APPENDIX E

NCHRP Project 25-44, Phase 1 (Sound-Reflecting Barriers)—Detailed Protocols and Results

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CHAPTER E-1

Introduction to Appendix E

This appendix to *NCHRP Research Report 886* presents details of the Phase 1 research for NCHRP Project 25-44, "Field Evaluation of Reflected Noise from a Single Noise Barrier," covering data collection and analysis protocols, and the results at five sound-reflecting single-barrier locations. This appendix does not provide background on the Phase 1 subject, overall findings, applications, recommendations, or suggested research; these topics are discussed in the main report, and additional details are provided in *NCHRP Web-Only Document 218: Field Evaluation of Reflected Noise from a Single Noise Barrier—Phase 1*. Phase 2 of NCHRP Project 25-44 focused on sound-absorbing barriers. The Phase 2 research is reported on in the main body of *NCHRP Research Report 886*, with additional details printed in Appendix B. Site photographs documenting the Phase 1 and Phase 2 measurement locations are provided in two online appendices, Appendix F and Appendix G, which can be accessed for viewing or download from the *NCHRP Research Report 886* webpage.

The purpose of the measurements and analysis was to see if sound levels increased on the opposite side of the road from a sound-reflecting 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, along with one-third octave band sound pressure levels.

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

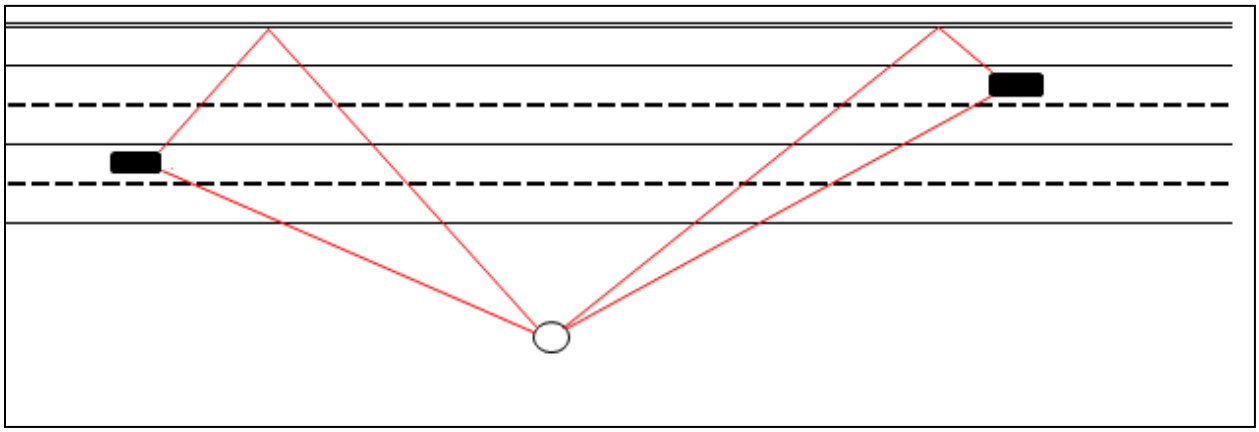


Figure 1. Plan view of the relationship between direct and reflected sound paths to a receptor across the highway from a noise barrier.

The next chapter addresses the research approach. The subsequent chapters 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} (5 min.), 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 one-third octave band sound pressure level differences at the microphone pairs. Sample one-third 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, and one-third 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.

Some material contained herein duplicates information provided 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 F of the Final Report (available online) includes photos of the microphone positions, meteorological station, and traffic data collection site for each Phase 1 location.

CHAPTER E-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 10 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 or reflective (the Phase 1 focus shifted to sound-reflecting barriers only at the Phase 1 Interim Meeting).
- 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 (ROW) (near the receiver).

Field reviews at the most promising locations identified eight acceptable locations. From those eight, five were chosen for study.

Acceptable Locations

The eight acceptable locations are listed below:

1. BA-1, I-24, Murfreesboro, Tennessee.
2. BA-3, Briley Parkway (SR 155), Nashville, Tennessee.
3. ATS-3, SR-71, Chino Hills, California.
4. BA-4, I-240, Memphis, Tennessee.

5. EA-4, Hampstead Bypass, Hampstead, Maryland.
6. EA-5, MD Route 5, Hughesville, Maryland.
7. RSG-3, US 3/FE Everett Turnpike, Nashua, New Hampshire.
8. SID-1, I-90, north of Spring Creek Rd Rockford, Illinois.

The originally selected California location was ATS-2, SR-99 in Bakersfield, California. 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, California, was chosen to replace ATS-2.

Table 1 summarizes the characteristics of the eight acceptable 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 Phase 1 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's barrier was sound-absorbing and, being a depressed highway, was not the best location to include as a sound-absorbing location in Phase 2. 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 pass-bys 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 selected locations offered multiple characteristics:

- Daily traffic volumes range from 18,000 to 80,000 vehicles per day.
- The cross-sections range from four lanes to eight lanes.
- Four locations are on freeways and one location is on an arterial.
- Four of the sites are essentially at-grade with surrounding terrain and one is on a 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 ft. to 96 ft.
- All barriers are sound-reflecting: 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 ft. to 19 ft.

Most of the measurement points were within the highway ROW, 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 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 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. Acceptable Phase 1 locations.

Location	Roadway	City, State	Road Class	Lanes	Pavement Type	Geometry Relative to Adjacent Land Uses	AADT (vpd)	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 ft. (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 ft.
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 ft.
BA-4	I-240, between Getwell Rd. and Perkins Rd.	Memphis, TN	Freeway	10	Asphalt (DGAC)	Slight Fill	151,700	11%	ROW	Precast Concrete	18 ft.
EA-4	Hampstead Bypass (MD Route 30), at N. Houcksville Rd.	Hampstead, MD	Arterial	2	Asphalt (DGAC)	Cut	18,000	9.4%	ROW	Precast Concrete	5-12 ft.
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 ft.
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 ft.
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 ft.

*Locations selected and measured in Phase 1.

The final five 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, can be found in the Results chapter for each location. More photos for each location are provided in Appendix F (available online from the *NCHRP Research Report 886* web page at www.trb.org) .

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

I-24 is an eight-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 (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, Tennessee

Briley Parkway is a six-lane freeway with dense-graded asphalt pavement. It carries 46,000 vehicles per day with 8% trucks. The barrier is a reflective cast-in-place concrete wall, located approximately 16 ft. from the center of the near travel lane, and it is 13 ft. tall (Figure 3). This road carries relatively light traffic in the nighttime hours and was studied in the night with the goal 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 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 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, Illinois

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 and it is 15 ft. tall (Figure 4).

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, California

SR-71 is a six-lane freeway in Chino Hills, California, 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 ROW line at distance of approximately 50 ft. from the center of the near travel lane (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% 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 and it is 16 ft. tall (Figure 6). This road carries relatively light traffic in the nighttime hours and was studied in the evening and the daytime to measure individual vehicle pass-bys.

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:

- The 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 and followed by the data processing steps. 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 Windows Audio Format (.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 to study individual vehicle pass-bys, with particular interest in the change in the signature of the noise level of the pass-by 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. The project team minimized potential variations in traffic volume and speed between the two sites. This was done by avoiding interchanges or intersections between the Barrier and No Barrier sites, whose measurements were to be made simultaneously. 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. Demonstrating source equivalence and meteorological equivalence in real time in the field can be difficult and time consuming. As a result, the field protocol was as follows:

- Collect four hours of data at each site, averaged in 1-minute periods.
- Videotape the traffic and measure speeds with a laser speed gun.
- Collect wind speed and direction and temperature data at two heights, averaged in 1-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 are called "traffic classes." Unfortunately, the video data was not collected at the BA-3 Briley Parkway site. The researchers found an

alternative method of determining period equivalency—based on the reference microphone sound levels and the average speeds by direction of travel—that worked well and was adopted for the rest of the study.

In Technical Memorandum No. 2 prepared for Phase 1 of the study, the researchers used FHWA Traffic Noise Model (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 reduced to 0.3 dB or less across all 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 the sites, consisting of the following:

- Six Type I sound level analyzers with one-third 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.
- 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 pass-bys 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 gauge a vector wind speed in the direction from the roadway to the microphones 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 (all times will be based on a 24-hour clock).

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 (pointed 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 the microphones. One-second broadband A-weighted levels and unweighted sound pressure levels and one-third-octave band unweighted sound pressure levels between 12.5 Hz and 20,000 Hz were saved and 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 1-second wind speed and direction and temperature for later processing into 1-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 1-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.

Traffic video loss at the Briley location precluded traffic counts. As noted, 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—most 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 measurement, it was necessary to adjust the speeds afterwards. In addition to speed, the laser gun reports the range in ft. to the vehicle when the speed was sampled. The range and the perpendicular offset distance of the gun from the lane of interest were used to compute angles and corresponding speed adjustments for each speed sample during data processing.

All the data were then downloaded onto personal computers, with a common file-naming convention for all 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 11 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 Secure Digital (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 1 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 one-third 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 10 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). 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 to 12:06, 12:02 to 12:07, and 12:03 to 12:08 would be three consecutive running 5-minute periods. Using 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 5 minutes be in the same class. All 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, 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 TNM 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 few periods that were equivalent, this criterion was relaxed to 15%. (A change in volume of 10% 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—the traffic equivalency of the 5-minute periods was determined based on the BarRef01 L_{eq} (5 min.) and the 5-minute running average speeds because there were no traffic counts.

For L_{eq} (5 min.), 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 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 the final calibration levels at all 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 one-third 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 as follows:

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

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} one-third 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} one-third 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} one-third 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 dB

For the I-24 and SR-71 locations, the BarRef01 and NoBarRef02 microphones were located 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 setup simplified the sound level increase calculations to three comparisons:

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

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

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

For the I-90 and MD-5 locations, the barrier was close to the road. 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 one-third 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 average differences were also computed to study the possible effect of meteorological class on the results. After study of the average differences for each equivalent group for each meteorological class, 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 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 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 one-third octave bands in one-eighth-second intervals. The data were then displayed using spectrogram-type graphs. In-house MATLAB code allowed 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 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 like one-third-octave bands, but they vary in frequency width in a way more representative of human hearing. 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 one-third-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 like 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 or pure tone components. It uses one-third-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 developed by Aures (1985):

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

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:

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

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 occurs when the metric changes by more than approximately 17%.

Fluctuation Strength

Fluctuation Strength (FS), expressed in "vacils," is similar to Roughness as measure of temporal variation of sound. However, FS reaches a maximum at modulation frequencies of about 4 Hz, much "slower" than the modulations attributed to Roughness. Like Roughness, FS 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, FS has not been defined in an international standard, but the typical implementation is:

$$FS = 0.032 \sum_{0}^{24} \frac{\Delta L(z) \Delta z}{\left[\frac{f_{\text{mod}}}{4} + \frac{4}{f_{\text{mod}}}\right]}$$

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 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. Many noise ratings exist. 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 with reported annoyance.

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

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

UBA is a function of the following:

- Loudness exceeded 10% of the time (N_{10}) in sones.
- Mean Sharpness (S) in acums.

- Mean Fluctuation Strength (FS) in vacils.

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

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

PA is a function of the following:

- Loudness exceeded 5% of the time (N_5) in sones.
- Mean Sharpness (S) in acums.
- Mean Fluctuation Strength (FS) in vacils.
- Mean Roughness (R) in aspers.

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

where:

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

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

This expression is like that of UBA. 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 (FS and Roughness). Each of these, in turn, is weighted by the Loudness in a "slower-than-linear" way.

In Ref. (6), another multicomponent metric for annoyance was introduced, called CSA. Their work was based on "neutralized" product sounds 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 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 FS.

CSA is a function of the following:

- Loudness exceeded 5% of the time (N_5) in sones.
- Sharpness exceeded 50% of the time (S_{50}) in acums.
- 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 .wav format. These data were used to calculate the basic sound quality metrics of Loudness, Sharpness, Roughness, and FS. 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 preceding equations. 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%). The sound quality software did not directly compute the 95th percentile Loudness, $N_{5:}$ instead, the recordings were reprocessed to 1-second blocks of Loudness (48,000 samples), from which the 95th percentile values for each 1-minute interval were extracted using Microsoft Excel. The 1-minute interval metrics were exported to Excel spreadsheets for further processing.

For each 1-minute interval, the resulting sound quality metrics were combined using the equations for UBA, PA, and CSA within 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 along with data trends over each monitoring period.

Further, simple descriptive statistical analyses were applied to each time series 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 a statistically meaningful difference could be found between the annoyance metrics computed in the presence and absence of the barrier, respectively.

CHAPTER E-3

Results—I-24, Murfreesboro, Tennessee (Location BA-1)

The I-24 measurements were conducted from 13:13 to 17:20 on August 13, 2014. 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 5 ft. 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 setback, 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 F (available online) contains 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 like at BarRef01. The microphone positions were as shown in Table 4.

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)

Mic. Name	Side of Road	Distance from Center of Near Travel Lane (ft.)	Height Above Roadway Plane (ft.)
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 ft. 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.)

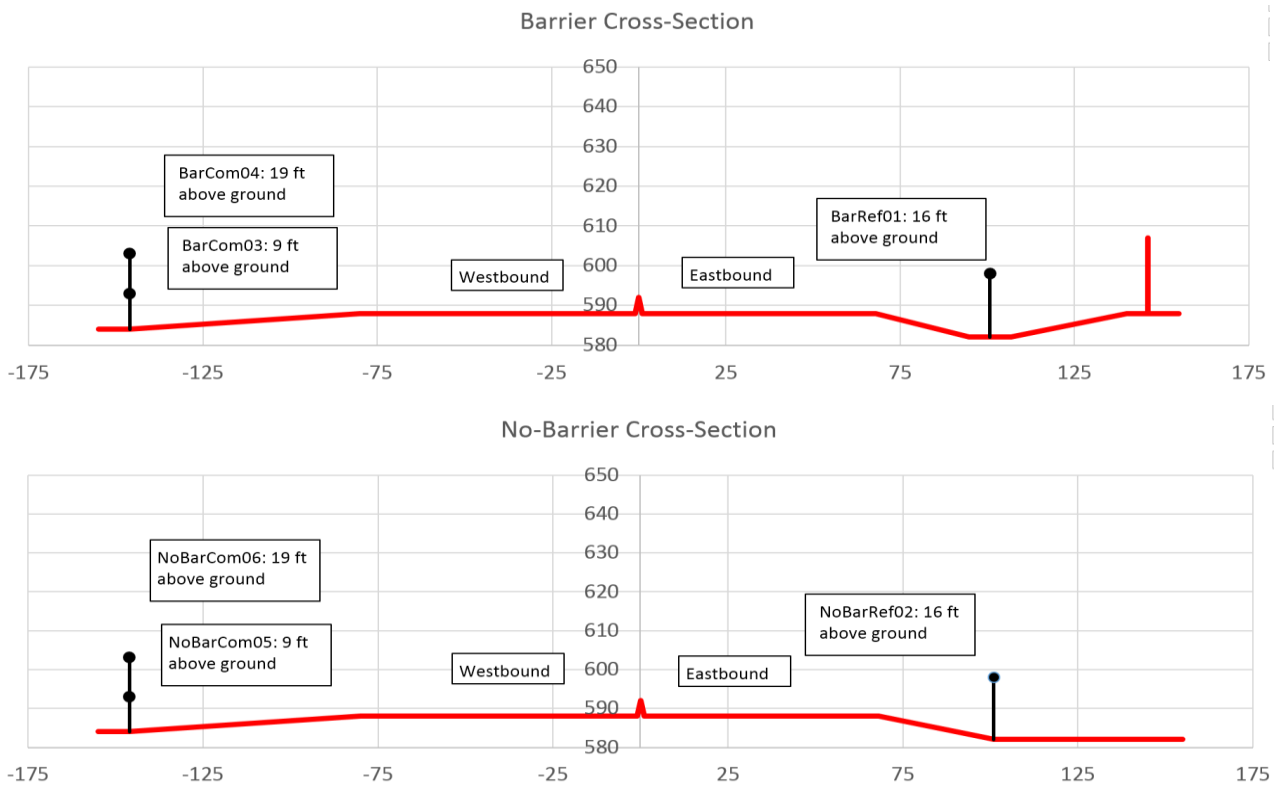


Figure 8. Cross-sections at the I-24 Barrier (top) site and No Barrier (bottom) sites.

Measurement Observations

As observed at the traffic count and speed site, initially, the traffic volumes appeared roughly equal in each direction. However, the eastbound lane volumes seemed to increase 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 exiting—the eastbound HOV lane. Heavy trucks tended to use the outer two lanes (this stretch of I24 was signed to restrict trucks to the two right lanes). Toward 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. Automobiles and heavy trucks dominated the traffic flow. Medium trucks, buses, and motorcycles were infrequent, and an attempt was made to acquire their speeds whenever present, regardless of their lane of travel. Speeds typically ranged from 65 to 70 mph, with no difference by direction. 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 slowing down from around 70 mph to 55 mph back by the Barrier site; traffic did not slow 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 to 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 similar; however, the ground at his position was six ft. below the roadway elevation—a suboptimal 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 substantial 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 pass-by noise.

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 one-third-octave band) around 14:30, but 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 BarCom03/04.

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 sounds. 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. Generally, all westbound vehicles were easily identifiable by their sound.

Measured Broadband Levels and Level Differences for I-24

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

For most of the running 5-minute L_{eq} periods, the BarCom03 levels, both unweighted and A-weighted, are higher than the NoBarCom05 levels by 0.0 dB 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 0.0 dB 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.

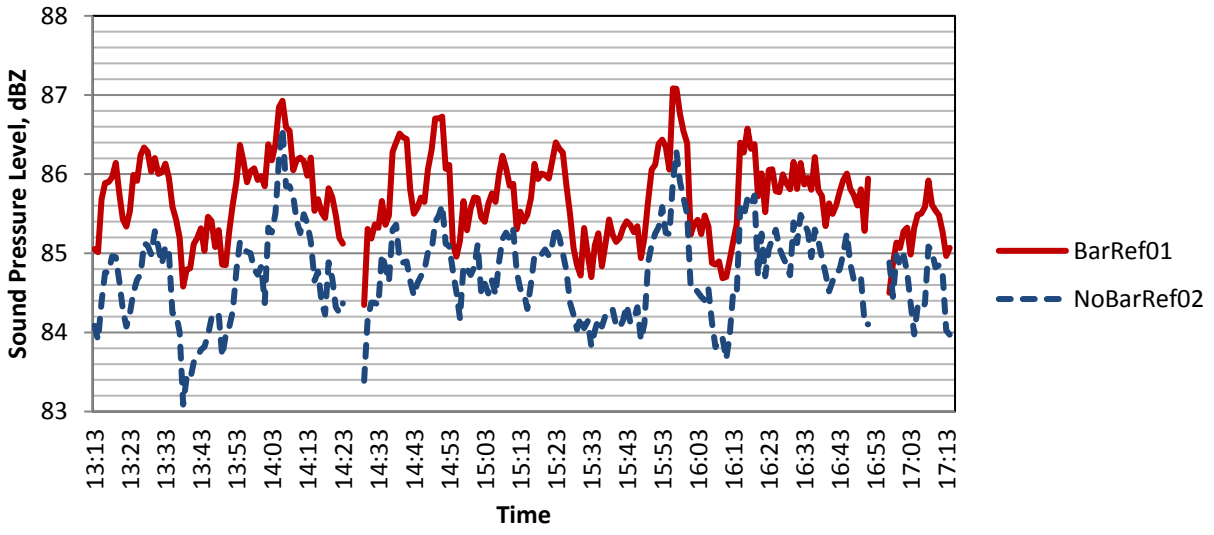


Figure 9. Running L_{eq} (5 min.), I-24, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

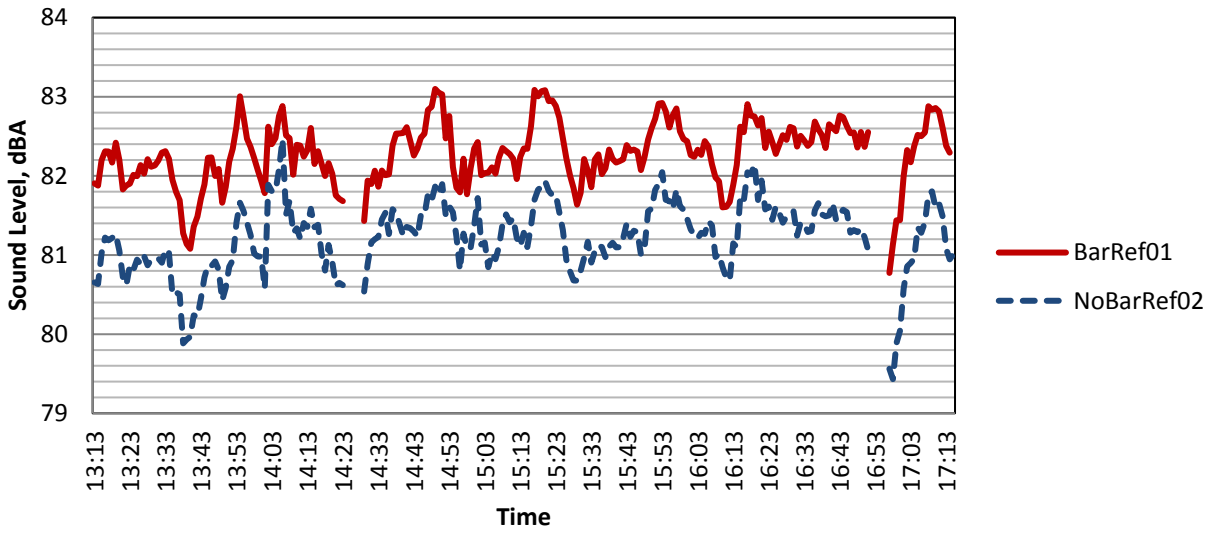


Figure 10. Running L_{eq} (5 min.), I-24, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

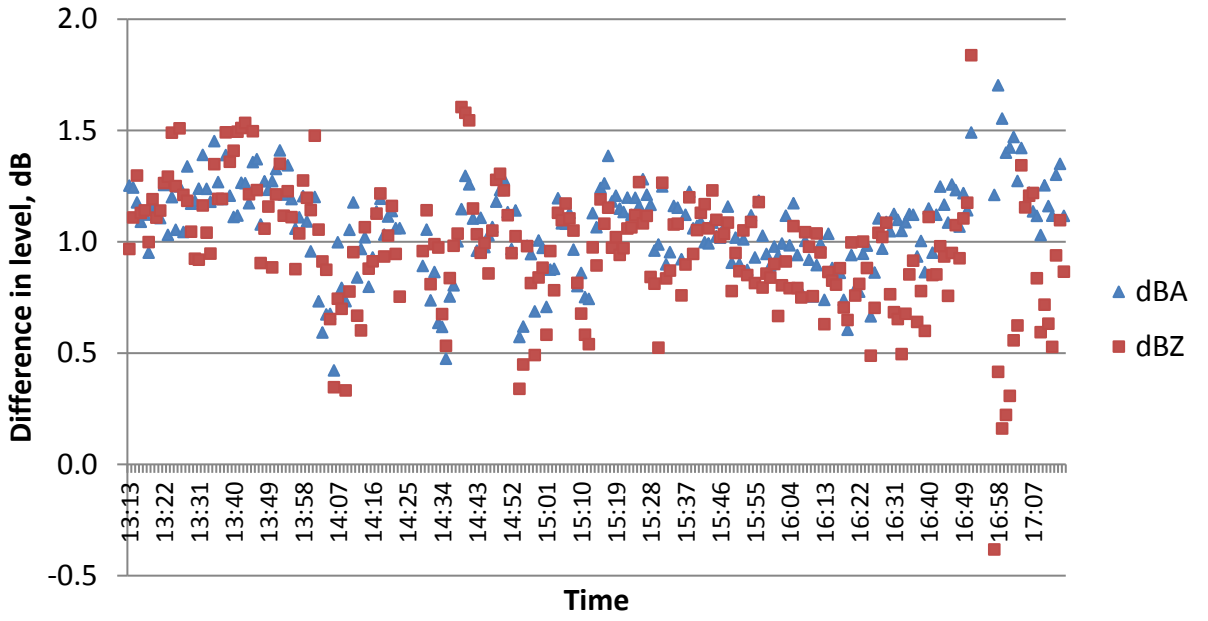


Figure 11. Differences in running L_{eq} (5 min.), I-24, BarRef01 minus NoBarRef02.

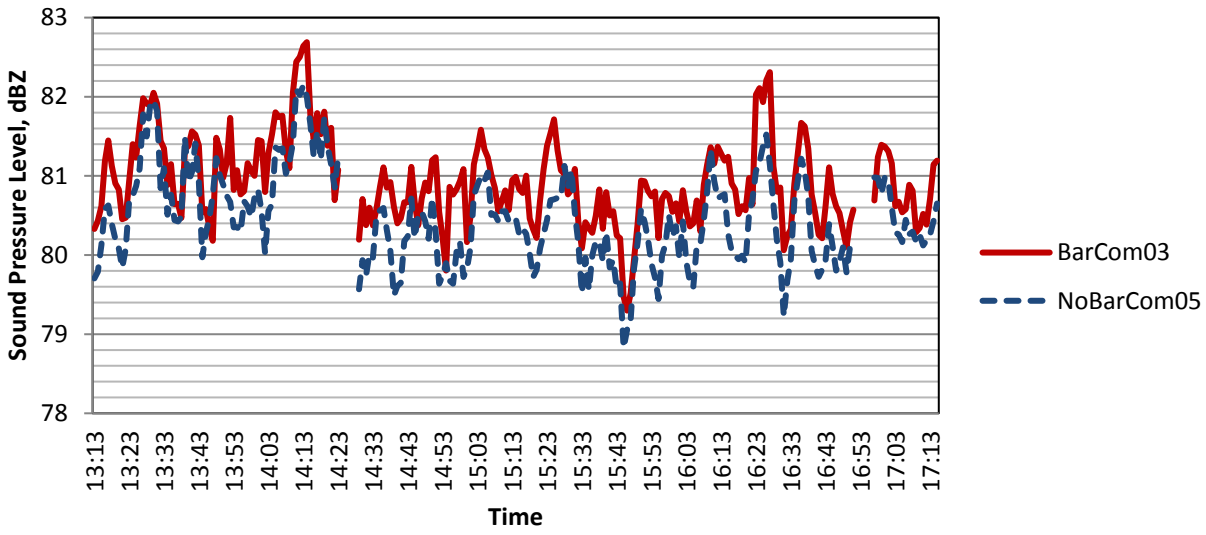


Figure 12. Running L_{eq} (5 min.), I-24, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

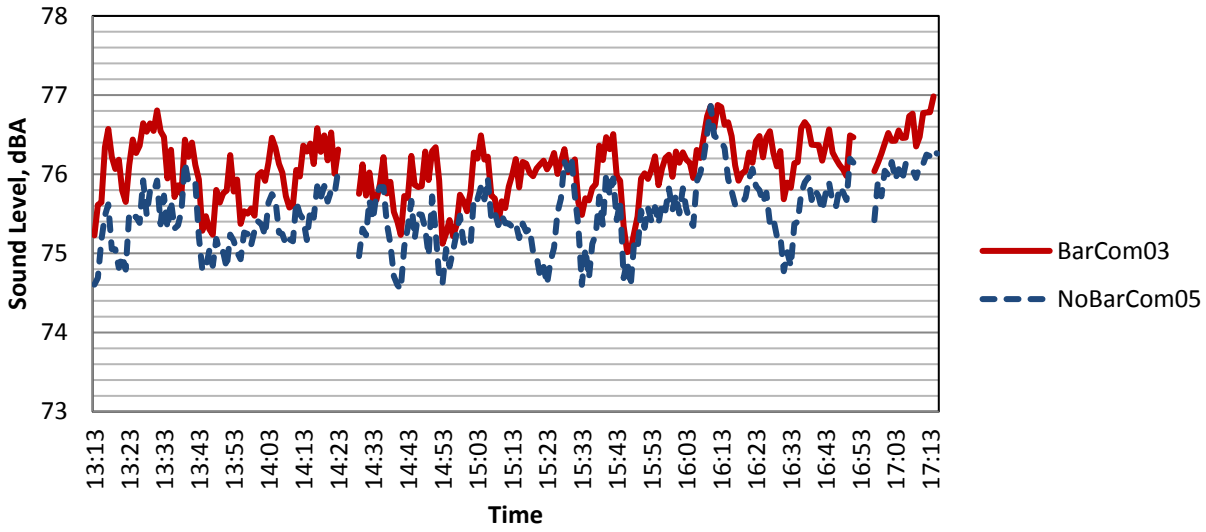


Figure 13. Running L_{eq} (5 min.), I-24, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

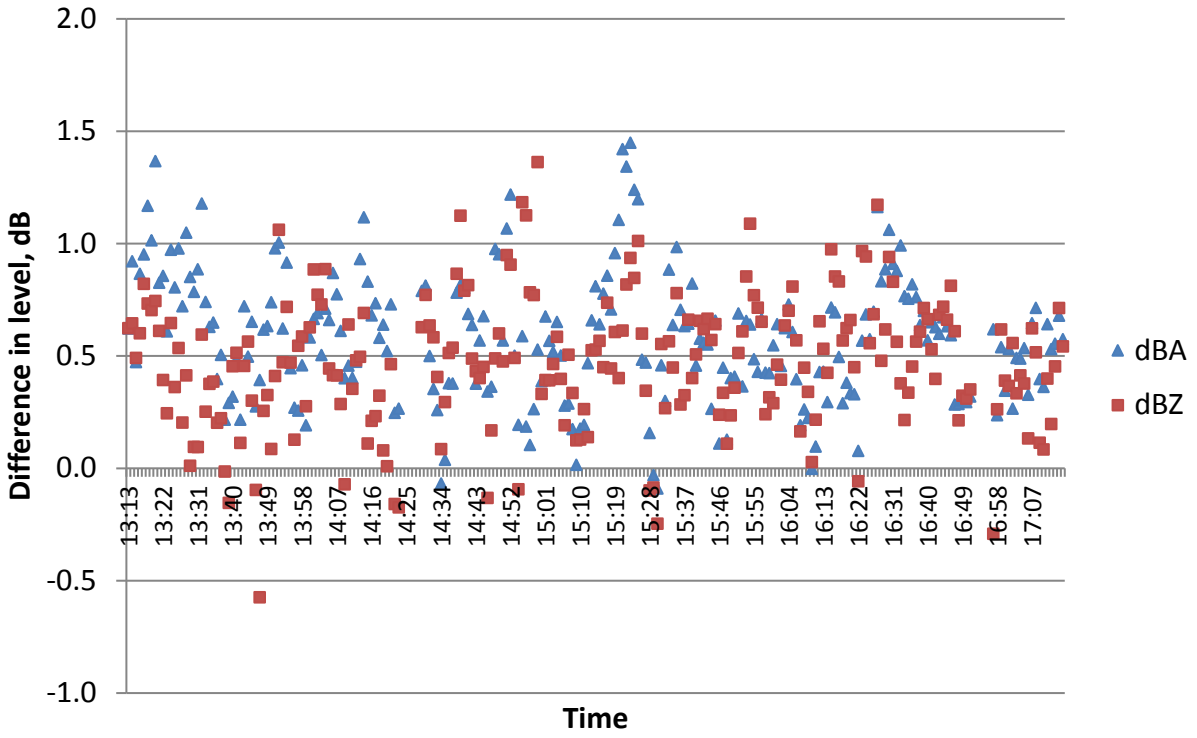


Figure 14. Differences in running L_{eq} (5 min.), I-24, BarCom03 minus NoBarCom05.

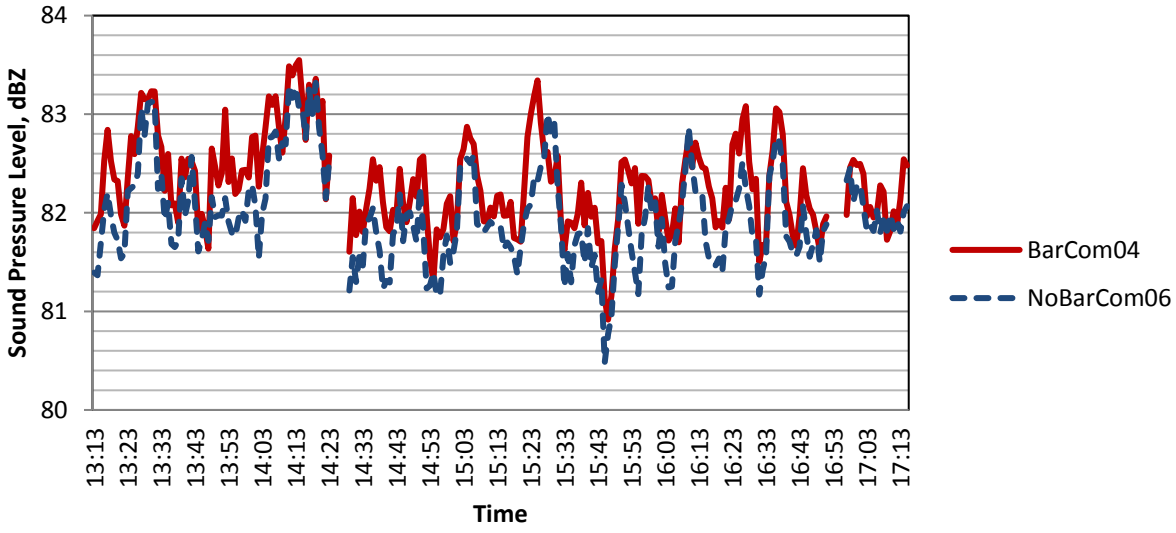


Figure 15. Running L_{eq} (5 min.), I-24, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

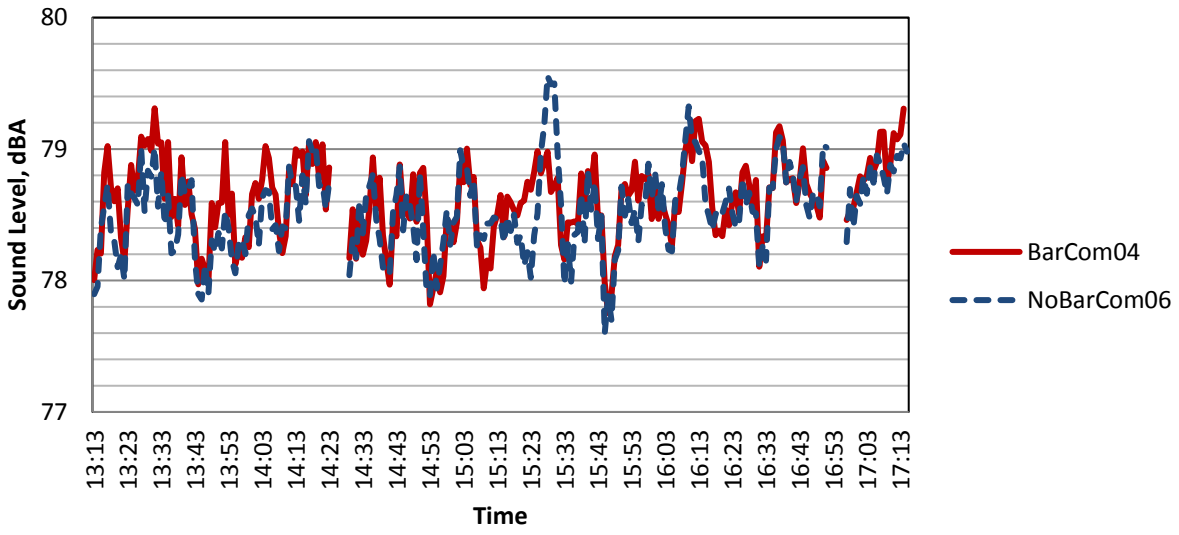


Figure 16. Running L_{eq} (5 min.), I-24, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

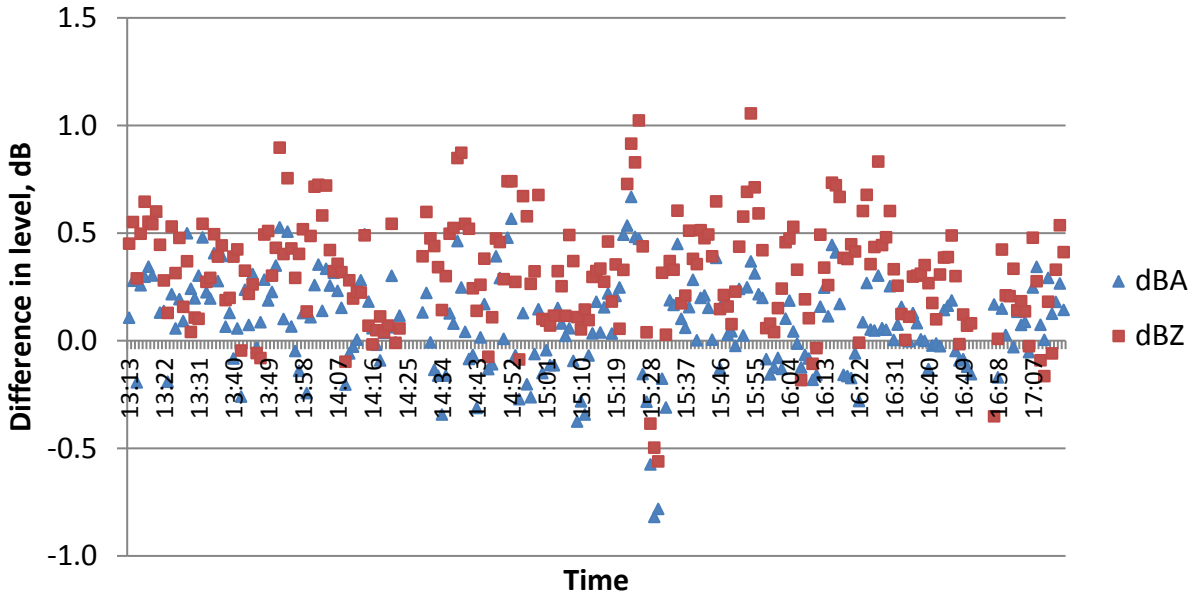


Figure 17. Differences in running L_{eq} (5 min.), I-24, BarCom04 minus NoBarCom06.

Equivalent Groups

All 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 visually depicts groupings 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-." While all 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 shown 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.

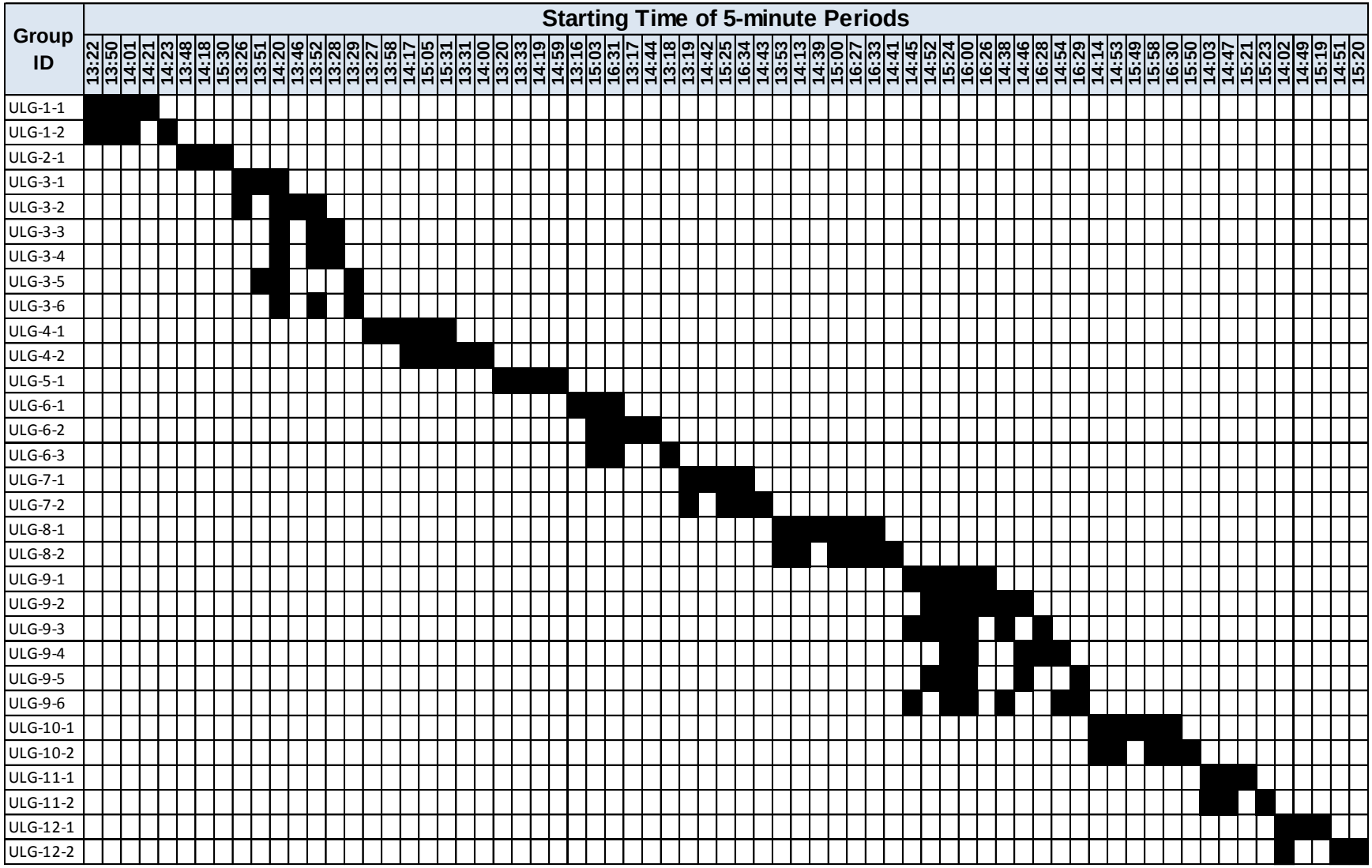


Figure 18. Equivalent 5-minute periods for Upwind Lapse groups at I-24.

