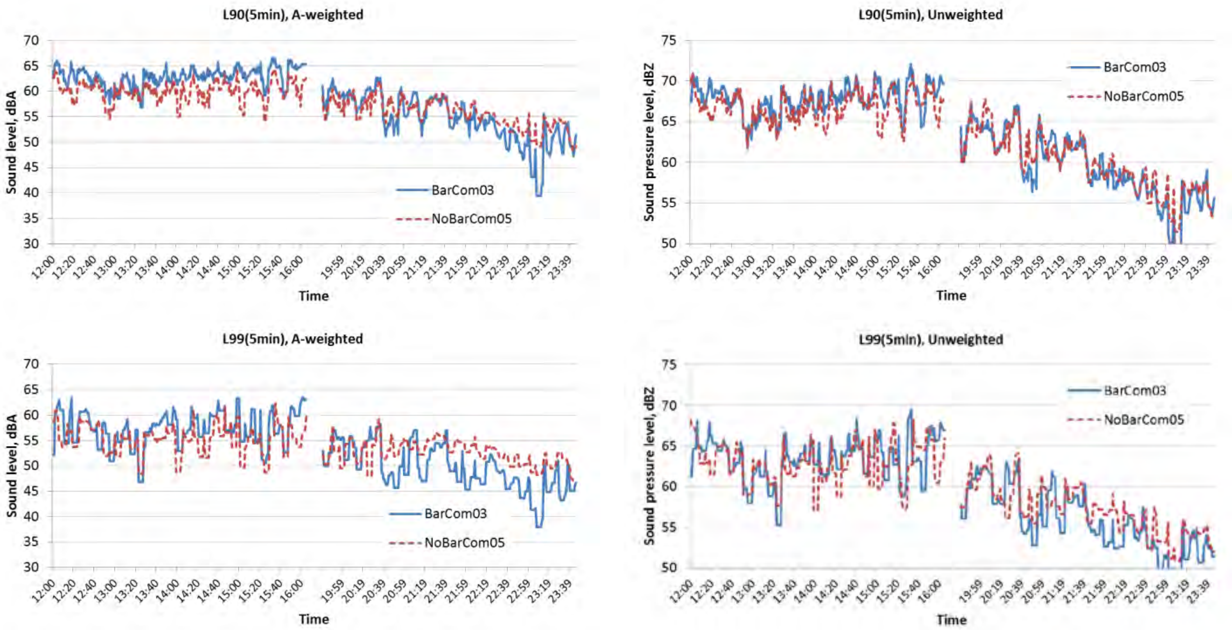


***Figure 178.** L_{90}(5min) and L_{99}(5min), MD-5, BarCom03 and NoBarCom05 – broadband A-weighted sound level (left) and sound pressure level (right).*

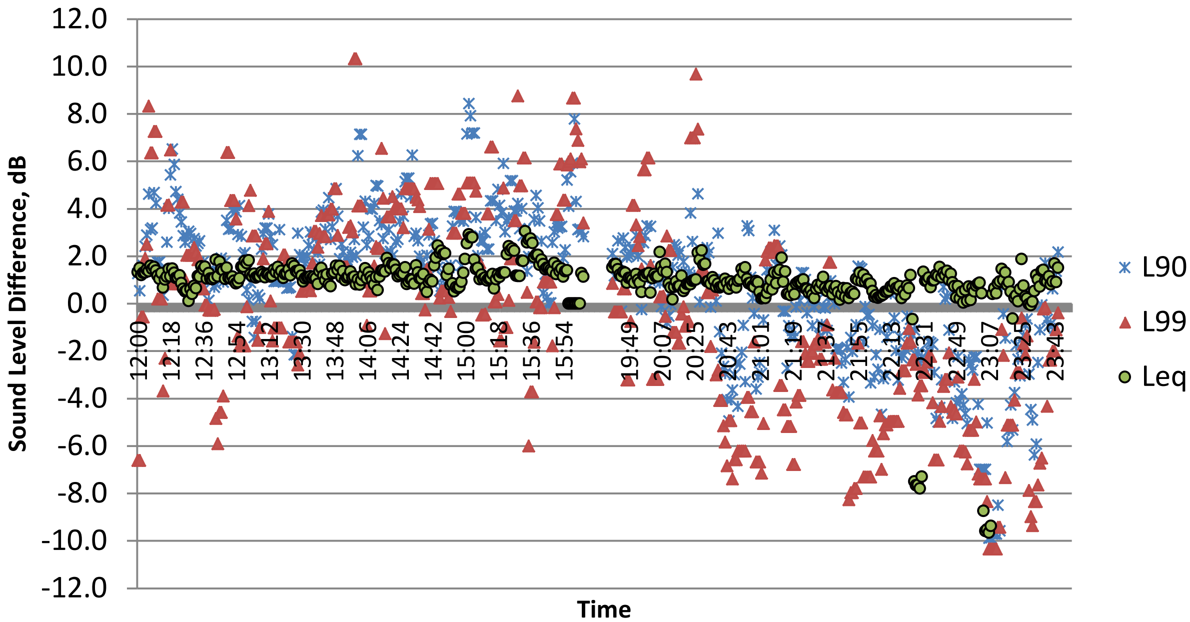


***Figure 179.** Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, MD-5, BarCom03 and NoBarCom05.*

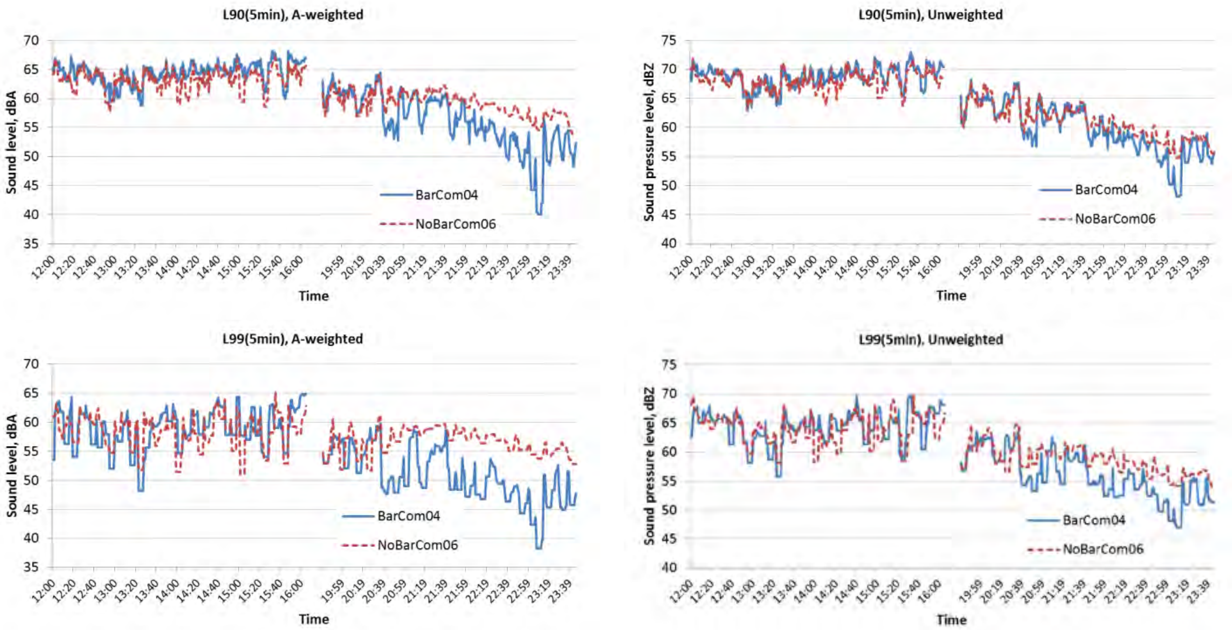


Figure 180. L_{90}(5min) and L_{99}(5min), MD-5, BarCom04 and NoBarCom06 – broadband A-weighted sound level (left) and sound pressure level (right).

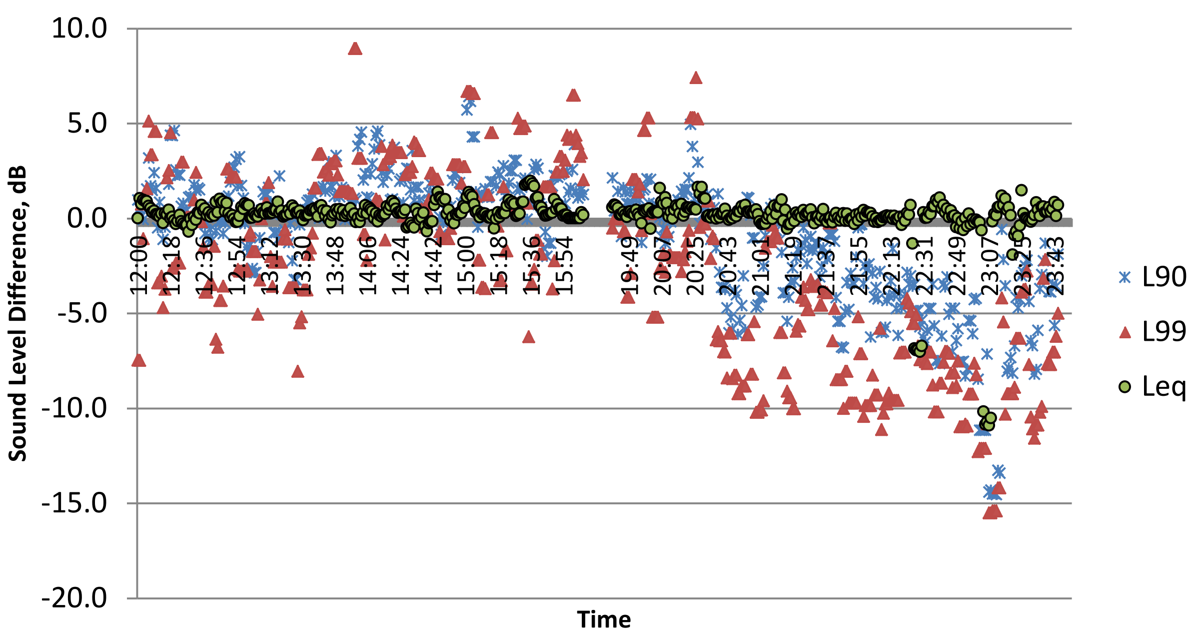


Figure 181. Differences in broadband A-weighted 5-min L_{90}, L_{99} and L_{eq}, MD-5, BarCom04 and NoBarCom06.