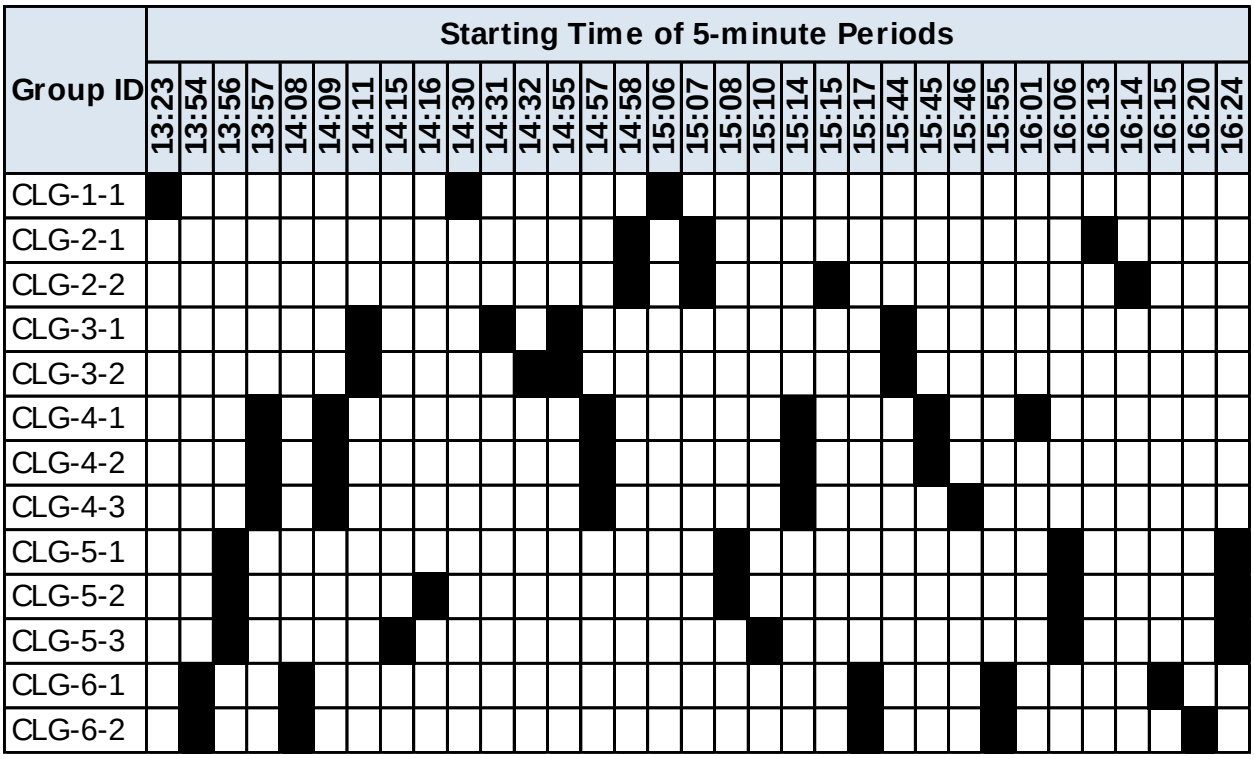


Figure 19. Equivalent 5-minute periods for Calm Lapse groups at I-24.

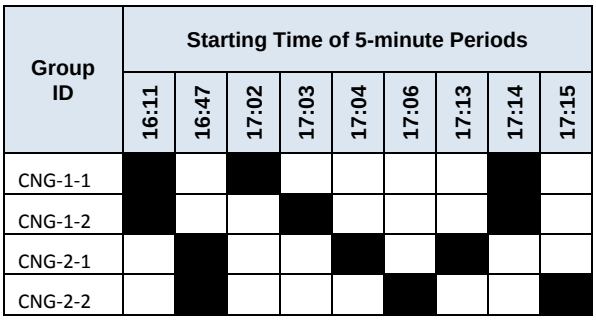


Figure 20. Equivalent 5-minute periods for Calm Neutral groups at I-24.

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

Group	Two-Way Traffic Volumes (5 minutes)						Factored Hourly Volume (vph)
	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	
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

Group	Two-Way Traffic Volumes (5 minutes)						Factored Hourly Volume (vph)
	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	
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 on 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.

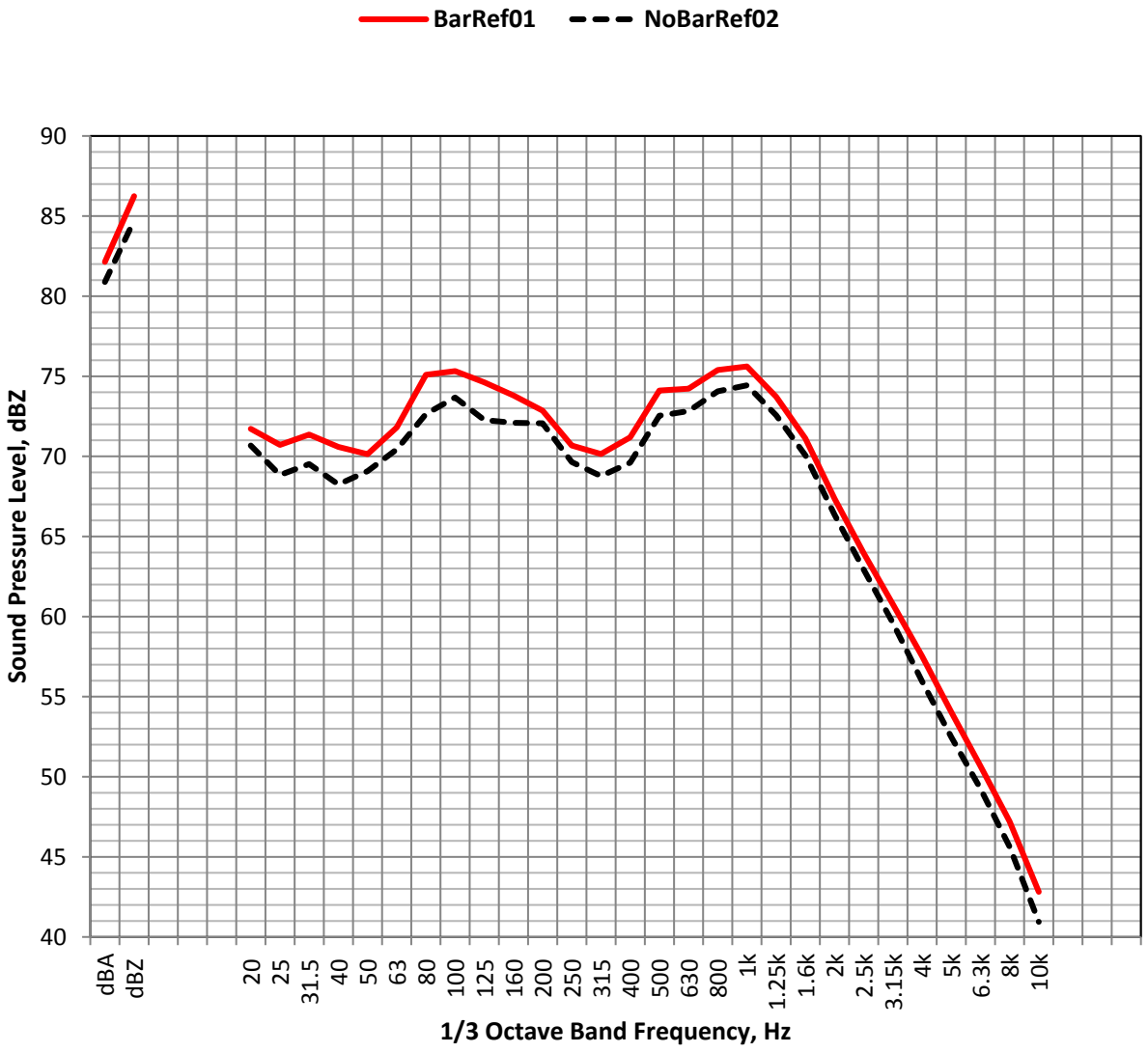


Figure 21. Sample sound pressure level spectra for BarRef01 and NoBarRef02, I-24, Upwind Lapse group ULG-3-2, 13:26 to 13:31 (L_{eq} (5 min.), dBZ).

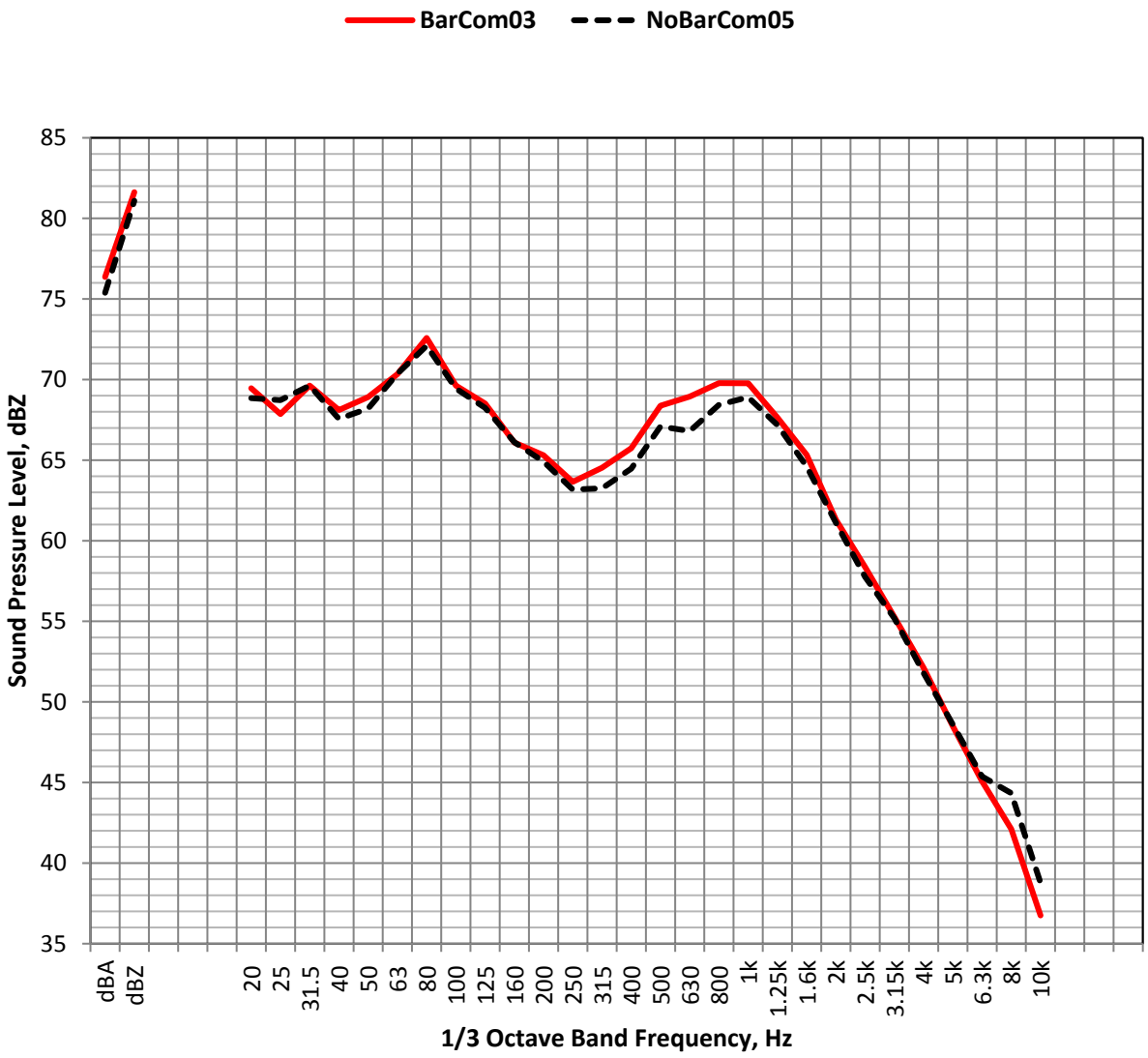


Figure 22. Sample sound pressure level spectra for BarCom03 and NoBarCom05, I-24, Upwind Lapse group ULG-3-2, 13:26 to 13:31 (L_{eq} (5 min.), dBZ).

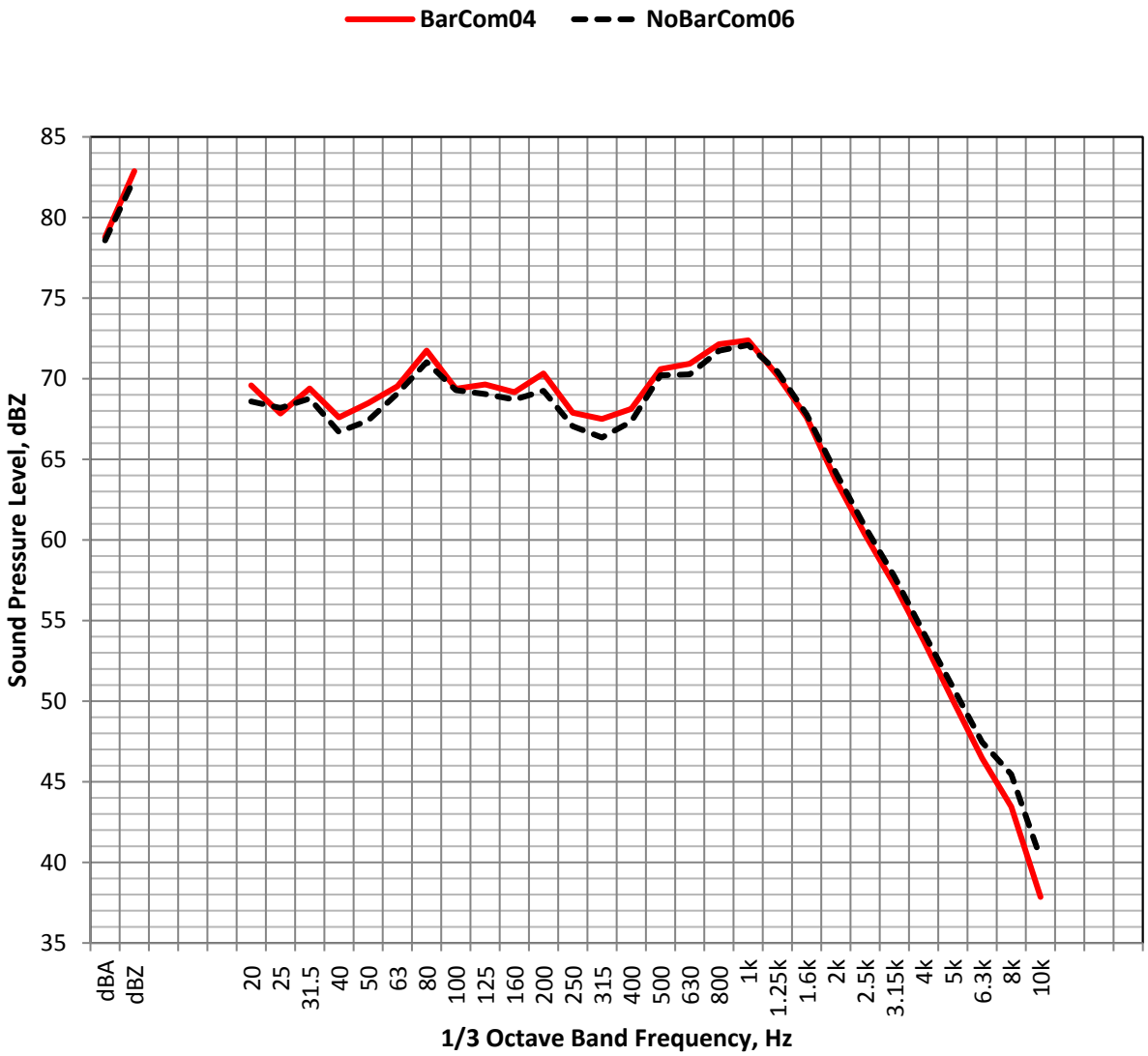


Figure 23. Sample sound pressure level spectra for BarCom04 and NoBarCom06, I-24, Upwind Lapse group ULG-3-2, 13:26 to 13:31 (L_{eq} (5 min.), dBZ).

Upwind Lapse Class

Figure 24 shows three graphs of the differences in level between comparable microphones for an average of all 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.
- 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 one-third octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all the individual Upwind Lapse groups are in spreadsheet files in the project record. The trends across the one-third 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 5 ft. 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 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 ft. above the roadway surface. The results show that the BarCom04 levels in the frequency bands from 20 Hz 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 the 5-minute periods in all the groups were not equivalent in traffic volume and speed across all the groups, these average differences show consistency with the results in the individual groups.

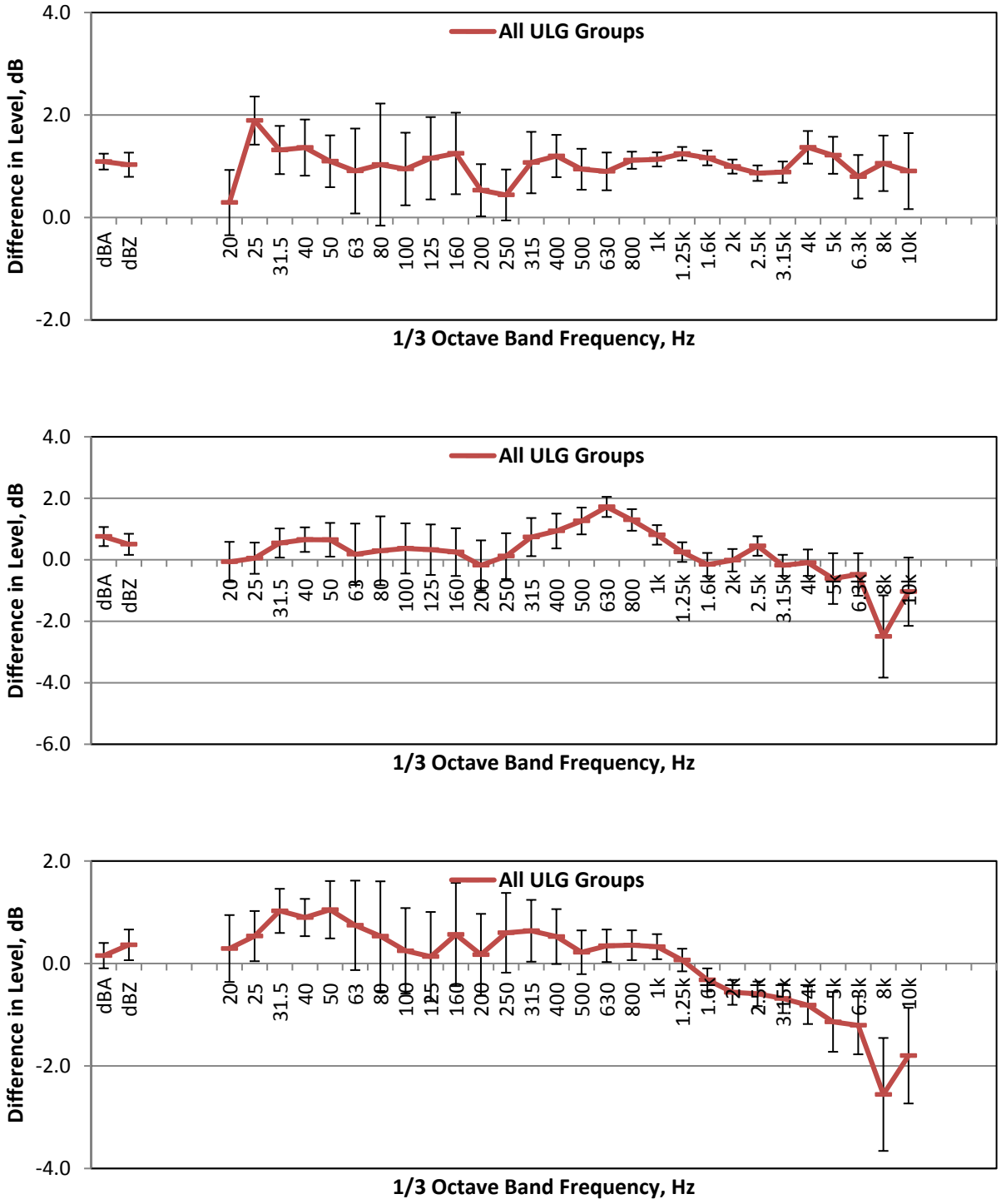


Figure 24. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Upwind Lapse groups, I-24.

Calm Lapse Class

Figure 25 shows the averages of the average level differences between the Barrier and No Barrier microphones' levels for all 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 like those for the Downwind Lapse class for all three microphone pairs.

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

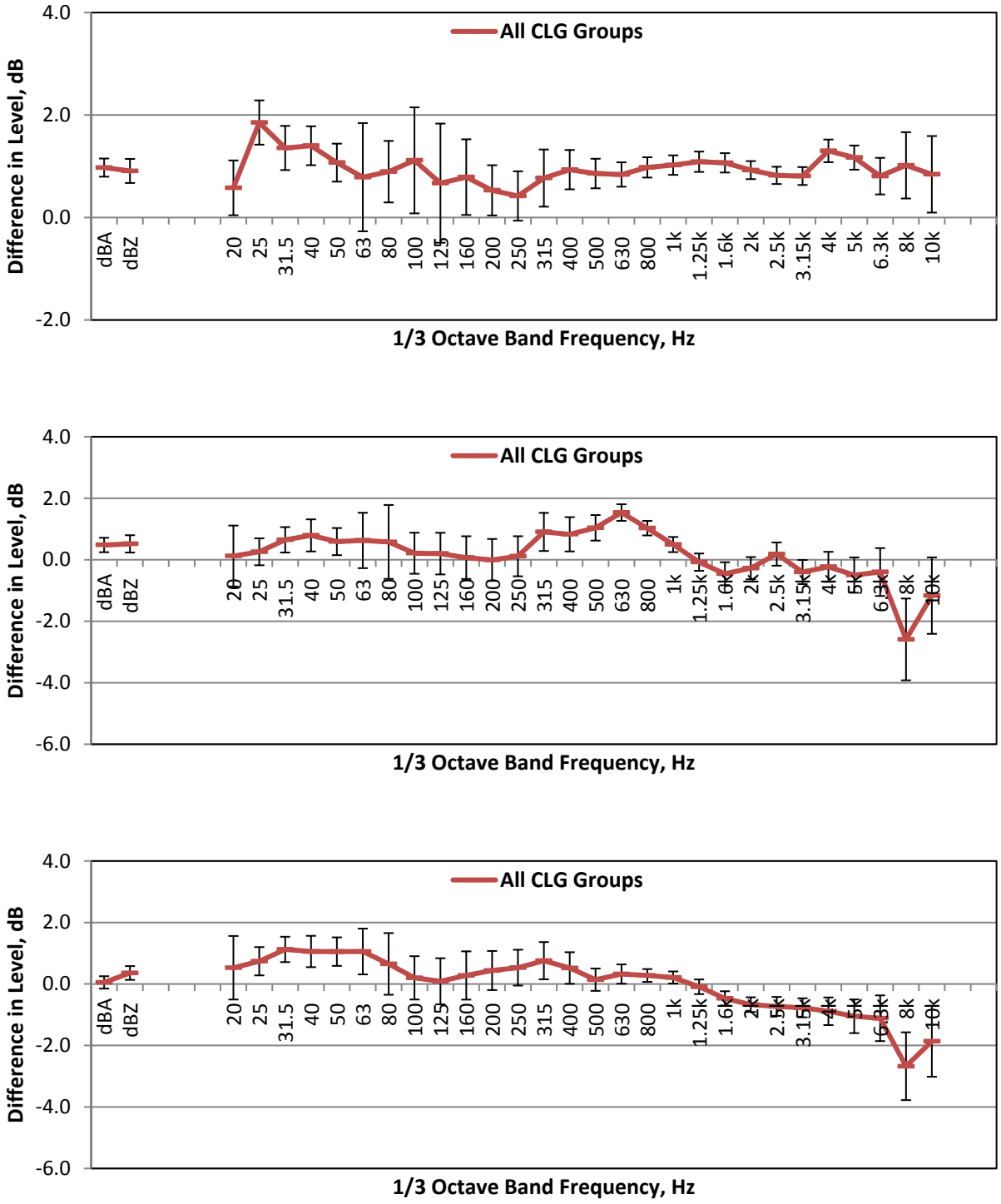


Figure 25. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Lapse groups, I-24.

Calm Neutral Class

Figure 26 shows the averages of the average level differences between the Barrier and No Barrier microphones' levels for all the Calm Neutral groups, with their error bars. Graphs for all 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 the 5-minute periods in all the groups were not equivalent in traffic volume and speed across all the groups, these average differences show consistency with the results in the individual groups.

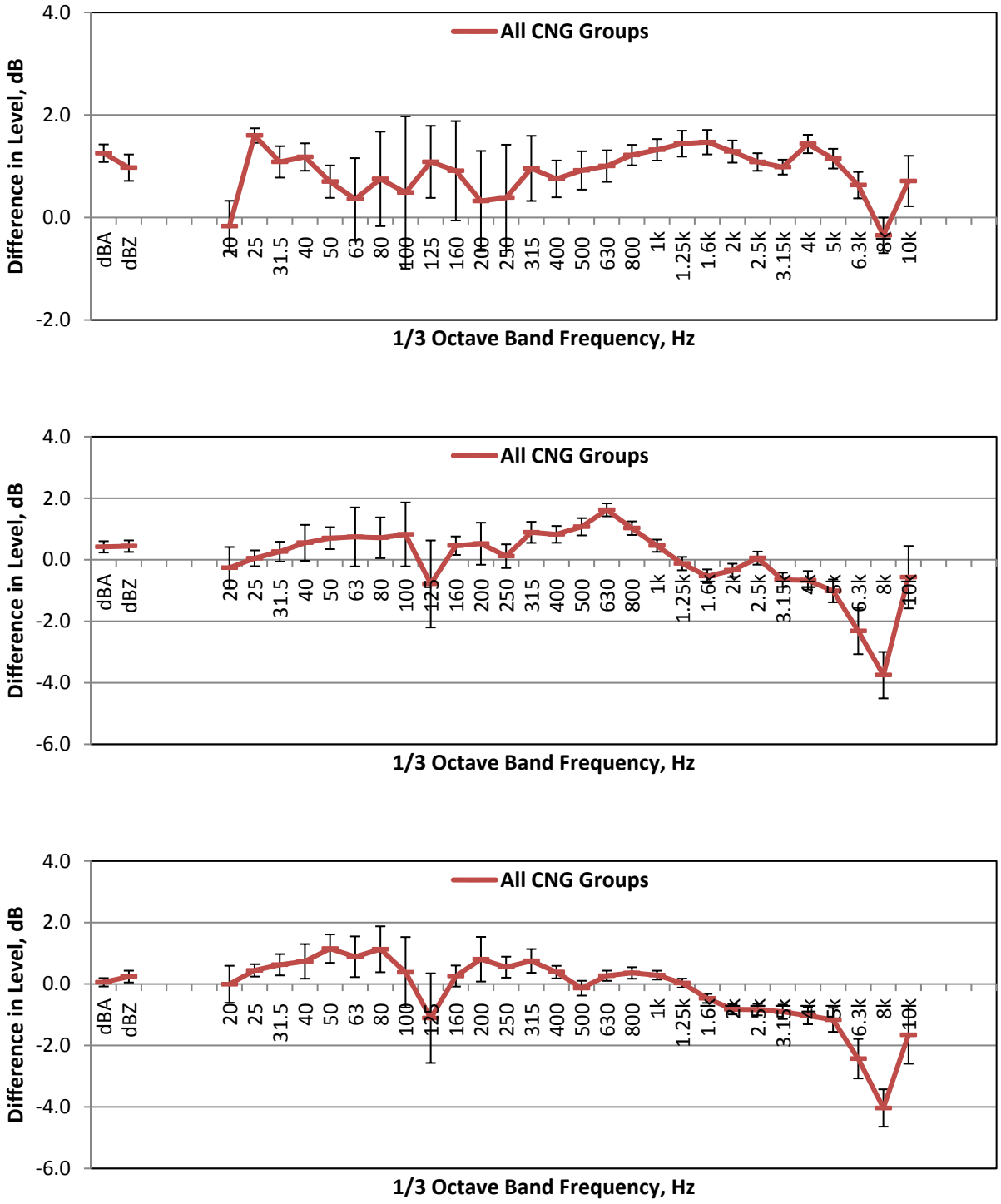


Figure 26. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Neutral groups, I-24.

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 Upwind Lapse average differences tend to be as follows:

- Slightly smaller than the Calm Lapse average differences in the lower-frequency bands.
- 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.

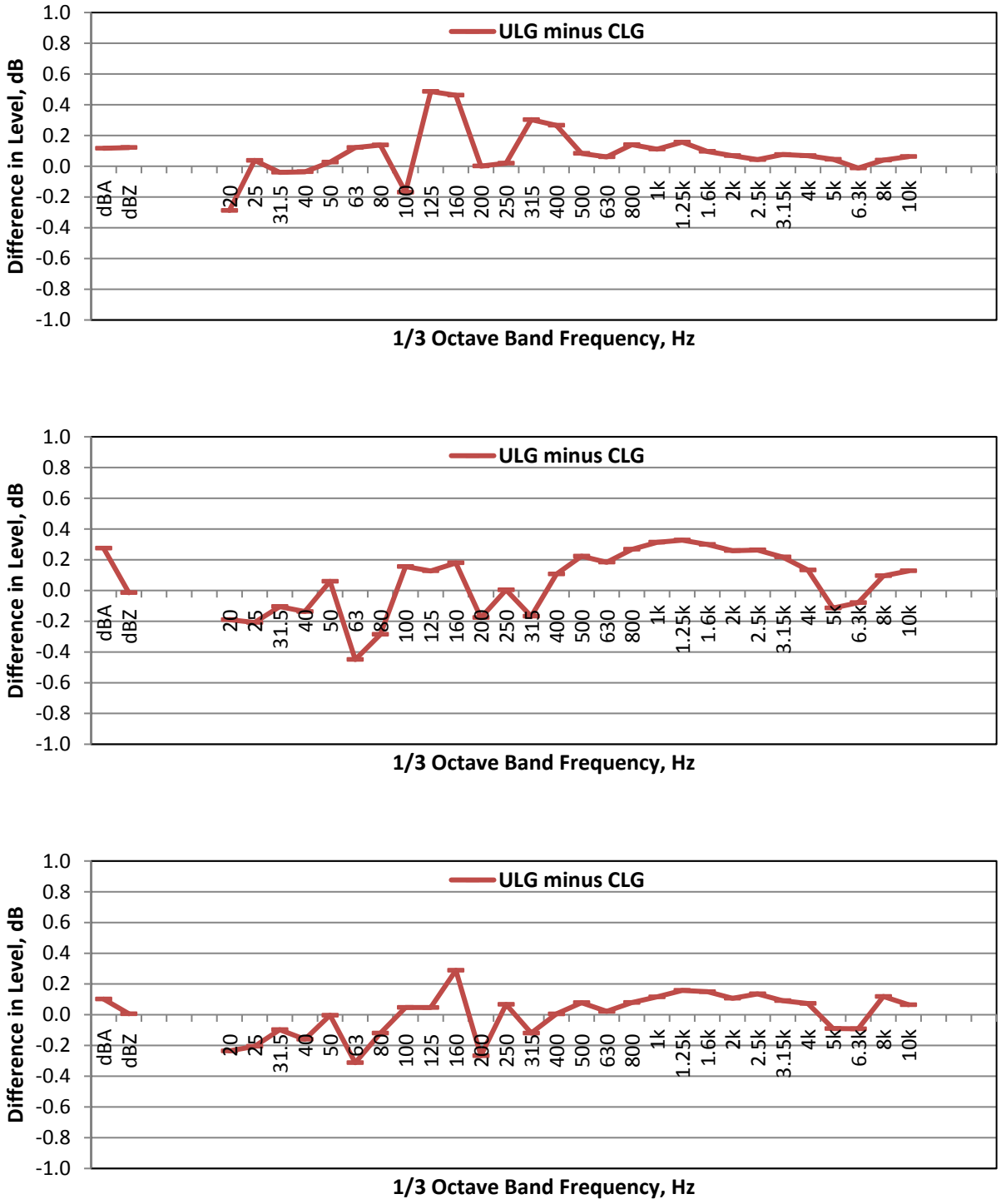


Figure 27. Differences in the Upwind Lapse average differences and the Calm Lapse average differences (L_{eq} (5 min.) +/- one standard deviation, dB), all microphones, I-24.

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-minute L_{eq} data, an investigation was made of the differences in the L_n descriptors for the overall data without segregation into equivalent periods. This investigation focused on the possible change in the background level in the presence of the noise barrier. Figure 28 presents the L_{90} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.), computed as BarRef01 minus NoBarRef02 for the A-weighted sound levels.

The results show that while the L_{eq} (5 min.) 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} (5 min.) and L_{99} (5 min.)—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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05. Less evidence exists of the elevated background level at BarCom03 compared to NoBarCom05, which is expected given the dominance of the direct sound from the nearby vehicles. Then, Figure 32 presents the L_{90} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06. More evidence exists 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.

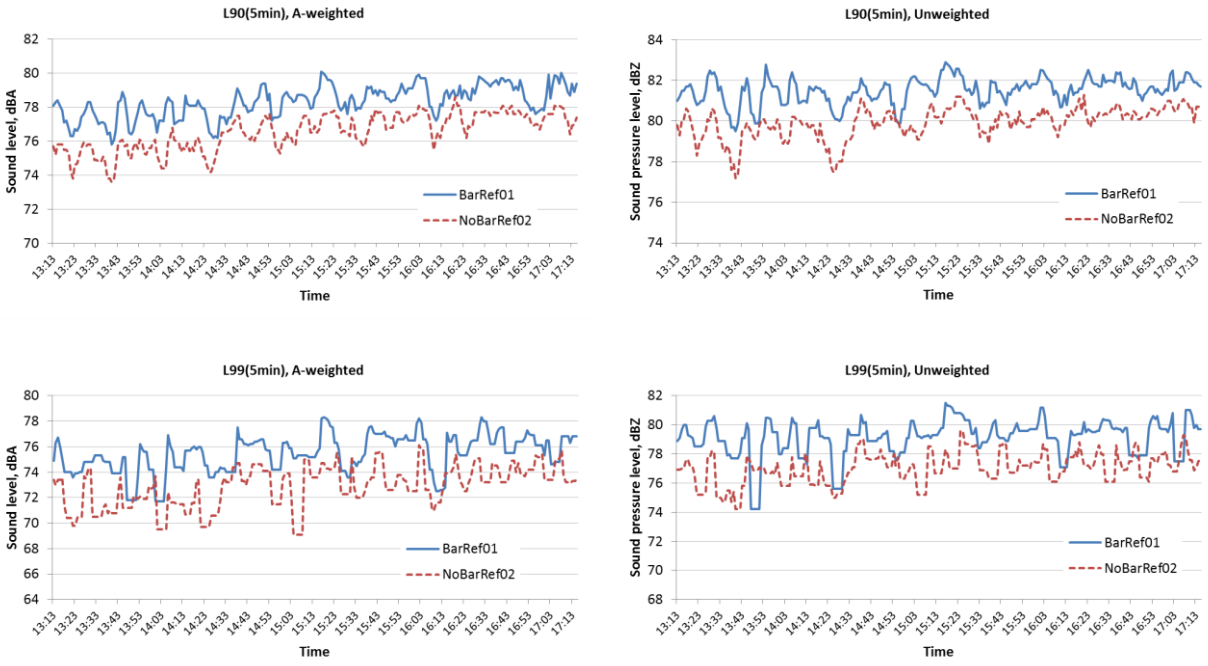


Figure 28. L_{90} (5 min.) and L_{99} (5 min.), I-24, BarRef01 and NoBarRef02—broadband A-weighted sound level and sound pressure level.

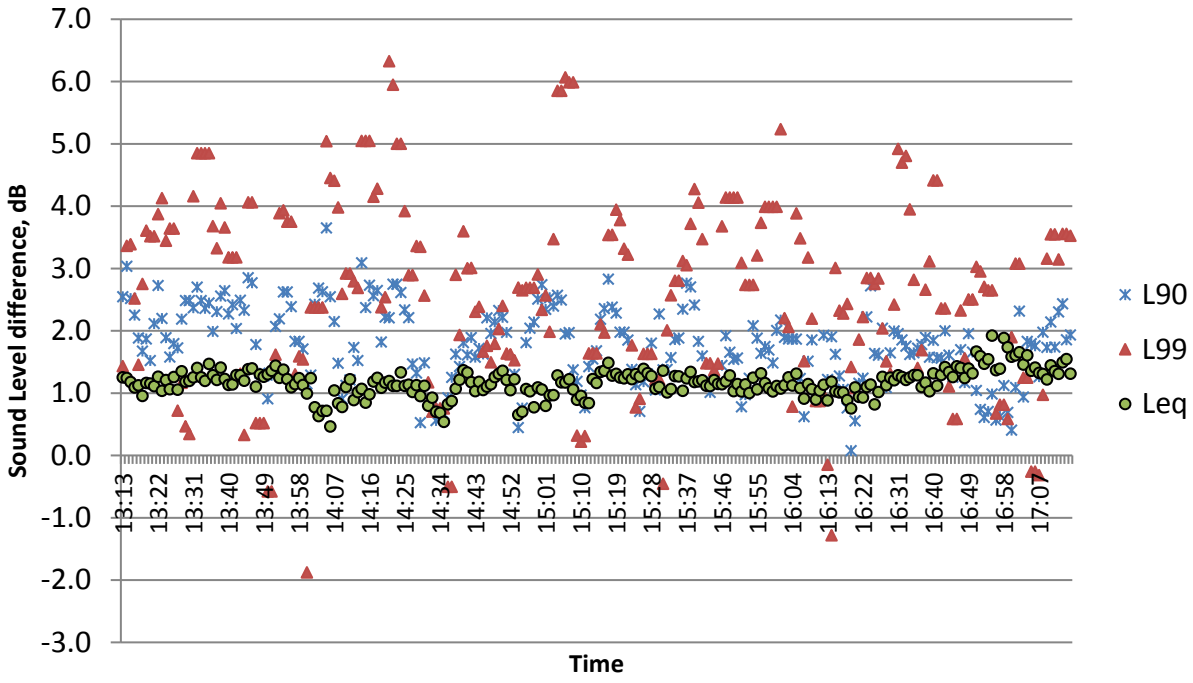


Figure 29. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, I-24, BarRef01 and NoBarRef02.

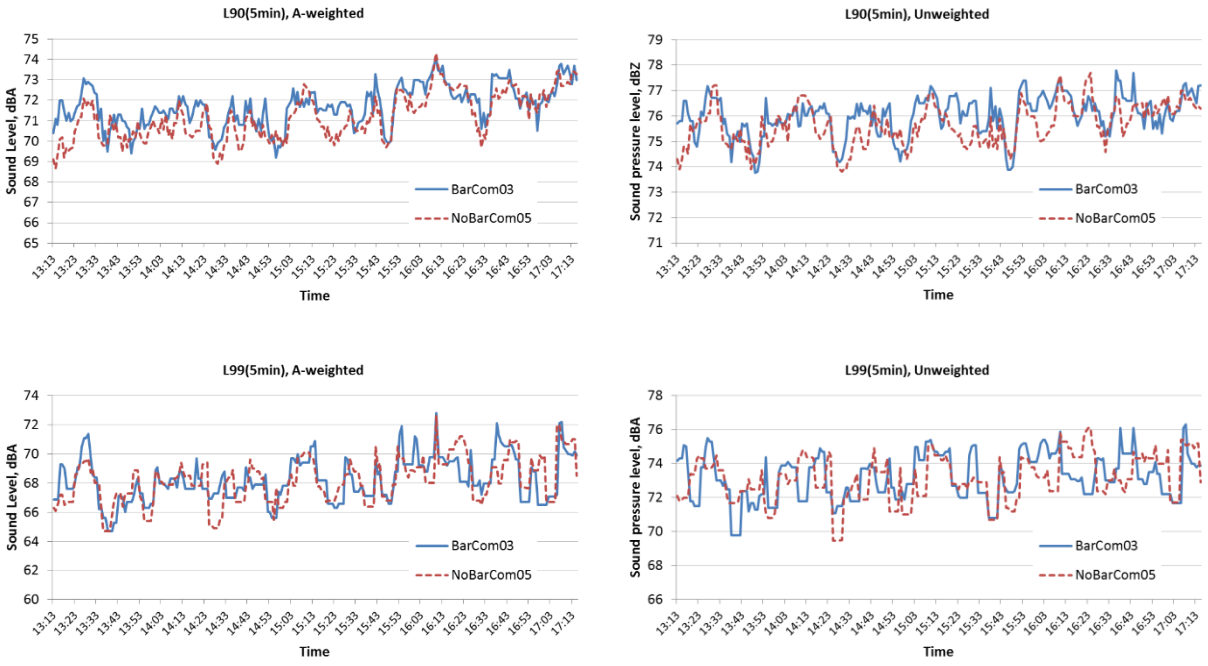


Figure 30. L_{90} (5 min.) and L_{99} (5 min.), I-24, BarCom03 and NoBarCom05—broadband A-weighted sound level (left) and sound pressure level (right).

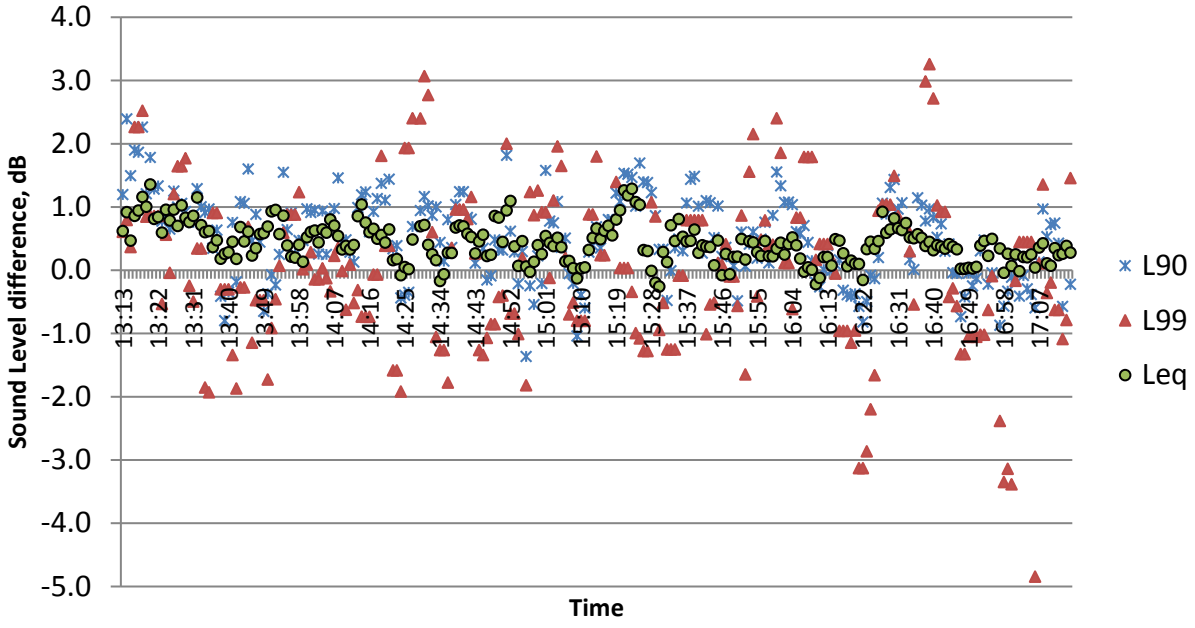


Figure 31. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, I-24, BarCom03 and NoBarCom05.