The above graphs were for the broadband A-weighted sound levels and unweighted sound pressure levels. The next graphs broaden the analysis to include the individual 1/3 octave bands by use of color shading, where brown means that the Barrier levels are higher than the No Barrier levels and blue means that No Barrier levels are higher. In each graph, time runs from top to bottom, with the afternoon session on top and the evening session on the bottom. The 1/3 octave bands run across from left to right with the broadband A-weighted sound levels and unweighted sound pressure levels on the far left. Within each band's data are the differences for the seven L_n sound pressure level values (L_1, L_5, L_{10}, L_{33}, L_{50}, L_{90} and L_{99}) and L_{eq}).

Figure 182 compares BarRef01 and NoBarRef02. The most obvious difference is the large increase in the background levels at NoBarRef02 in the evening due to the frog noise, as evidenced by the blue streaks at 3.15 kHz and higher. This elevated background level shows up in the broadband columns on the left of the figure as well. There is some evidence of higher background levels at BarRef01 in the afternoon session in the bands from 630 Hz up through 2.5 kHz, as evidenced by the brown streaks on the right side of the 1/3 octave band columns of data.

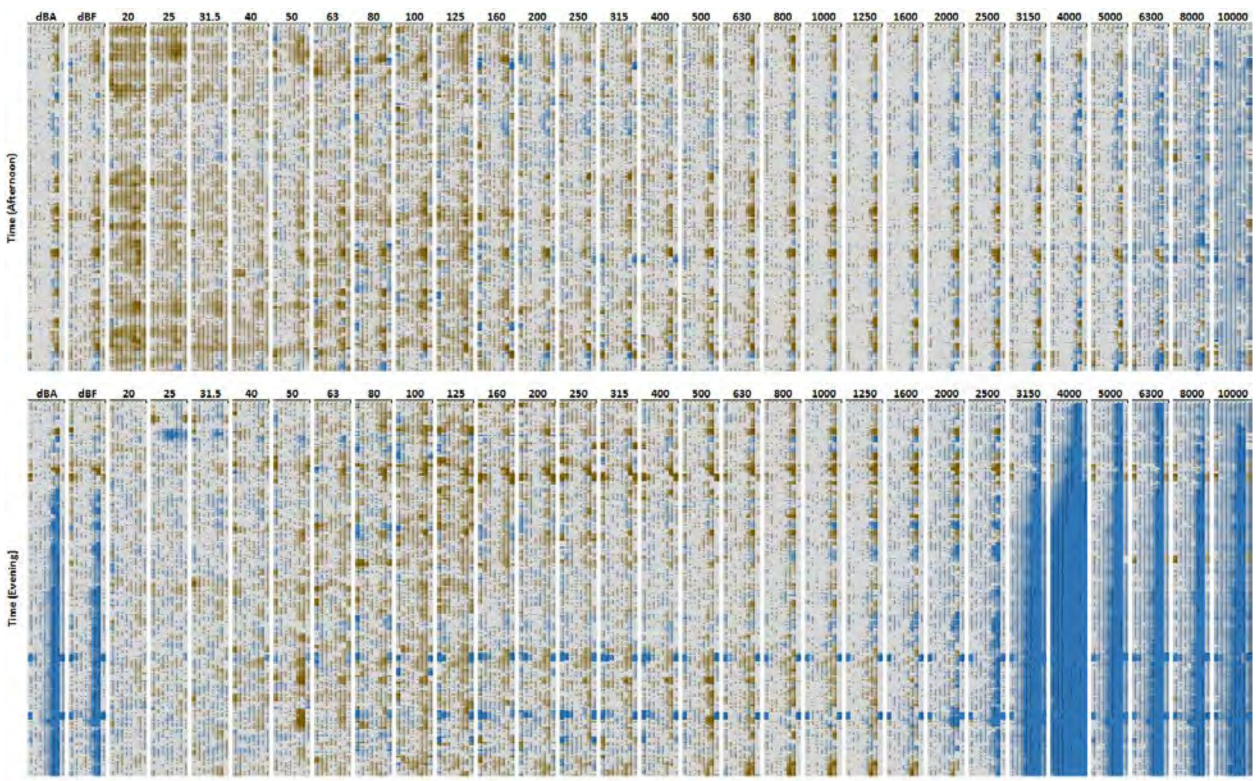


Figure 182. MD-5 Differences in L_n(5min) by 1/3 octave frequency bands: BarRef01 and NoBarRef02.

Figure 183 presents the L_n differences for BarCom03 and NoBarCom05. Again, brown means Barrier levels are higher and blue means the No Barrier levels are higher.

These results show increases in the BarCom03 levels relative to those for NoBarCom05 across most of the L_n descriptors in the bands centered on 250 through 400 Hz, interpreted as evidence of increases in sound pressure levels due to reflections off the barrier. The daytime data also show higher levels at BarCom03 in the background L_n values for L_{90} and L_{99} for the bands from 500 Hz through 3,150 Hz, as indicated by the brown streaks on the right side of those bands' columns. The elevated background is evidence of a sustaining of a vehicle's passby noise due to the creation of an image source for each vehicle as the sound reflects off the barrier.

The blue streaks in the evening's high frequency bands represent the frog and insect noise in the No Barrier area.

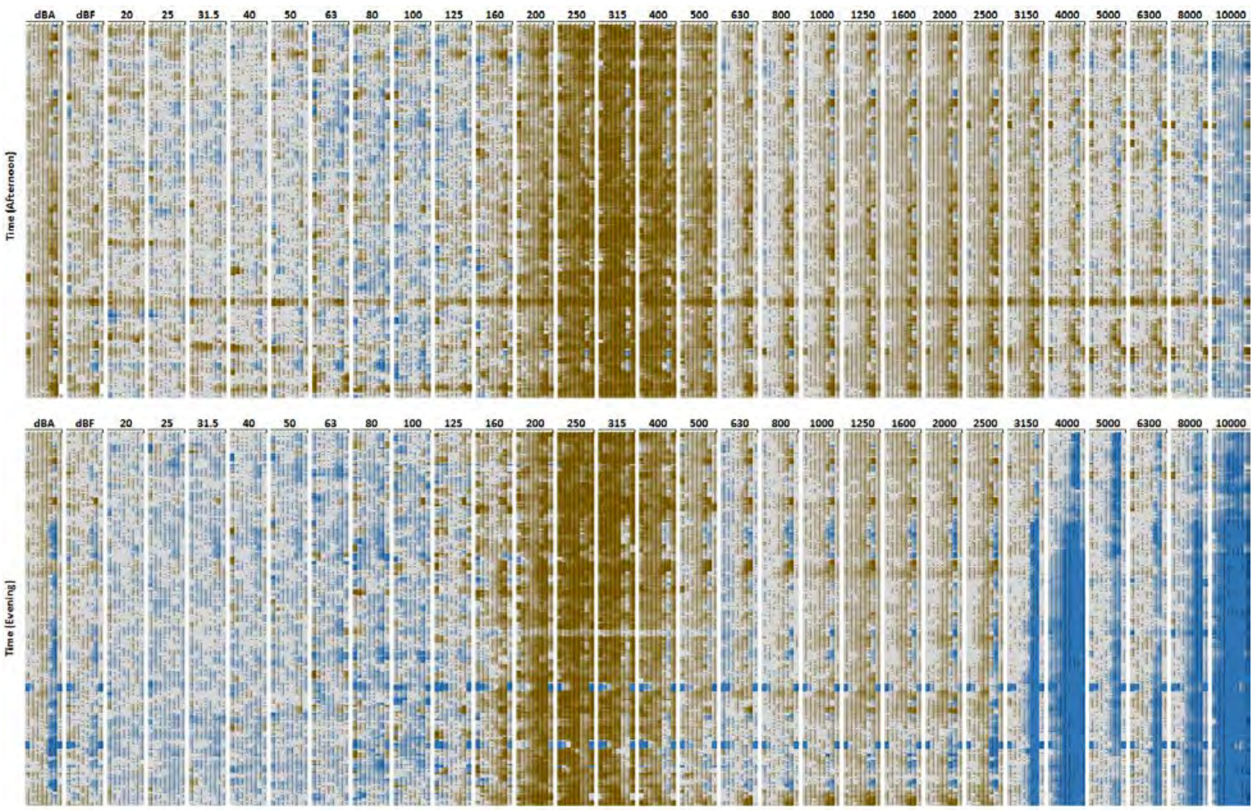


Figure 183. MD-5 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom03 and NoBarCom05.

Figure 184 presents the L_n differences for BarCom04 and NoBarCom06. These results show increases in the BarCom03 levels relative to those for NoBarCom05 across most of the L_n descriptors in the bands centered on 100 through 160 Hz, which is some evidence of increases in sound pressure levels due to reflections off the barrier. The daytime data also show higher levels at BarCom03 in the background L_n values for L_{90} and L_{99} for the bands from 630 Hz through 2.5 kHz, as indicated by the brown streaks on the right side of those bands' columns. The elevated background is evidence of a sustaining of a vehicle's passby noise due to the creation of an image source for each vehicle as the sound reflects off the barrier.

The blue streaks in the evening's high frequency bands represent the frog and insect noise in the No Barrier area. There are also two horizontal lines of blue shading in the latter part of the evening sampling for L_1 and L_{eq}, which indicate a short-term loud event at NoBarCom06, contrasting with the constant background level of the frog noise evidenced by the vertical clue streaks in the 3.125 kHz and 4 kHz bands.