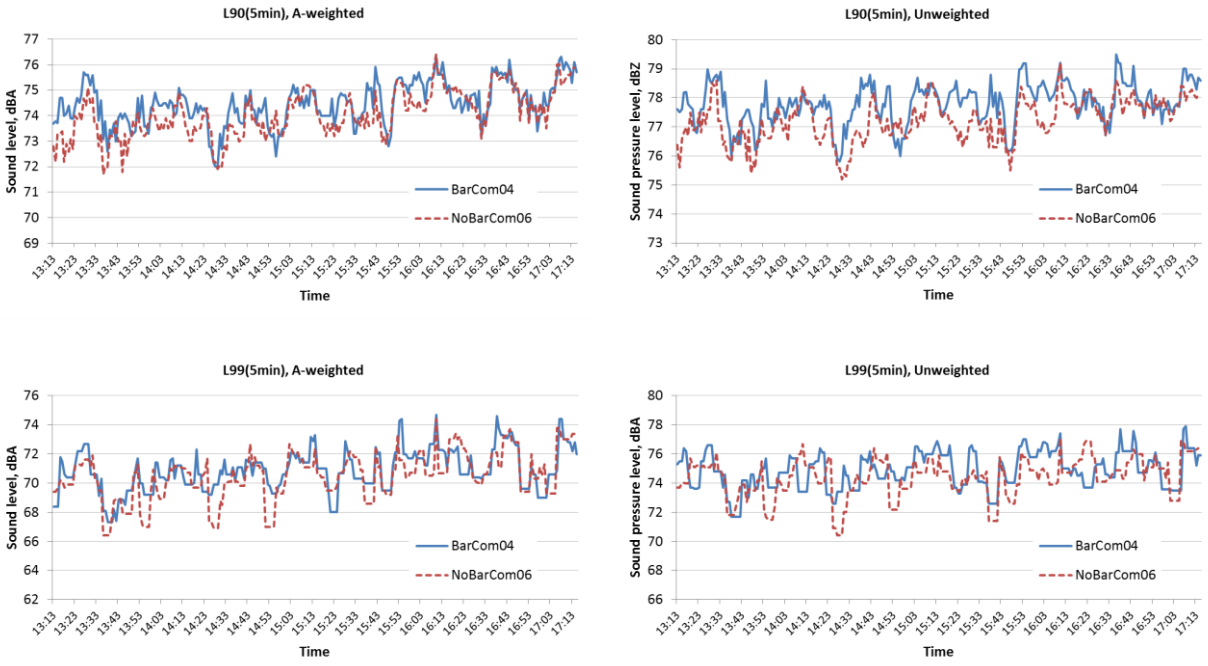


Figure 32. L_{90} (5 min.) and L_{99} (5 min.), I-24, BarCom04 and NoBarCom06—broadband A-weighted sound level (left) and sound pressure level (right).

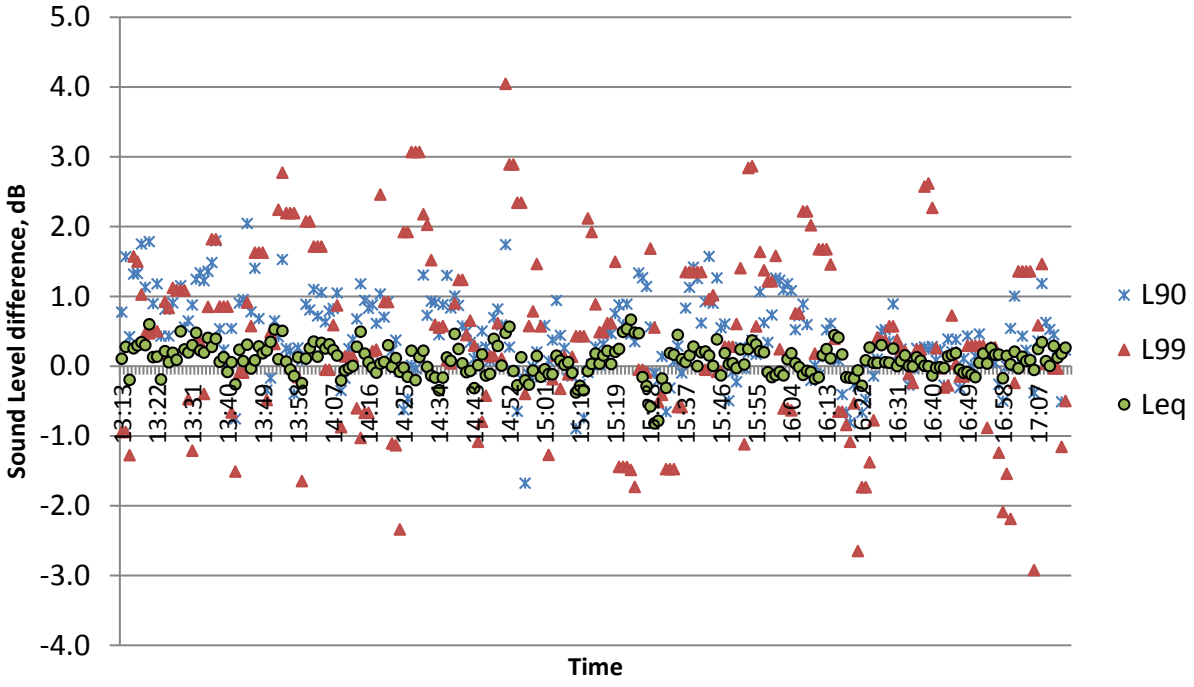


Figure 33. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, I-24, BarCom04 and NoBarCom06.

The preceding graphs were for the broadband A-weighted sound levels and unweighted sound pressure levels only. Figure 34 broadens the analysis to include the individual one-third 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 4 hours. The one-third 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 L_n 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 35 for a single one-third octave band.

Vertical brown streaks are on the right sides of the data columns (representing L_{90} (5 min.) and L_{99} (5 min.)) in the frequency bands from 400 Hz through 2 kHz for most of the sample period and 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, which is evidence of a sustaining of a vehicle's pass-by 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.

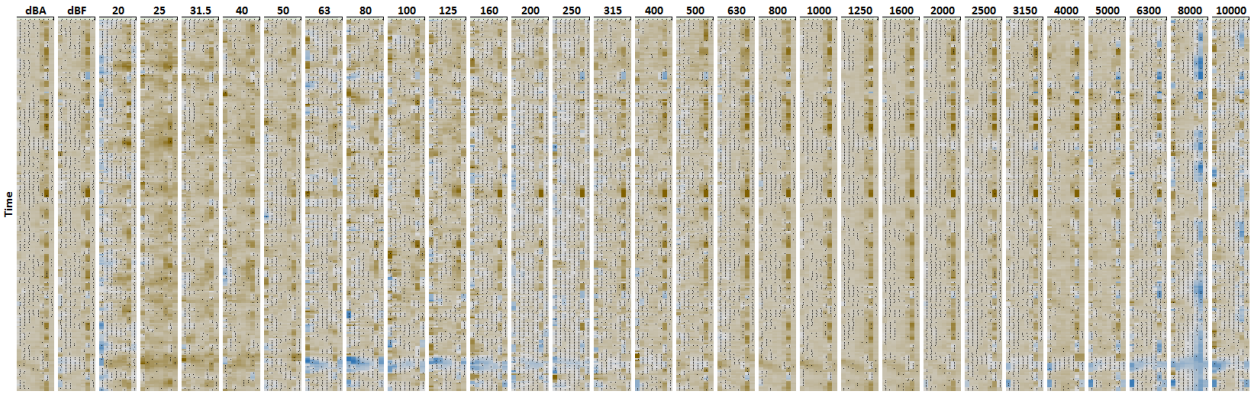


Figure 34. I-24 Differences in L_n (5 min.) by one-third octave frequency bands: BarRef01 and NoBarRef02.

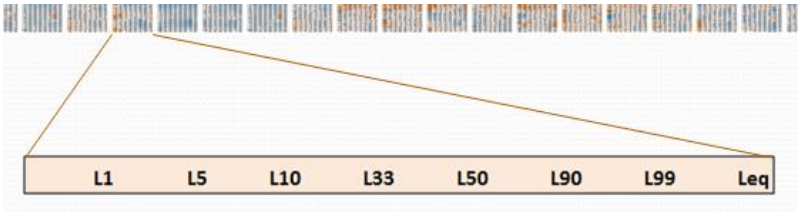


Figure 35. Order of statistical levels for a single one-third octave band.

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. Some evidence exists 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-second data at start of the 5-minute period.

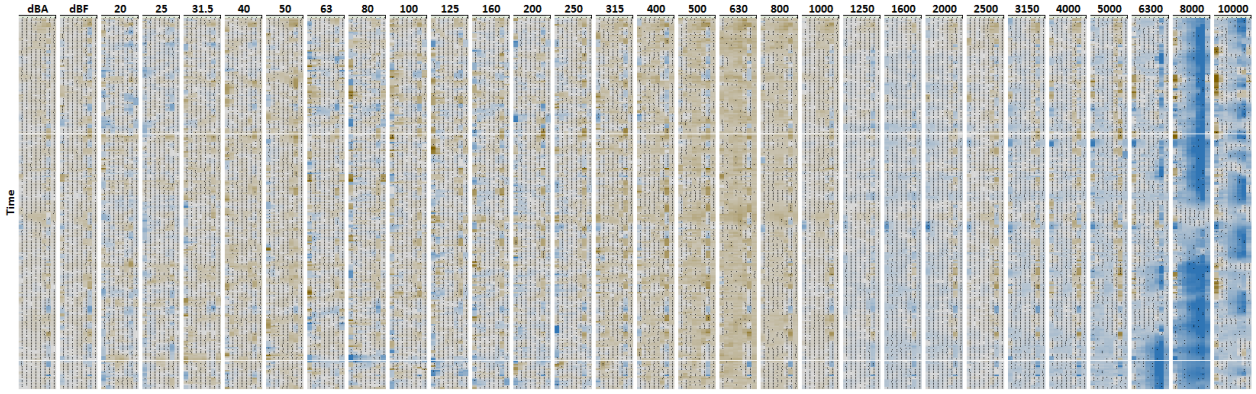


Figure 36. I-24 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom03 and NoBarCom05.

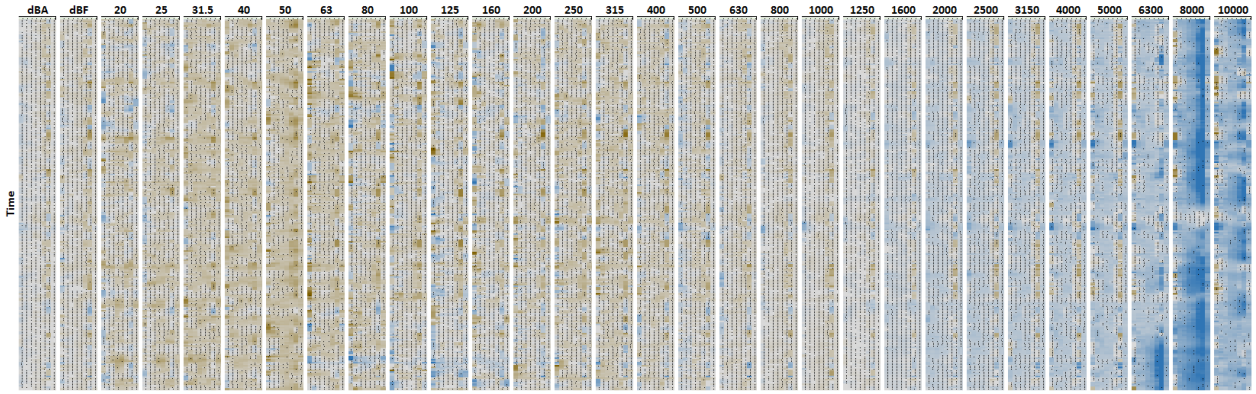


Figure 37. I-24 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom04 and NoBarCom06.

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 and 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; 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 are spectrograms for the reference positions and the high microphone positions, comparing the Barrier and No Barrier sites. Figure 41 shows 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, results indicate 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 to 20 seconds later.
2. For the high and low microphone positions across the highway from the barrier, results indicate 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 to 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.

No clear trends are identified comparing upwind and calm conditions.

Further evidence exists 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 2-minute time block that includes a group of eastbound heavy trucks. The hot spots are broader in frequency and time.

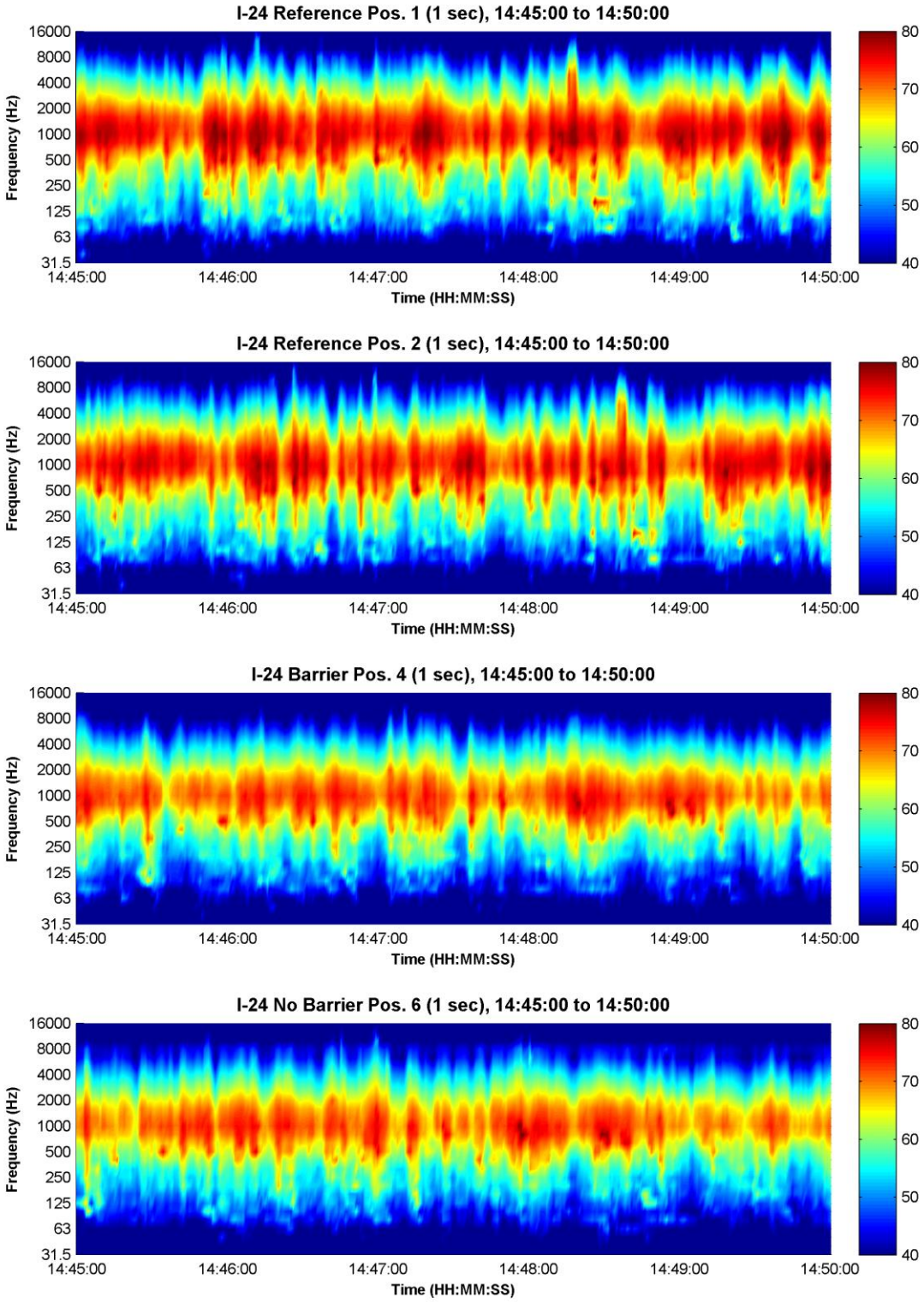


Figure 38. I-24 5-minute spectrograms; top to bottom: BarRef01, NoBarRef02, and high mics (BarCom04 and NoBarCom06); for Upwind Lapse group ULG-9-1, start time 14:45.

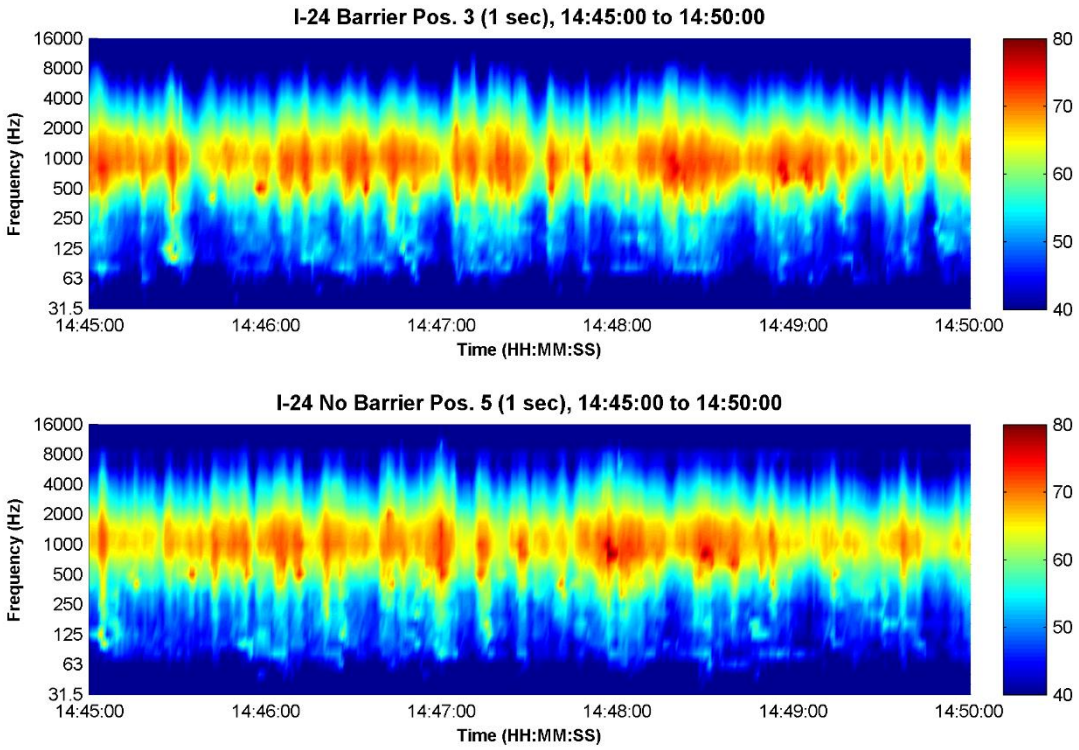


Figure 39. I-24 5-minute spectrograms; top to bottom: low mics BarCom03 and NoBarCom05; for Upwind Lapse group ULG-9-1, start time 14:45.

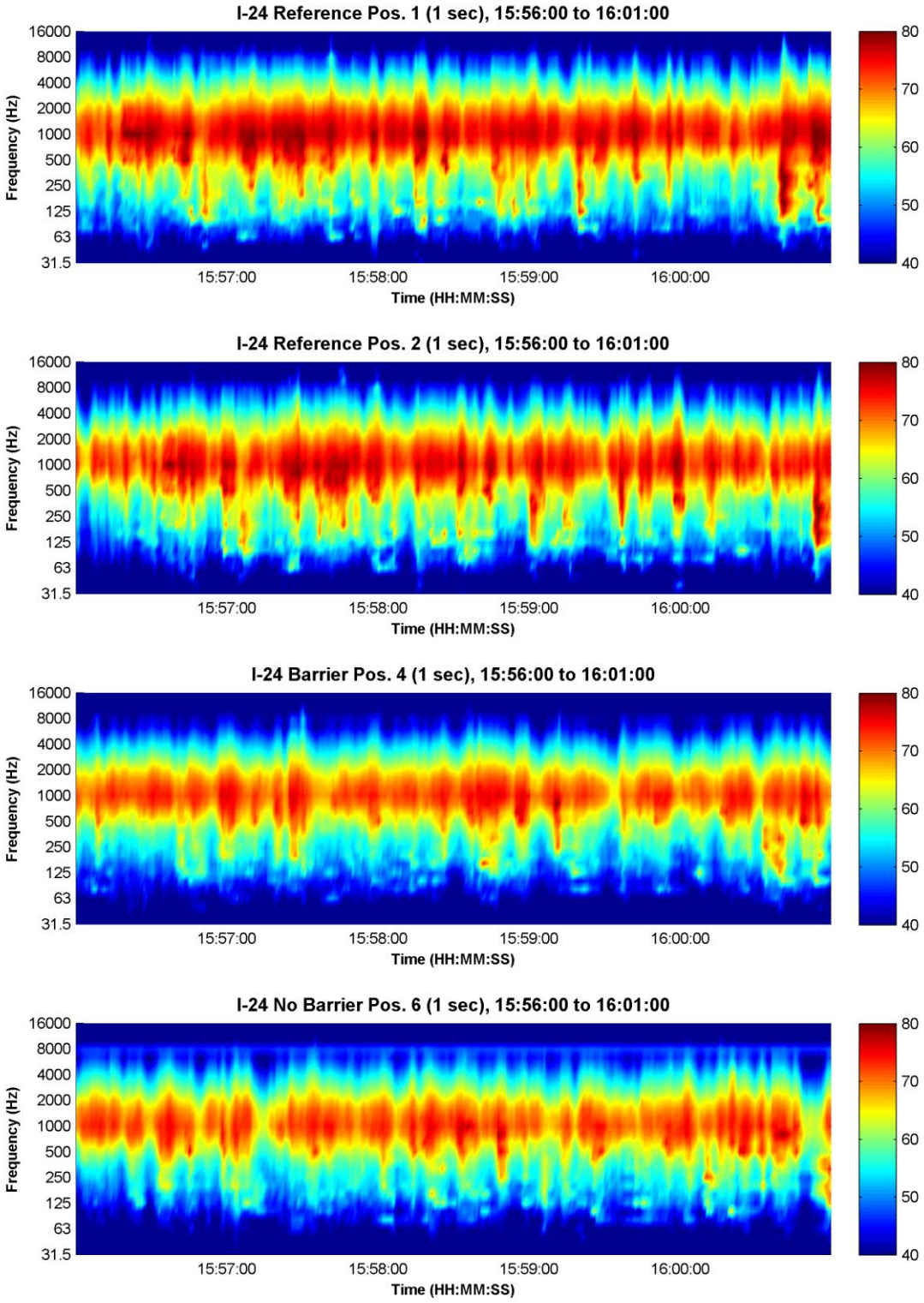


Figure 40. I-24 5-minute spectrograms; top to bottom: BarRef01, NoBarRef02, high mics (BarCom04 and NoBarCom06); for Calm Lapse group CLG-6-1, start time 15:56.

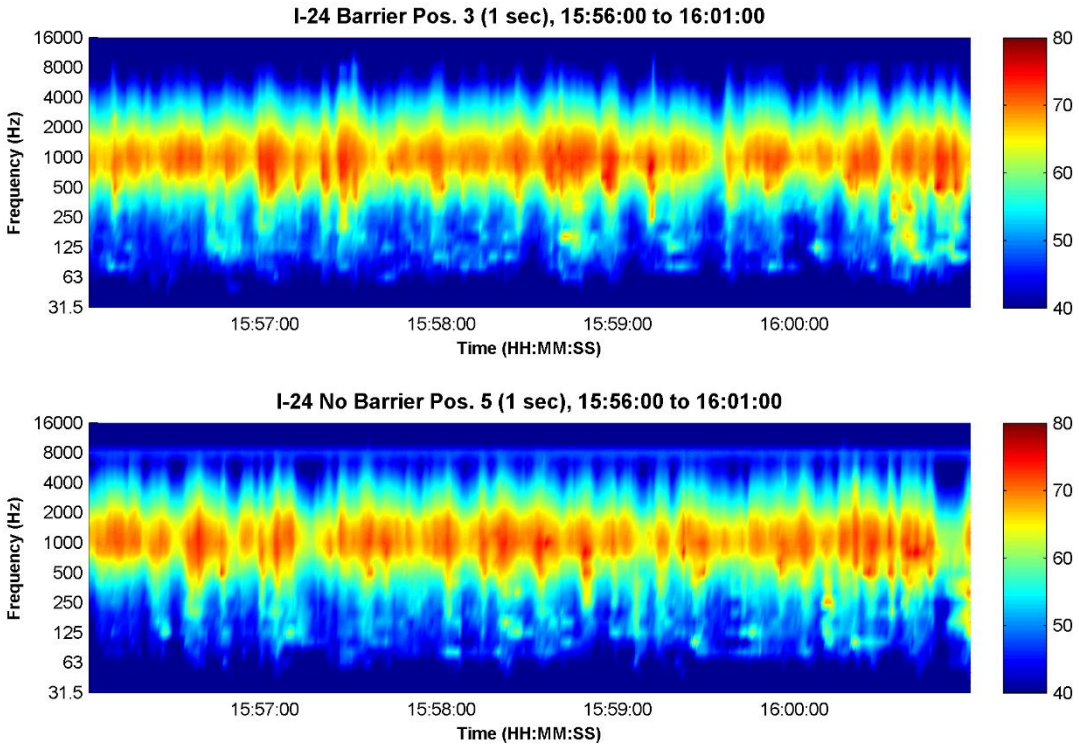


Figure 41. I-24 5-minute spectrograms; top to bottom: low mics BarCom03 and NoBarCom05; for Calm Lapse group CLG-6-1, start time 15:56.

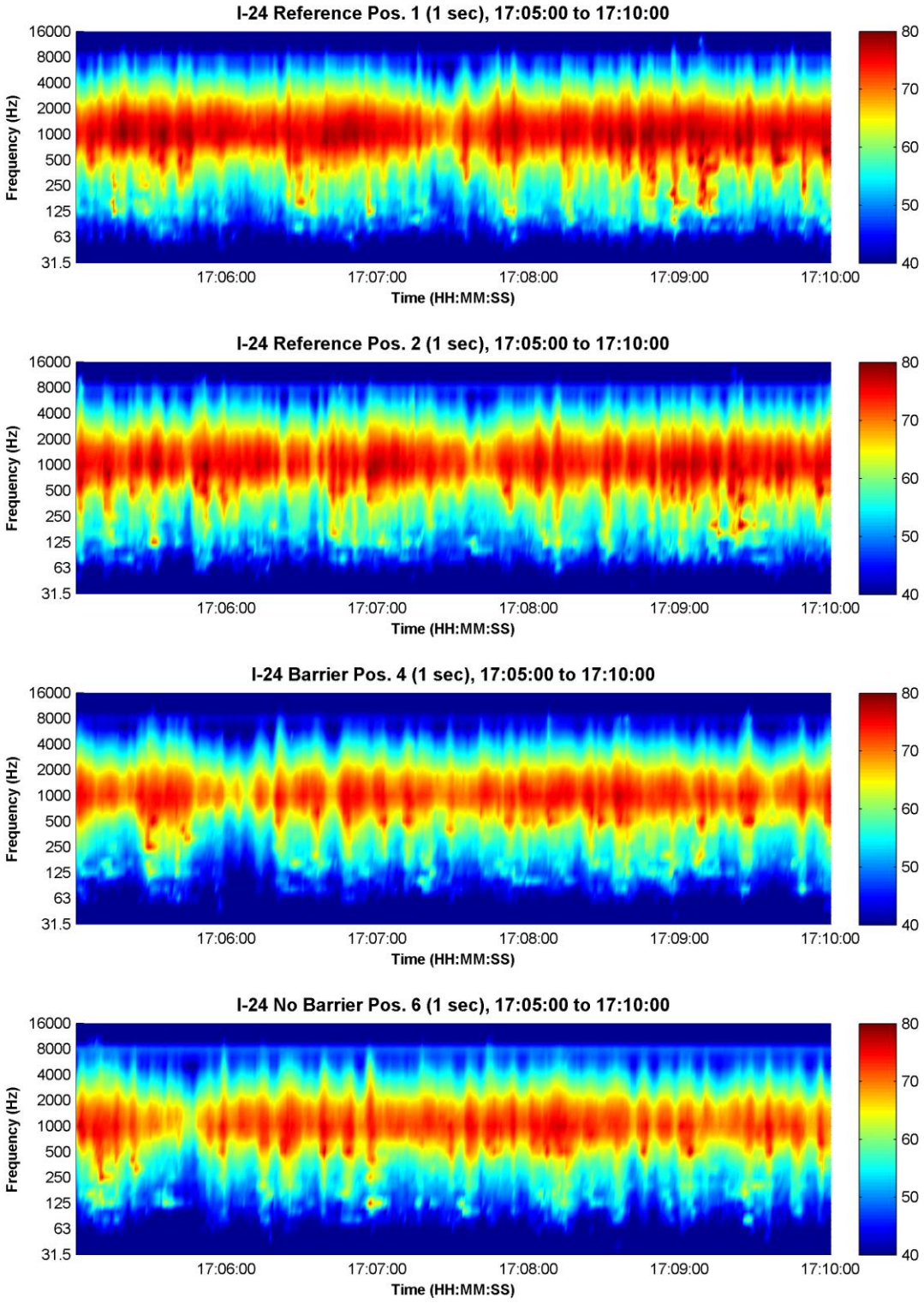


Figure 42. I-24 5-minute spectrograms; top to bottom: BarRef01, NoBarRef02, high mics (BarCom04 and NoBarCom06); for Calm Neutral group CNG-2-1, start time 17:05.

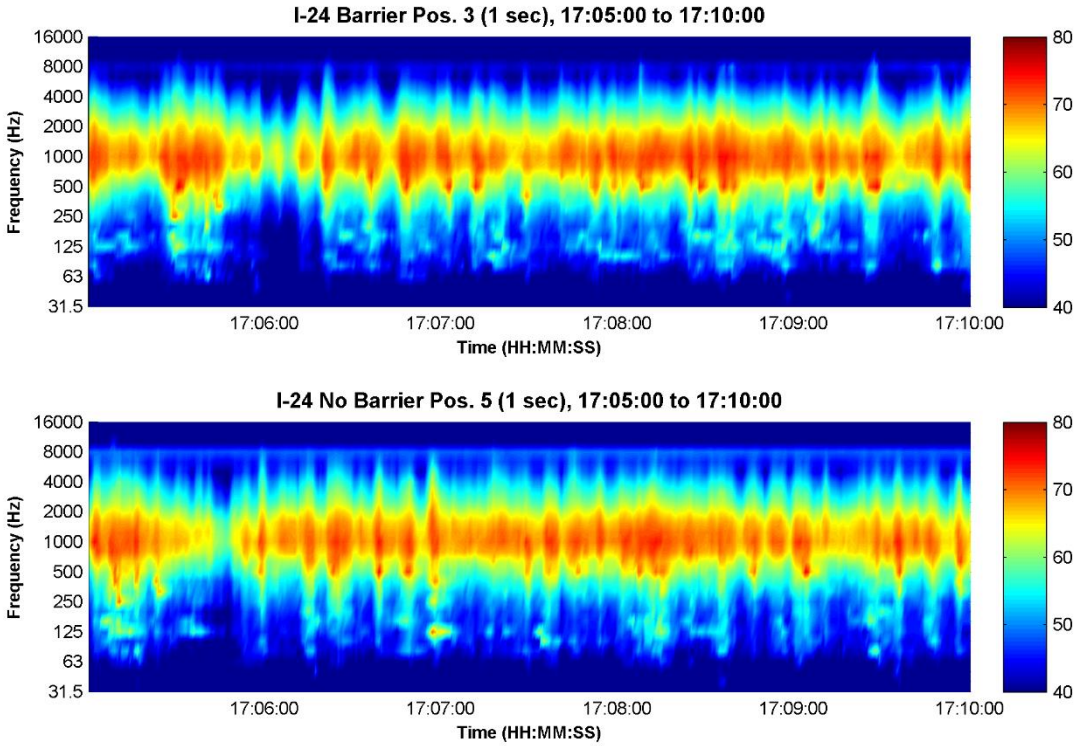


Figure 43. I-24 5-minute spectrograms; top to bottom: low mics BarCom03 and NoBarCom05; for Calm Neutral group CNG-2-1, start time 17:05.

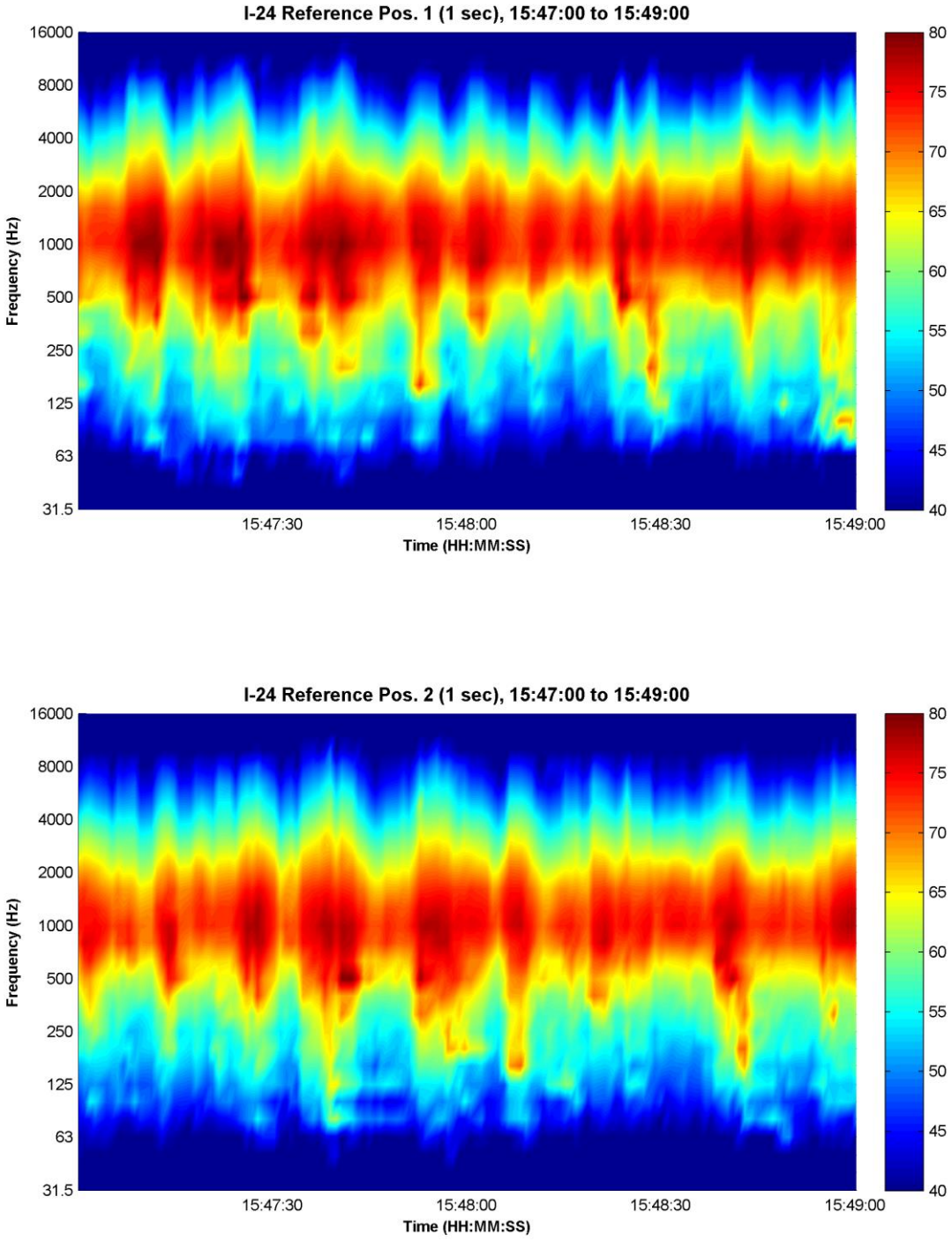


Figure 44. I-24 spectrograms for a group of heavy trucks; top to bottom: BarRef01, NoBarRef02.

Data Analysis—Psychoacoustics for I-24

Table 6 summarizes descriptive statistics for the computed annoyance metrics at I-24. 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. Significant electronic noise contamination occurred at very high frequencies throughout the audio recordings. The contamination differed for each microphone channel. The contamination strongly influenced 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 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 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 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.

A clear difference exists in the means of the UBA between the Barrier and No Barrier locations for both the higher and lower microphones. The same difference is seen in the PA. Since the microphones at this site were stacked and share the same moderate distance to the roadway, the similarity in deviations of the means (slightly less than one standard deviation) may indicate a true difference in the metrics. However, the Barrier microphones have lower mean annoyance than 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.

No significant difference exists in the means of the CSA 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	Microphone	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

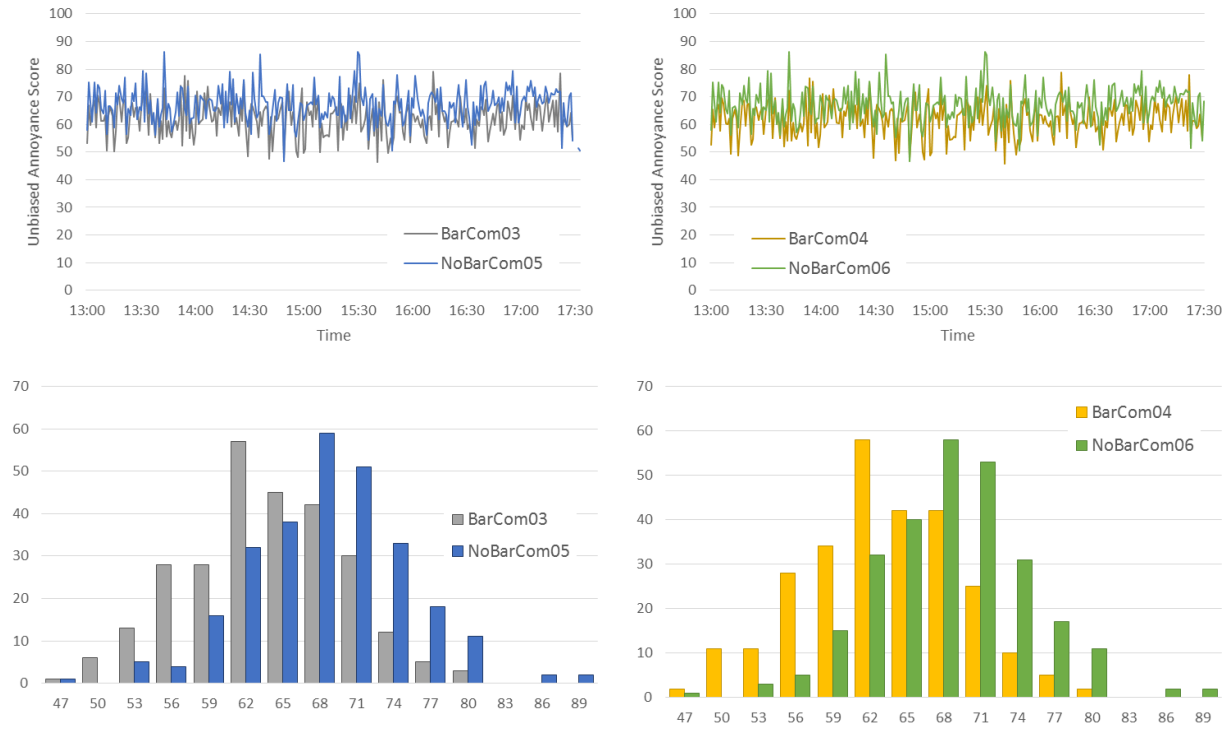


Figure 46. UBA metric vs. time and histograms, I-24.

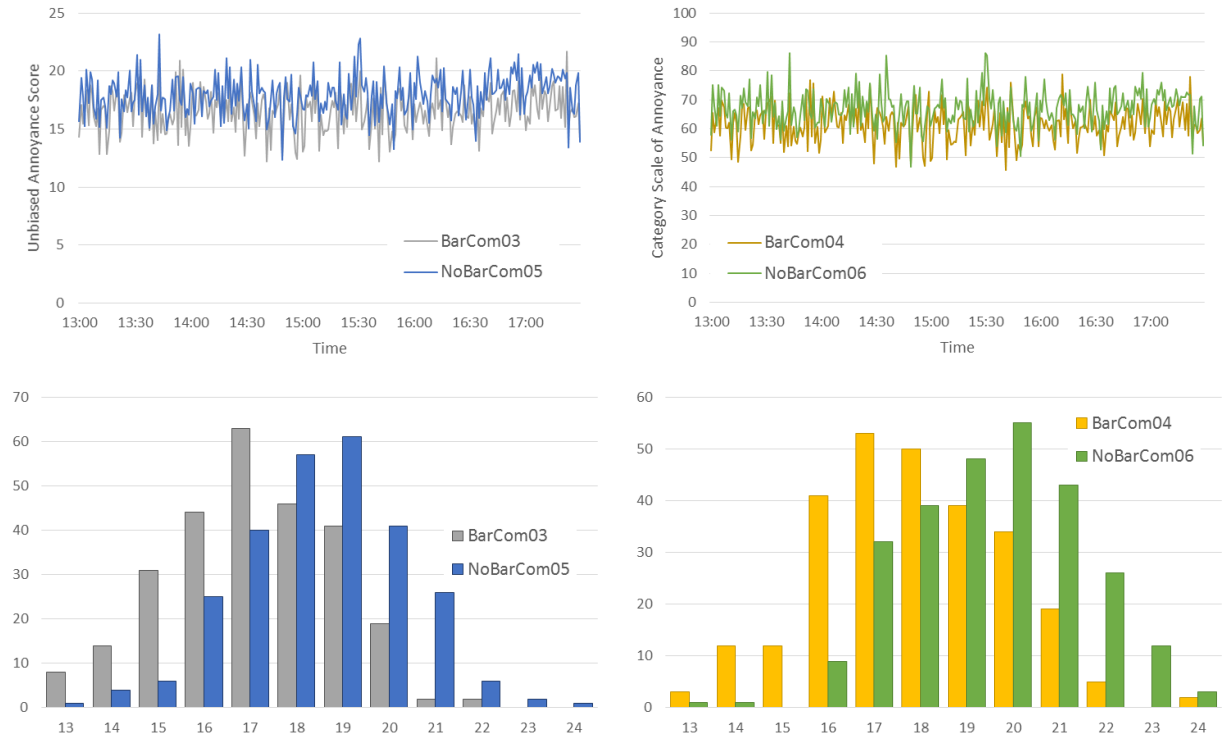


Figure 47. PA vs. time and histograms, I-24.