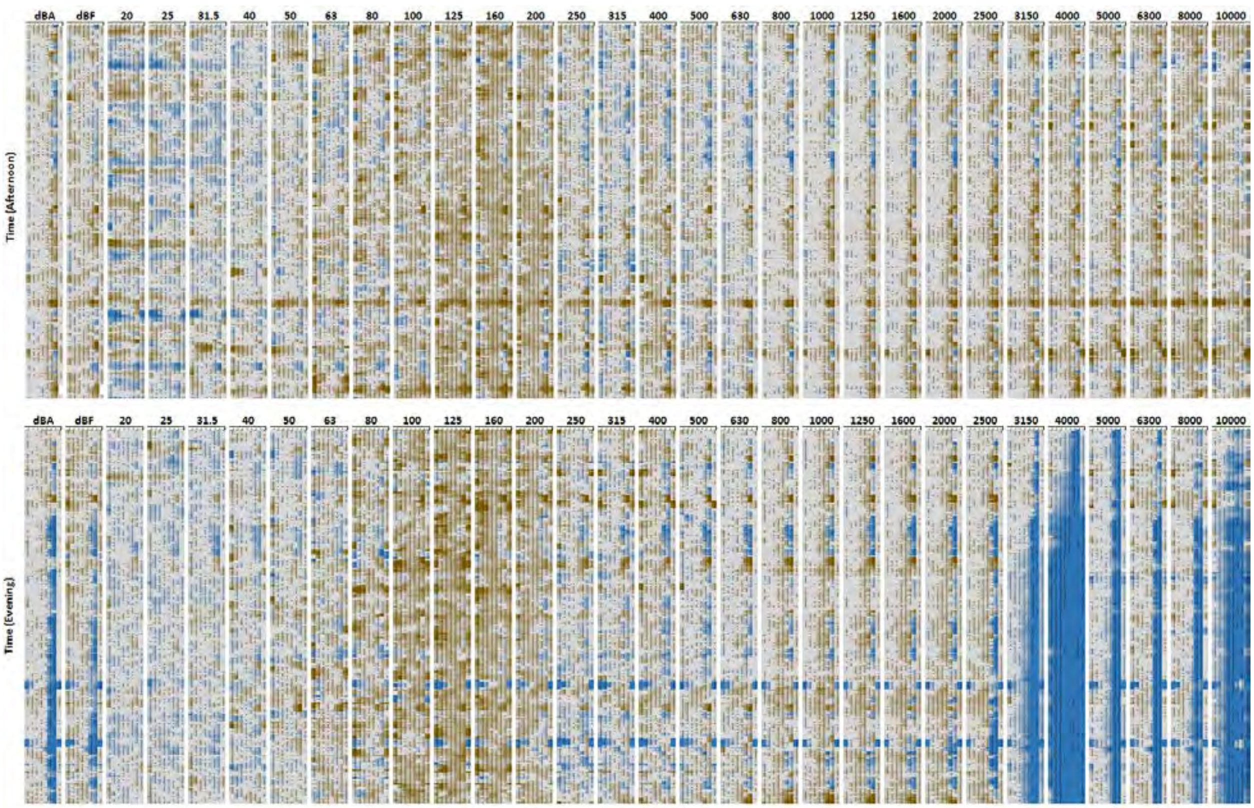


Figure 184. MD-5 Differences in L_n(5min) by 1/3 octave frequency bands: BarCom04 and NoBarCom06.

Data Analysis for MD-5 - Spectrograms

Refer to Table 14 for the MD-5 location six microphone positions.

There are two equivalent microphones comparing a site with a barrier and one without: BarCom03 and NoBarCom05 and BarCom04 and NoBarCom06. The reference microphones BarRef01 and NoBarRef02 are not intended to be compared for purposes of determining barrier effect for this site and so are not discussed further in the analysis.

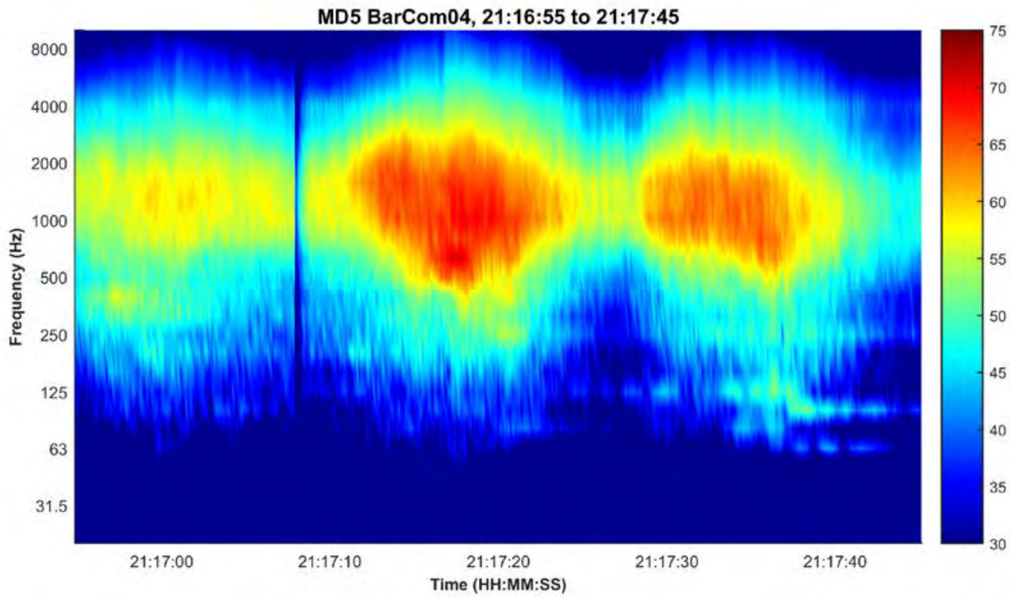
Spectrograms from MD-5 vehicle pass-by events are shown in the figures below. Data are shown for the high microphones BarCom04 (upper plot) and NoBarCom06 (lower plot) on the community side of the highway. Since there were some slight elevation differences between the Barrier and No Barrier sites and there could potentially be some ground influences that would be slightly different at the two sites, it was determined that the higher microphone positions, where there is less ground influence, would provide the most accurate comparison. It should be noted that results were similar for the low microphones, just with lower sound levels.

Figure 185 shows a heavy truck traveling northbound. The pass-by event is around 21:17:20 at the barrier site and 21:17:05 at the No Barrier site. The event is followed by another vehicle about 15 seconds behind.

Figure 186 shows a pickup truck traveling southbound. The pass-by event is around 20:09:20 at the barrier site and 20:09:35 at the No Barrier site.

Figure 187 shows a motorcycle traveling northbound. The pass-by event is around 20:03:35 at the barrier site and 20:03:22 at the No Barrier site. The event is preceded and followed by additional vehicles.

The barrier effect can be seen in the spectrograms for the vehicles traveling in either the northbound or southbound direction. For the barrier site, the hot spots are wider and taller than for the No Barrier site for a broad range of frequencies. The darkest red areas (highest sound levels) fill in more and become wider and taller with the barrier present. Depending on the pass-by event, the red is centered around 800 Hz or 1 kHz. The same effect occurs in the surrounding frequency bands, stepping through various colors of the spectrum. The intensifying and expanding hot spots indicates that the barrier is causing higher sound levels at frequencies which contribute most to the overall sound level and causing these levels to be sustained for a longer period for each vehicle pass-by event.



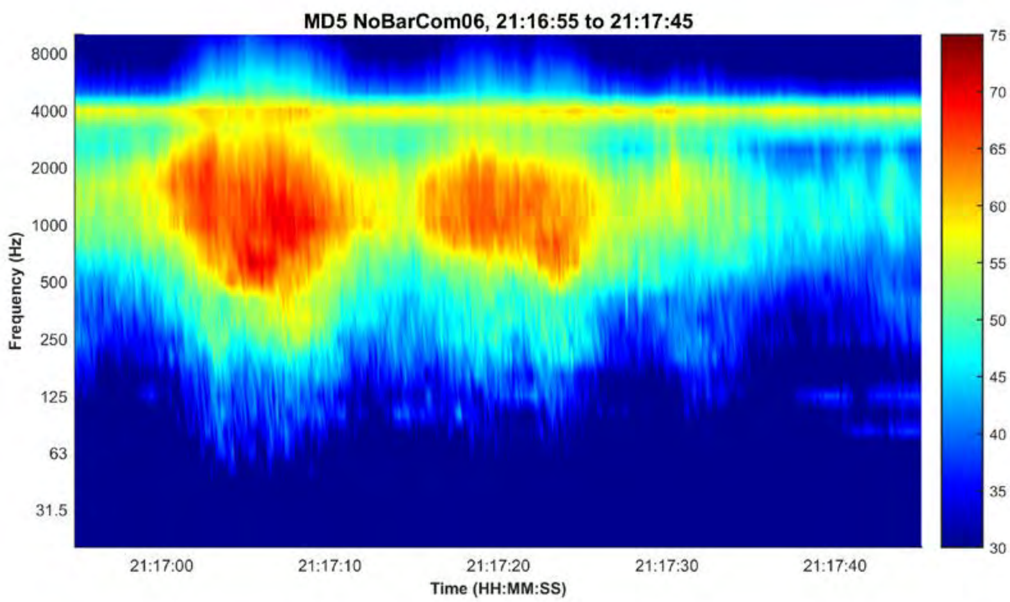


Figure 185. MD-5 spectrograms for heavy truck on northbound (community) side (approximate event times: Barrier site 21:17:20, No Barrier site 21:17:05.) Additional vehicle follows the heavy truck: top is BarCom04; bottom is NoBarCom06.

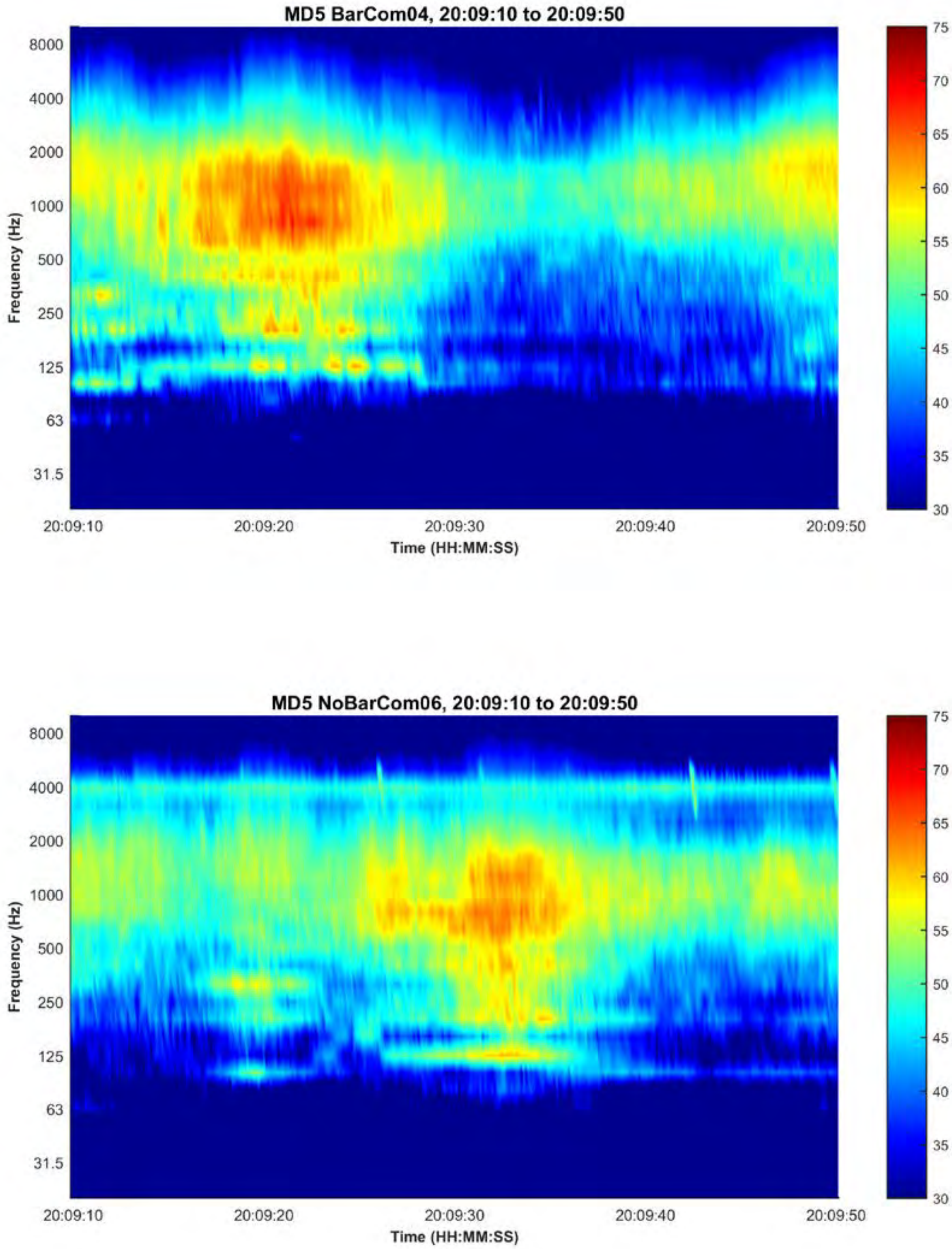
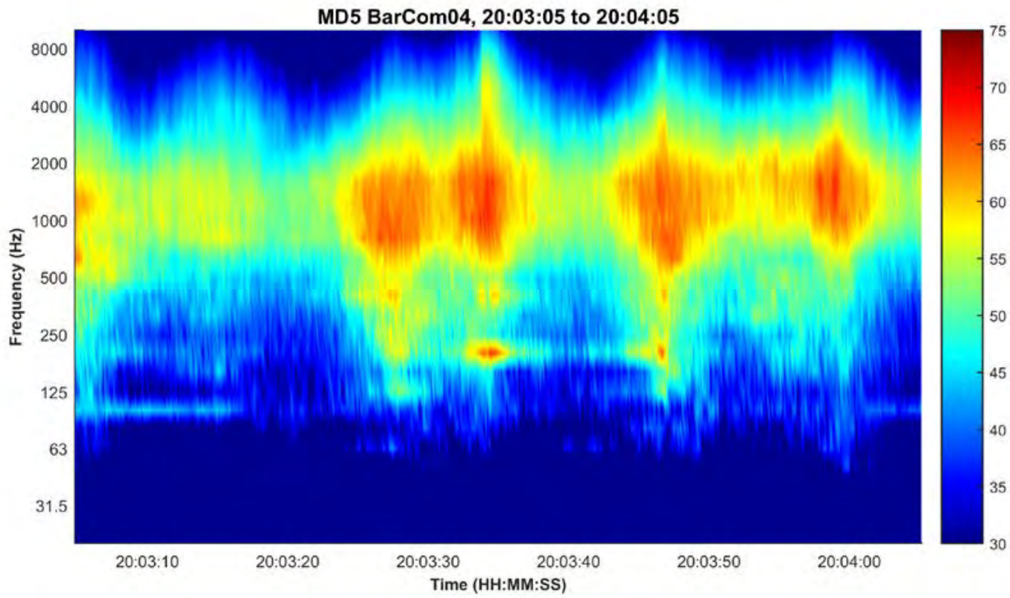


Figure 186. MD-5 spectrograms for a pickup truck on southbound (barrier) side (approximate event times: Barrier site 20:09:20, No Barrier site 20:09:35.) Additional vehicle follows the heavy truck: top is BarCom04; bottom is NoBarCom06.



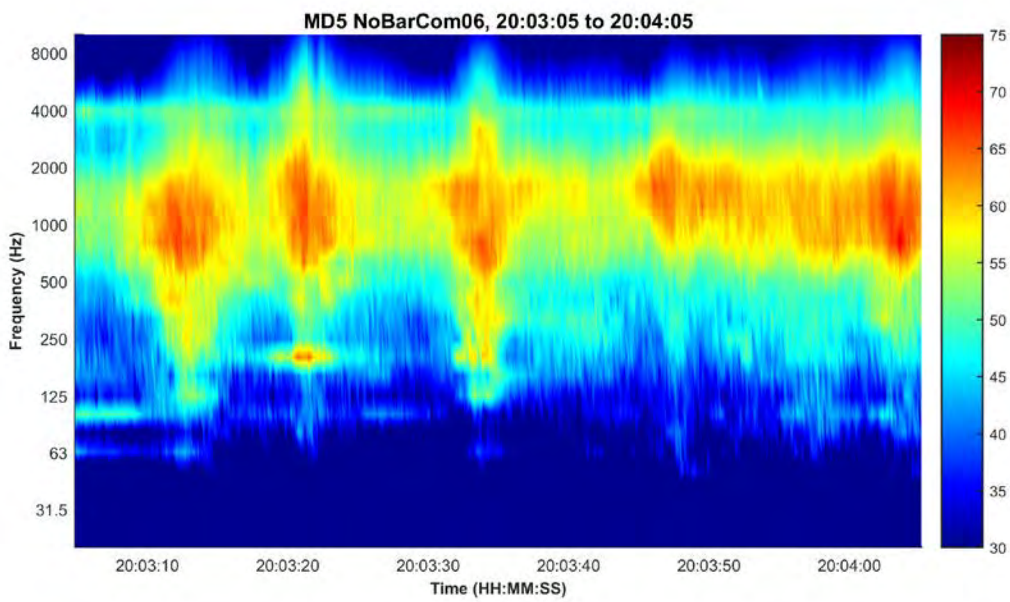
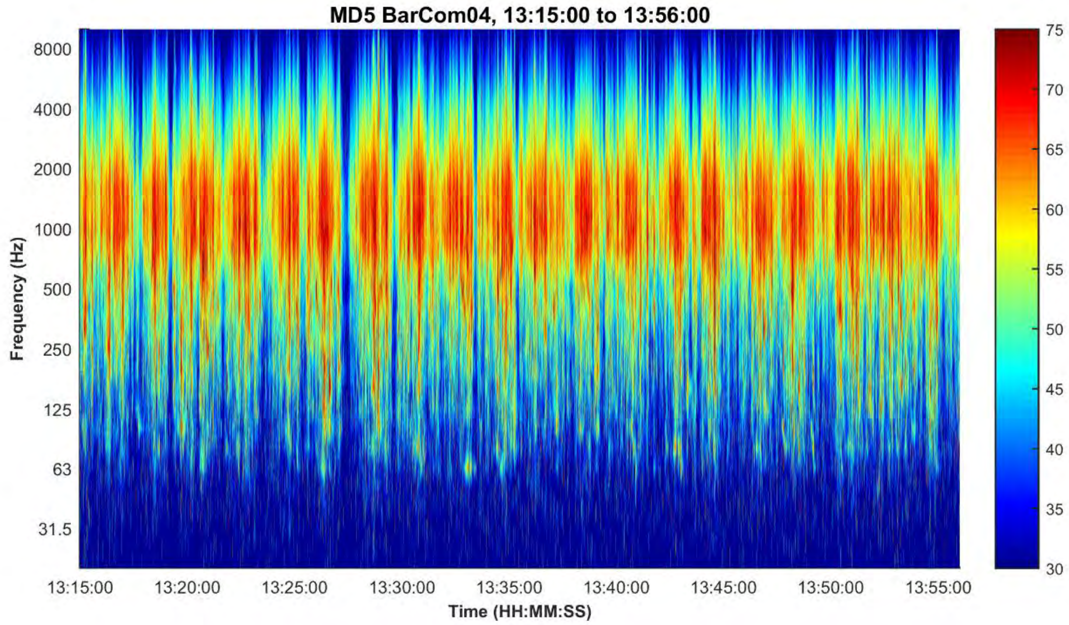


Figure 187. MD-5 spectrograms for Motorcycle on northbound (community) side. (approximate event times: Barrier site 20:03:35, No Barrier site 20:03:22.) Additional vehicles come before and after the motorcycle: top is BarCom04; bottom is NoBarCom06.

In addition to examining vehicle pass-by events, spectrograms for blocks of data were also examined. An example is provided in Figure 188 for the high microphones at a distance of 75 ft (BarCom04/NoBarCom06) for a forty-one minute data block starting at 13:15:00. Other blocks of data show similar results.

For this site, it is difficult to see a clear difference between the Barrier and the No Barrier sites since the traffic was not very dense. However, upon careful examination, it can be seen that hot spots are both wider and taller for a broad range of frequencies. The highest levels are increasing in the 1 kHz region, and again, this indicates that the barrier is causing higher sound levels at frequencies which contribute most to the overall sound level and cause these levels to be sustained for a longer period for each vehicle pass-by event.

Something also to note about the spectrogram data is a band of light blue at 4 kHz at the No Barrier site, which is due to frogs and insects.



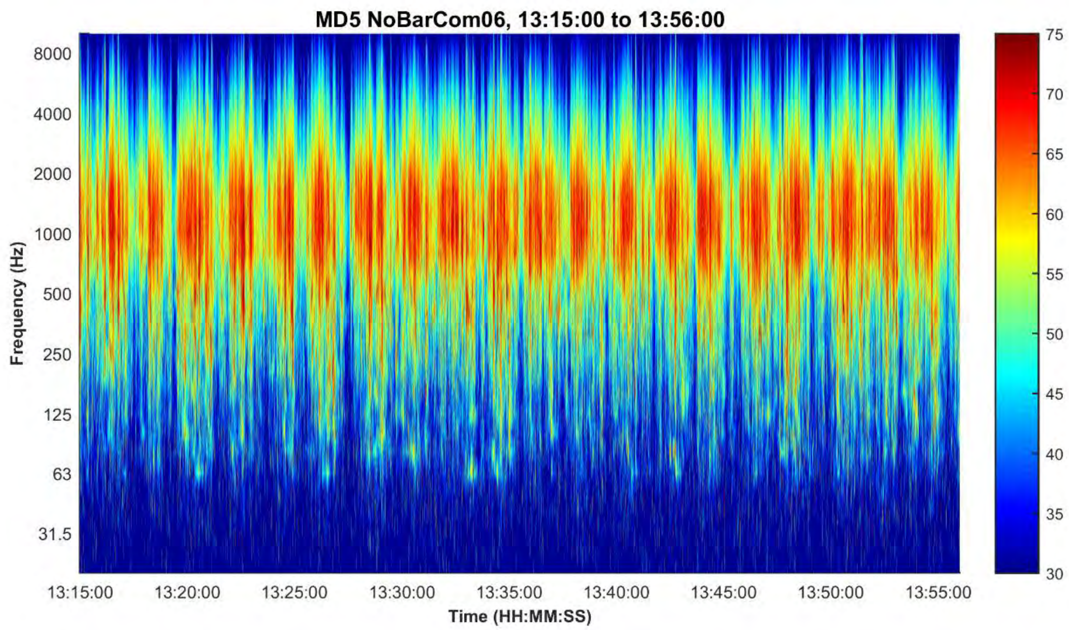


Figure 188. MD-5 spectrograms for Forty-one minutes of clean data (no contamination from other noise sources): top is BarCom04; bottom is NoBarCom06.