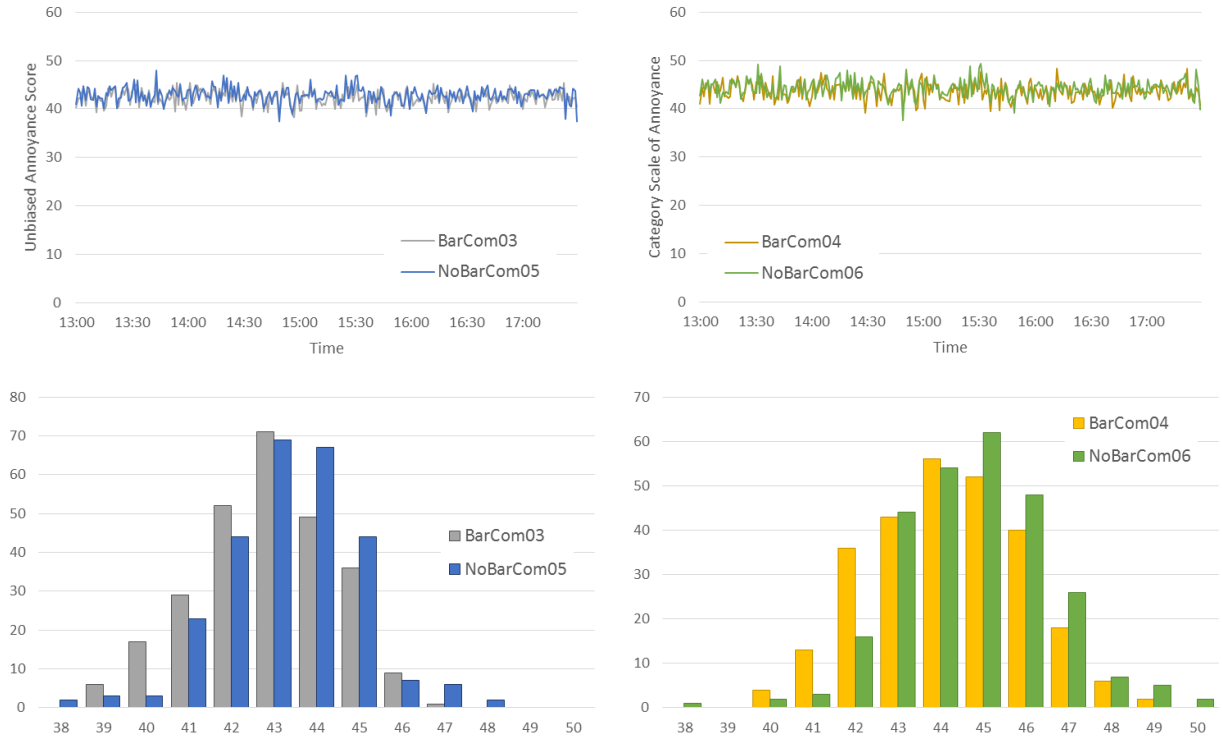


Figure 48. CSA vs. time and histograms, I-24.

CHAPTER E-4

Results—Briley Parkway (SR-155), Nashville, Tennessee (Location BA-3)

The Briley Parkway ("Briley") noise measurements and traffic speed measurements began at 17:04 on August 14, 2014, 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° F range, dropping into the low-70° F 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. 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, 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 F (available online) contains site photographs. Figure 50 shows cross-sections at the Barrier and No Barrier sites.

The microphone positions were as shown in Table 7.

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	n/a	n/a	n/a
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-shape parapet at the edge of shoulder

Figure 49. Briley microphone positions. (Source: Google Earth.)

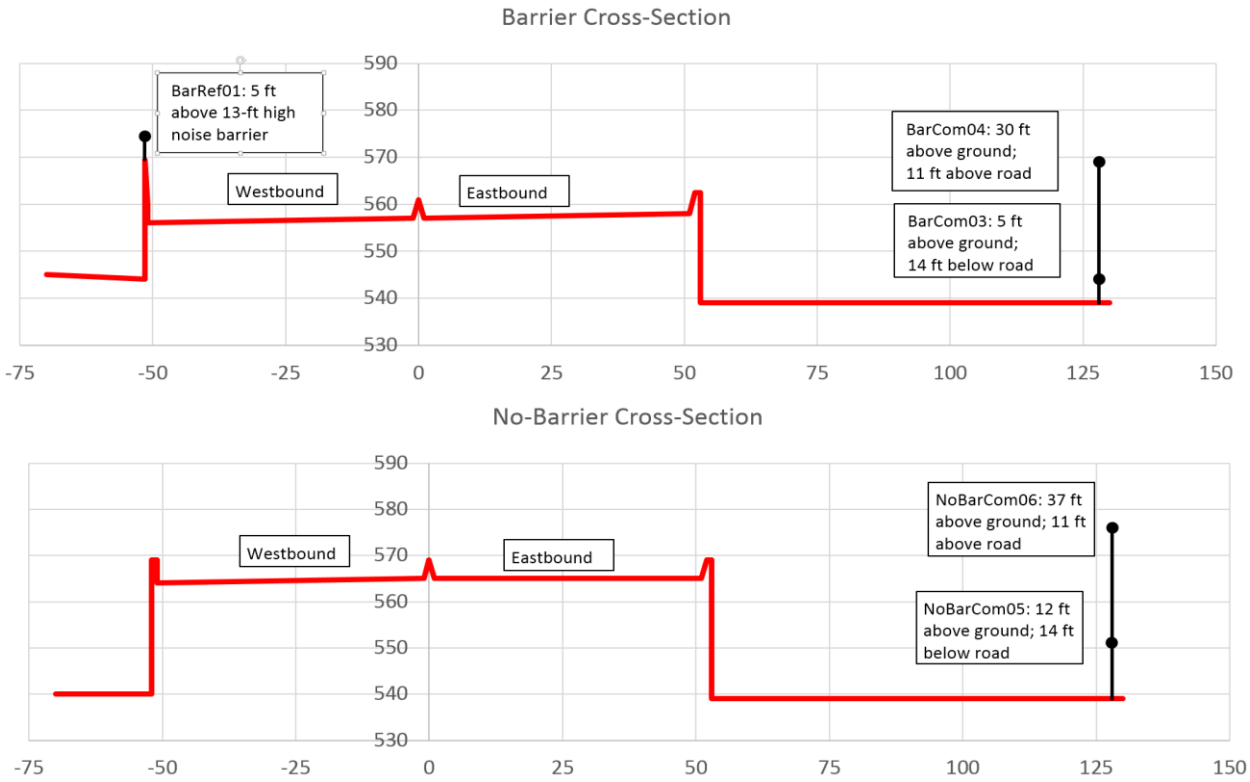


Figure 50. Cross-sections at the Briley Parkway Barrier (top) and No Barrier (bottom) sites.

Measurement Observations

Traffic was observed from an overpass about one-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 mph 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 common. 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 positions 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 pass-bys in both directions were distinguishable by vehicle type and by direction even though the vehicles could not be seen.

At BarCom03/04, 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 NoBarCom05/06 to BarCom03/04 halfway through the measurements, he noted that the westbound traffic noise was more audible than at NoBarCom05/06 and that westbound heavy truck pass-bys could be more readily identified. Eastbound automobiles were also more easily identified that at NoBarCom05/06. Part of the reason for them sounding louder is that the ground the observer was standing on was 7 ft. higher relative to Briley Parkway at BarCom03/04 than at NoBarCom05/06, although the microphone heights were set relative to the roadway elevation at each site. Some eastbound vehicle tire noise was audible at BarCom03/04, which was not the case at NoBarCom05/06. Eastbound truck pass-by 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 BarCom03/04 when traffic was light.

Starting at NoBarCom05/06 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 NoBarCom05/06 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 NoBarCom05/06, 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, a bird chirping in the 2,500 Hz range at around 18:30, and a small dog barking (800 to 1,200 Hz) at around 18:33 to 18:35.

Measured Broadband Levels and Level Differences for Briley Parkway

The running L_{eq} (5 min.) 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 ft. above the barrier top)—Figure 51 and Figure 52.
- BarCom03 and NoBarCom05 (14 ft. below the roadway)—Figure 53 and Figure 54.
- BarCom04 and NoBarCom06 (11 ft. above the roadway)—Figure 55 and Figure 56.

In general, the figures show how the running L_{eq} (5 min.) 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 become 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.

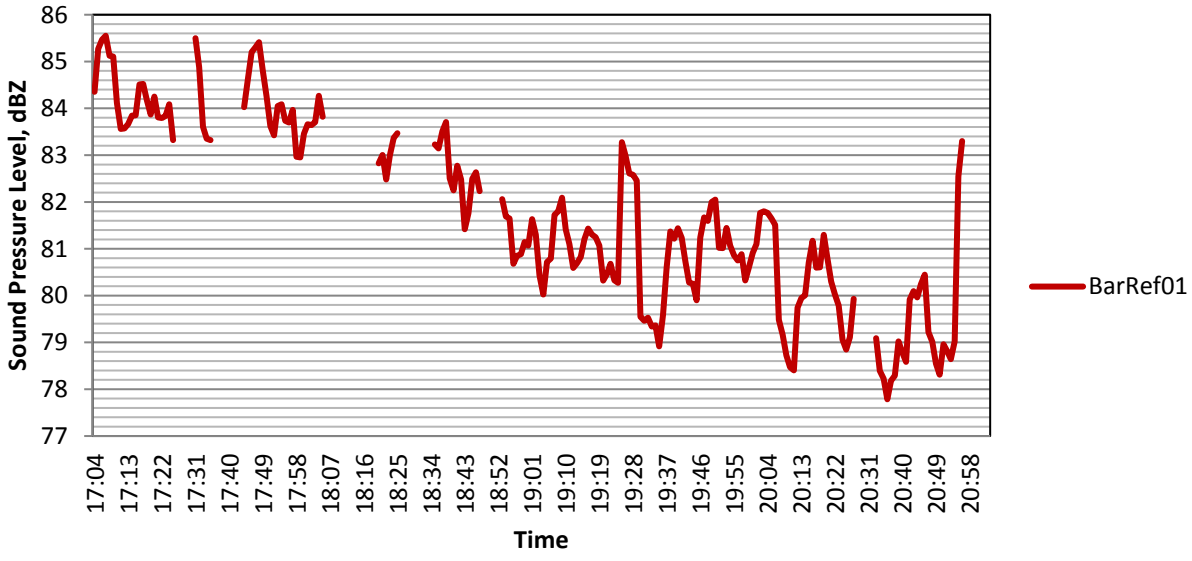


Figure 51. Running L_{eq} (5 min.), Briley Parkway, unweighted sound pressure level, dBZ, BarRef01.

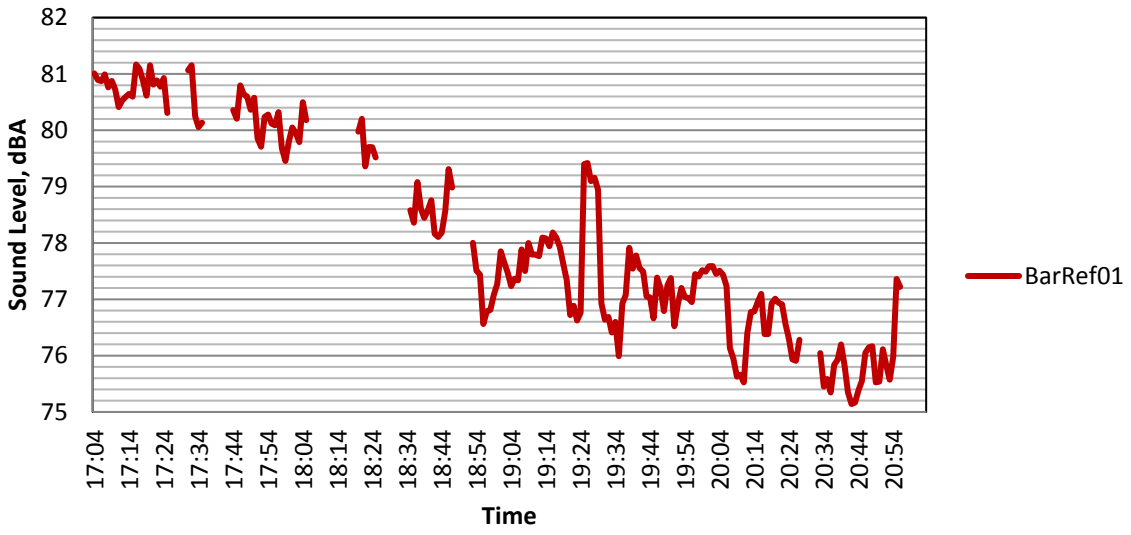


Figure 52. Running L_{eq} (5 min.), Briley Parkway, A-weighted sound level, dBA, BarRef01.

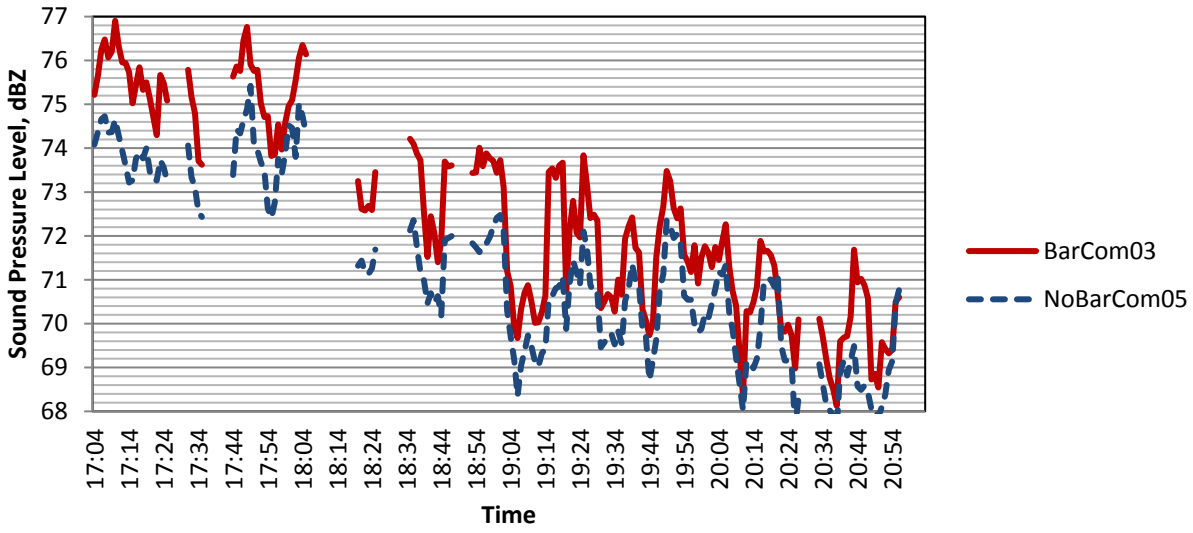


Figure 53. Running L_{eq} (5 min.), Briley Parkway, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

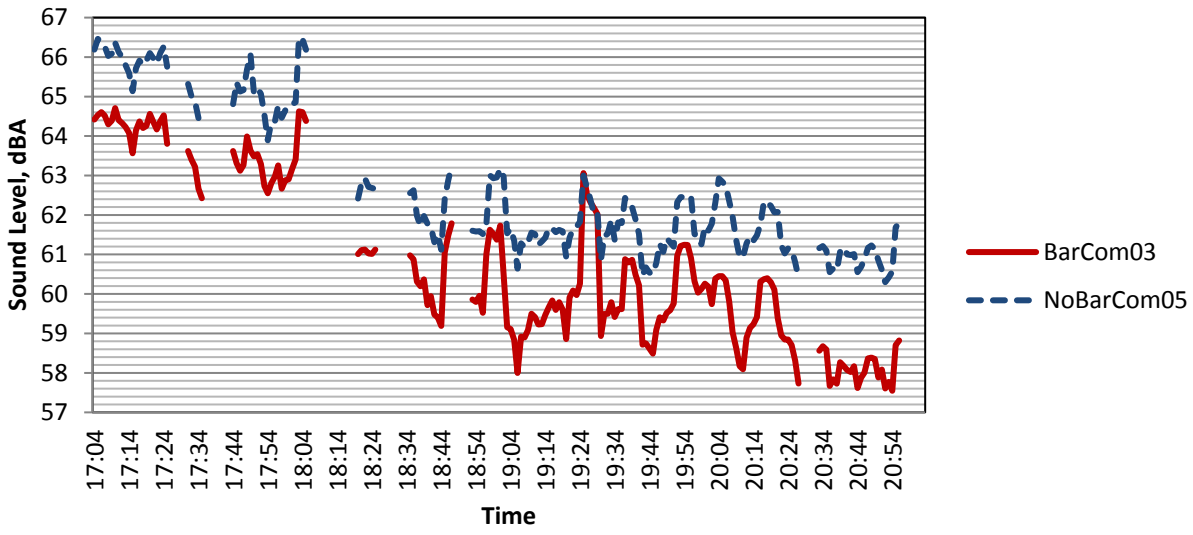


Figure 54. Running L_{eq} (5 min.), Briley Parkway, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

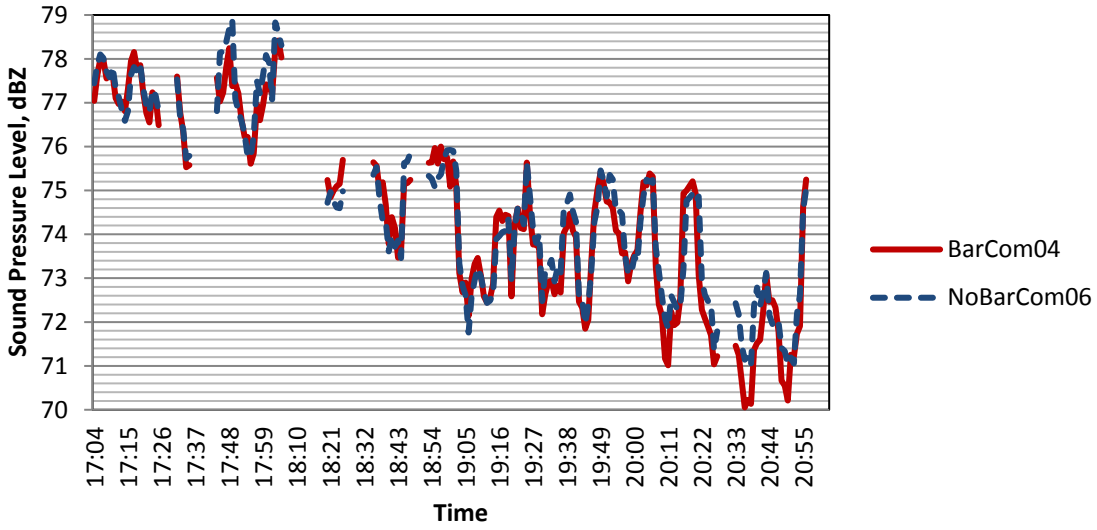


Figure 55. Running L_{eq} (5 min.), Briley Parkway, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

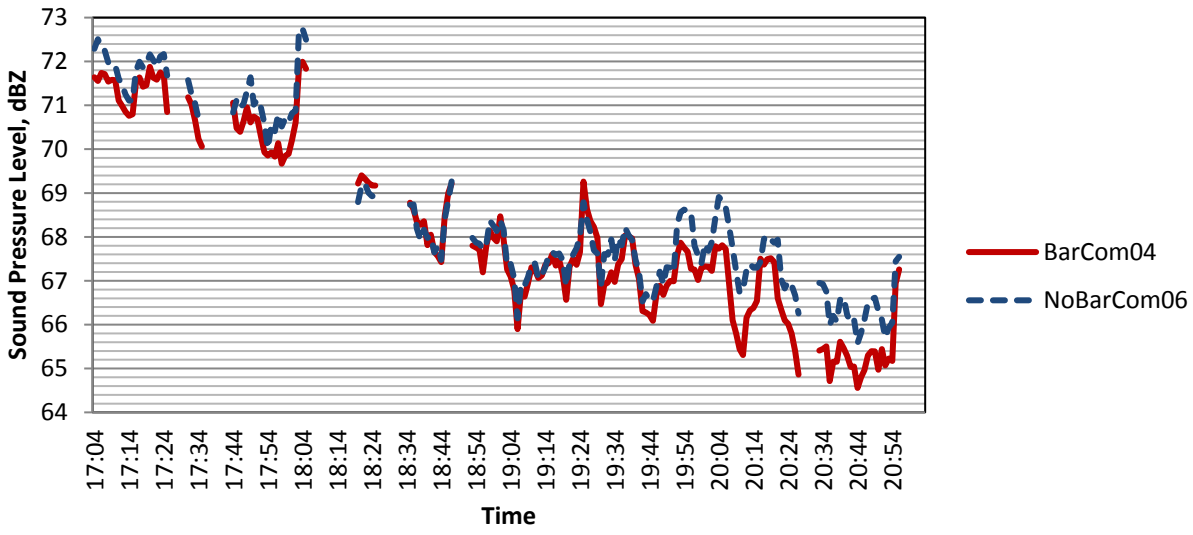


Figure 56. Running L_{eq} (5 min.), Briley Parkway, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

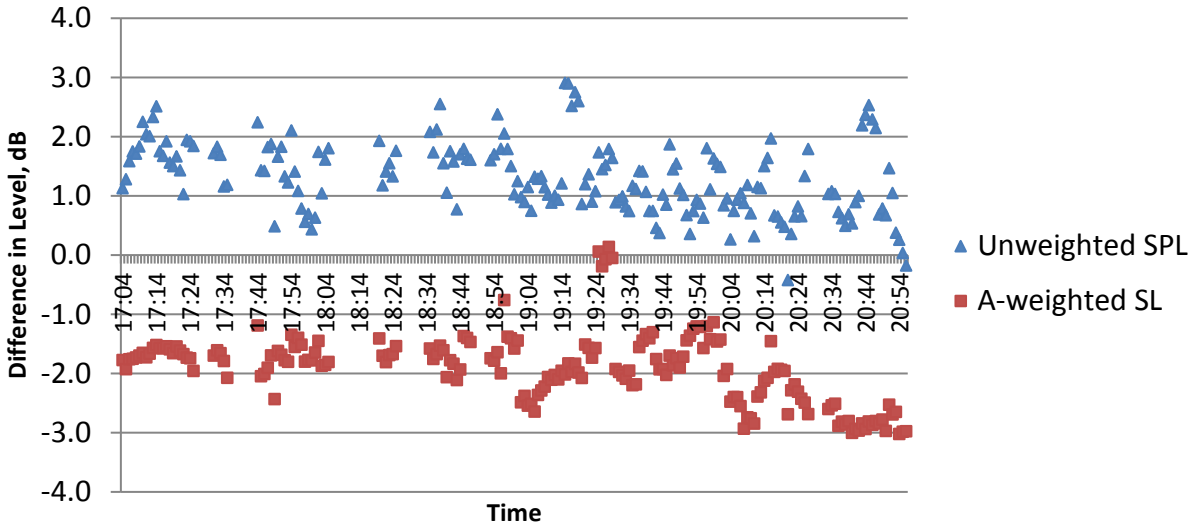


Figure 57. Difference in running L_{eq} (5 min.), BarCom03 minus NoBarCom05, Briley Parkway, dB

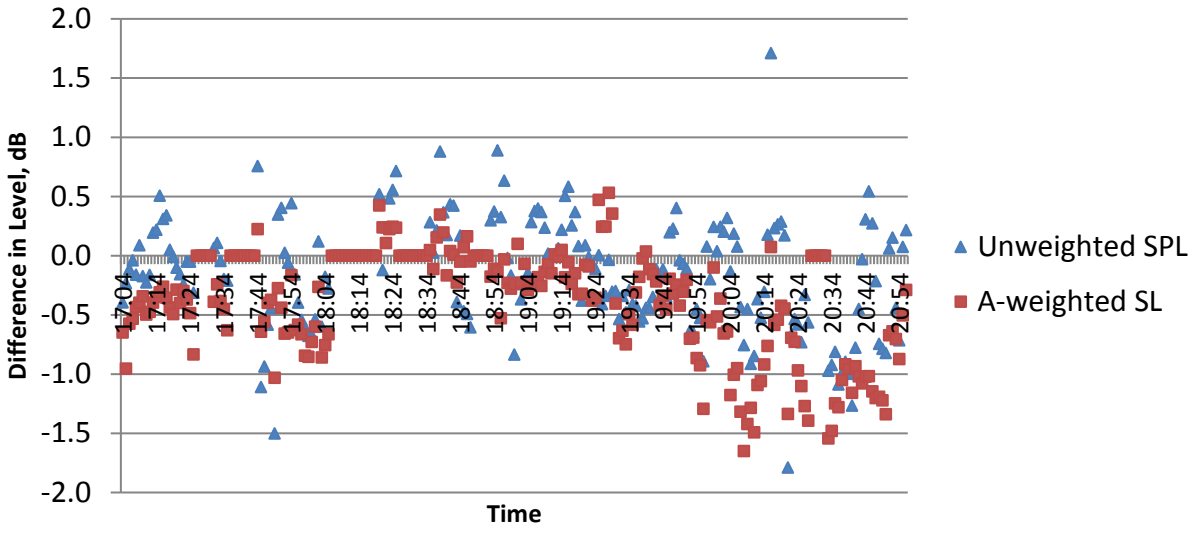


Figure 58. Difference in running L_{eq} (5 min.), BarCom04 minus NoBarCom06, Briley Parkway, dB

Data Analysis for Briley Parkway—FHWA Method

All 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 31 Calm Inversion groups each had from 3 to 7 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, but 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.

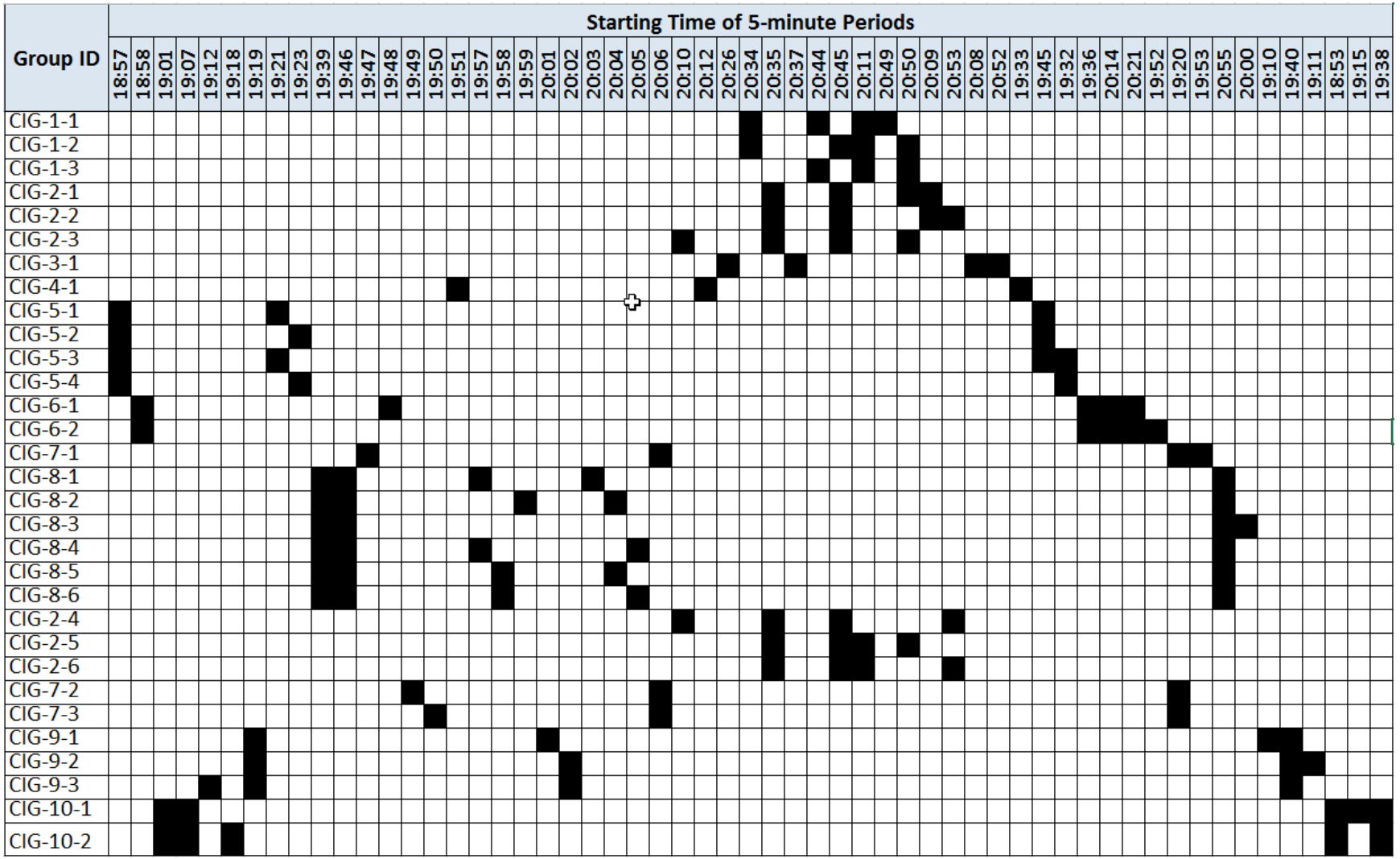


Figure 61. Equivalent 5-minute periods for Calm Inversion groups at Briley Parkway.

Calm Lapse Class

Figure 62 shows an example of the averages of the sound level differences across all the Calm Lapse groups. The lower graph of Figure 62 compares the upper microphones at the Briley Parkway Barrier and No Barrier sites: BarCom04 and NoBarCom06. These microphones were elevated substantially above the ground—approximately 11 ft. 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 ft. 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 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 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 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 pass-bys did 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 0.5 dB to 1.5 dB. The reason for the higher levels at NoBarCom06 in these midrange frequencies is unknown. The No Barrier level was also louder in the 8-kHz band, which is attributed to insect noise in the trees and 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 through 8 kHz. The differences range is from less than 1 dB 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.

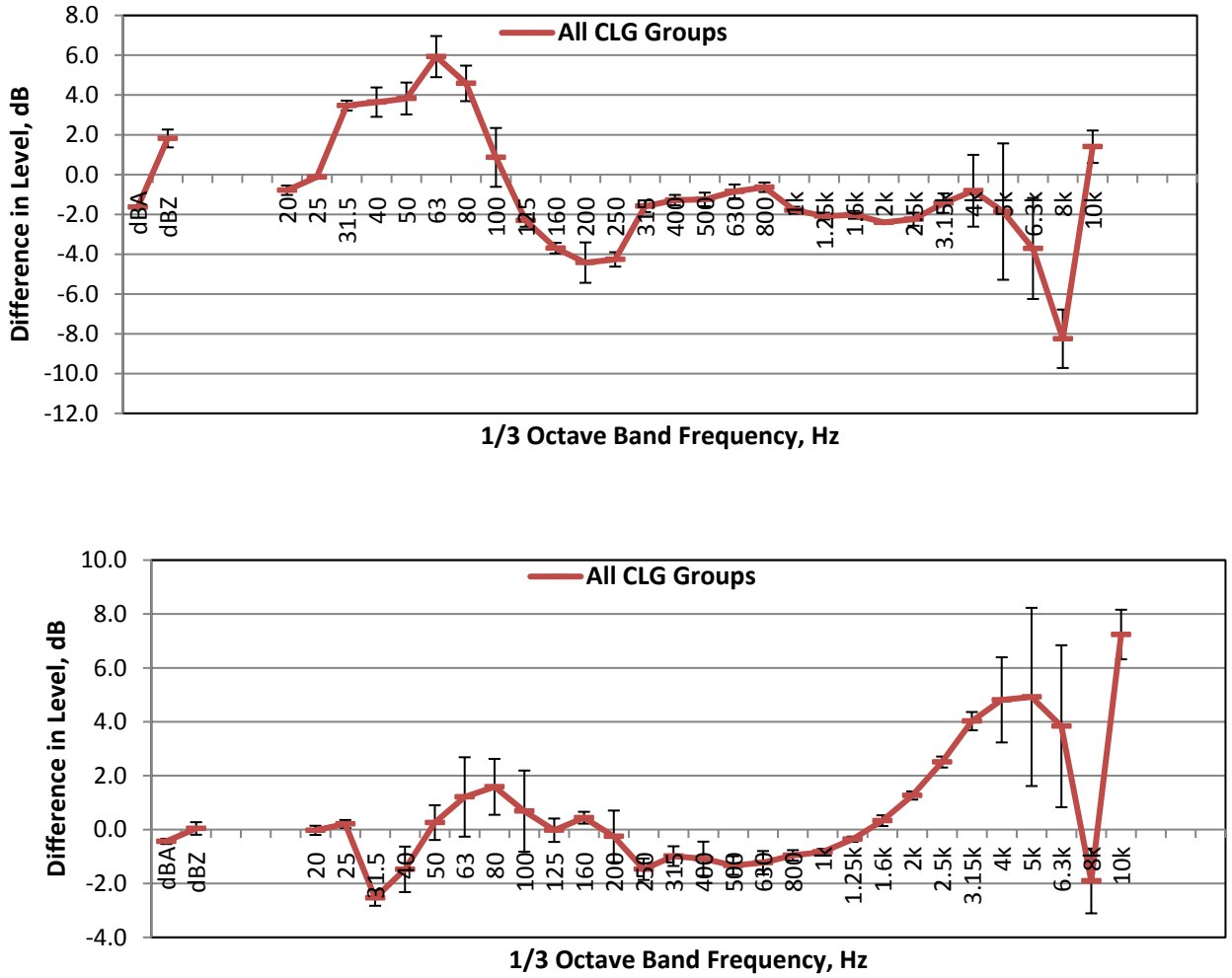


Figure 62. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Lapse groups, Briley Parkway.

Calm Neutral Class

Next is an example for one of the Calm Neutral groups at Briley Parkway. 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.

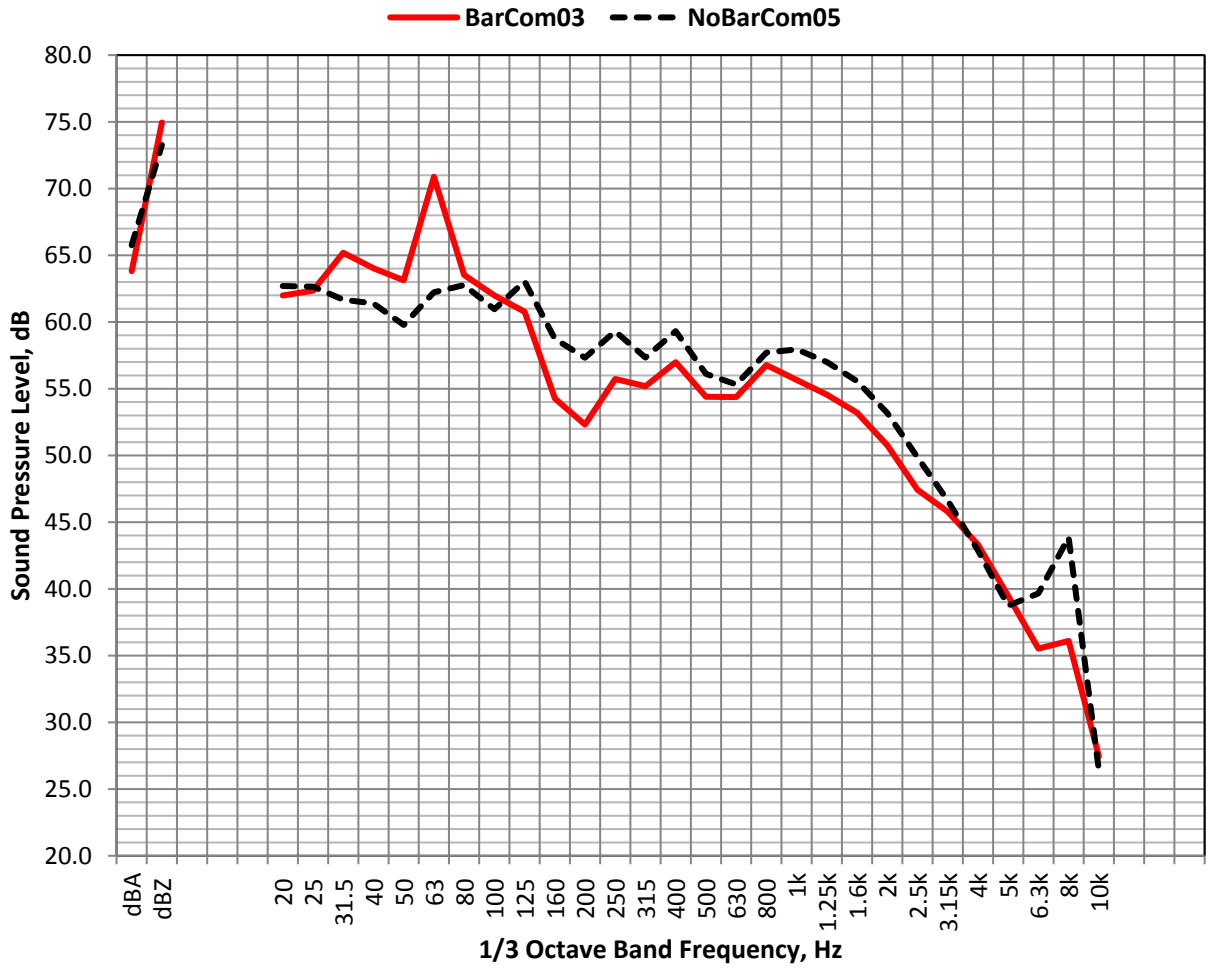


Figure 63. Sample sound pressure level spectra for BarCom03 and NoBarCom05, Briley Parkway, Calm Neutral group CNG-1-4, 17:25 to 17:30 (L_{eq} (5 min.), dBZ).

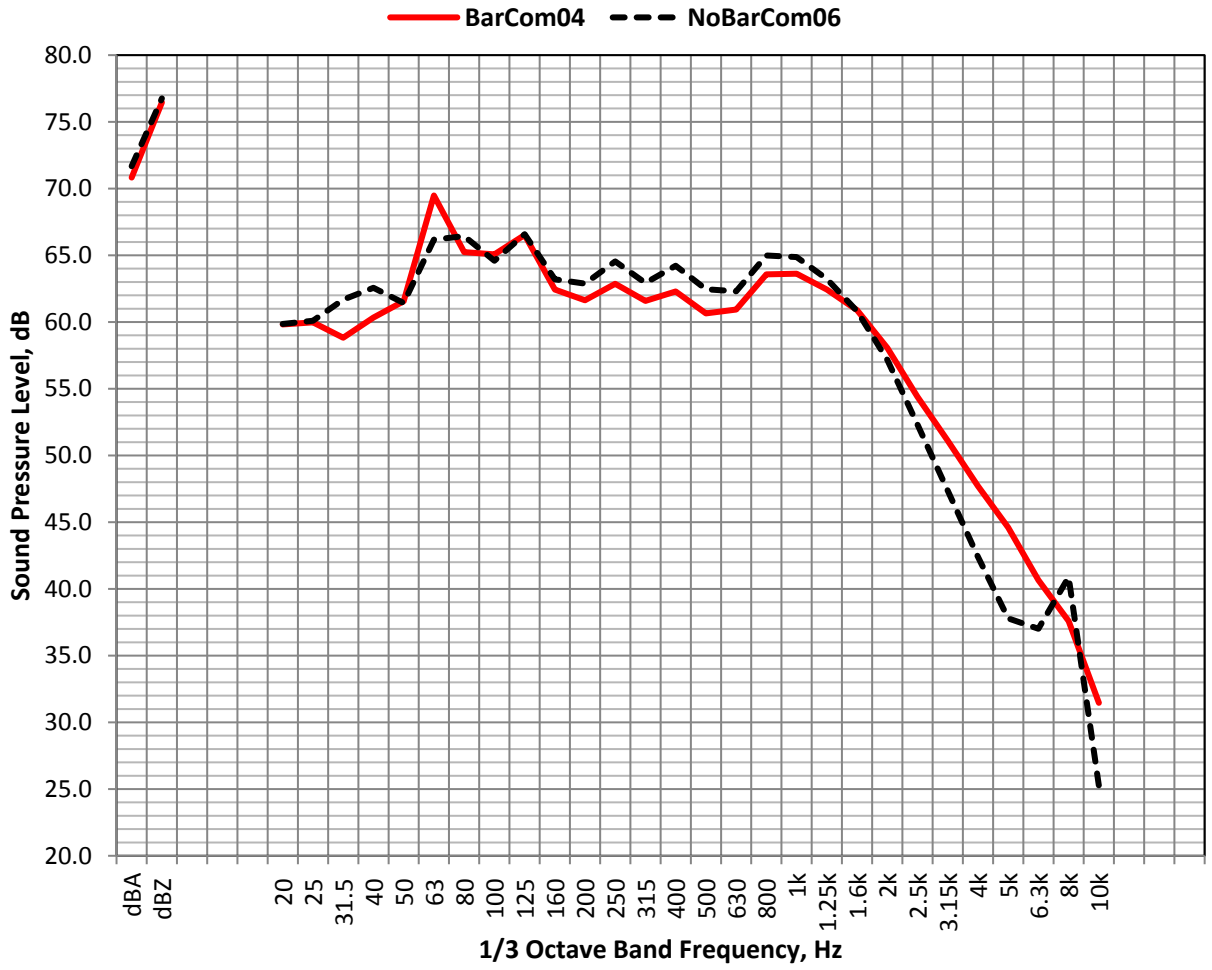


Figure 64. Sample sound pressure level spectra for BarCom04 and NoBarCom06, Briley Parkway, Calm Neutral group CNG-1-4, 17:25 to 17:30 (L_{eq} (5 min.), dBZ).

Figure 65 presents the averages of the sound level differences for all the Calm Neutral groups. For the Calm Neutral meteorological class, the patterns of the differences for the lower microphones and upper microphones were like 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—like 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. Except for 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 less than 1 dB 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 ft. east of the No Barrier site was audible at this site. However, this noise was short and not excessively loud such that the noise from the immediate pass-bys 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.

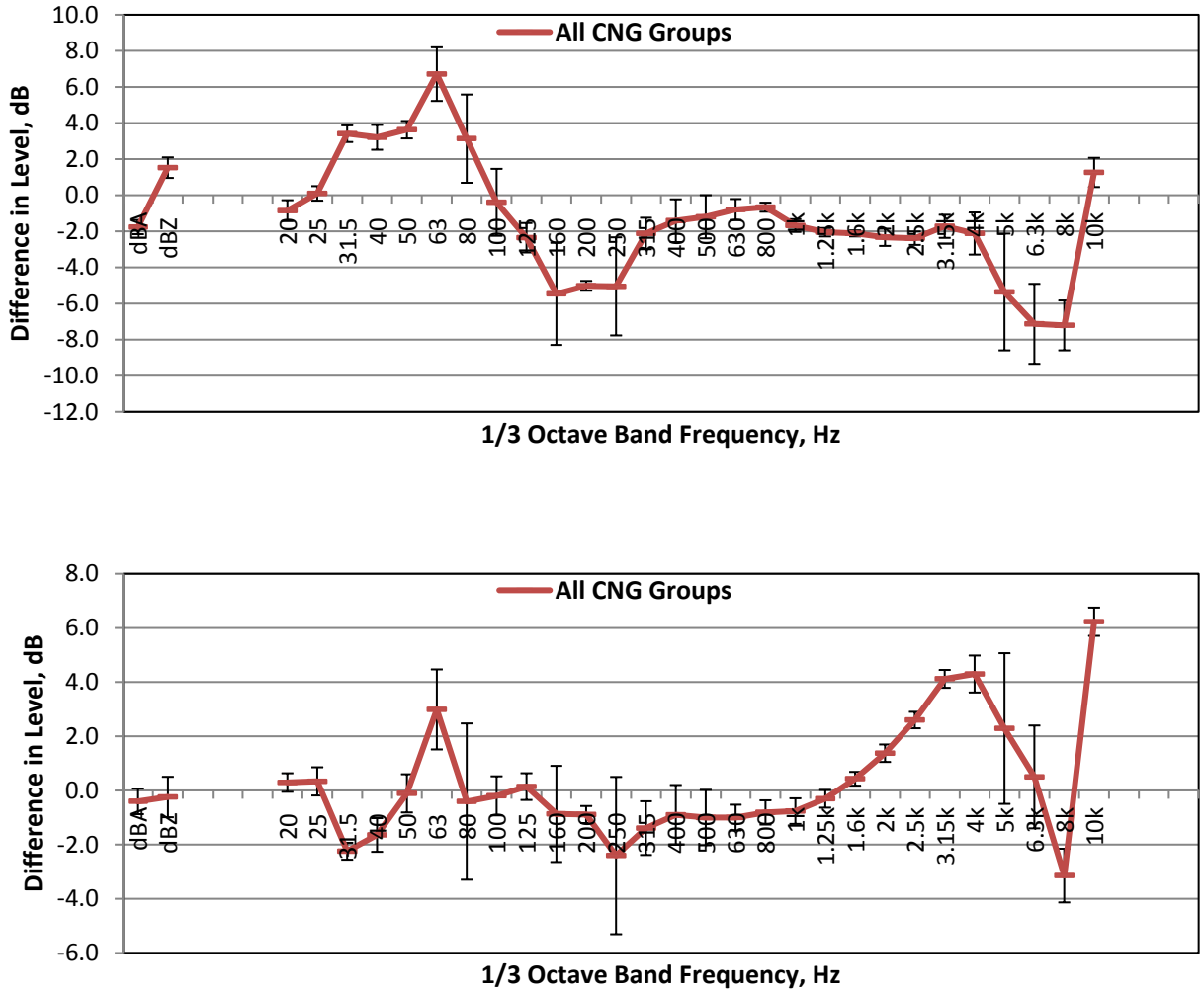


Figure 65. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Neutral groups, Briley Parkway.

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.

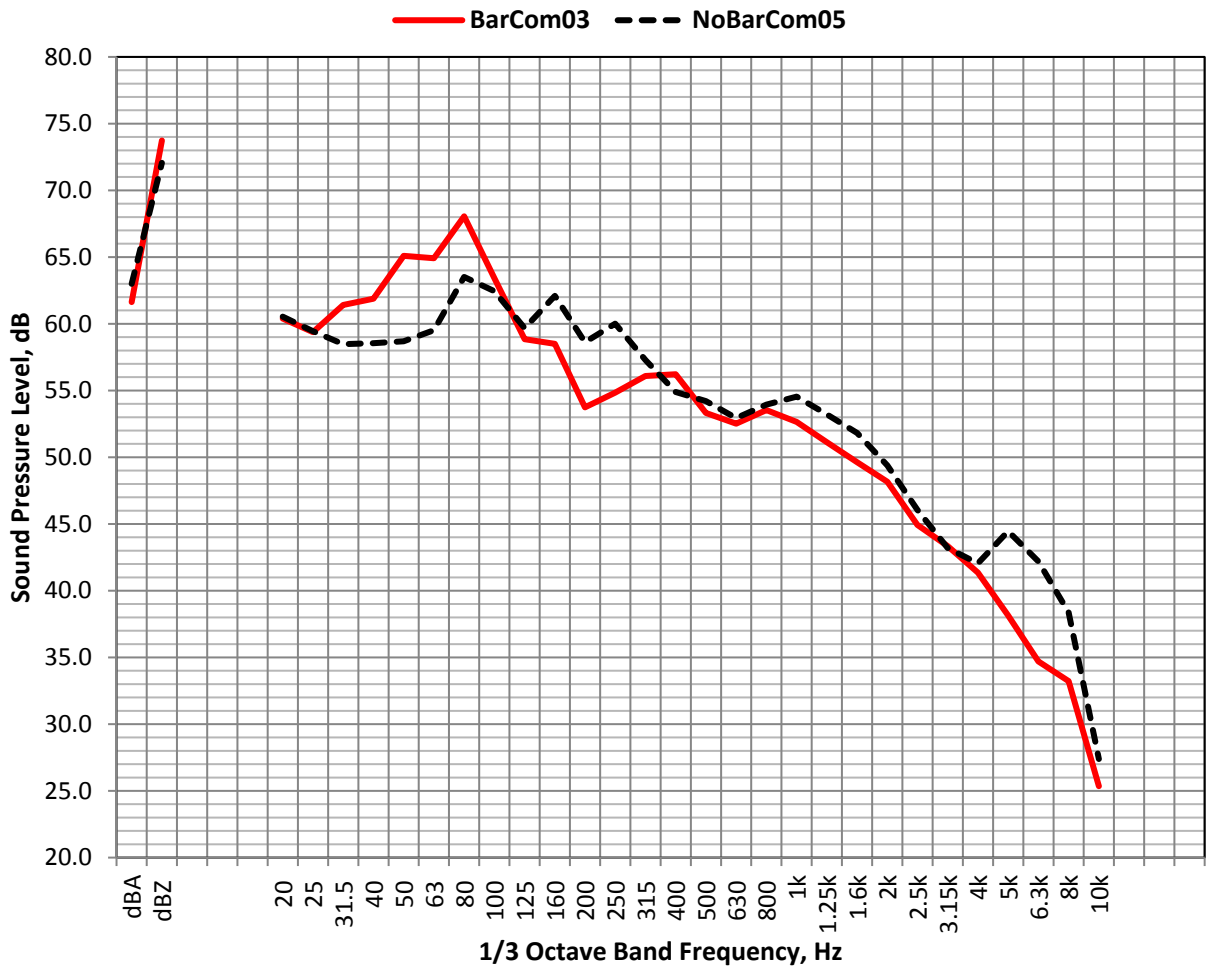


Figure 66. Sample Sound Pressure Level Spectra for BarCom03 and NoBarCom05, Briley, Calm Inversion group CIG-6-1, 18:58 to 19:03 (L_{eq} (5 min.), dBZ).

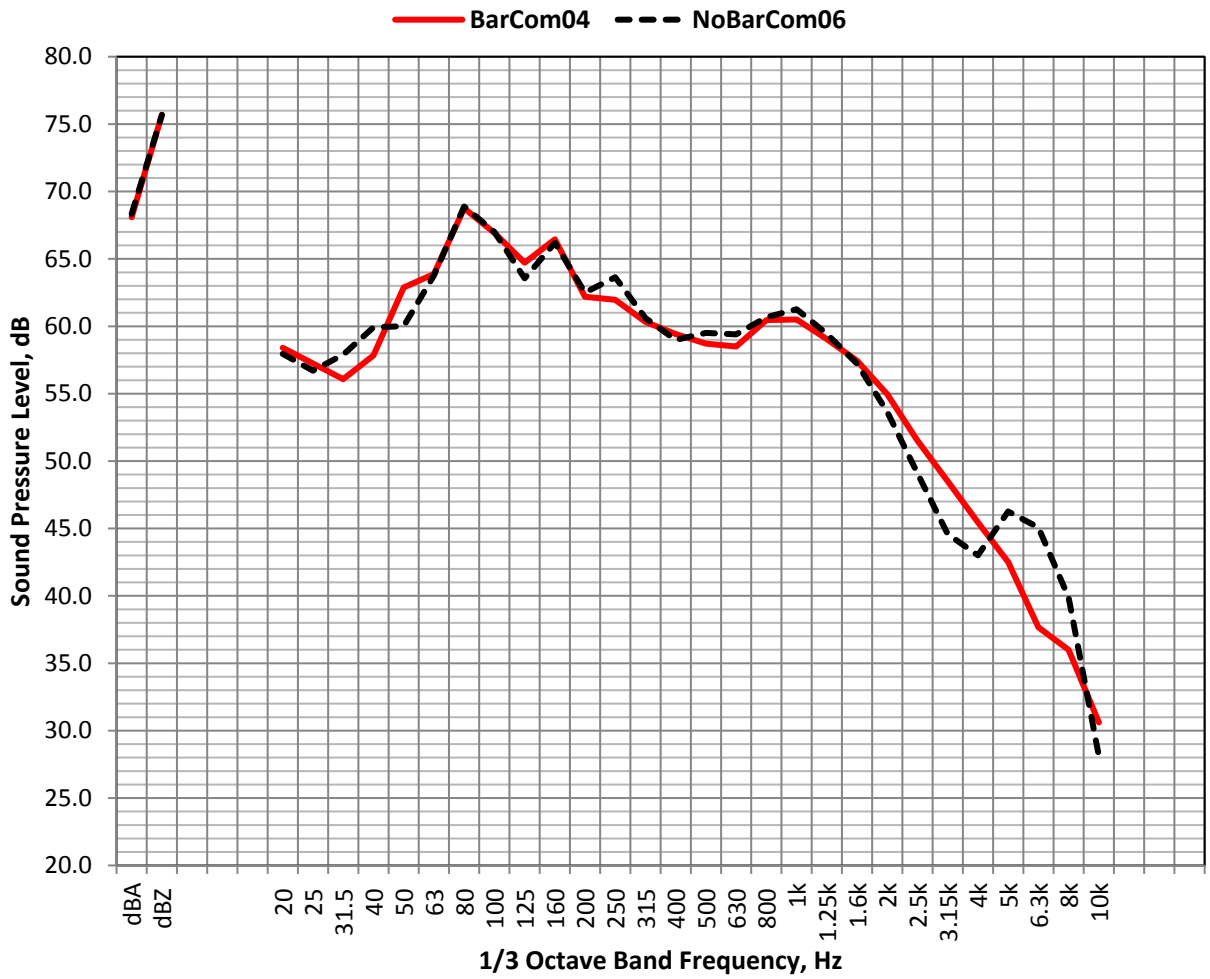


Figure 67. Sample Sound Pressure Level Spectra for BarCom04 and NoBarCom06, Briley, Calm Inversion group CIG-6-1, 18:58 to 19:03 (L_{eq} (5 min.), dBZ).

Figure 68 compares the levels at the Barrier and No Barrier sites for the averages of all 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 1 dB 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, like 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.

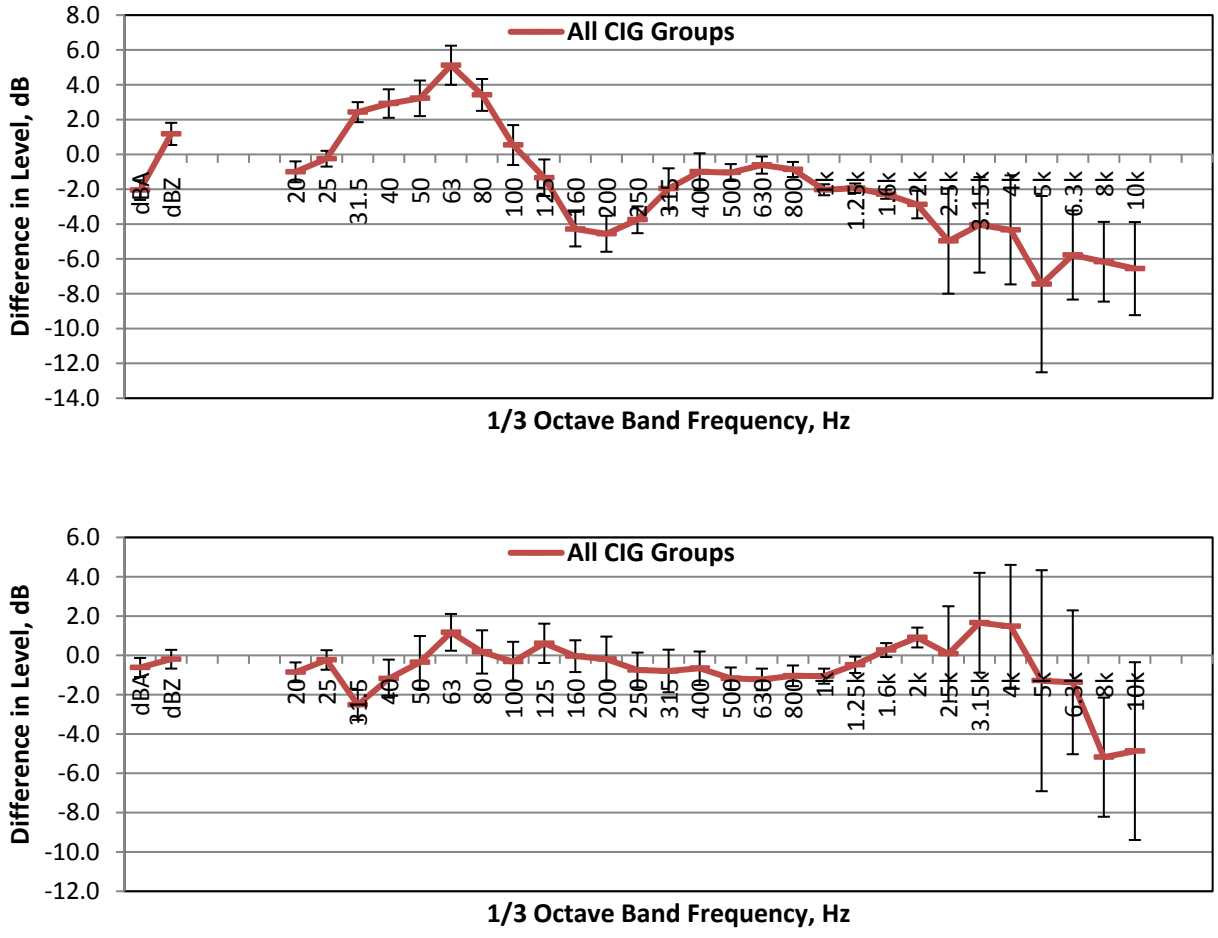


Figure 68. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Inversion groups, Briley Parkway.

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 and 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. 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 is 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.

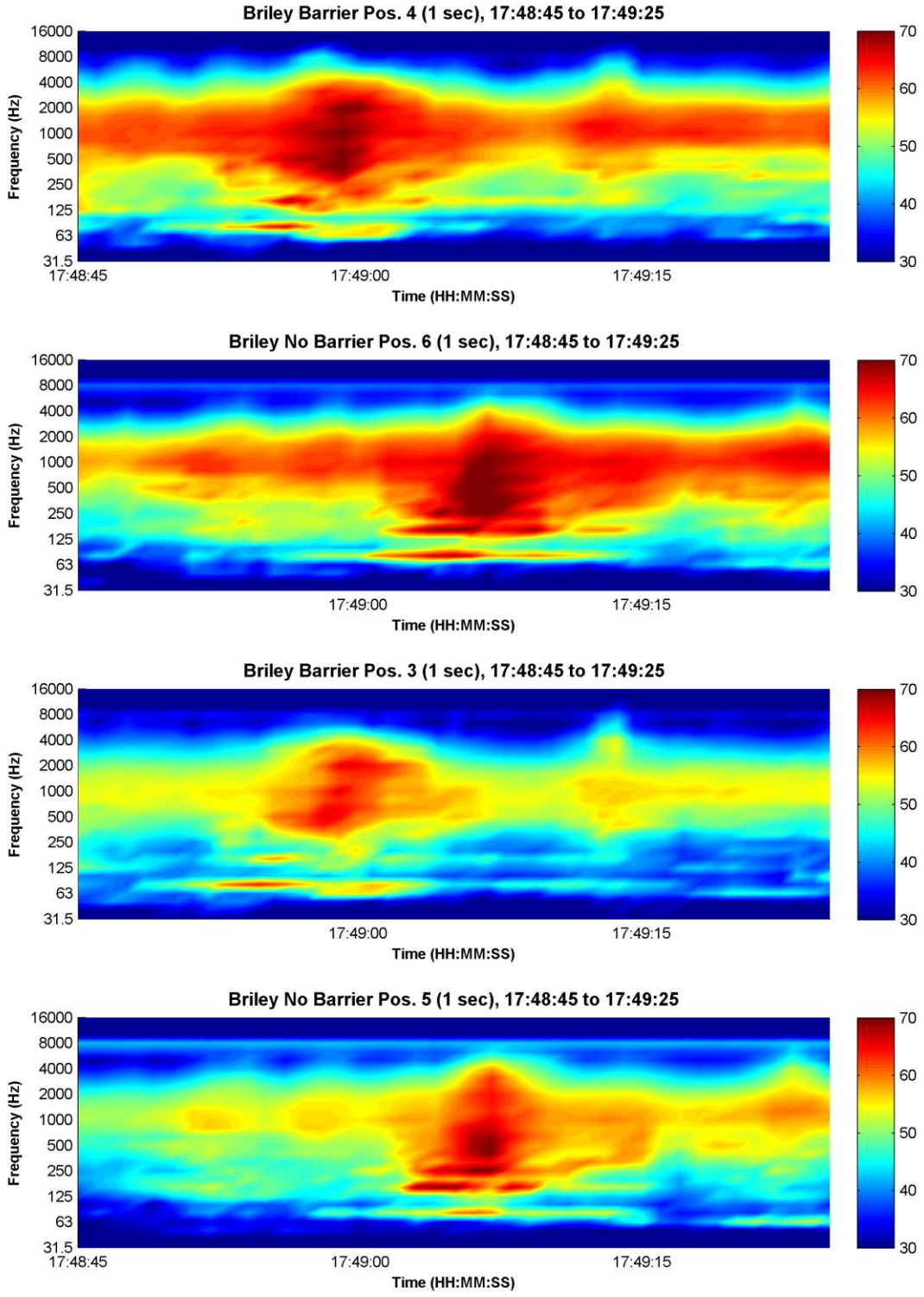


Figure 69. Spectrogram for a heavy truck eastbound (example 1); top to bottom: high mics (BarCom04 and NoBarCom06), low mics (BarCom03 and NoBarCom05); Briley Parkway.

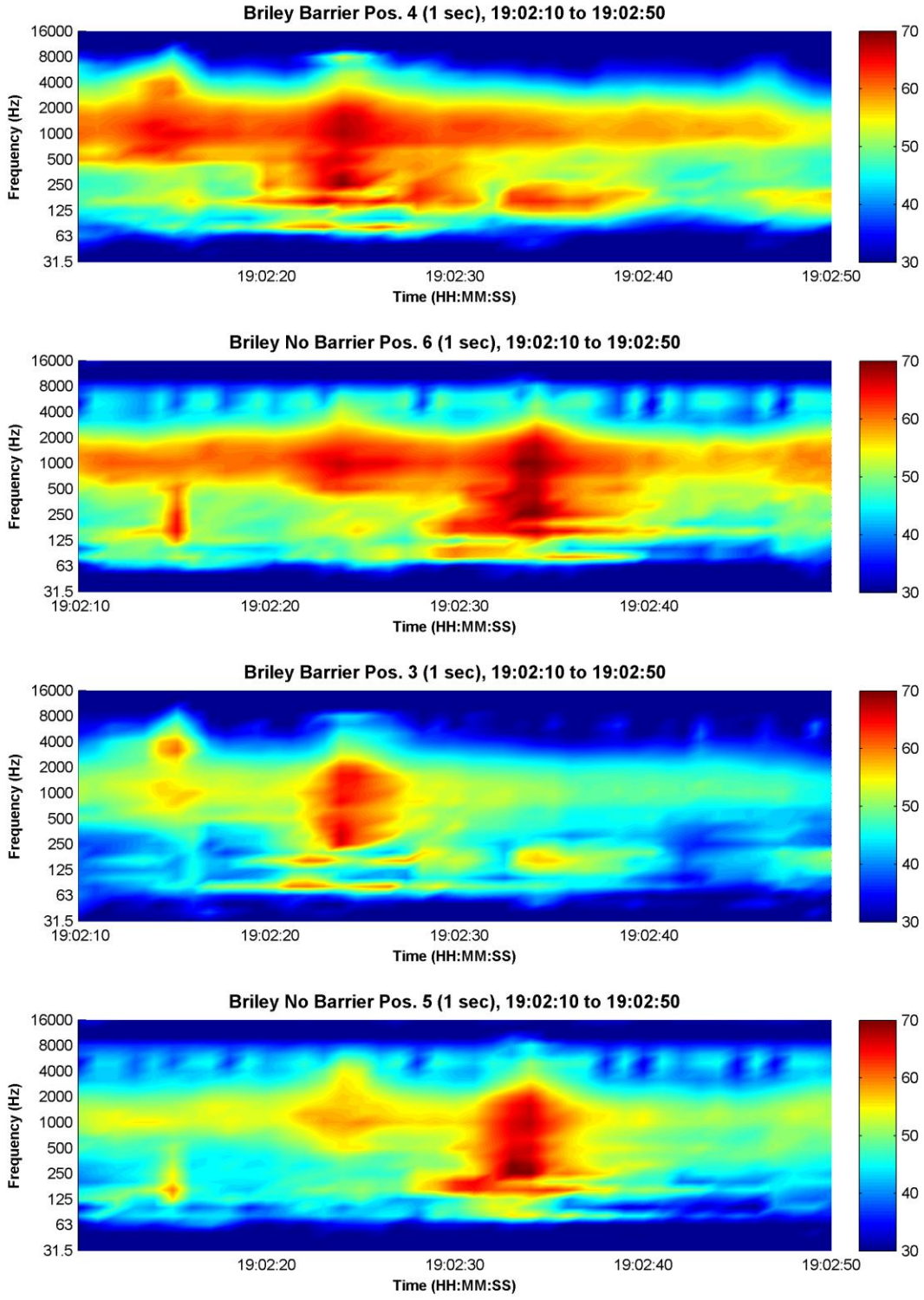


Figure 70. Spectrogram for a heavy truck eastbound (example 2); top to bottom: high mics (BarCom04 and NoBarCom06), low mics (BarCom03 and NoBarCom05); Briley Parkway.

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 psychoacoustics analyses and are omitted from this report.

CHAPTER E-5

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

The measurements on I-90 in Rockford, Illinois, took place on Dec. 26, 2014. Setup started at 07:00 and data collection occurred 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 shown in Table 8.

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 F (available online) contains site photographs.

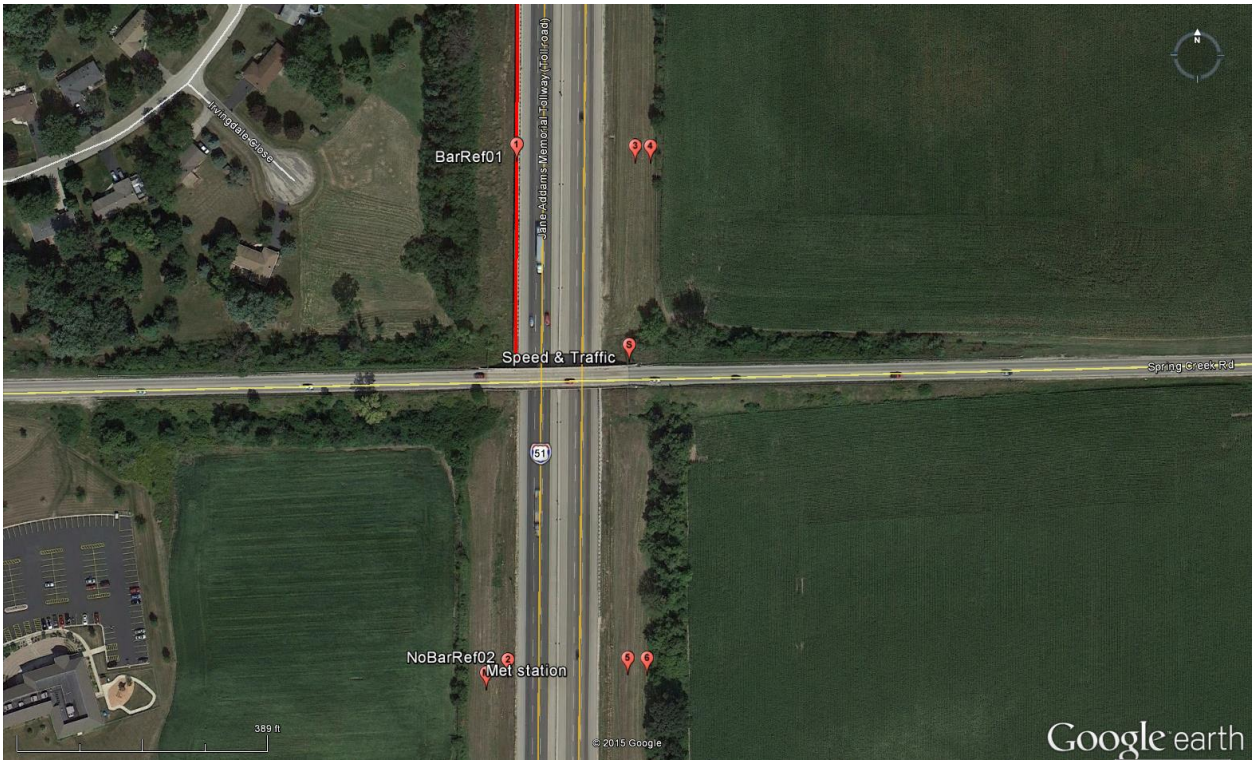


Figure 71. I-90 microphone positions. (Source: Google Earth).

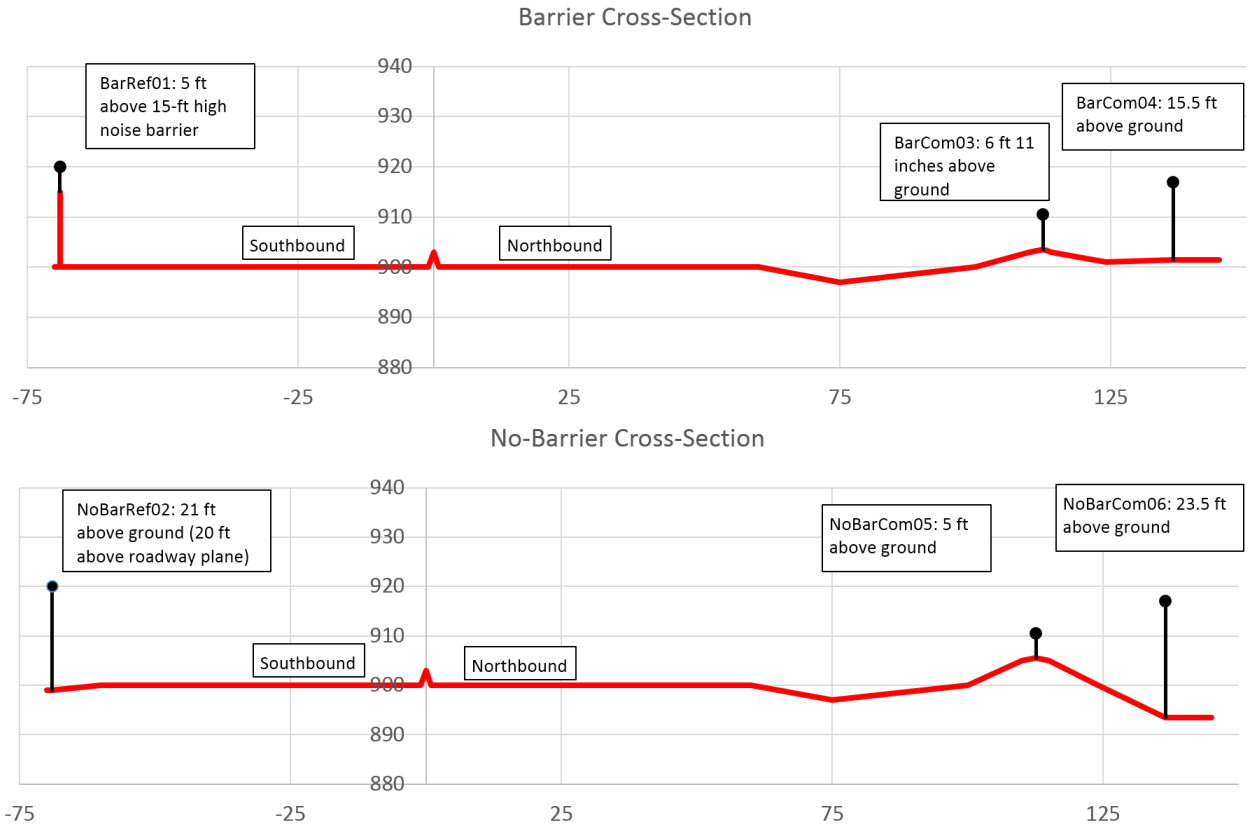


Figure 72. ***Cross-sections at the I-90 Barrier (top) and No Barrier (bottom) sites.***

Measurement Observations

Winds were low during the measurement period. There was also little noise contamination, with only an airplane overflight and a police siren.

Data collection went well, and the audio recorders required change of batteries 2.5 hours into the measurements. The battery change was done to minimize using external power supplies that could introduce electronic noise into the recordings. The batteries were changed in sequential order and for future sites the battery change will be done as fast as possible to minimize data collection interruption (like what was done at the Chino Hills location in California).

During these measurements, the cause of the audio noise experienced at the first two study locations was identified as 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 were clean.

Measured Broadband Levels and Level Differences for I-90

The running L_{eq} (5 min.) 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.
- 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 up to a range of 0.5 dB to 1.0 dB. The BarRef01 microphone was located atop the barrier and the barrier was 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 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 the microphones, as time passed the L_{eq} (5 min.) 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 one-half decibel.

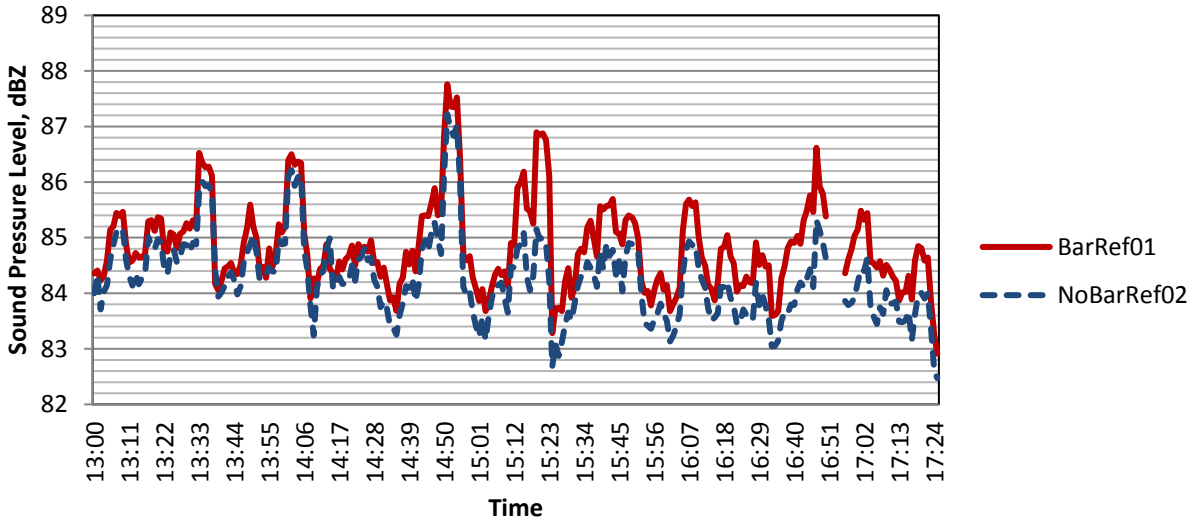


Figure 73. Running L_{eq} (5 min.), I-90, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

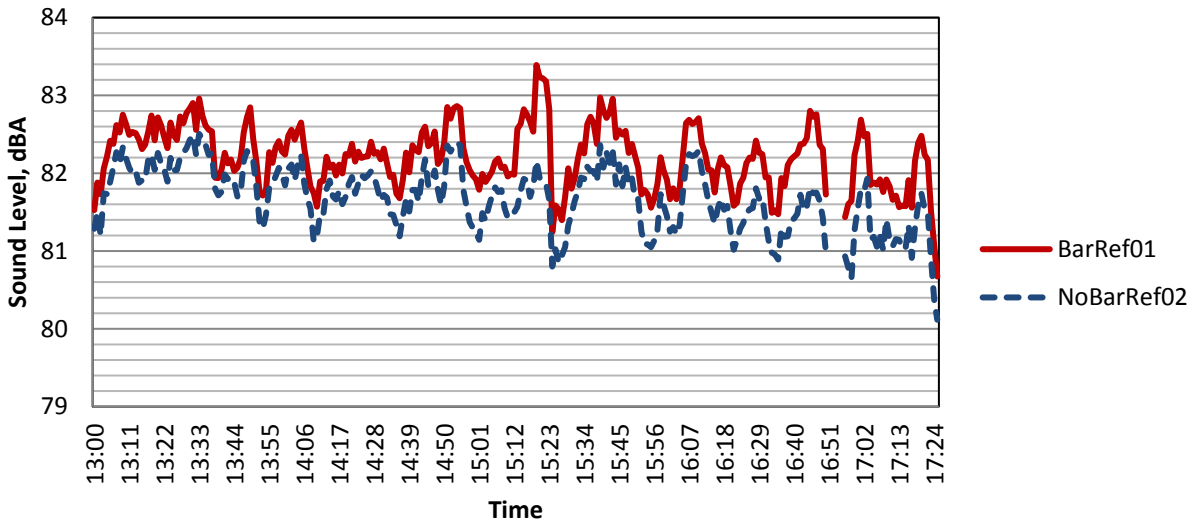


Figure 74. Running L_{eq} (5 min.), I-90, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

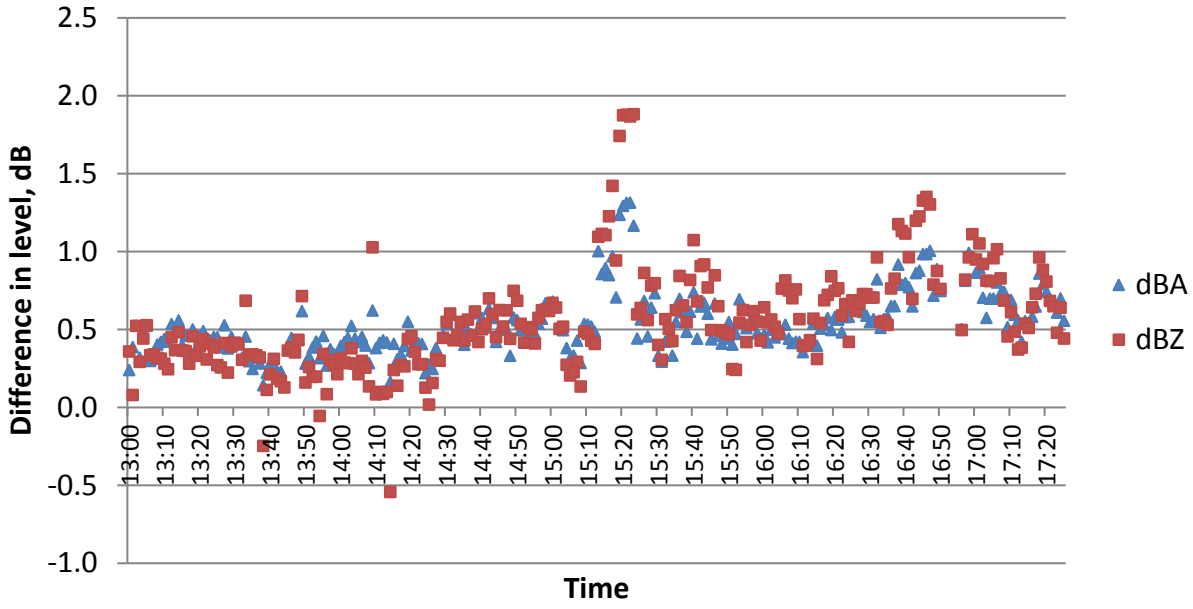


Figure 75. Differences in running L_{eq} (5 min.), I-90, BarRef01 minus NoBarRef02.

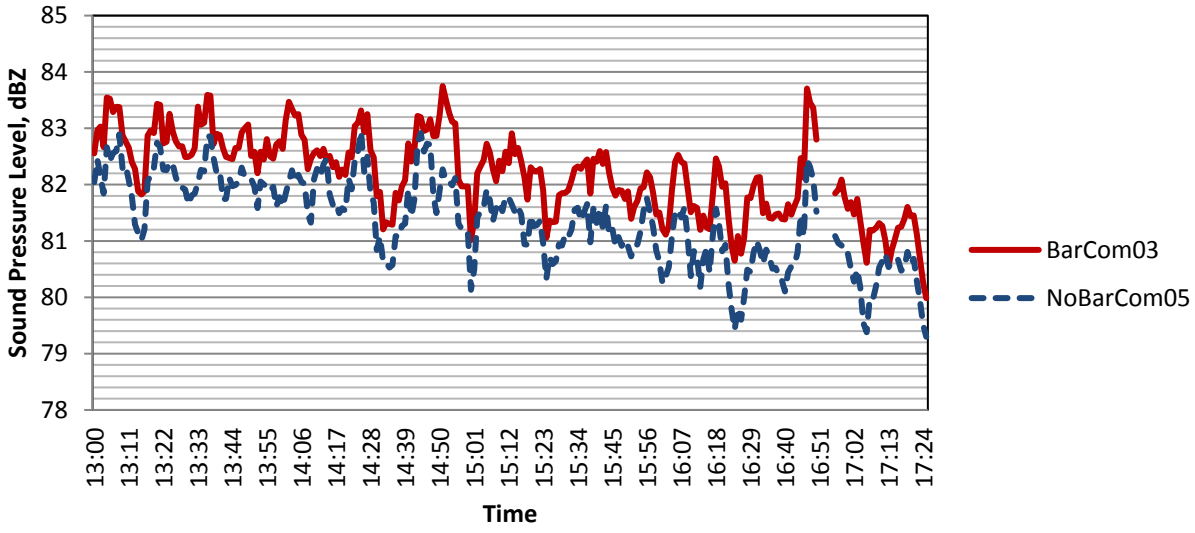


Figure 76. Running L_{eq} (5 min.), I-90, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

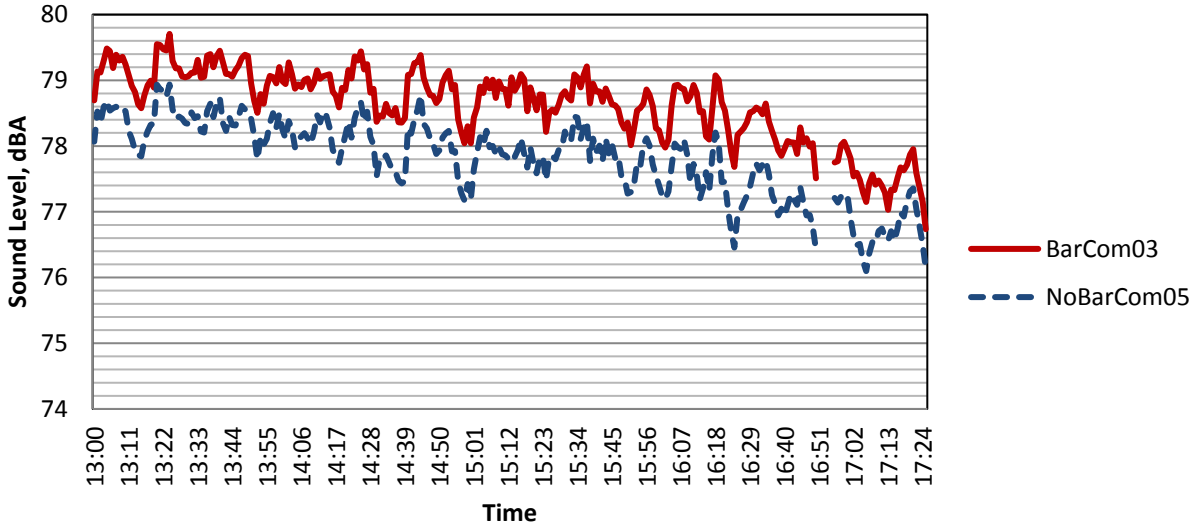


Figure 77. Running L_{eq} (5 min.), I-90, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

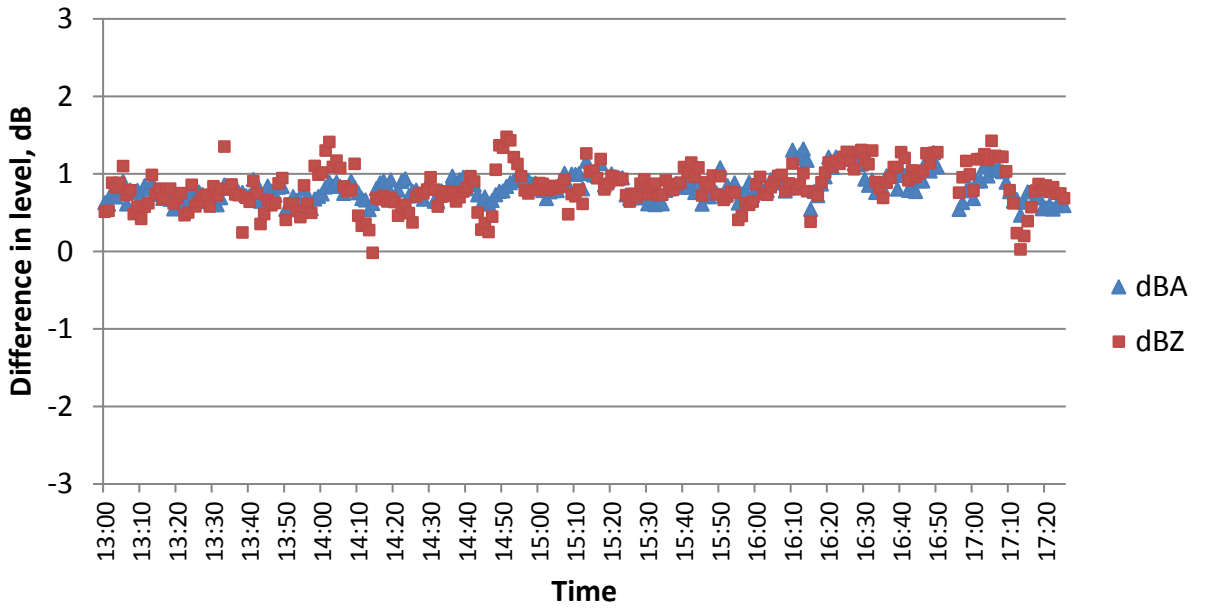


Figure 78. Differences in running L_{eq} (5 min.), I-90, BarCom03 minus NoBarCom05.