Data Analysis for MD-5 - Psychoacoustics

Psychoacoustical Annoyance Metrics, Afternoon

The results from the afternoon monitoring and the night monitoring at MD-5 were significantly different. This is most likely due to the large decrease in traffic volume at night compared to the daytime. Consequently, the results from these two periods are reported separately.

Descriptive statistics for the computed annoyance metrics at MD-5 during the afternoon are summarized in Table 16. The associated histograms in each of the subsequent Figures relate the distribution of magnitudes for each metric at each microphone to the descriptive statistics in the Table.

The Unbiased Annoyance (UBA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 190. The Psychoacoustic Annoyance (PA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 191. The Category Scale of Annoyance (CSA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 192.

The results for both the Unbiased Annoyance and the Psychoacoustic Annoyance between the Barrier and No Barrier locations, for both the higher and lower microphones, are much different than those seen at the other sites described above. First, there is a much wider relative spread in the histograms. Second, the annoyance metrics appear to have split and become “bi-modal”. Since the microphones were stacked vertically at the same moderate distance from the highway, this is most likely attributable to differences in Loudness of arriving sound from the near and far lanes. For the case of nearly continuous traffic, then, neither the UBA nor the PA substantiate an assumption of increased annoyance due to the presence of the barrier at this site.

There is no significant difference in the means of the Category Scale of Annoyance for either pair of microphones. The simple linear regression that forms CSA, and its derivation from product noise, do not apply well to highway traffic noise.

Table 16. Descriptive Statistics of annoyance metrics, MD-5, afternoon.

Metric	Location	Mean	Std. Dev.	Skewness	Kurtosis
UBA	BarCom03	35.0	7.7	0.064	-0.878
	NoBarCom05	30.8	8.4	0.220	-0.904
	BarCom04	37.2	8.8	-0.004	-0.982
	NoBarCom06	36.2	8.3	0.322	-0.616
PA	BarCom03	9.22	2.33	0.180	-0.735
	NoBarCom05	7.80	2.41	0.316	-0.738
	BarCom04	9.80	2.77	0.244	-0.619
	NoBarCom06	9.64	2.60	0.288	-0.845
CSA	BarCom03	35.4	3.7	-0.07	0.32
	NoBarCom05	33.5	3.7	0.07	-0.60

	BarCom04	36.4	3.8	0.14	-0.09
	NoBarCom06	35.9	3.7	0.16	-0.51

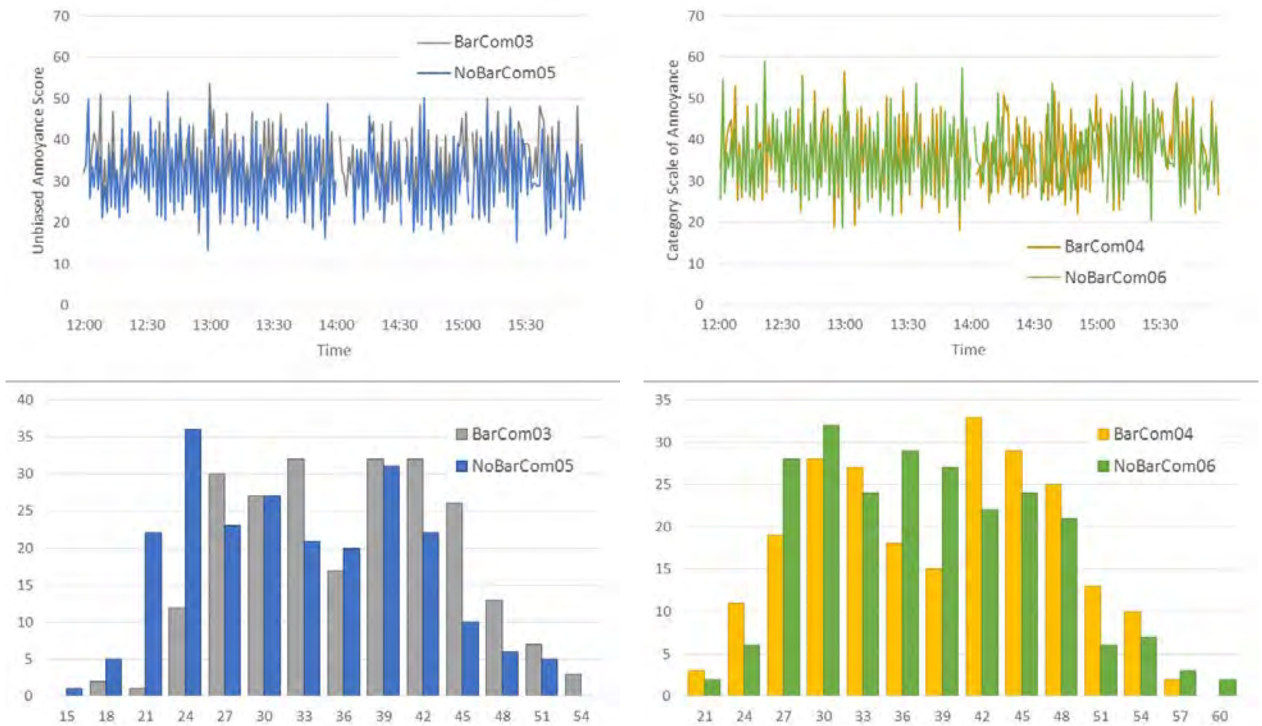


Figure 190. Unbiased annoyance vs. time and histograms, MD-5, afternoon.

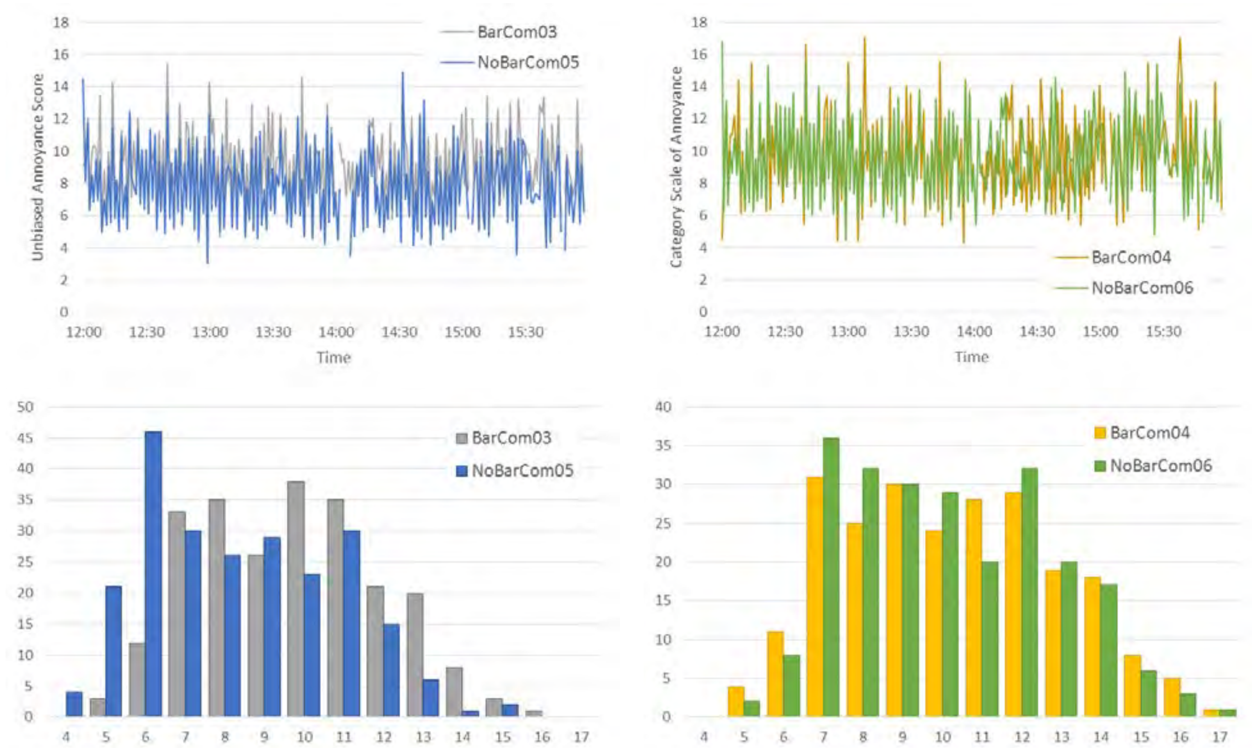


Figure 191. Psychoacoustic annoyance vs. time and histograms, MD-5, afternoon.

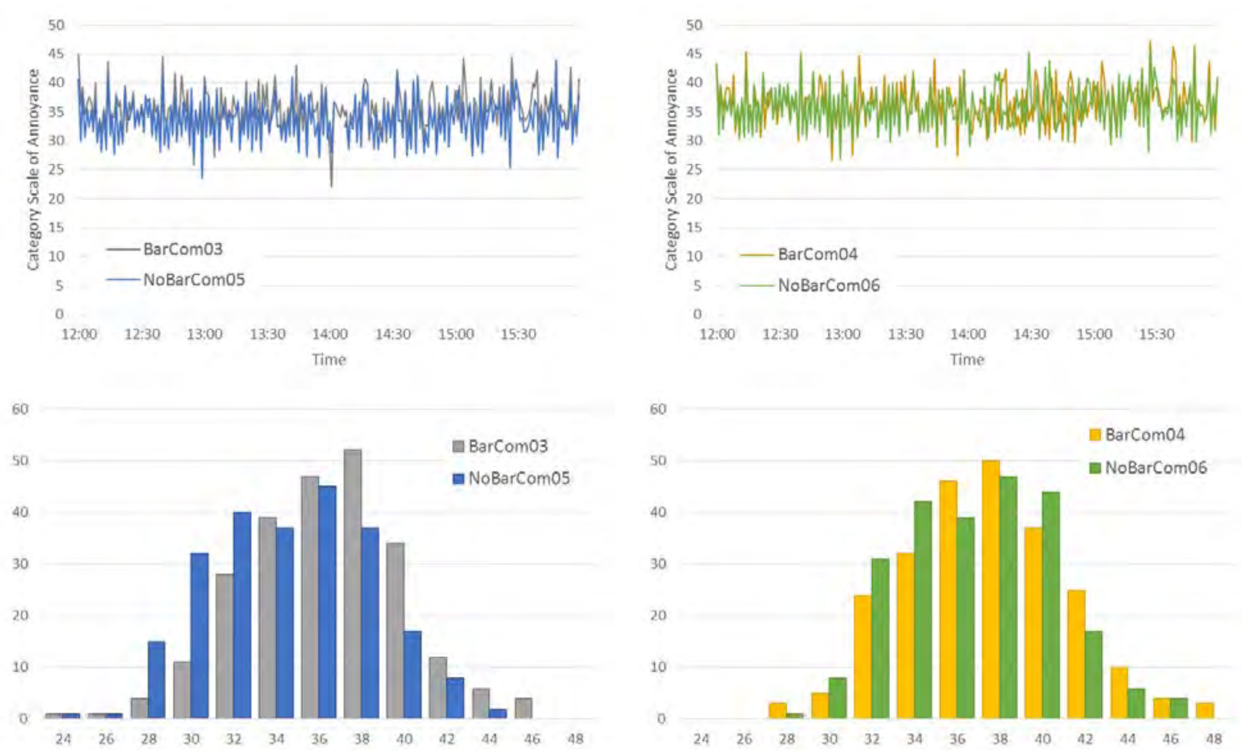


Figure 192. Category scale of annoyance vs. time and histograms, MD-5, afternoon.