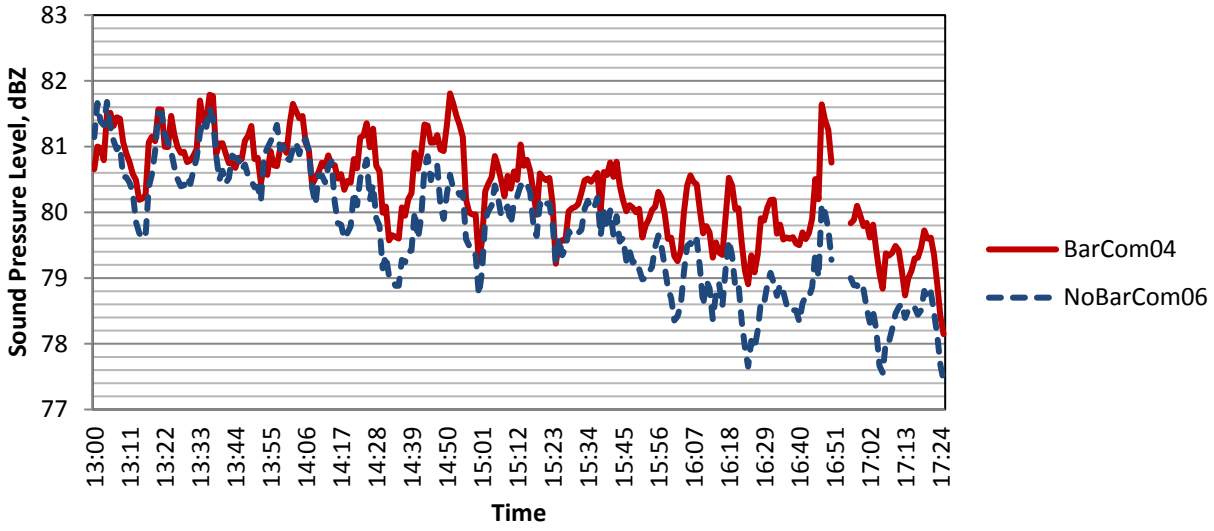


Figure 79. Running L_{eq} (5 min.), I-90, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

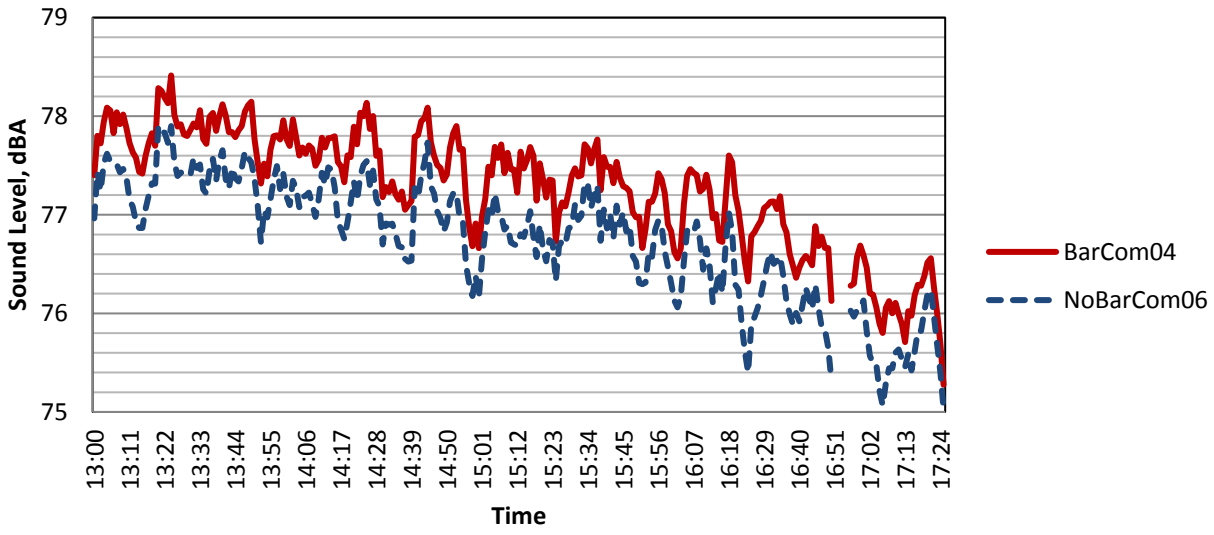


Figure 80. Running L_{eq} (5 min.), I-90, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

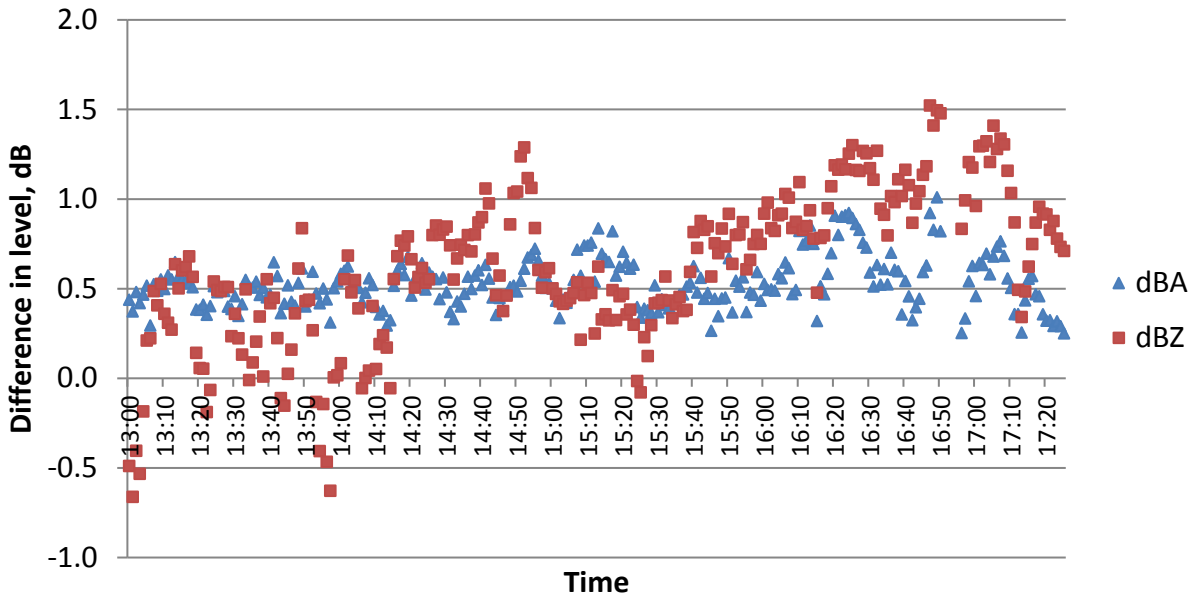


Figure 81. Differences in running L_{eq} (5 min.), I-90, BarCom04 minus NoBarCom06.

Data Analysis for I-90—FHWA Method

Equivalent Groups

All 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. The Downwind Lapse class has 12 groupings, 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 visually depicts these groupings 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-." While all 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 shown 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 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 Hz to 500 Hz bands.

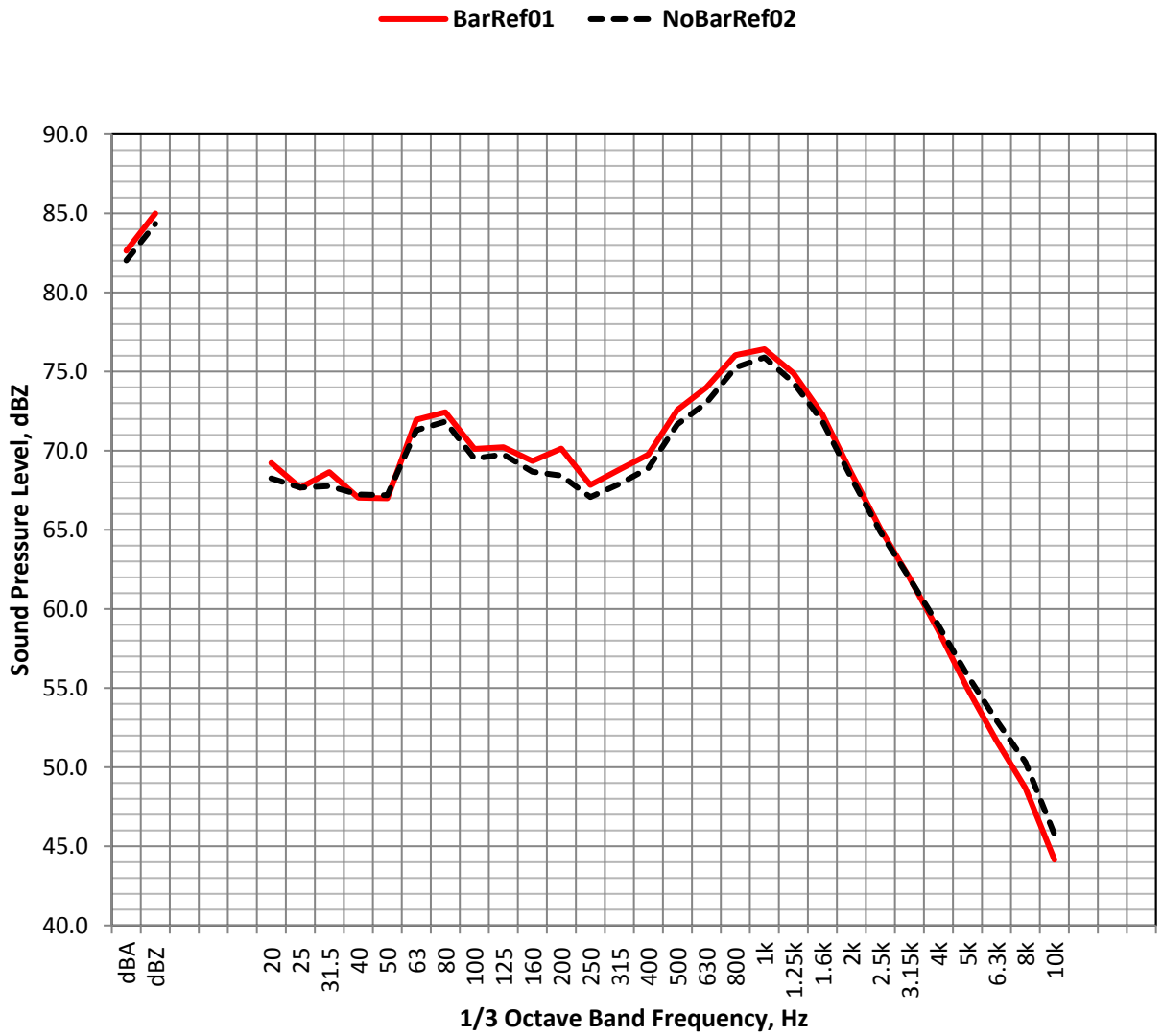


Figure 84. Sample sound pressure level spectra for BarRef01 and NoBarRef02, I-90, Calm Neutral class, CNG-1-1, Period 15:37 (L_{eq} (5 min.), dBZ).

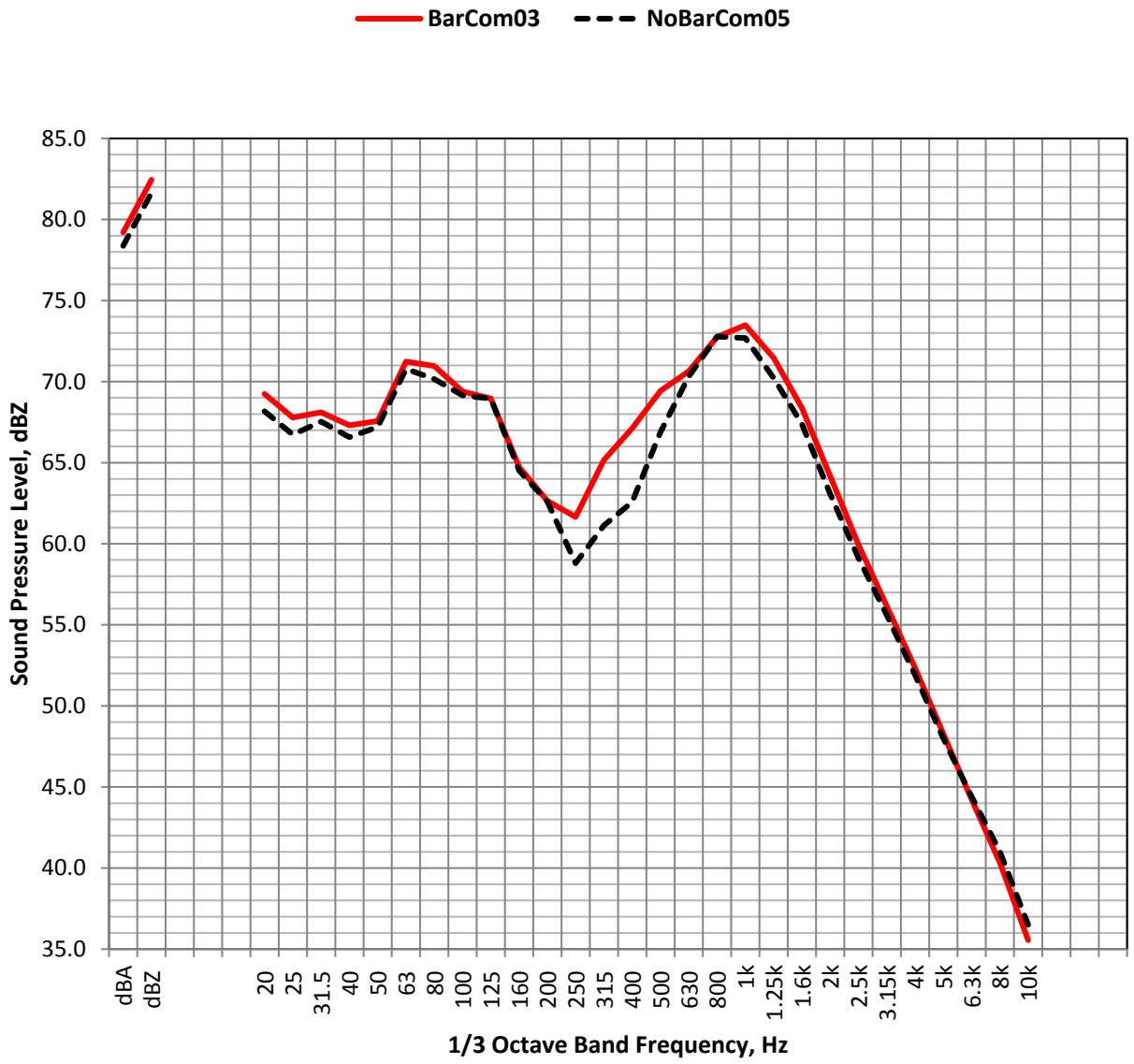


Figure 85. Sample sound pressure level spectra for BarCom03 and NoBarCom05, I-90, Calm Neutral class, CNG-1-1, Period 15:37 (L_{eq} (5 min.), dBZ).

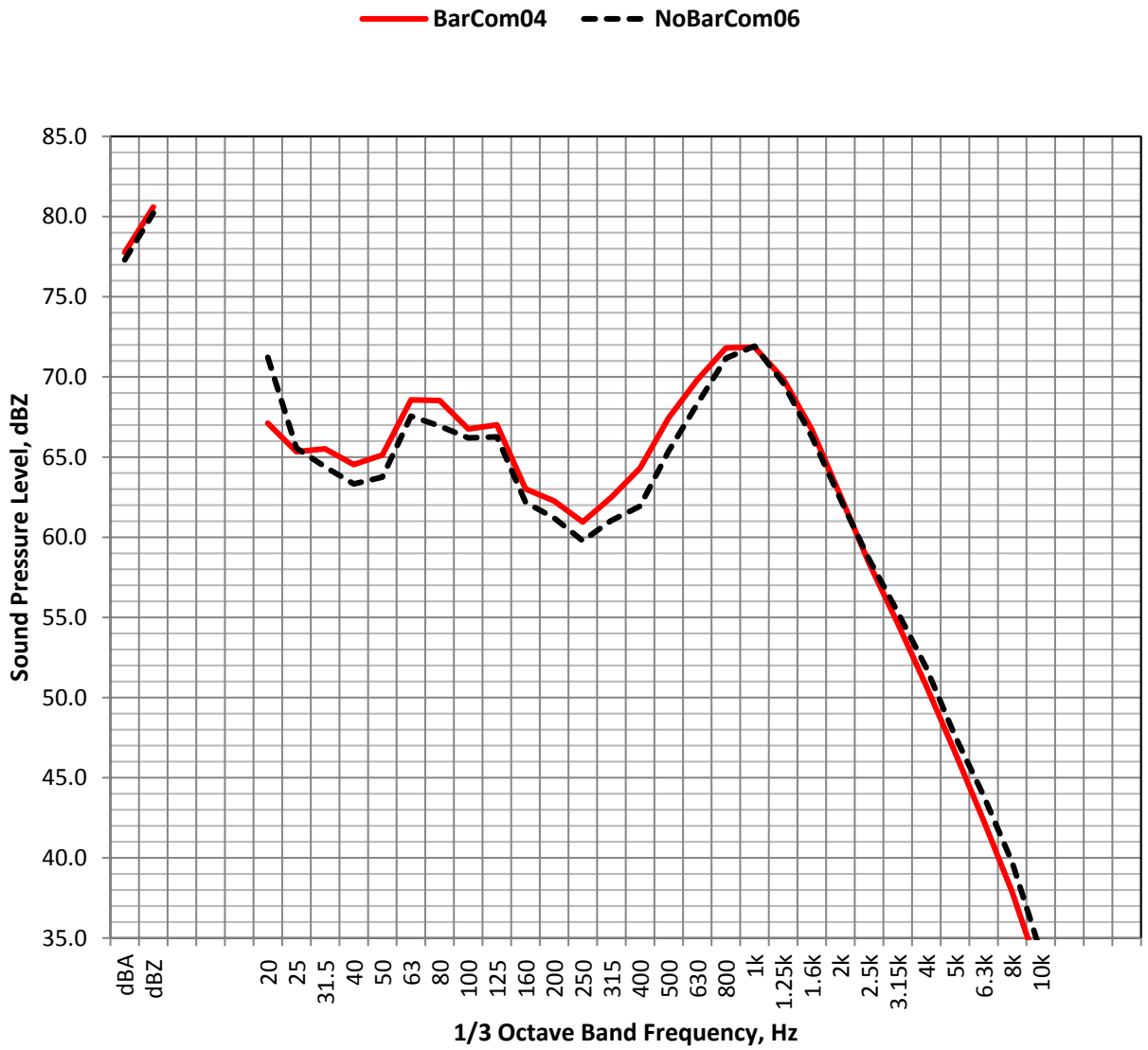


Figure 86. Sample sound pressure level spectra for BarCom04 and NoBarCom06, I-90, Calm Neutral class, CNG-1-1, Period 15:37 (L_{eq} (5 min.), dBZ).

Calm Neutral Class

Figure 87 shows the averages of the differences in the Barrier and No Barrier microphones' levels for all 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.
- 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 one-third octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all the individual Calm Neutral groups are in spreadsheet files in the project record. The

trends across the one-third 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 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 ft. from the center of the near travel lane and 17 ft. above the roadway surface. The levels in the frequency bands from 31.5 Hz 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 ft. from the center of the near travel lane and 10.4 ft. above the roadway surface. The levels in the frequency bands from 20 Hz through 80 Hz were 0.5 dB to 1 dB higher at BarCom03. For 1 kHz and higher, the BarCom03 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.

A possible explanation for the barrier effect being prominent in the low-frequency range (250 Hz 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 experiences a different propagation path than the direct sound, with different ground effects and wave interference with ground reflections; the dip in the 250 Hz to 500 Hz range is nonexistent or diminished. As a result, the barrier effect is pronounced in the 250 Hz to 500 Hz range.

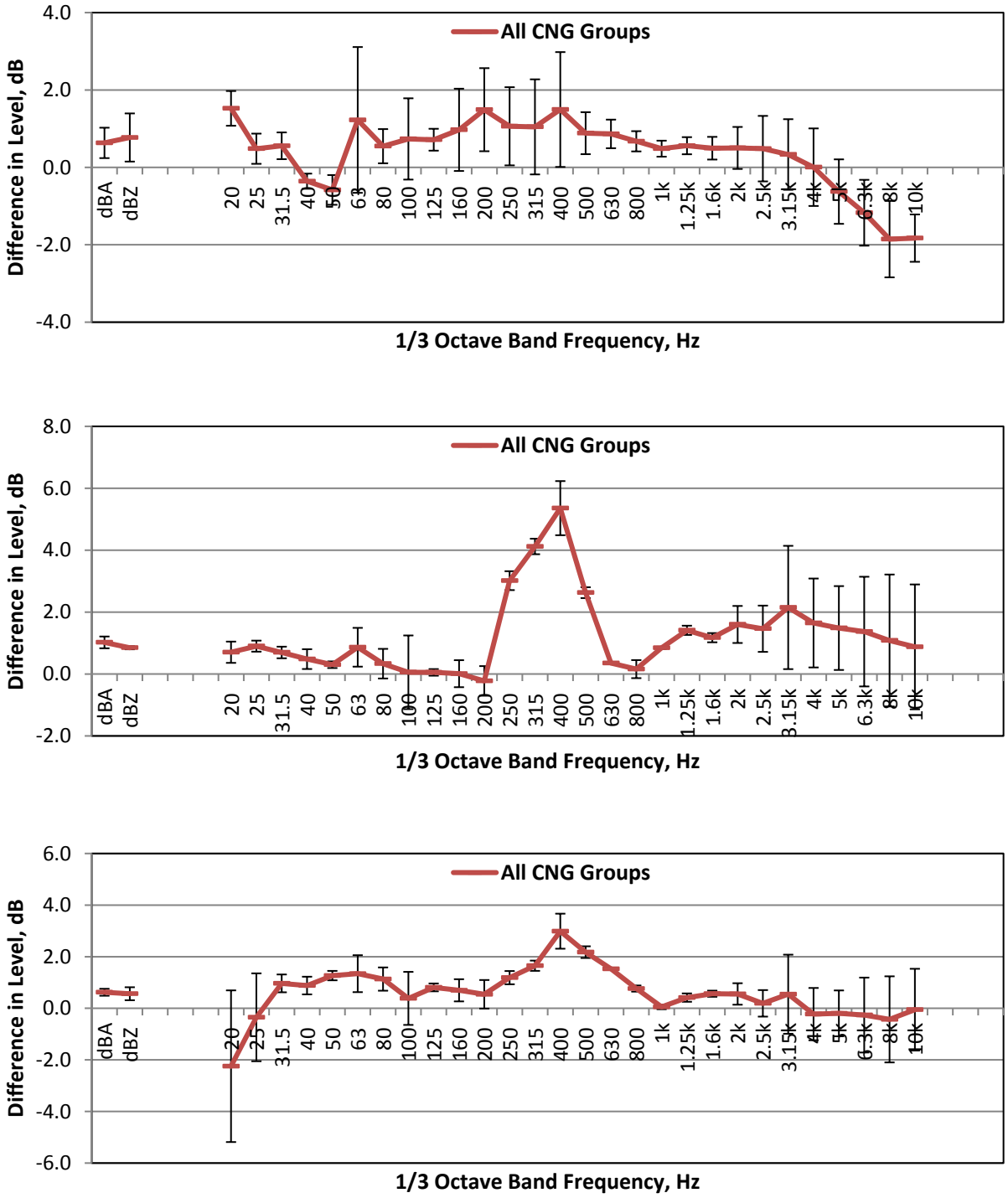


Figure 87. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Neutral groups, I-90.

Downwind Lapse Class

Figure 88 shows the averages of the differences in the Barrier and No Barrier microphones' levels for all 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 one-third octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all the individual Downwind Lapse groups are in spreadsheet files in the project record. Once again, the trends across the one-third octave band frequencies 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 through 2.5 kHz. Above 400 Hz 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 like the Calm Neutral class 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 like the Calm Neutral class, with the increase at 400 Hz being 2 dB compared to 3 dB for the Calm Neutral class.

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

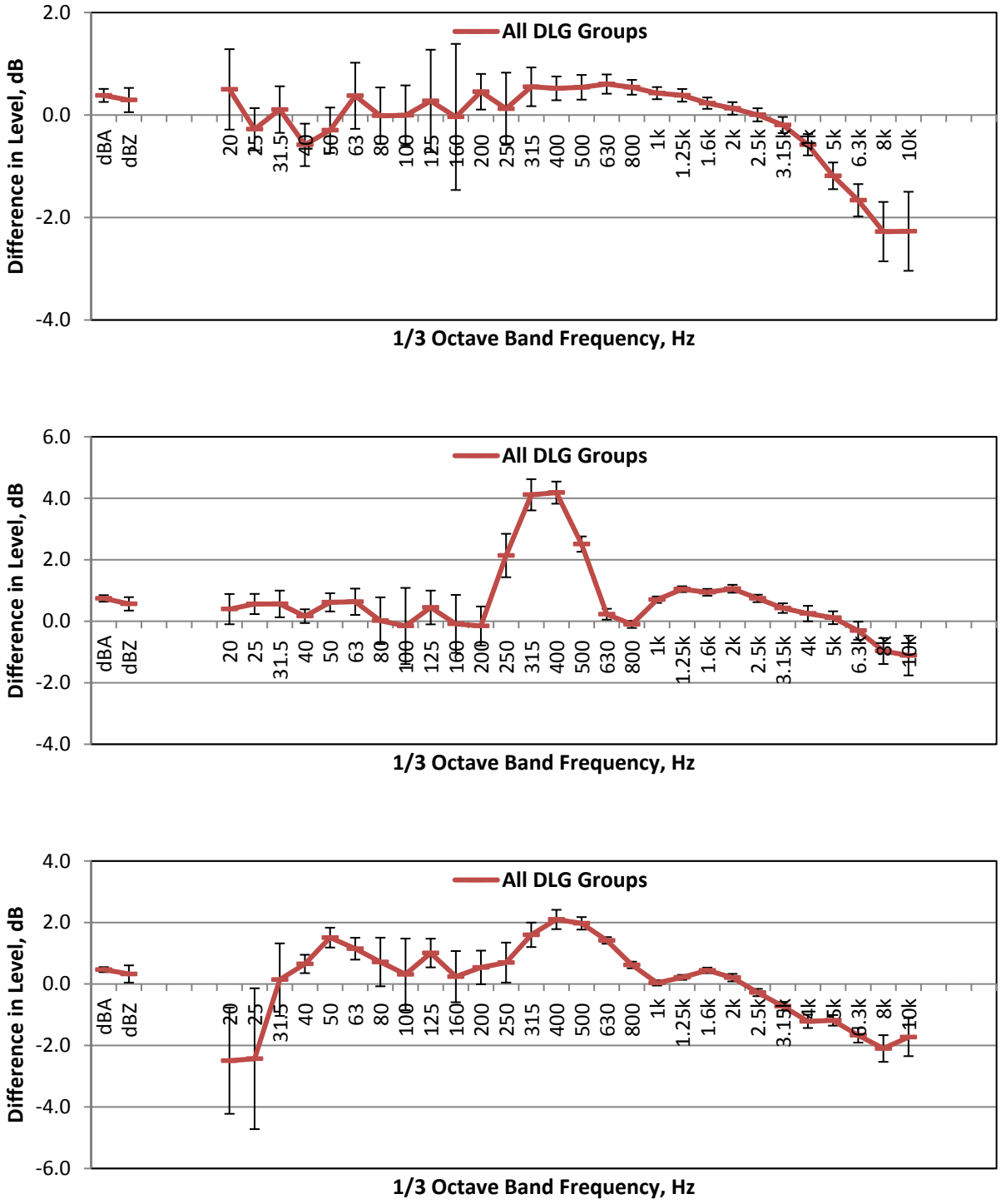


Figure 88. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Downwind Lapse groups, I-90.

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 off the edge of shoulder) and then back off the vehicle bodies.

Figure 88 shows the average differences for all the Downwind Lapse equivalent groups. In this case, "Downwind" refers to the microphones *across* the road. The reference microphones are *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).

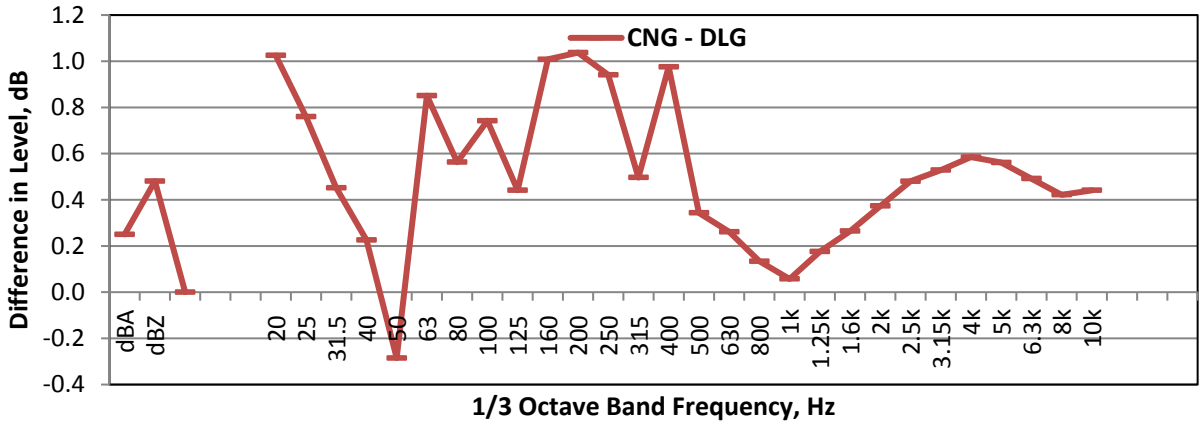
For the reference microphones, the differences are 1 dB or less. In other words, the difference in the BarRef01 and NoBarRef02 levels were slightly less for the Upwind Lapse class than for the Calm Neutral class. The data show that the Calm Neutral average differences tend to be slightly greater than the Downwind Lapse average differences across the frequency spectrum.

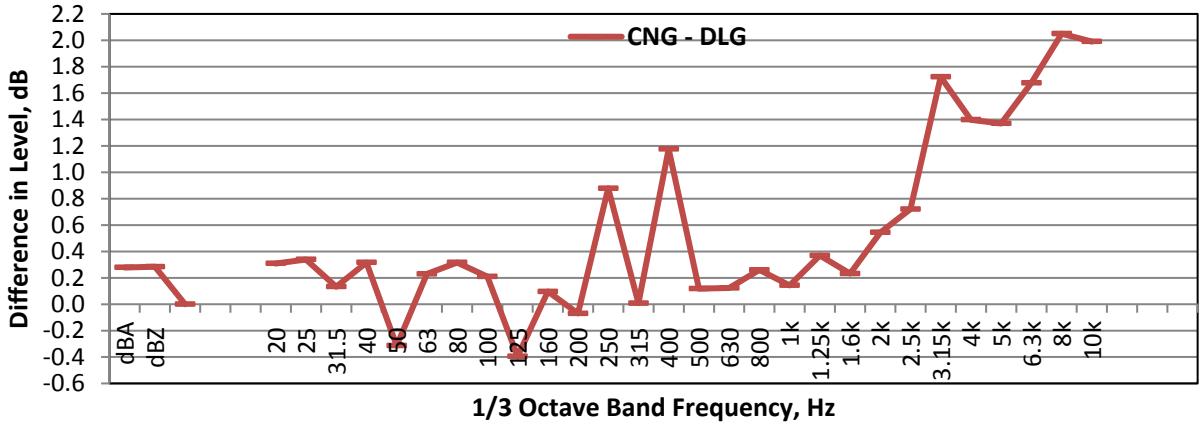
For both microphone pairs, the Calm Neutral differences are greater than the Downwind Lapse differences by 1 dB or less up though 2.5 kHz. (with the exception at 25 Hz, where the difference is 2 dB). At 3.15 kHz and above, the Calm Neutral differences range from 0.5 dB to 2 dB higher.

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.





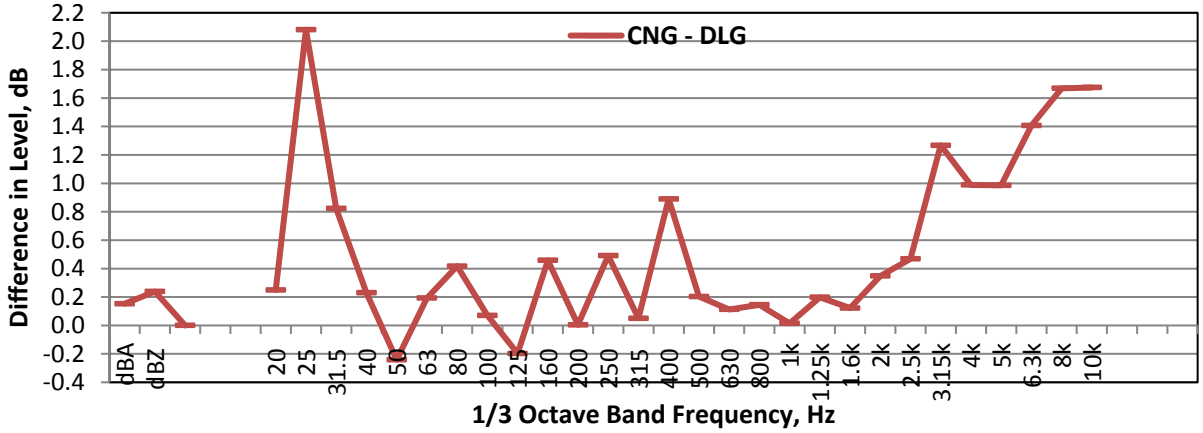


Figure 89. Differences in the Calm Neutral average differences and the Downwind Lapse average differences (L_{eq} (5 min.)), all microphone pairs, I-90.

Additional Sound Level Analysis for I-90—L_n Descriptors

Figure 90 presents the L_{90} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.), computed as BarRef01 minus NoBarRef2 for the A-weighted sound levels.

The results show that while the L_{eq} (5 min.) 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} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05.

No compelling evidence exists of the elevated background level at BarCom03. While the L_{eq} (5 min.) 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} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06.

Strong evidence exists of the elevated background level at BarCom04 compared to NoBarCom06, with the differences similar to the BarCom03 comparison to NoBarCom05.

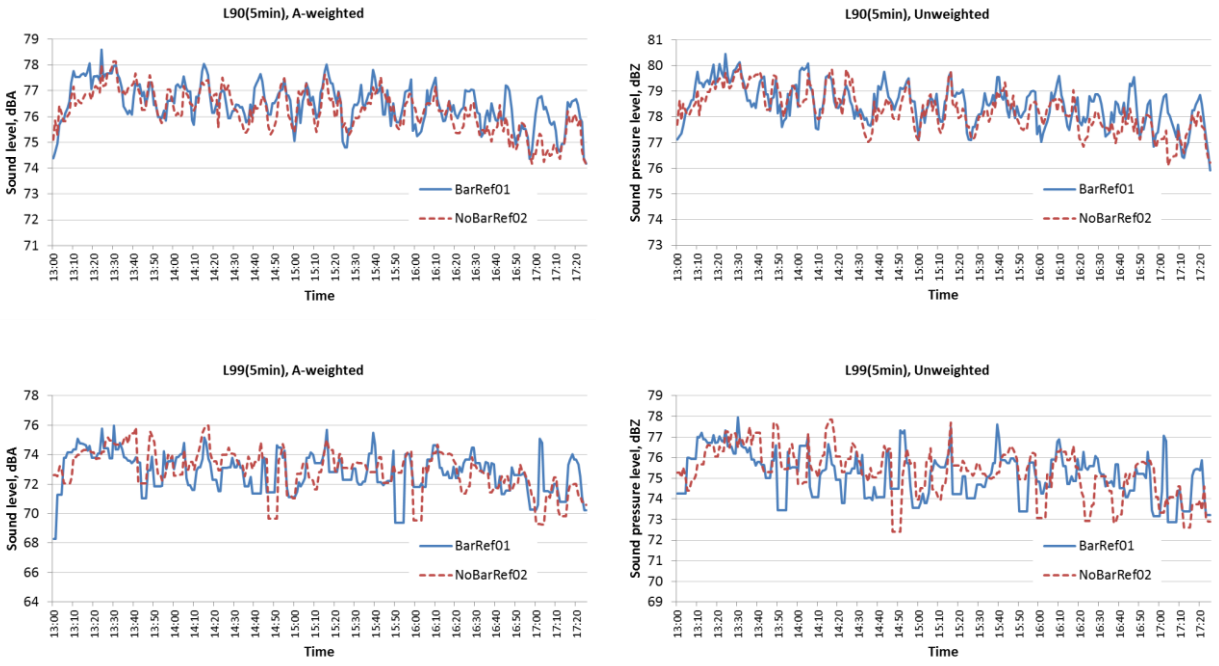


Figure 90. L_{90} (5 min.) and L_{99} (5 min.), I-90, BarRef01 and NoBarRef02—broadband A-weighted sound level (left) and sound pressure level (right).

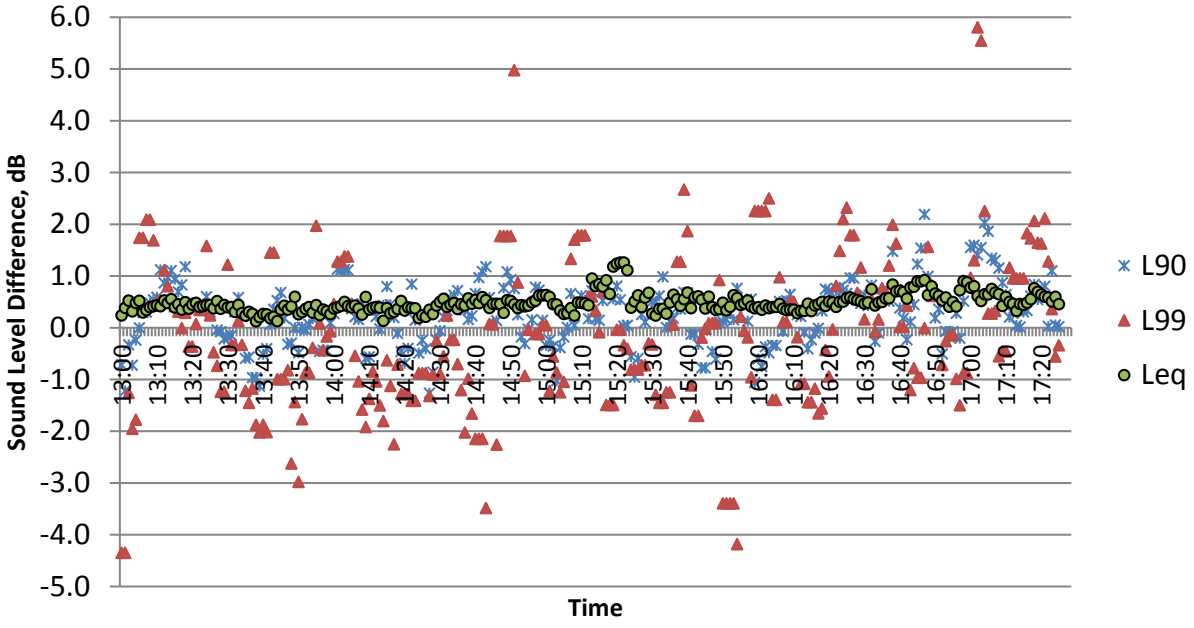


Figure 91. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, I-90, BarRef01 and NoBarRef02.

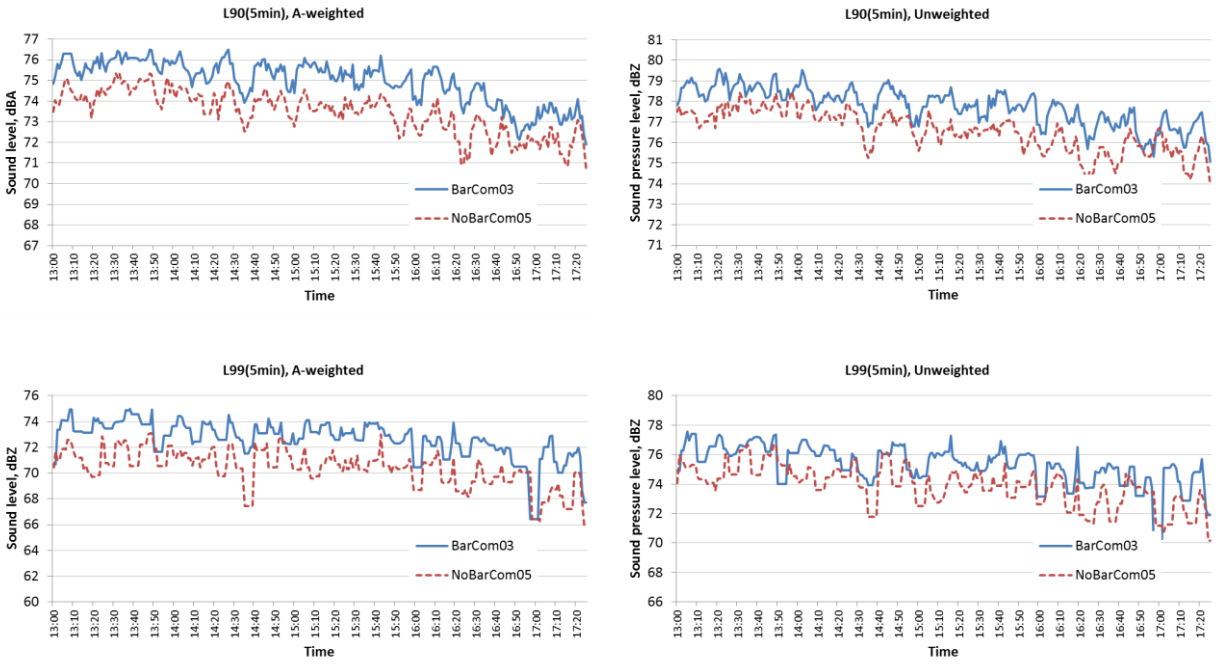


Figure 92. L_{90} (5 min.) and L_{99} (5 min.), I-90, BarCom03 and NoBarCom05—broadband A-weighted sound level (left) and sound pressure level (right).