Psychoacoustical Annoyance Metrics, Night

The audio recordings from nighttime monitoring at MD-5 were contaminated with very-high-frequency sound from amphibians. Therefore, a significant amount of high-frequency filtering was applied to the recordings prior to analysis. The 1/3 octave band filter coefficients applied to the recordings are shown in Figure 193.

Descriptive statistics for the computed annoyance metrics at MD-5 at night are summarized in Table 17. The associated histograms in each of the subsequent Figures relate the distribution of magnitudes for each metric at each microphone to the descriptive statistics in the Table.

The Unbiased Annoyance (UBA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 194. The Psychoacoustic Annoyance (PA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 195. The Category Scale of Annoyance (CSA) metrics, computed as a function of time for the two lower microphones (BarCom03 and NoBarCom05) and the two higher microphones (BarCom04 and NoBarCom06), are plotted in Figure 196.

The results for both the Unbiased Annoyance and the Psychoacoustic Annoyance between the Barrier and No Barrier locations at the lower microphones do not show a significant difference. This is a trend seen at SR-71 as well, despite the increased setback from the roadway. This seems to indicate that, for sound closer to ground level (level with the vehicles), the annoyance metrics do not separate the Barrier and No Barrier cases effectively.

The mean levels of annoyance at the higher microphones, however, do differ, to roughly one standard deviation. Again, this supports the supposition that the additional height, with its related difference in frequency content, yields a significant difference in the annoyance metrics. However, as seen at all of the other sites, that difference shows the Barrier location to have a lower annoyance metric than the No Barrier location. Therefore, neither the UBA nor the PA substantiate an assumption of increased annoyance due to the presence of the barrier at this site.

There is no significant difference in the means of the Category Scale of Annoyance for either pair of microphones. The simple linear regression that forms CSA, and its derivation from product noise, do not apply well to highway traffic noise.

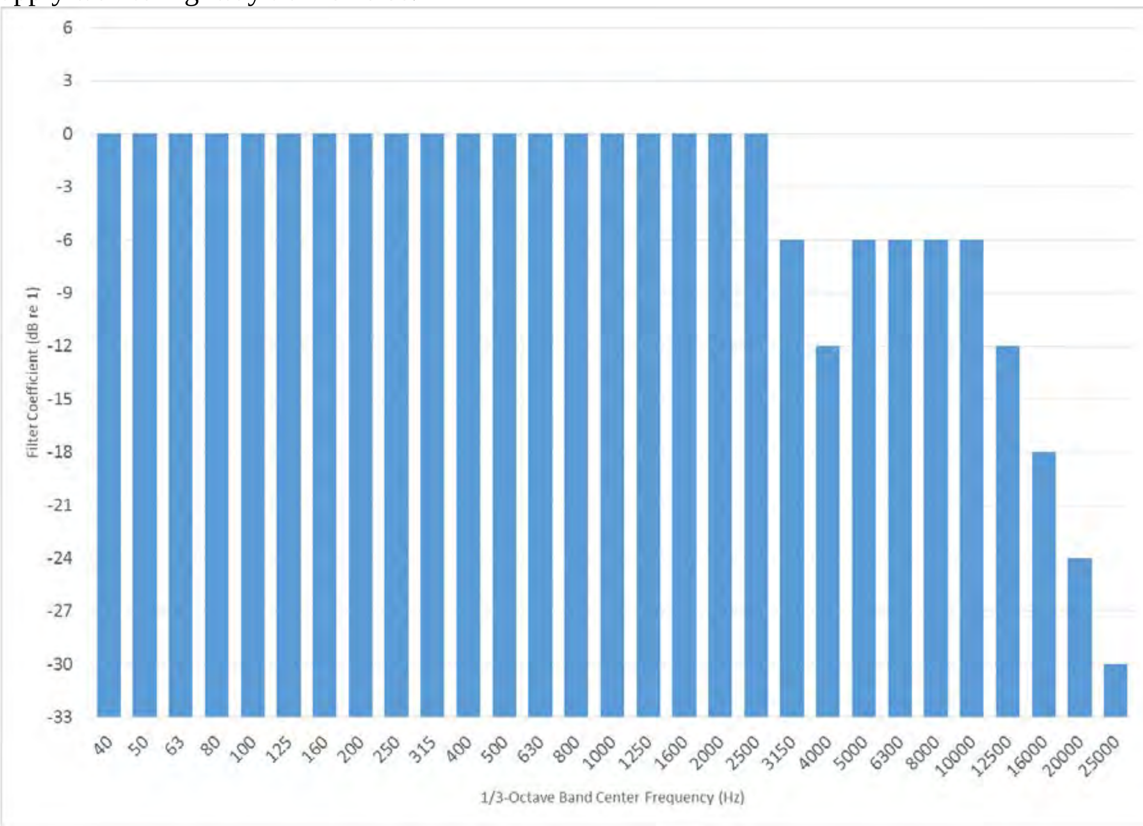


Figure 193. 1/3-octave band graphic equalization applied to nighttime audio.

Table 17. Descriptive statistics of annoyance metrics, MD-5, night.

Metric	Location	Mean	Std. Dev.	Skewness	Kurtosis
UBA	BarCom03	13.8	3.3	0.49	0.49
	NoBarCom05	15.1	3.3	0.22	0.09
	BarCom04	13.5	3.8	0.68	0.74
	NoBarCom06	17.9	3.3	0.08	0.26
PA	BarCom03	3.59	0.93	0.89	2.09
	NoBarCom05	3.84	0.91	0.82	1.57

	BarCom04	3.75	0.96	0.95	2.77
	NoBarCom06	4.50	0.92	0.42	1.57
CSA	BarCom03	27.3	3.1	0.68	1.59
	NoBarCom05	27.0	2.9	0.45	0.52
	BarCom04	28.0	3.4	0.44	1.41
	NoBarCom06	28.5	3.1	0.15	1.28

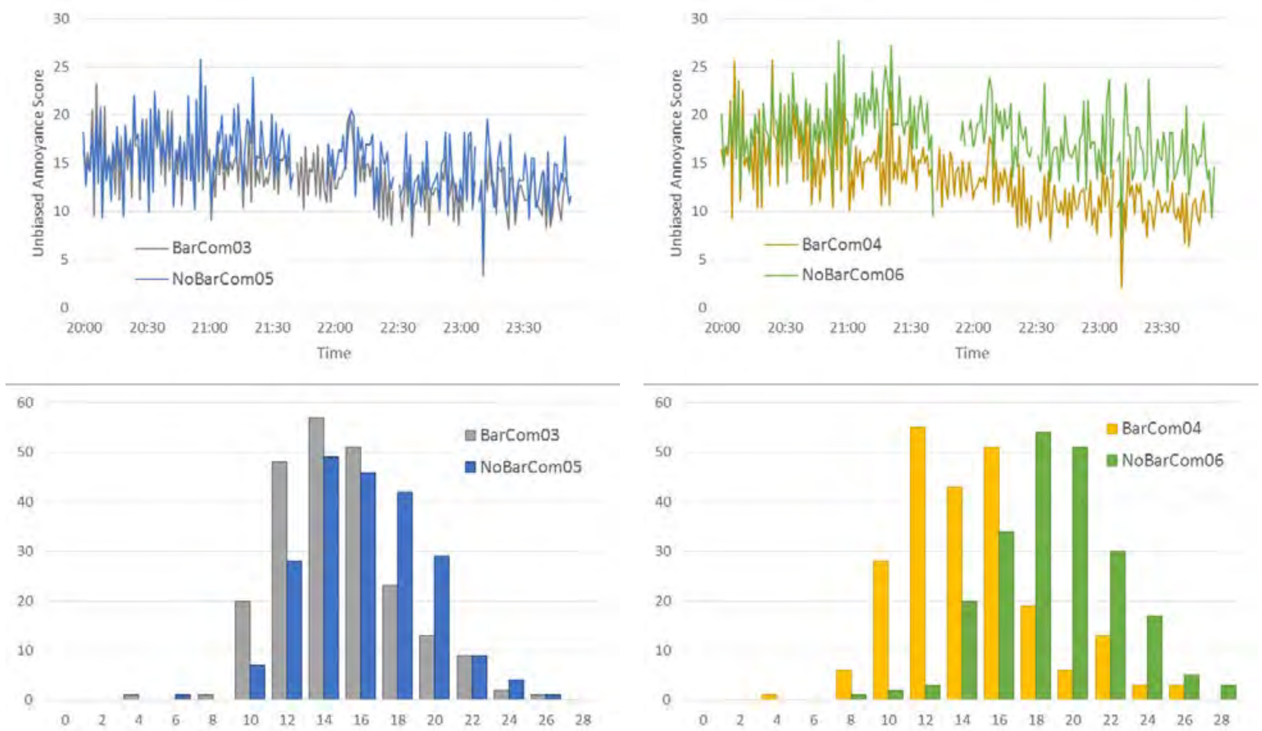
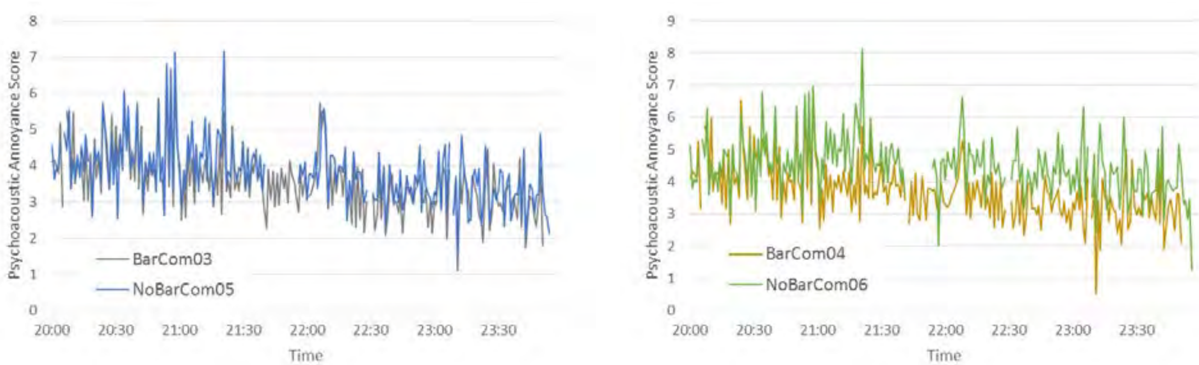


Figure 194. Unbiased annoyance vs. time and histograms, MD-5, night.