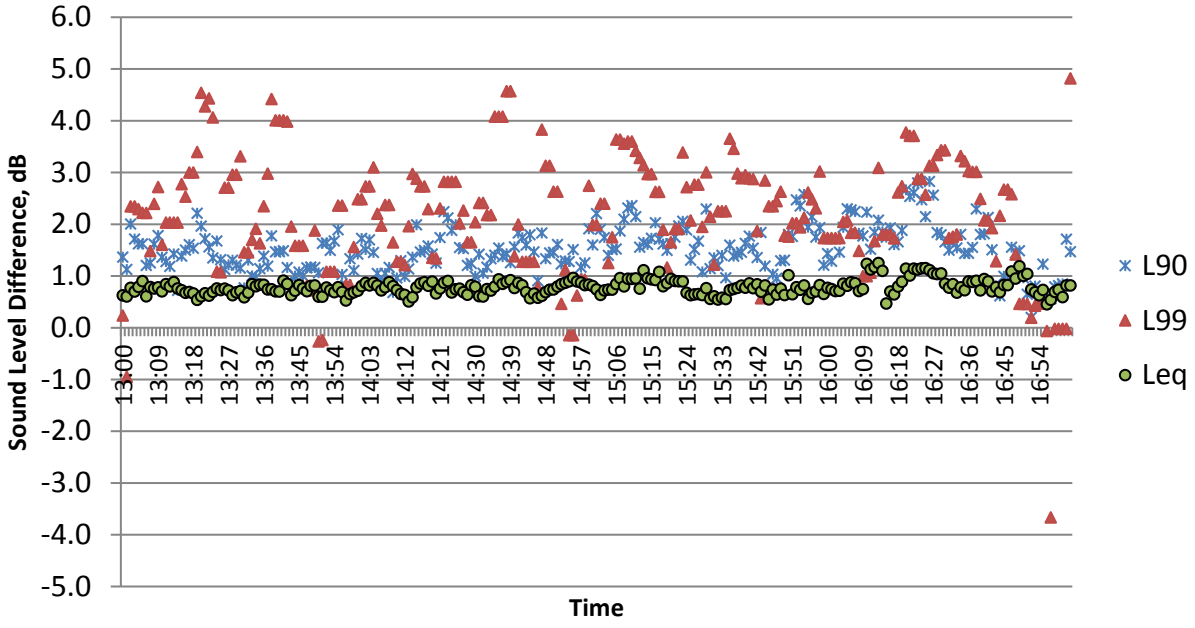


Figure 93. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, I-90, BarCom03 and NoBarCom05.

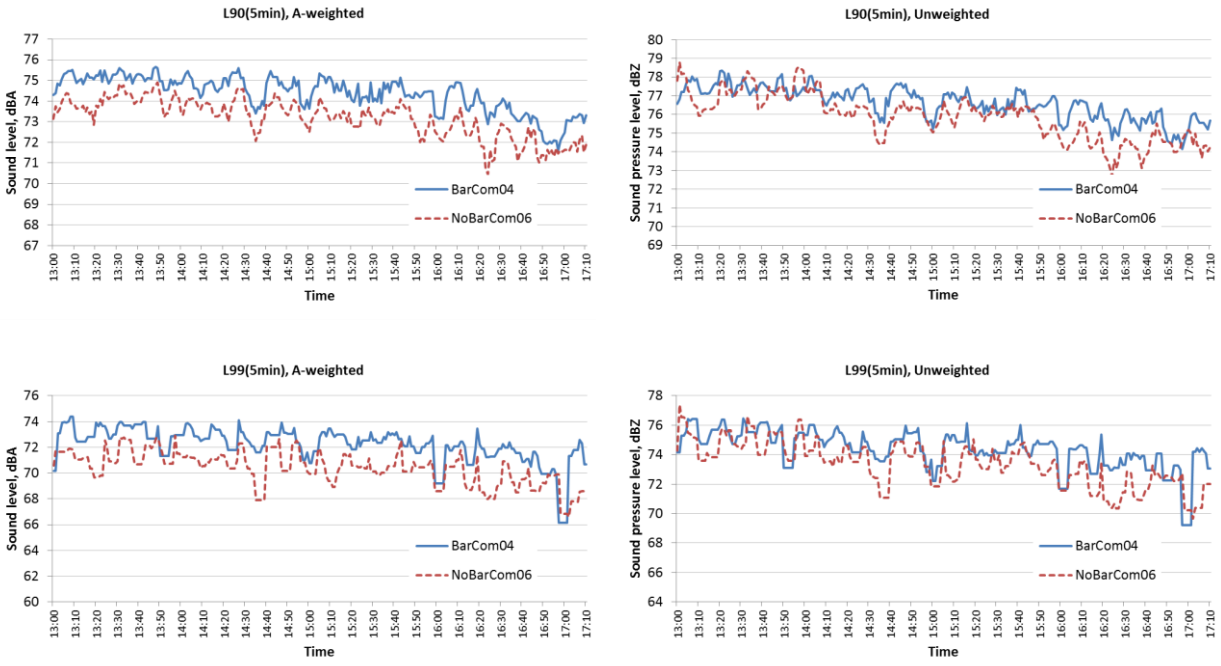


Figure 94. L_{90} (5 min.) and L_{99} (5 min.), I-90, BarCom04 and NoBarCom06—broadband A-weighted sound level (left) and sound pressure level (right).

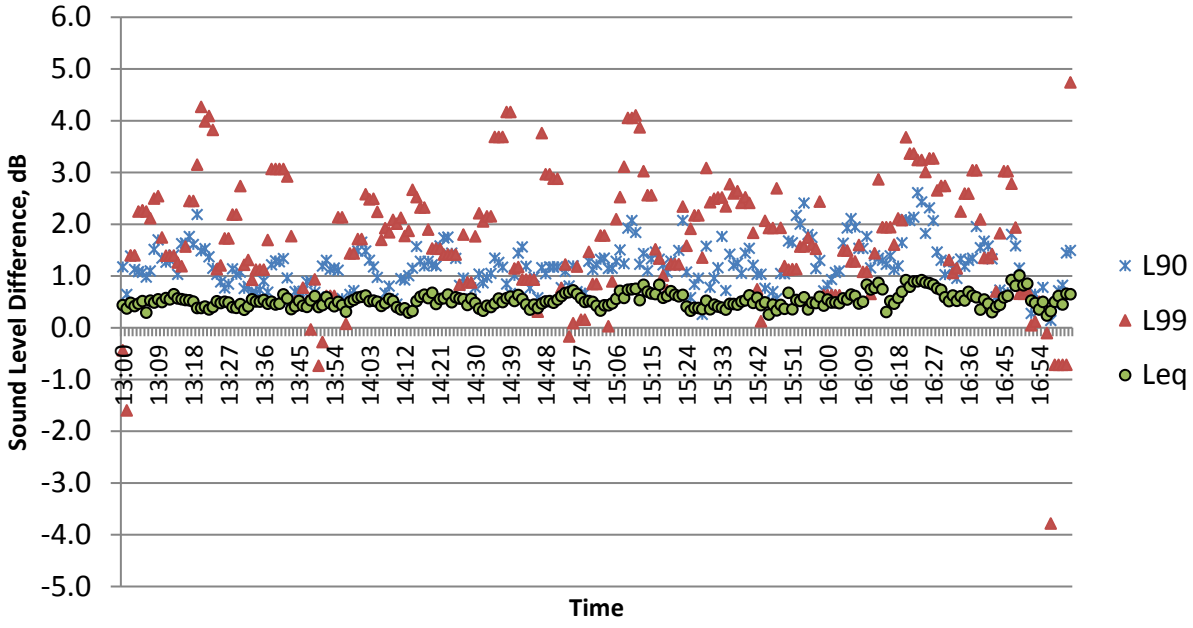


Figure 95. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, I-90, BarCom04 and NoBarCom06.

The preceding graphs were for the broadband A-weighted sound levels and unweighted sound pressure levels only. Figure 96 broadens the analysis to include the individual one-third 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 5-minute period) and the total block representing approximately 4 hours. The one-third 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}.

Little evidence exists 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 attributable to insect noise.

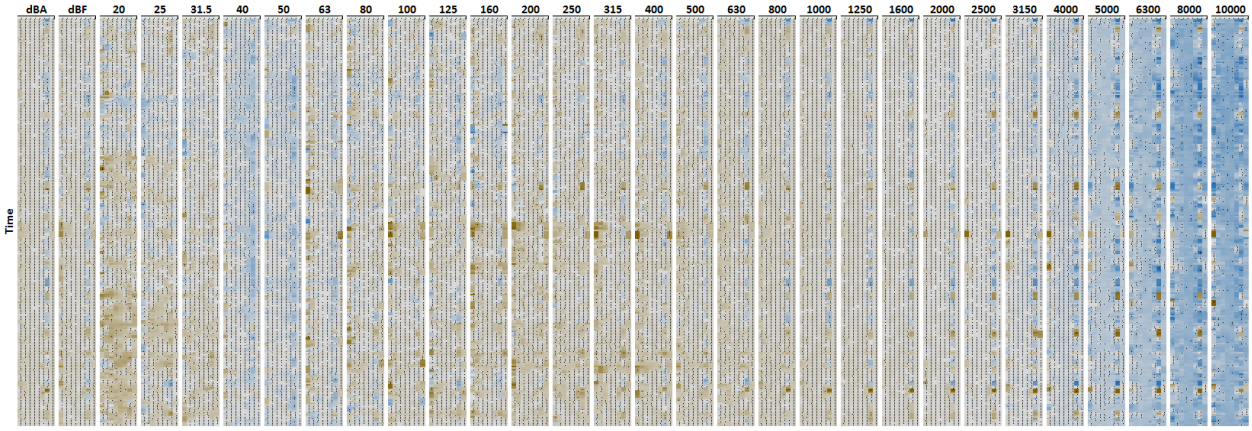


Figure 96. I-90 Differences in L_n (5 min.) by one-third octave frequency bands: BarRef01 and NoBarRef02.

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 Hz to 500 Hz bands in Figure 96 indicates an increase in all 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 through 3.15 kHz mean that the BarCom03 background levels are higher than the NoBarCom05 background levels.

Figure 98 includes less brown, 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 Hz to 500 Hz bands in Figure 96 indicates an increase in all the L_n descriptors and means 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 through 3.15 kHz mean that the BarCom03 background levels are higher than the NoBarCom05 background levels.

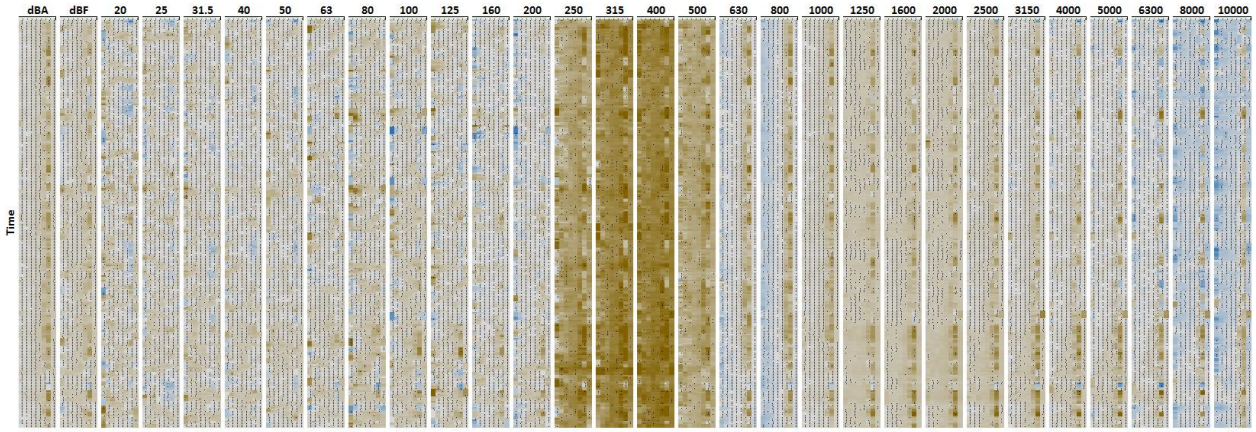


Figure 97. I-90 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom03 and NoBarCom05.

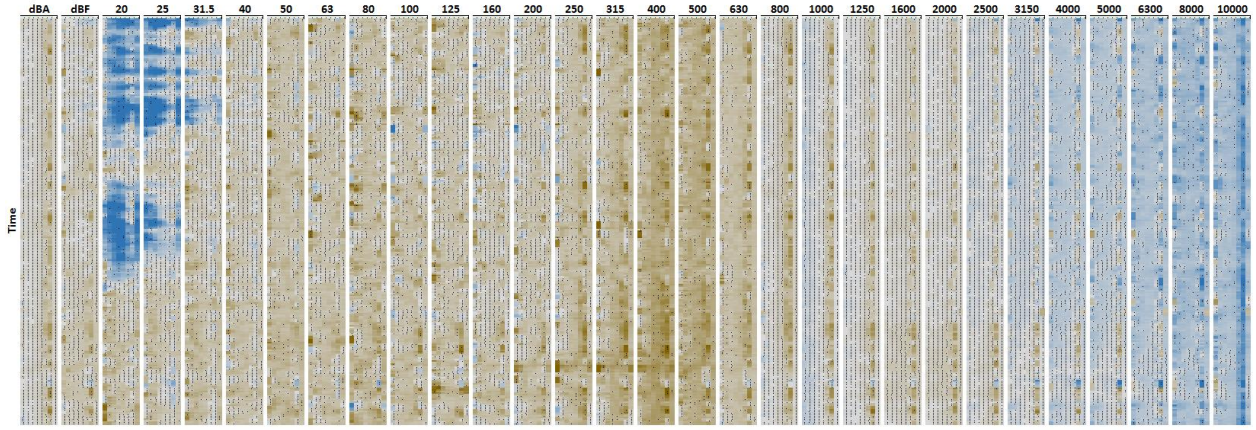


Figure 98. I-90 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom04 and NoBarCom06.

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.

Two equivalent microphones compare 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 are not discussed further in the analysis.

Spectrograms from I-90 Rockford vehicle pass-by events are shown in the following figures. 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 like 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 yellow/orange band (around 62 dBA), shifting over time 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. 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 that contribute most to the overall sound level and sustaining these levels longer 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.

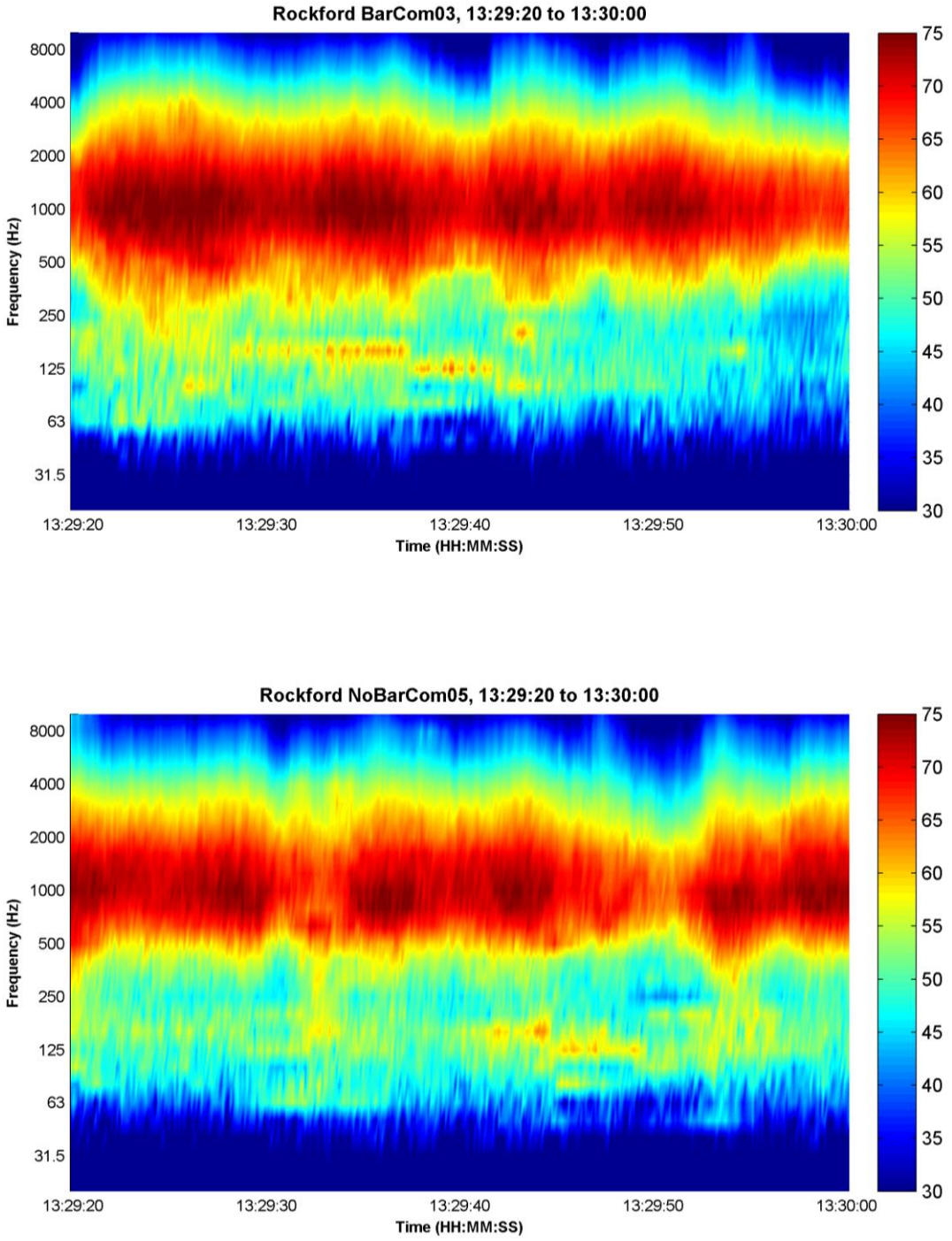


Figure 99. I-90 spectrograms for a heavy truck on southbound (community) side: top is BarCom03; bottom is NoBarCom05 (approximate event times: Barrier site 13:29:36, No Barrier site 13:29:43).

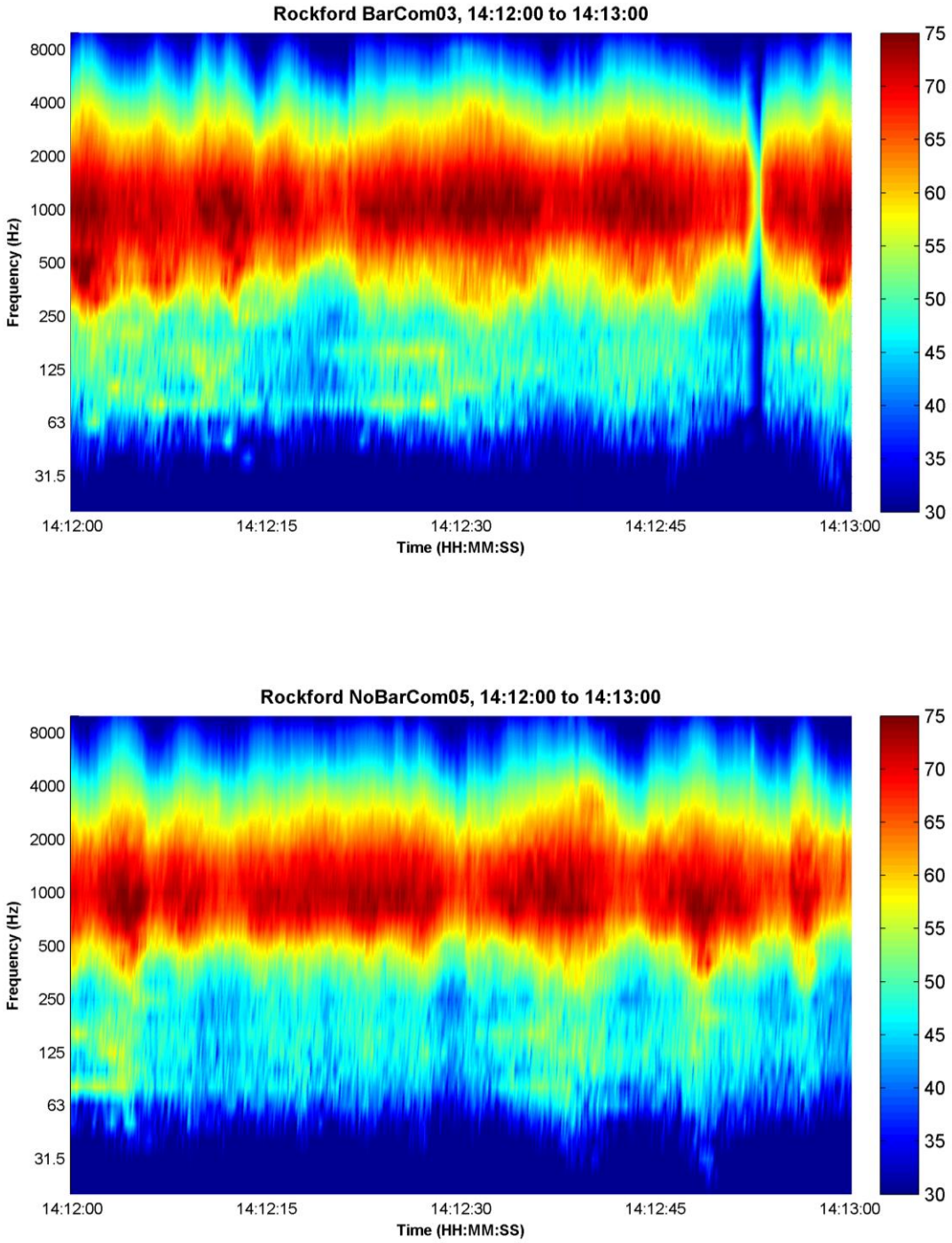


Figure 100. ***I-90 spectrograms for a second heavy truck on southbound (community) side: top is BarCom03; bottom is NoBarCom05 (approximate event times: Barrier site 14:12:34, No Barrier site 14:12:40).***

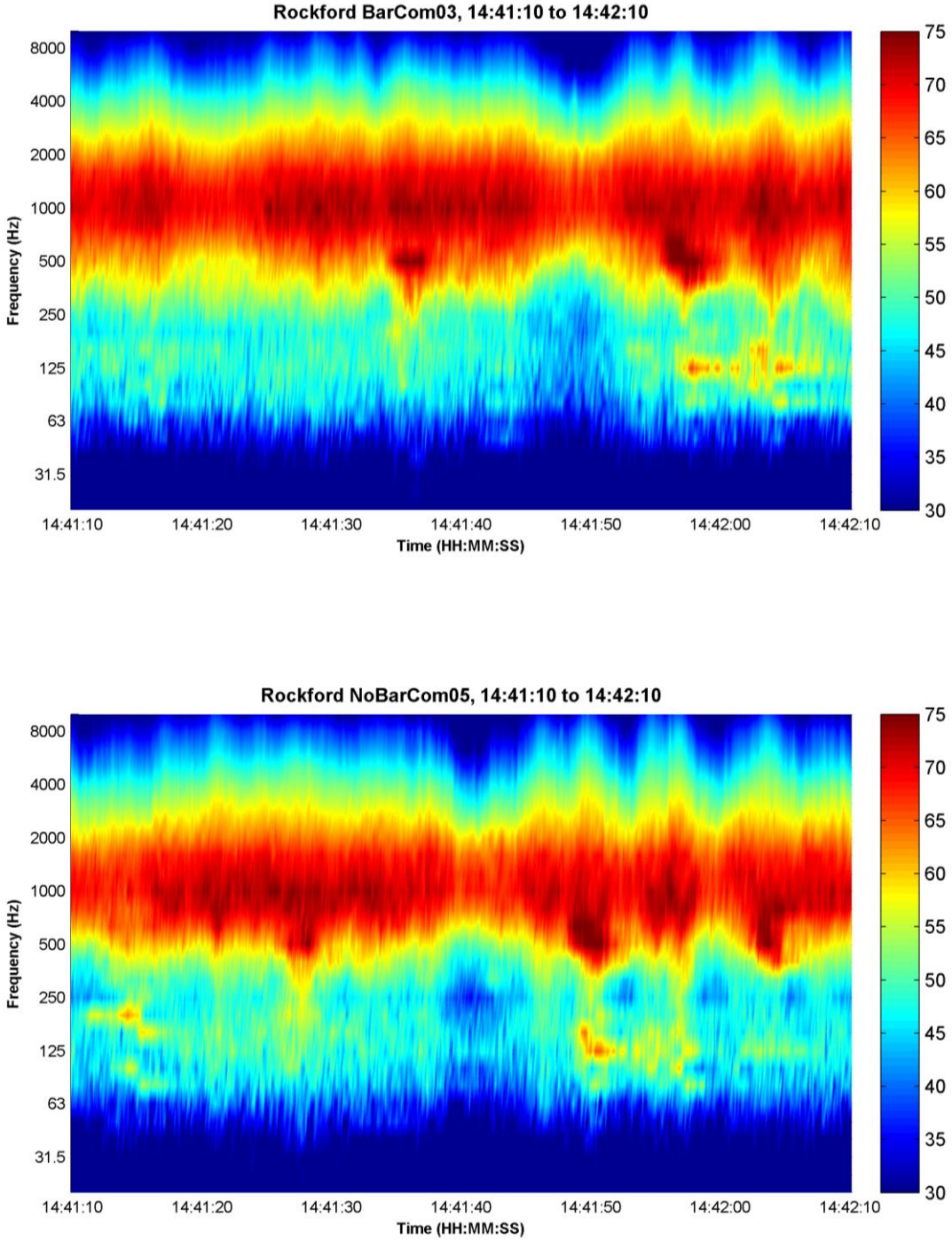


Figure 101. I-90 spectrograms for a third heavy truck on northbound (barrier) side: top is BarCom03; bottom is NoBarCom05 (approximate event times: Barrier site 14:41:36, No Barrier site 14:41:27).

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, the tallest darkest red band (highest sound level band) centered around 1,000 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 that contribute most to the overall sound level and sustaining these levels longer for each vehicle pass-by event.

The spectrogram data also includes 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 Hz to 500 Hz range, the differences span from 2 dB to 5 dB. The spectrogram data show a clear indication of differences between the two sites at 250 Hz. These larger differences in the 250 Hz to 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.

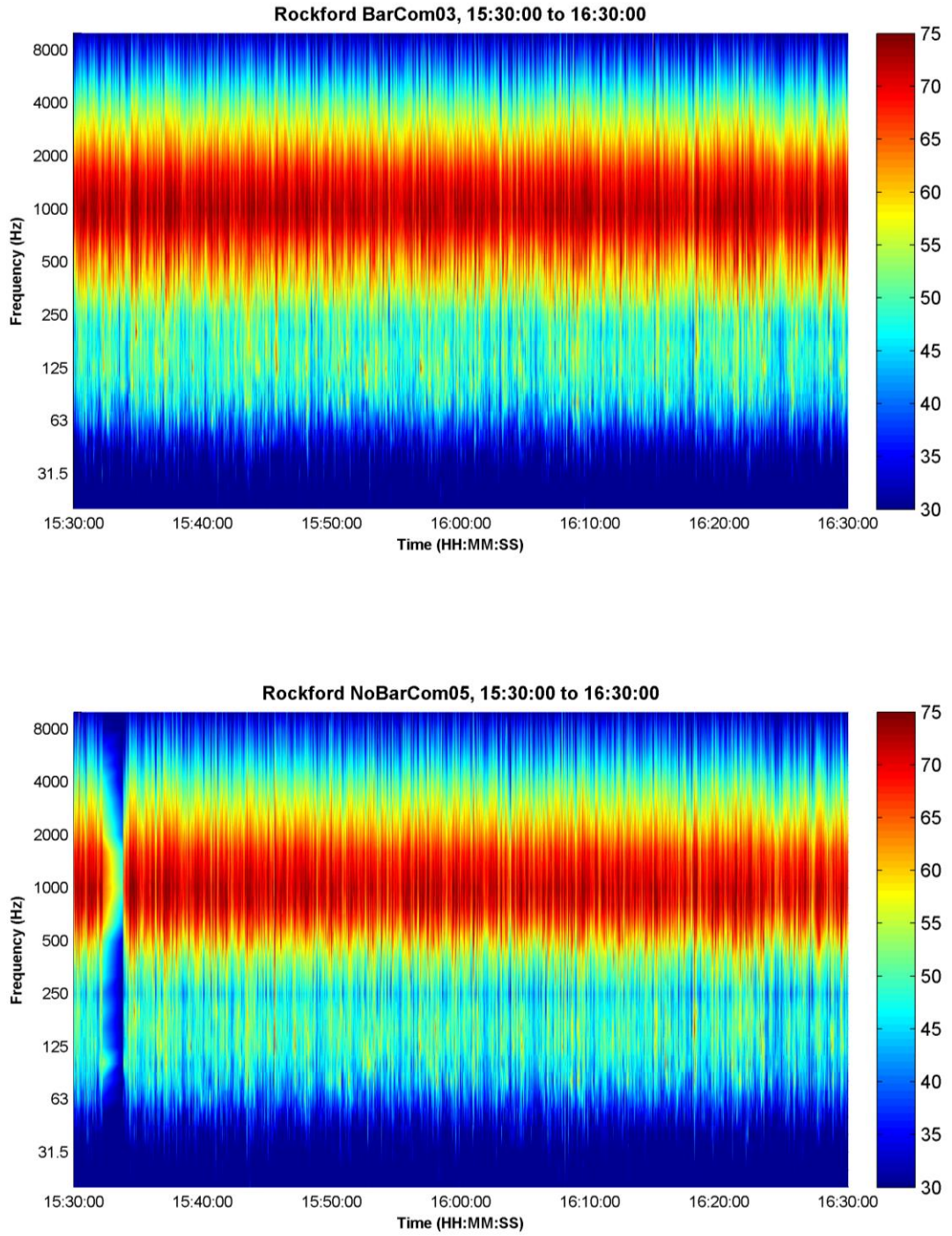


Figure 102. I-90 spectrograms for an hour-long block of data from 15:30 to 16:30: top is BarCom03; bottom is NoBarCom05.

Data Analysis for I-90—Psychoacoustics

Table 10 summarizes the descriptive statistics for the computed annoyance metrics at I-90. 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 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 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 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.

A clear difference exists in the means of the UBA 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 PA. 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.

No significant difference exists in the means of the CSA 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	Microphone	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

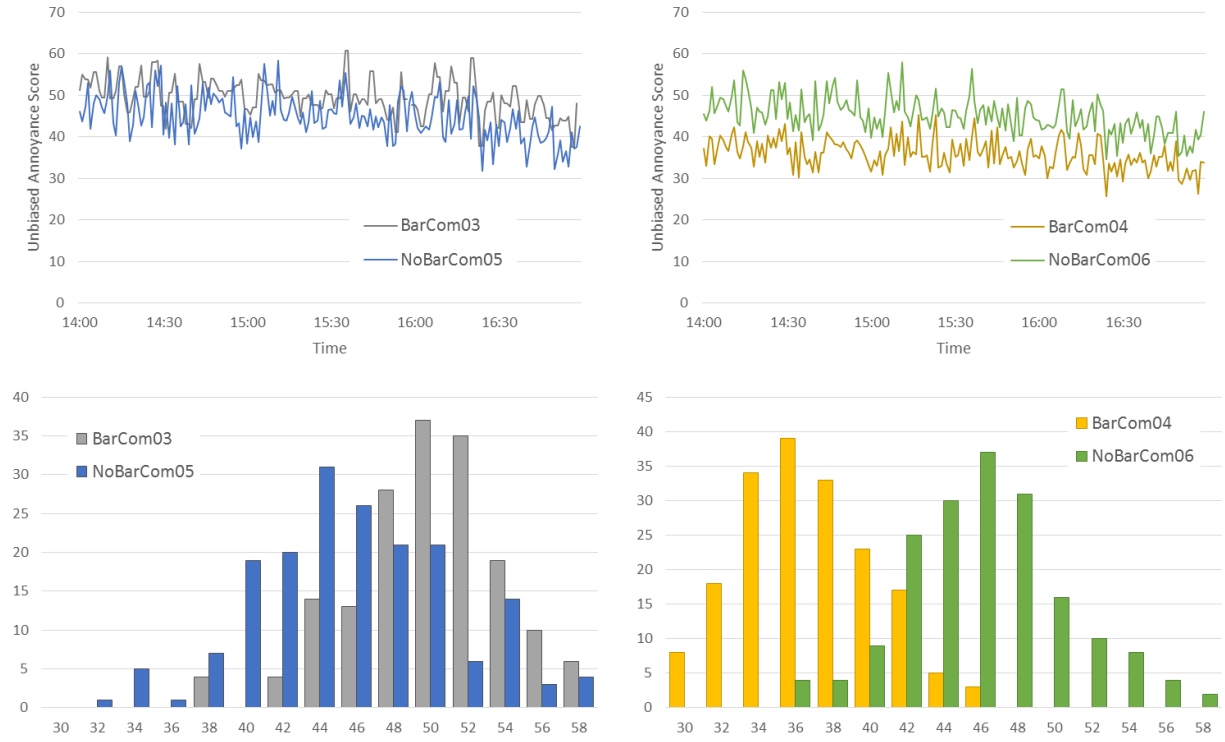


Figure 104. UBA vs. time and histograms, I-90.

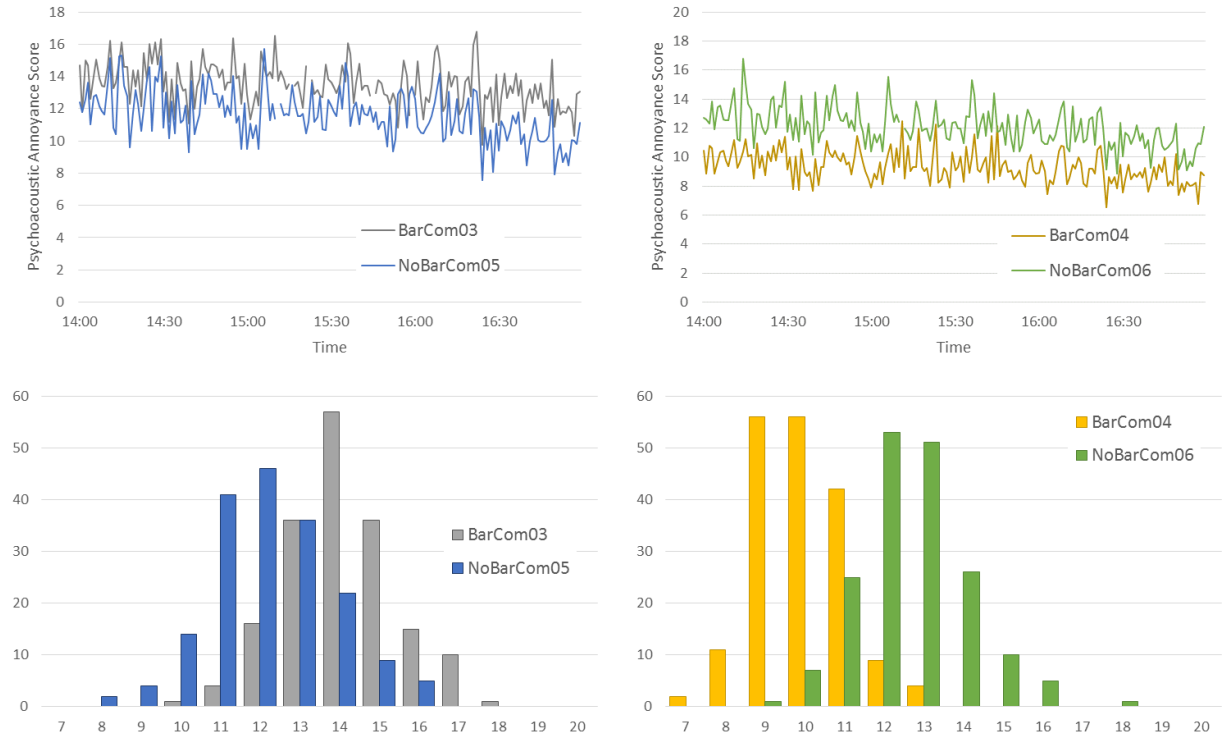


Figure 105. PA vs. time and histograms, I-90.

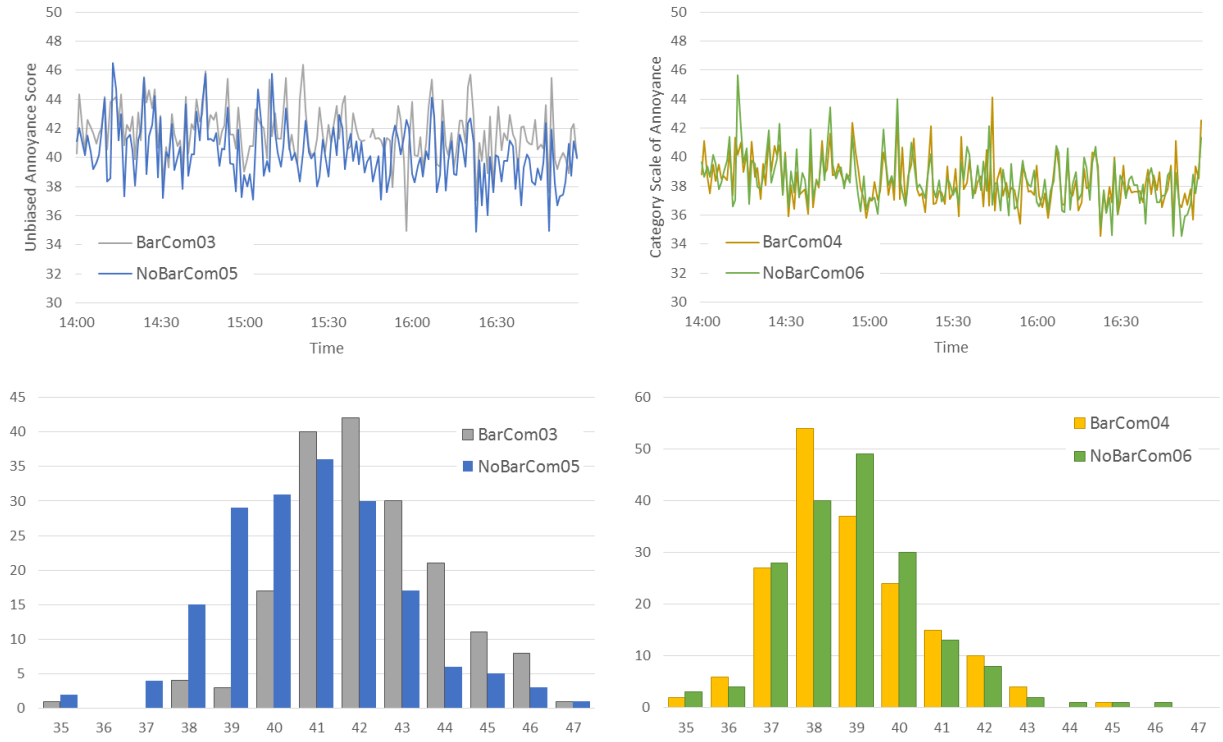


Figure 106. CSA vs. time and histograms, I-90.

CHAPTER E-6

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

On January 28, 2015, data were successfully collected at the fourth location, SR-71, in Chino Hills, California. Data were collected from about 09:00 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.

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 F (available online) contains site photographs.

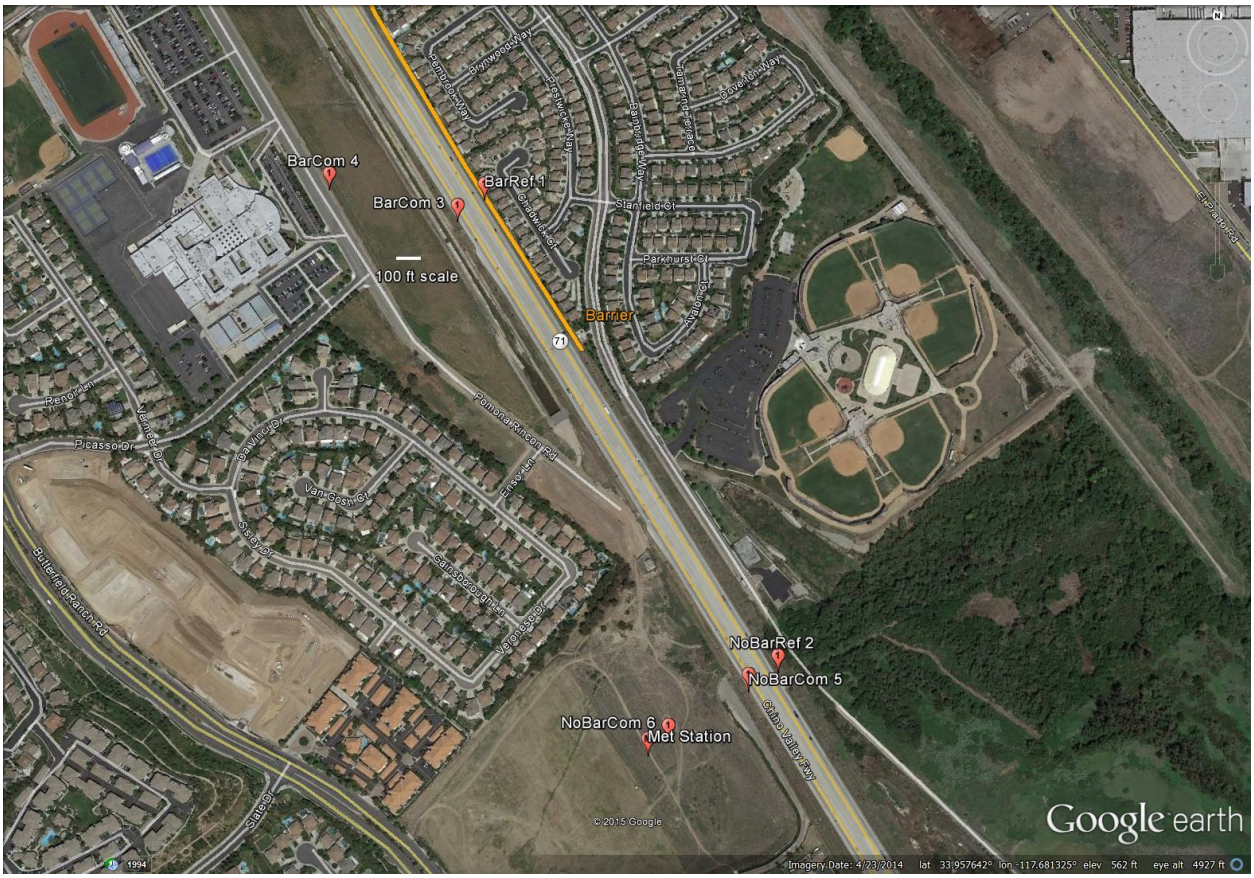


Figure 107. SR-71 microphone positions. (Source: Google Earth.)