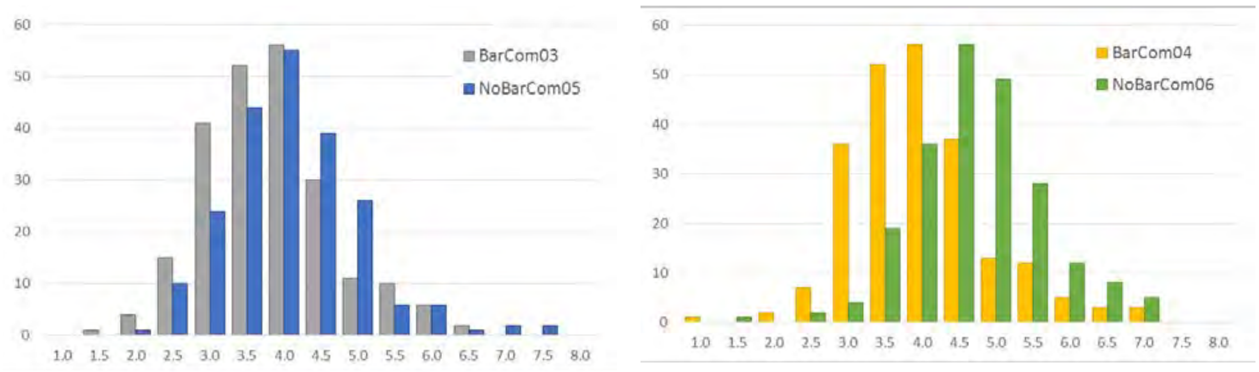


Figure 195. Psychoacoustic annoyance vs. time and histograms, MD-5, night.

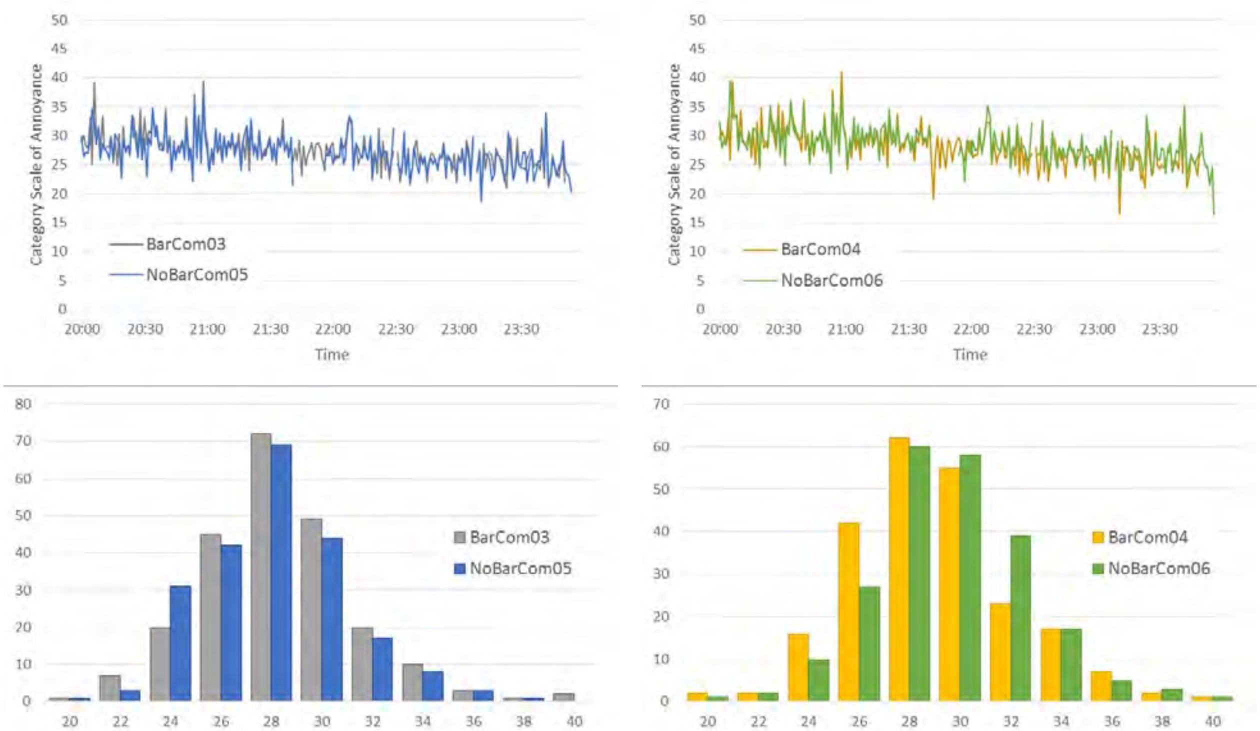


Figure 196. Category scale of annoyance vs. time and histograms, MD-5, night.

CHAPTER B-8

Summary of Appendix B

This Appendix presented the details of the research data collection and analysis protocols and the results at five studied single-barrier locations. The purpose of the measurements and analysis was to see if sound levels increased on the opposite side of the road from a noise barrier due to sound reflections off that barrier, and whether differences could be detected using spectrogram analysis or psychoacoustic metrics.

The analysis was done using: (1) a modification to a method in a Federal Highway Administration (FHWA) noise measurement manual ("FHWA Method"); (2) acoustical spectrograms, which show the frequency content of sound as a function of time; and (3) the psychoacoustic measures of Loudness, Sharpness, Roughness, and Fluctuation Strength combined into metrics of Annoyance. Additionally, changes in the statistical exceedance (L_n) descriptors were also addressed.

Five locations in Tennessee, Illinois, California and Maryland were selected for study. With one exception, six sound level analyzers were deployed at each location: three at the Barrier site and three at the adjacent No Barrier site. Each site had a reference microphone on the barrier-side of the road and two pairs of "community" microphones on the opposite side of the road from the barrier. A meteorological station collected simultaneous wind speed and direction, and a video camera and laser speed gun were used to collect traffic volume and classification data and travel speeds.

Two of the locations afforded the opportunity to place the Barrier reference microphone between the barrier and the road so that it could be compared to the No Barrier reference microphone as a primary point that might be affected by reflected noise.

Four hours of one second data were collected at each location, process into 1-minute periods. The 1-minute periods were then combined into 5-minute periods. The 5-minute periods were then tested for source equivalence in terms of the reference sound level data and speed data and for meteorological equivalence. Where possible, isolated single vehicle pass-by events were examined using the spectrogram method. When three or more equivalent periods were identified, they were grouped together and the sound level differences were examined. Evening measurements at two of the locations were scheduled to study individual vehicle passby events.

Overall findings, applications, recommendations and suggested future are topics covered in the main report.

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6. W. Ellermeier, A. Zeitler, and H. Fastl. 2004. "Predicting annoyance judgments from psychoacoustic metrics: Identifiable versus neutralized sounds." Proceedings of the 33rd International Congress on Noise Control Engineering. Prague.

APPENDIX C – PHOTOGRAPHS FROM ALL MEASUREMENT SITES

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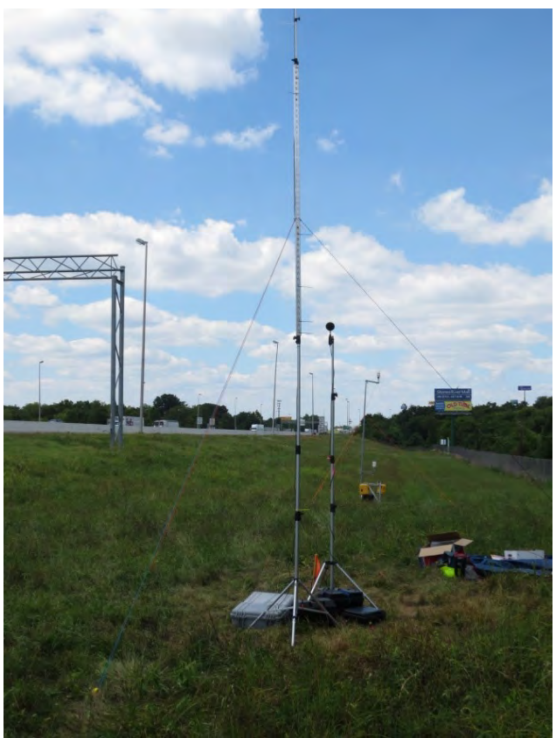

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Photograph 34. BA_Briley_NoBar_Com5and6_20140814_WB06

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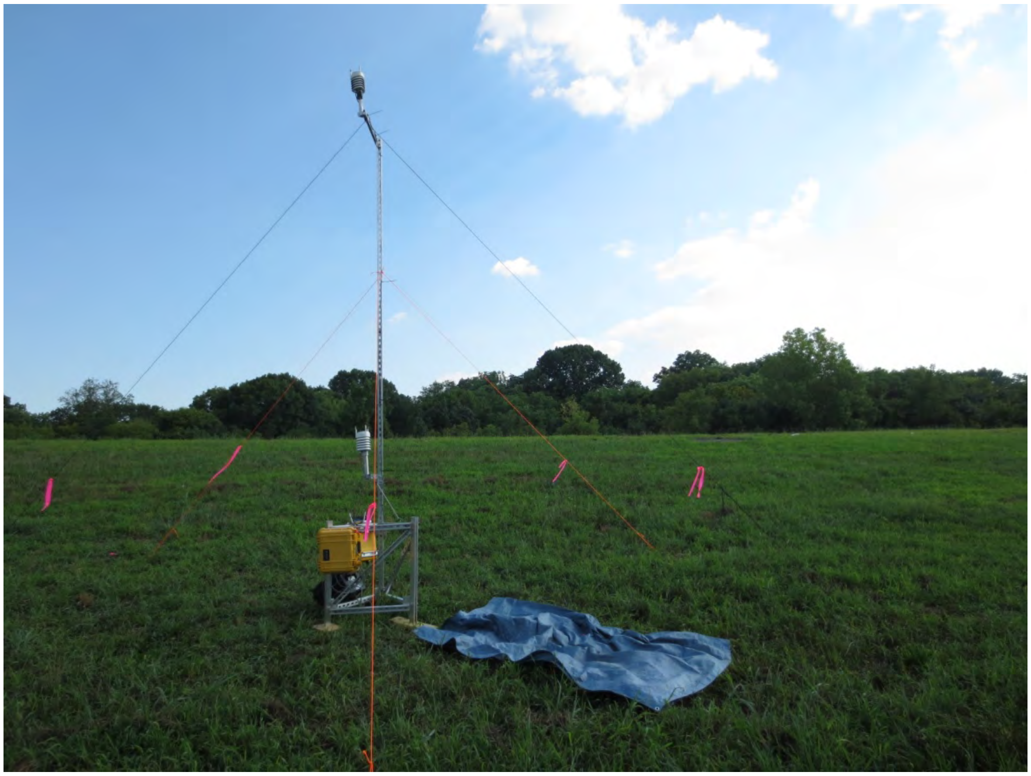

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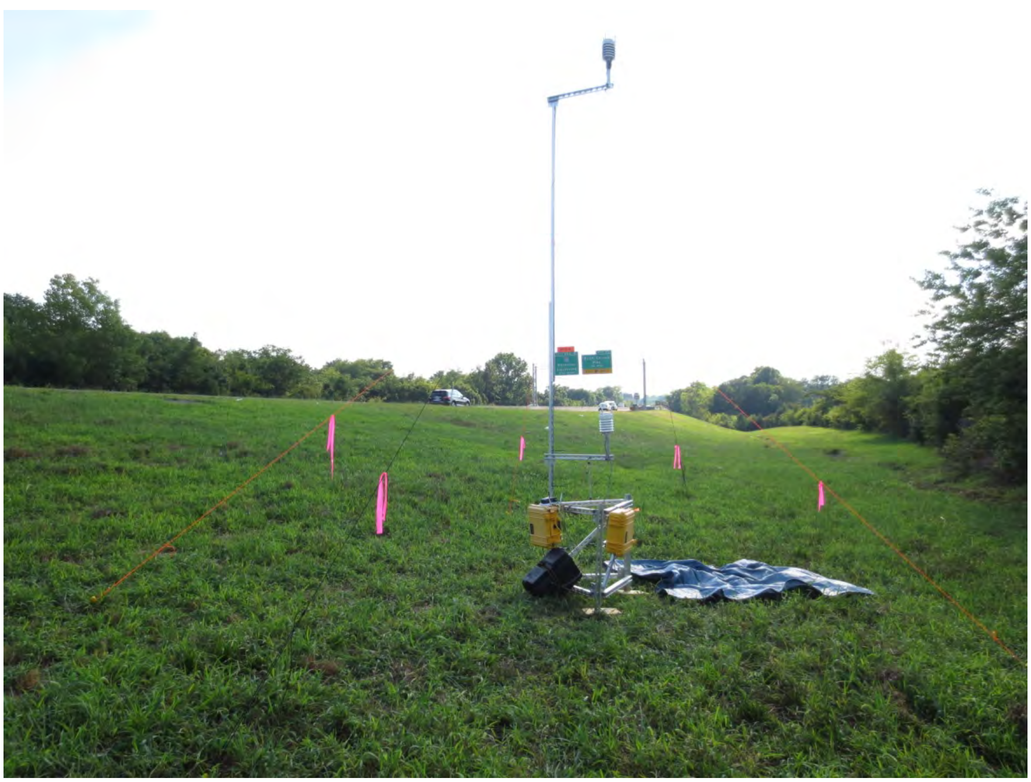

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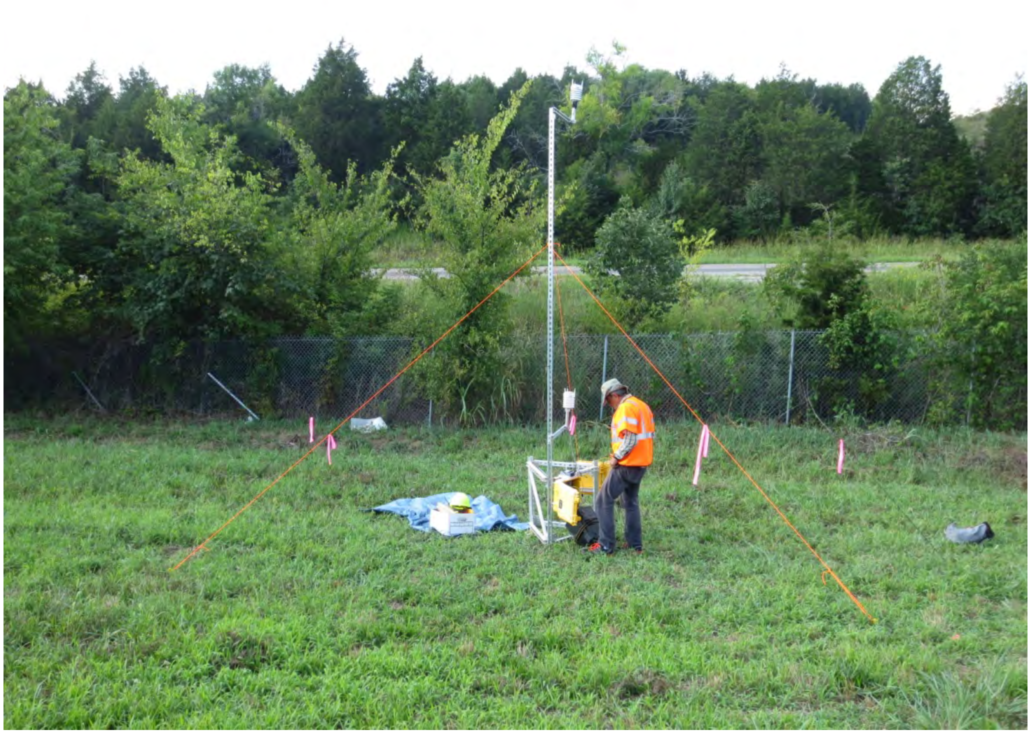

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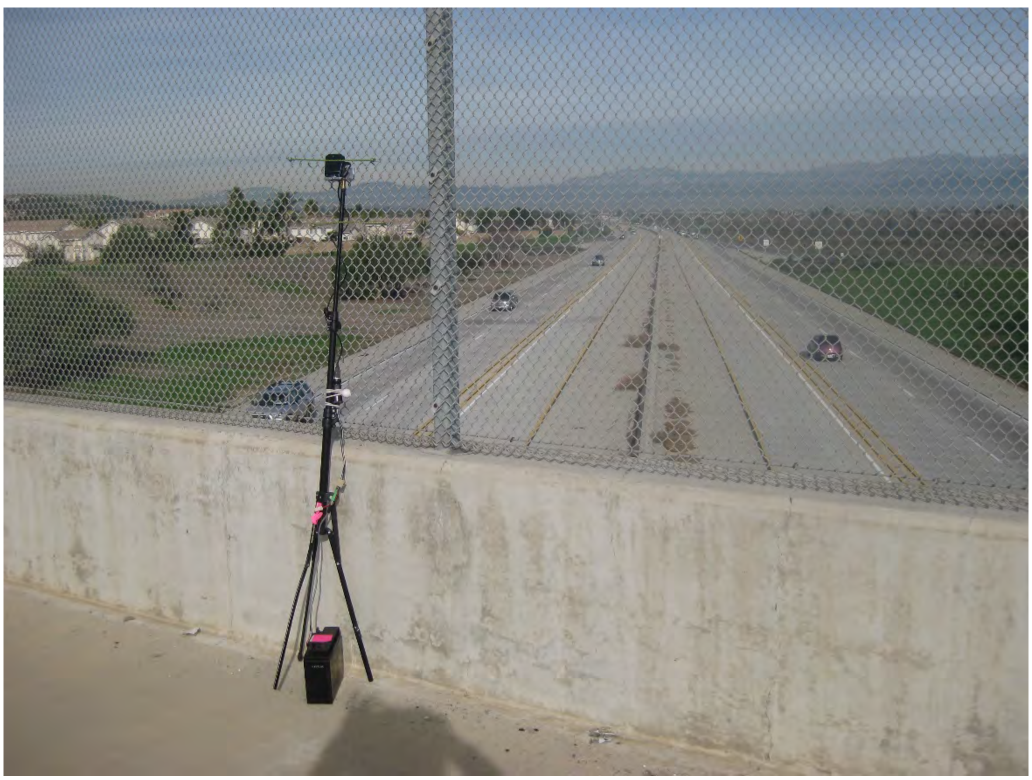
Photograph 67. ATS_SR71_NoBar_Com_Met_20150128

Photograph 68. ATS_SR71_traffic speed_20150128



Photograph 69. ATS_SR71_traffic video_20150128

MD-5, HUGHESVILLE, MD

Photograph 70. EA_MD-5_Bar_Ref01_06292015_Pic1

Photograph 71. EA_MD-5_Bar_Ref01_06292015_Pic4

Photograph 72. EA_MD-5_NoBar_Ref02_06292015_Pic3

Photograph 73. EA_MD-5_NoBar_Ref02_06292015_Pic4

Photograph 74. EA_MD-5_Bar_Com03and04_06292015_Pic1

Photograph 75. EA_MD-5_Bar_Com03and04_06292015_Pic2

Photograph 76. EA_MD-5_Bar_Com03and04_06292015_Pic3

Photograph 77. EA_MD-5_Bar_Com03and04_06292015_Pic6

Photograph 78. EA_MD-5_NoBar_Com05and06_06292015_Pic6

Photograph 79. EA_MD-5_NoBar_Com05and06_06292015_Pic2

Photograph 80. EA_MD-5_NoBar_Com05and06_06292015_Pic3

Photograph 81. EA_MD-5_NoBar_Com05and06_06292015_Pic4

Photograph 82. EA_MD-5_NoBar_Met_Setup_06292015_Pic3

Photograph 83. EA_MD-5_NoBar_Met_Setup_06292015_Pic4

Photograph 84. EA_MD-5_Speed-Count_06292015_Pic3

Photograph 85. EA_MD-5_Video-Count_06292015_Pic4

Photograph 86. EA_MD-5_Pavement_06292015_Pic1

Photograph 87. EA_MD-5_Pavement_06292015_Pic2