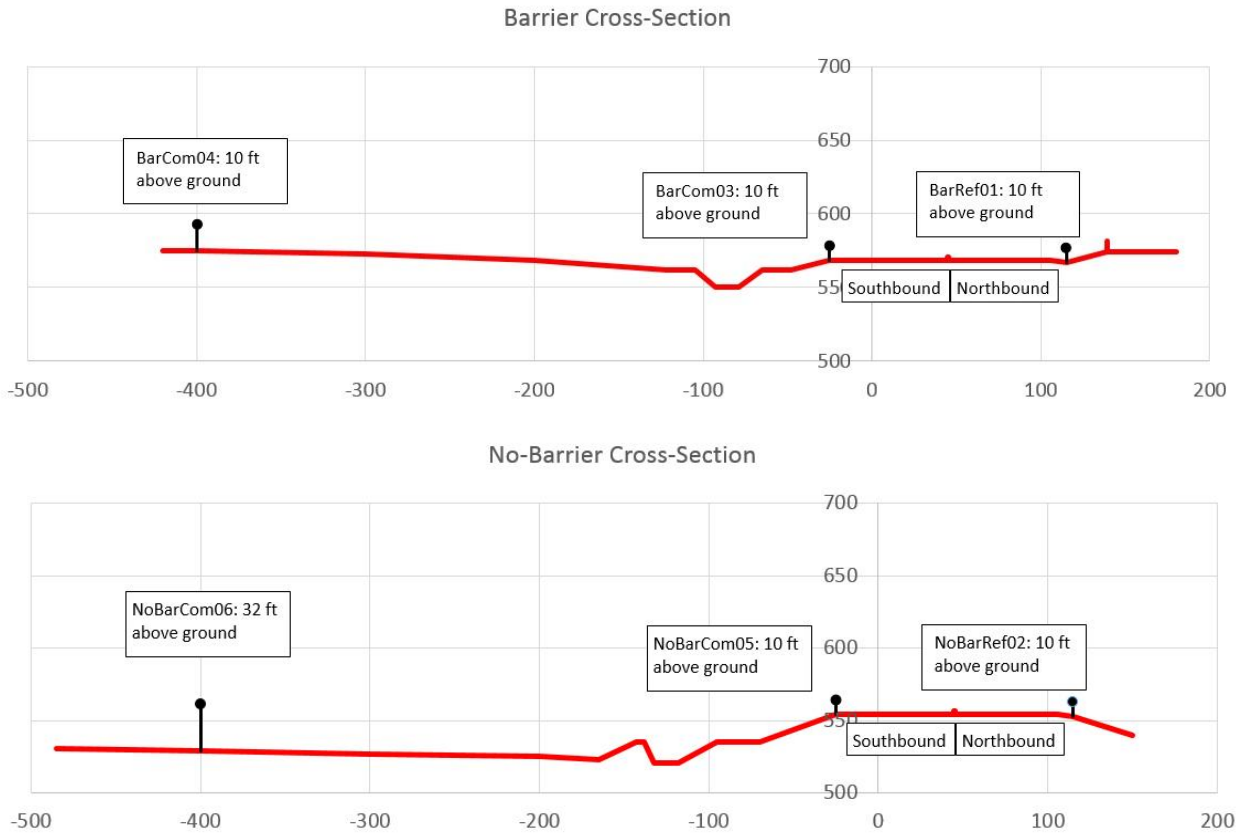


Figure 108. Cross-sections at the SR-71 Barrier (top) and No Barrier (bottom) sites.

The SR-71 location consisted of six microphone locations as shown in Table 11.

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.

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 one-half 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 mph to 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. 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} (5 min.) 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.
- 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 to 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 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.

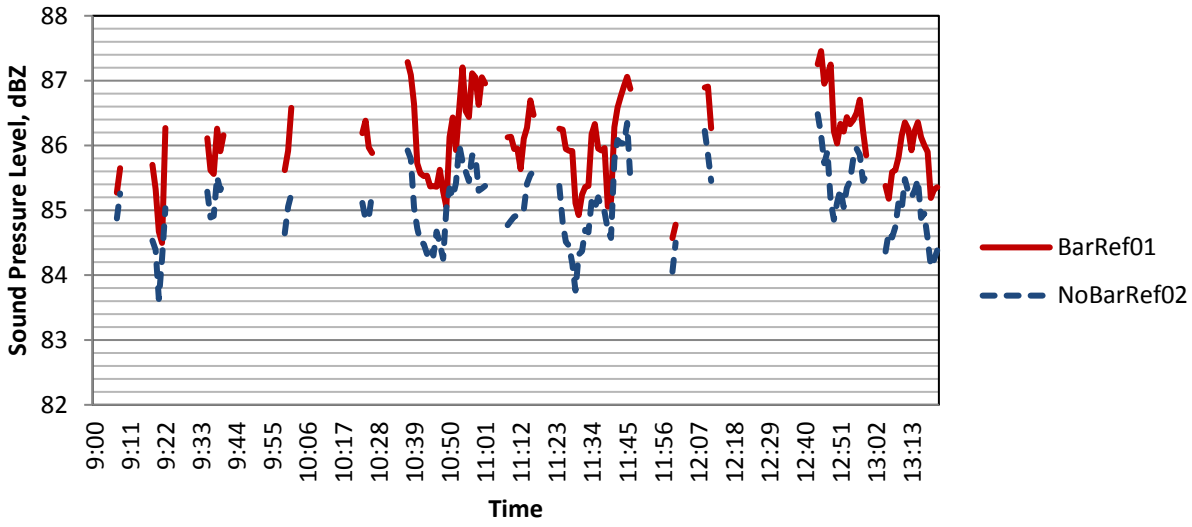


Figure 109. Running L_{eq} (5 min.), SR-71, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

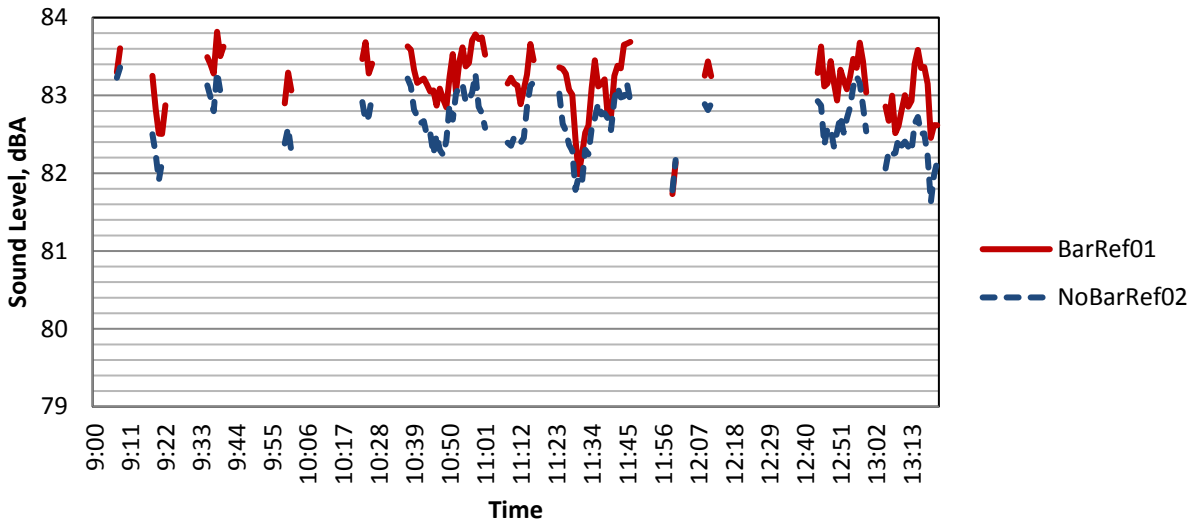


Figure 110. Running L_{eq} (5 min.), SR-71, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

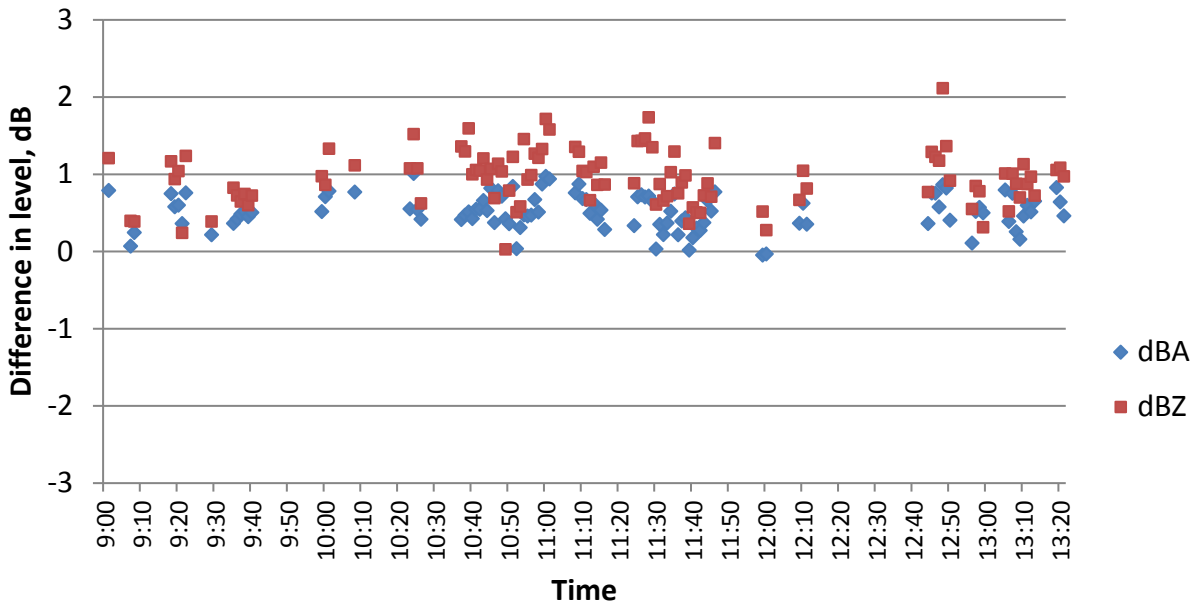


Figure 111. Differences in running L_{eq} (5 min.), SR-71, BarRef01 minus NoBarRef02.

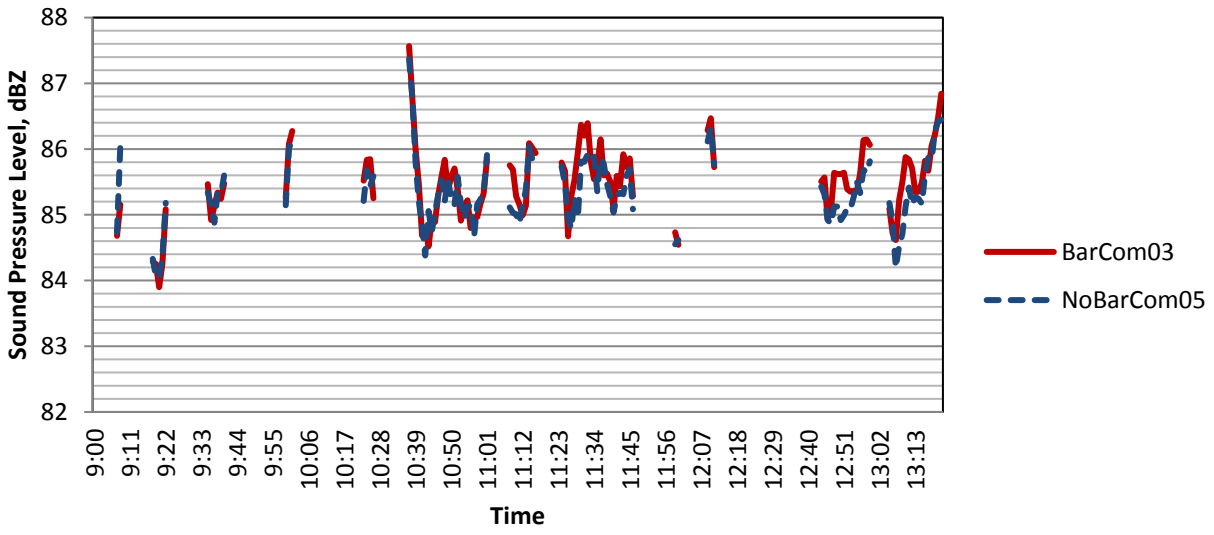


Figure 112. Running L_{eq} (5 min.), SR-71, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

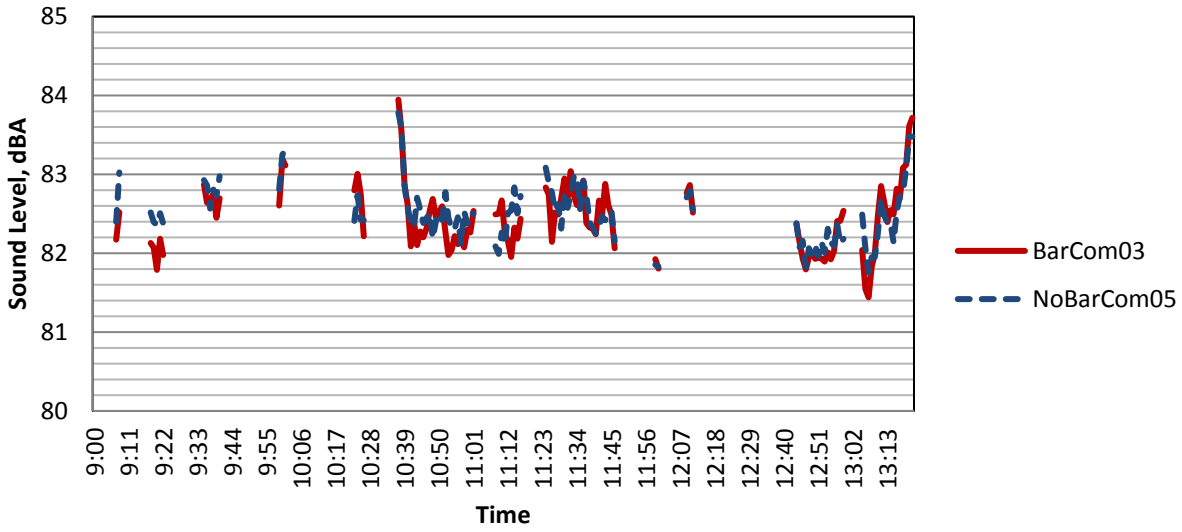


Figure 113. Running L_{eq} (5 min.), SR-71, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

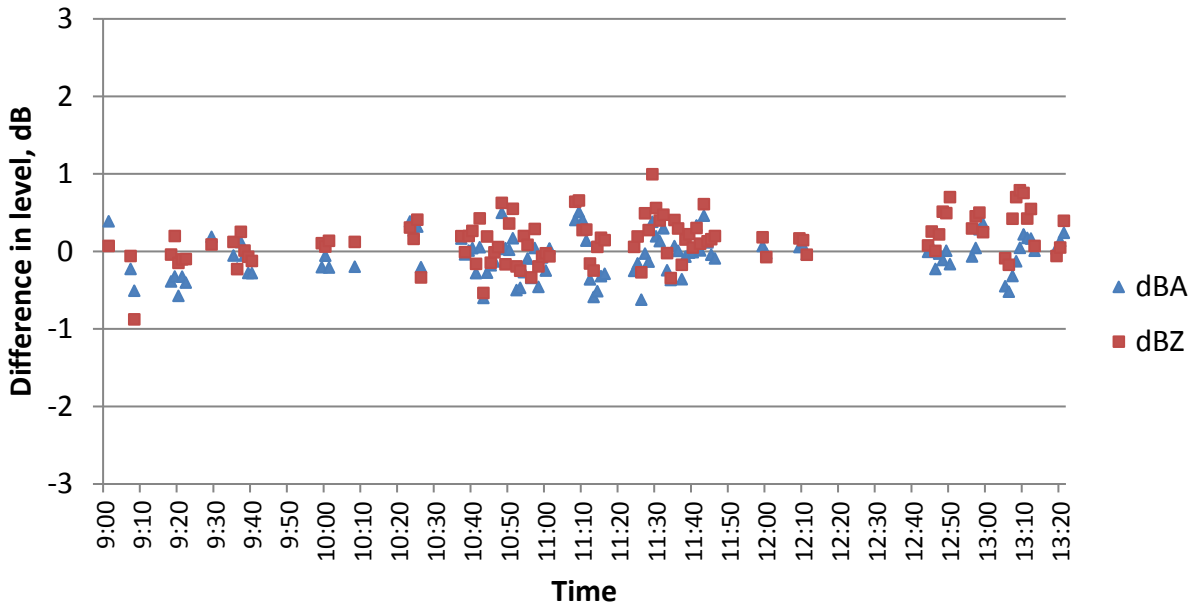


Figure 114. Differences in running L_{eq} (5 min.), SR-71, BarCom03 minus NoBarCom05.

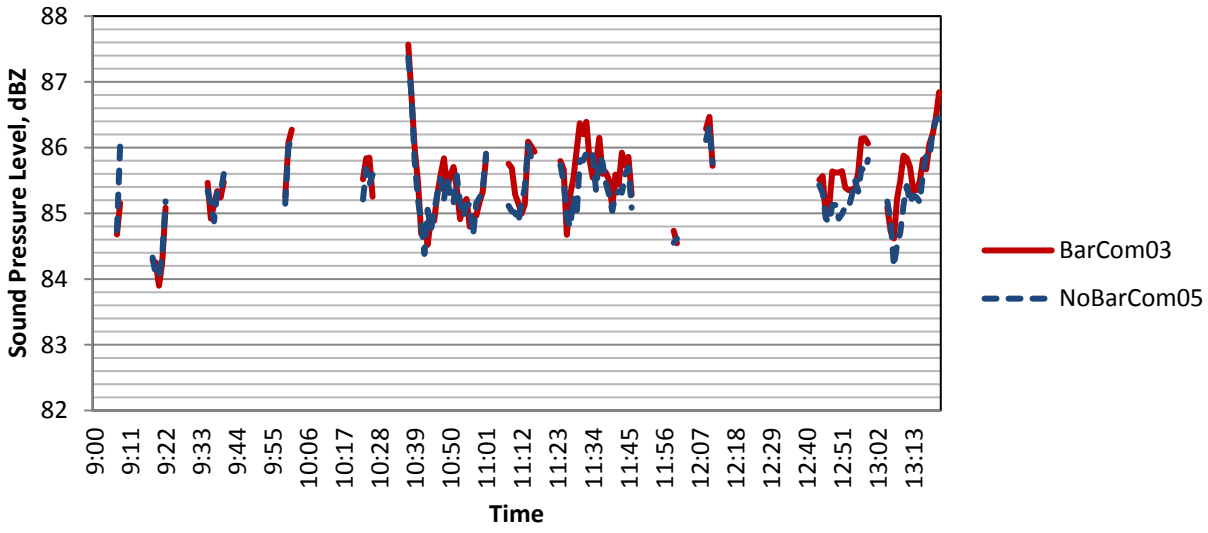


Figure 115. Running L_{eq} (5 min.), SR-71, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

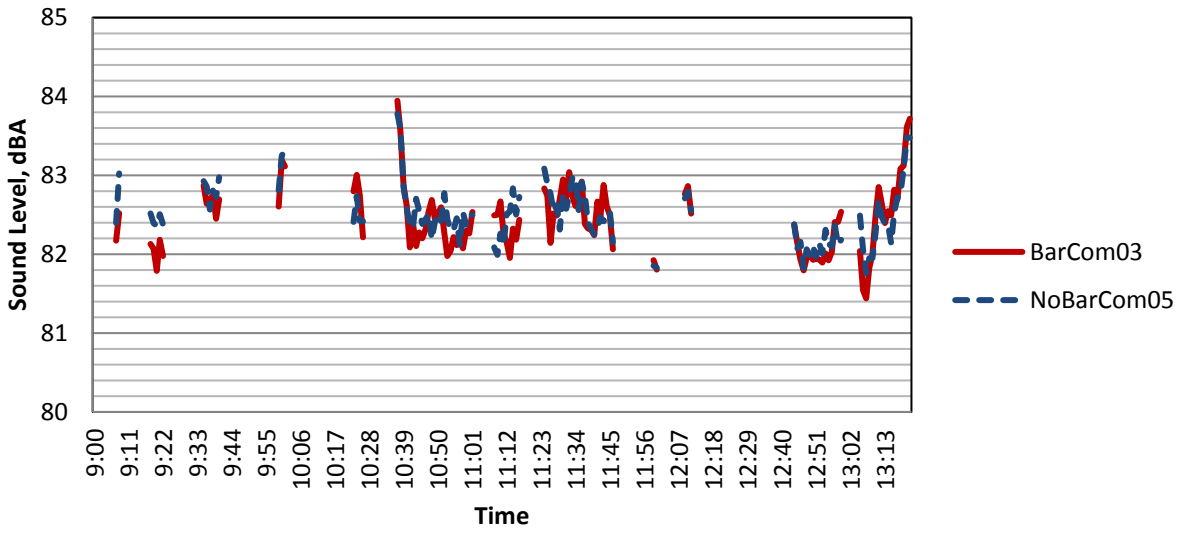


Figure 116. Running L_{eq} (5 min.), SR-71, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

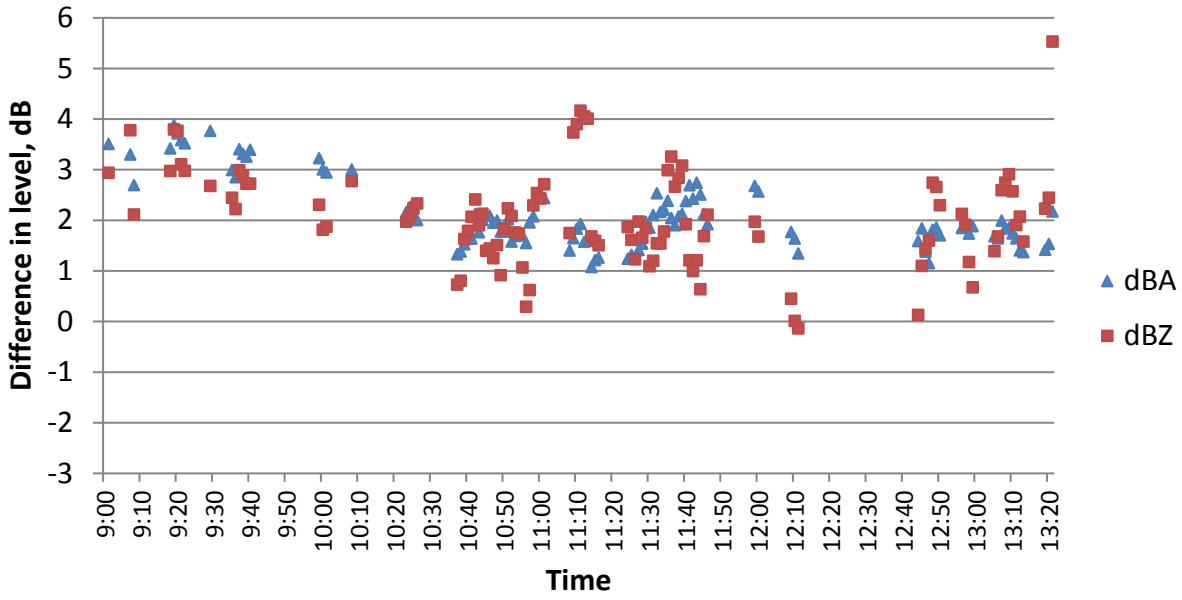


Figure 117. Differences in running L_{eq} (5 min.), SR-71, BarCom04 minus NoBarCom06.

Data Analysis for SR-71—FHWA Method

Equivalent Groups

All 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." While all 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 consistent traffic volumes, as shown in Table 12. In terms of equivalent hourly volumes, the overall range was only from 3,628 vph 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 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.

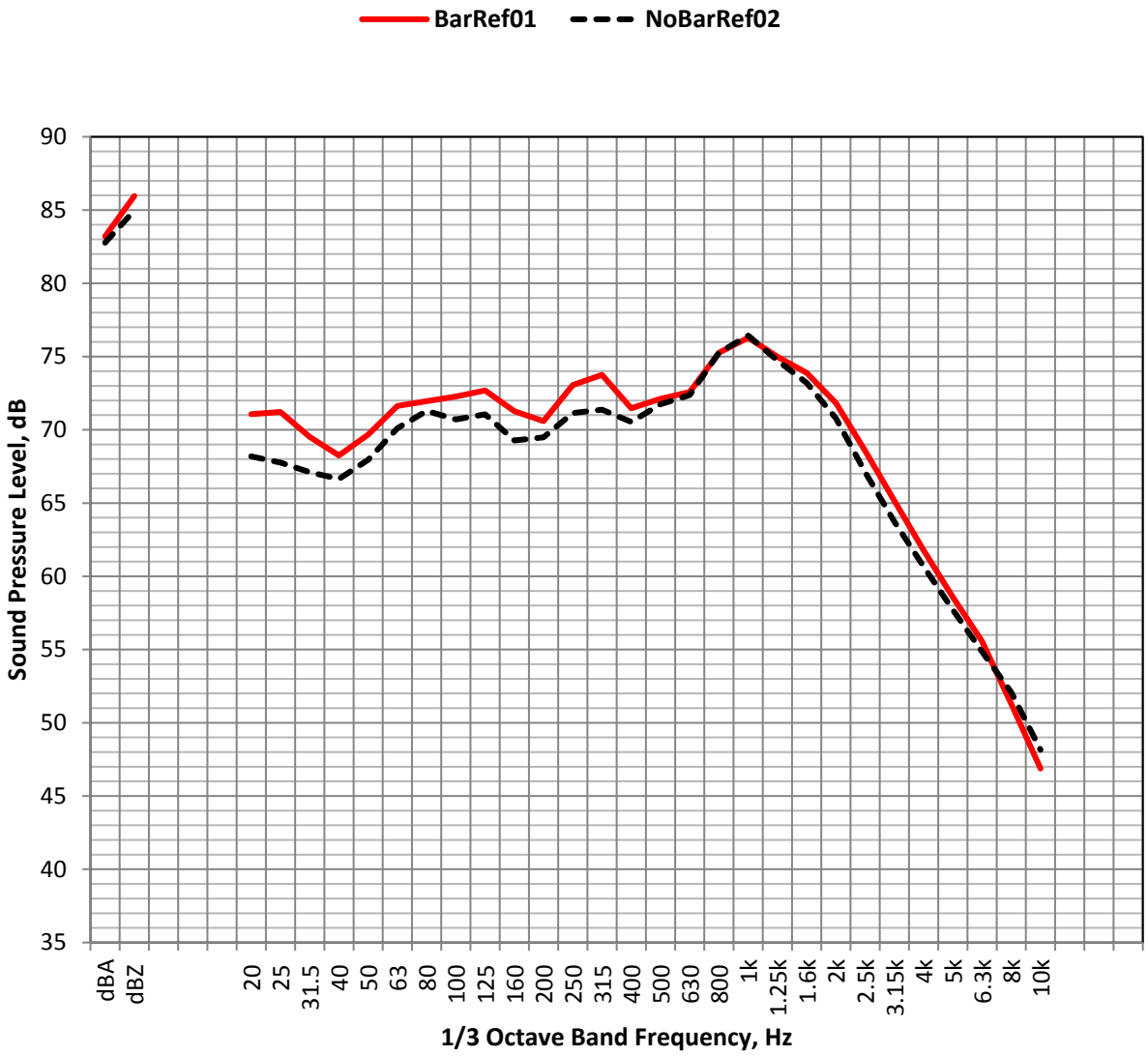


Figure 119. Sample sound pressure level spectra for BarRef01 and NoBarRef02, SR-71, Downwind Neutral group DNG-3-2, 11:38 to 11:43 (L_{eq} (5 min.), dBZ).

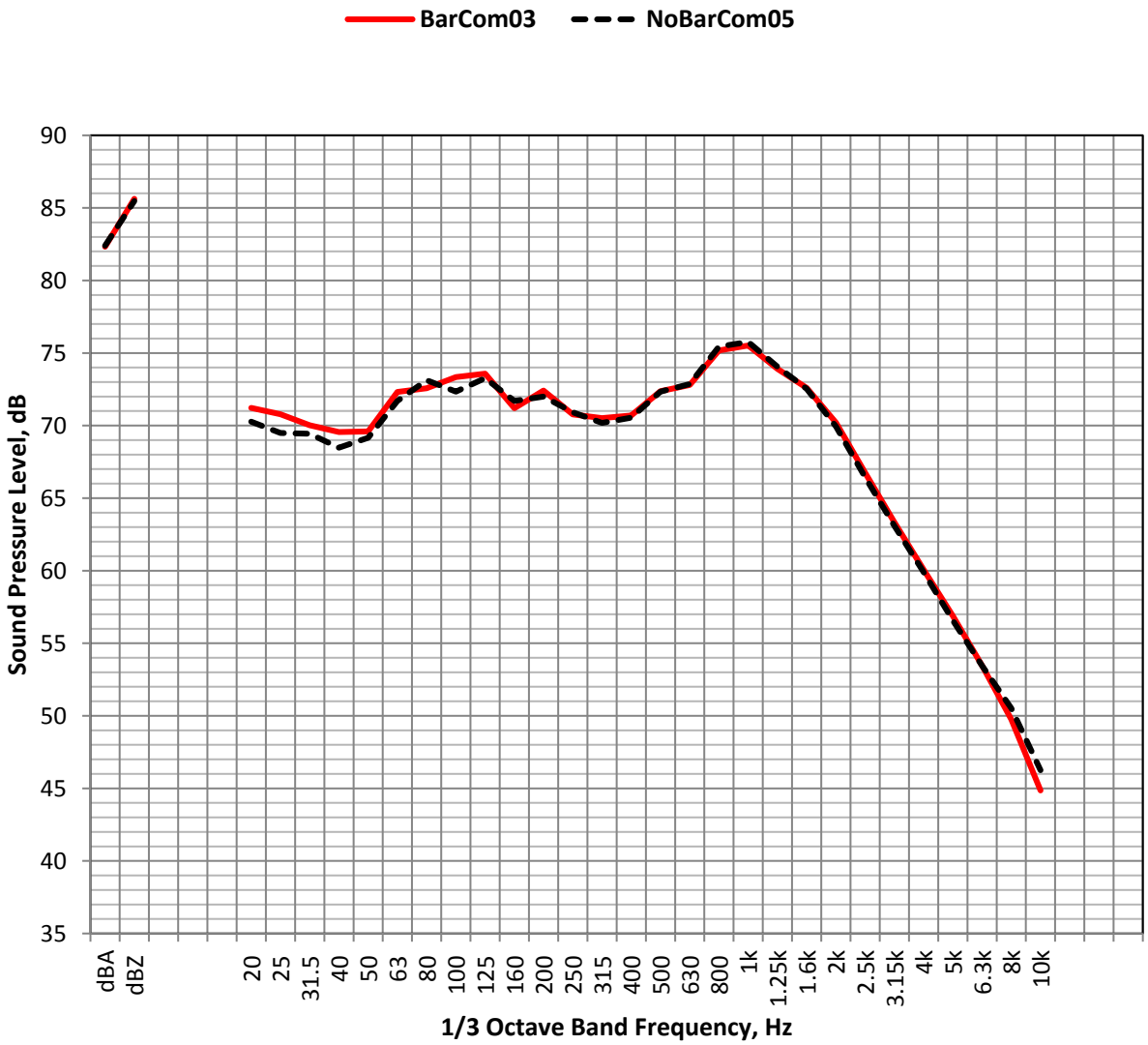


Figure 120. Sample sound pressure level spectra for BarCom03 and NoBarCom05, SR-71, Downwind Neutral group DNG-3-2, 11:38 to 11:43 (L_{eq} (5 min.), dBZ).

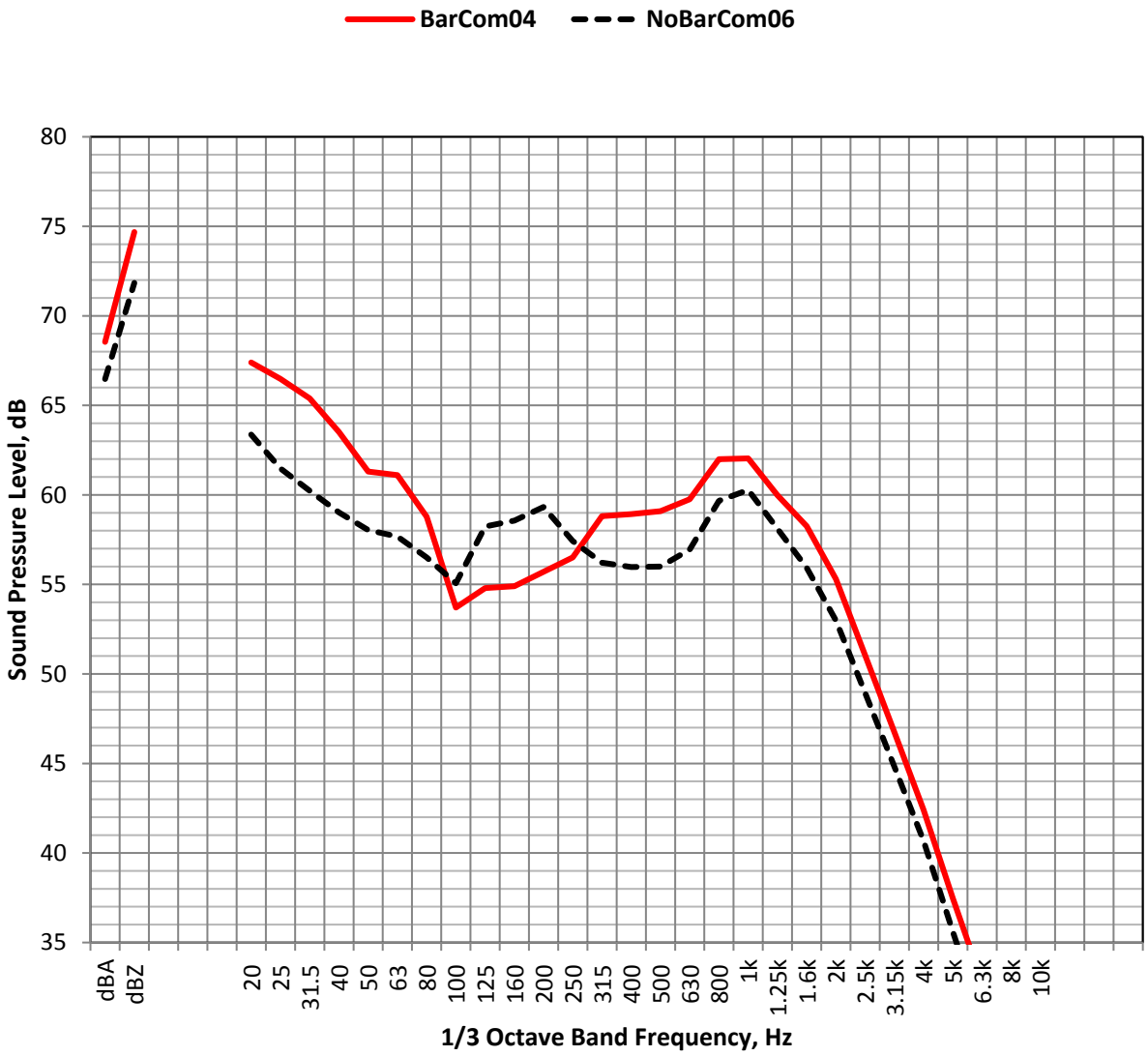


Figure 121. Sample sound pressure level spectra for BarCom04 and NoBarCom06, SR-71, Downwind Neutral group DNG-3-2, 11:38 to 11:43 (L_{eq} (5 min.), dBZ).

Downwind Neutral Class

Figure 122 shows the averages of the differences in the Barrier and No Barrier microphones' levels for all the Downwind Neutral groups, with their error bars. The error bars are +/- one standard deviation for each average value. Figure 122 compares the following:

- BarRef01 and NoBarRef02 in the upper graph.
- BarCom03 and NoBarCom05 in the middle graph.
- 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 one-third octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all the individual Downwind Neutral groups are in spreadsheet files in the project record. The trends across the one-third 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 across virtually the entire spectrum, except for 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 through 125 Hz are 0.5 dB to 1.5 dB higher at BarCom03. From 160 Hz 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 0.5 dB 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 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.

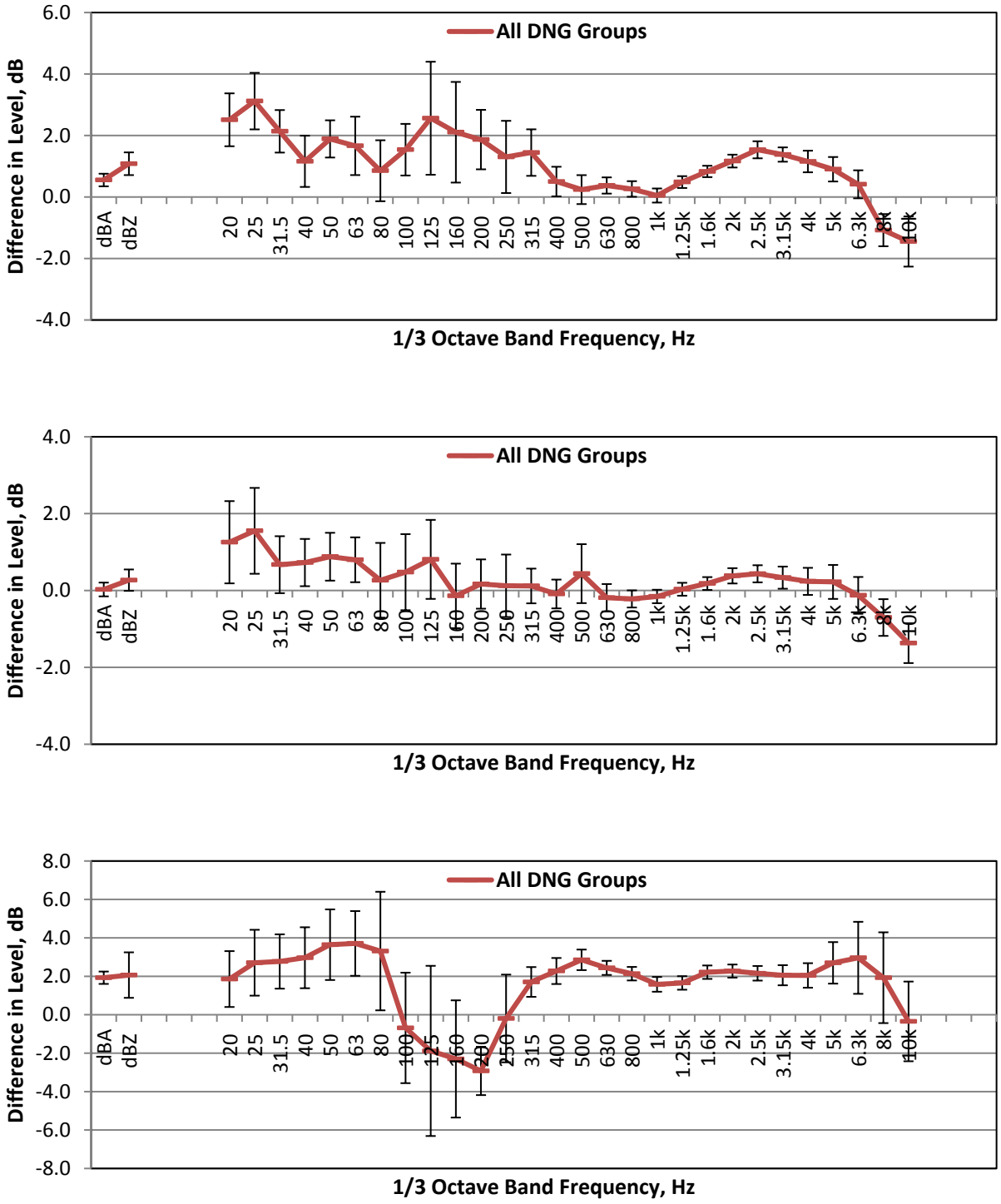


Figure 122. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Downwind Neutral groups, SR-71.

Additional Sound Level Analysis for SR-71—L_n Descriptors

Figure 123 presents the L_{90} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.), computed as BarRef01 minus NoBarRef2 for the A-weighted sound levels.

Much like the I-24 data, the results show that while the L_{eq} (5 min.) averages about 0 dB to 1 dB higher at BarRef01 than at NoBarRef02, the L_{90} (5 min.) and L_{99} (5 min.) 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. The result is sustained sound that keeps the background level from dropping off during gaps between vehicles.

Figure 125 then presents the L_{90} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05.

Some evidence exists of the elevated background level at BarCom03 compared to NoBarCom05 even though these two microphones are close to the edge of the shoulder for the far-lane traffic across from the barrier. While the L_{eq} (5 min.) at BarCom03 ranges about 0.5 dB higher to 1 dB lower than NoBarCom05, the L_{90} at BarCom03 are, on average, about 1 dB 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 L_{90} and L_{99} to be higher at the Barrier microphone.

Then, Figure 127 presents the L_{90} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06. Both figures start 45 minutes into the measurement period. There 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 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} (5 min.) 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} (5 min.) and L_{99} (5 min.) 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} (5 min.) difference became more variable, from 0.5 dB to 2.5 dB higher at BarCom04. During this period, L_{90} (5 min.) differences also became more variable, being 0 dB to 3.5 dB

higher at BarCom04. The L_{99} (5 min.) 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, the meteorological class was Downwind Neutral. On average over the full measurement period, the BarCom04 L_{eq} (5 min.), L_{90} (5 min.), and L_{99} (5 min.) were 1.7 dB, 2.0 dB, and 2.1 dB higher than at NoBarCom06.

Combined, these results 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.

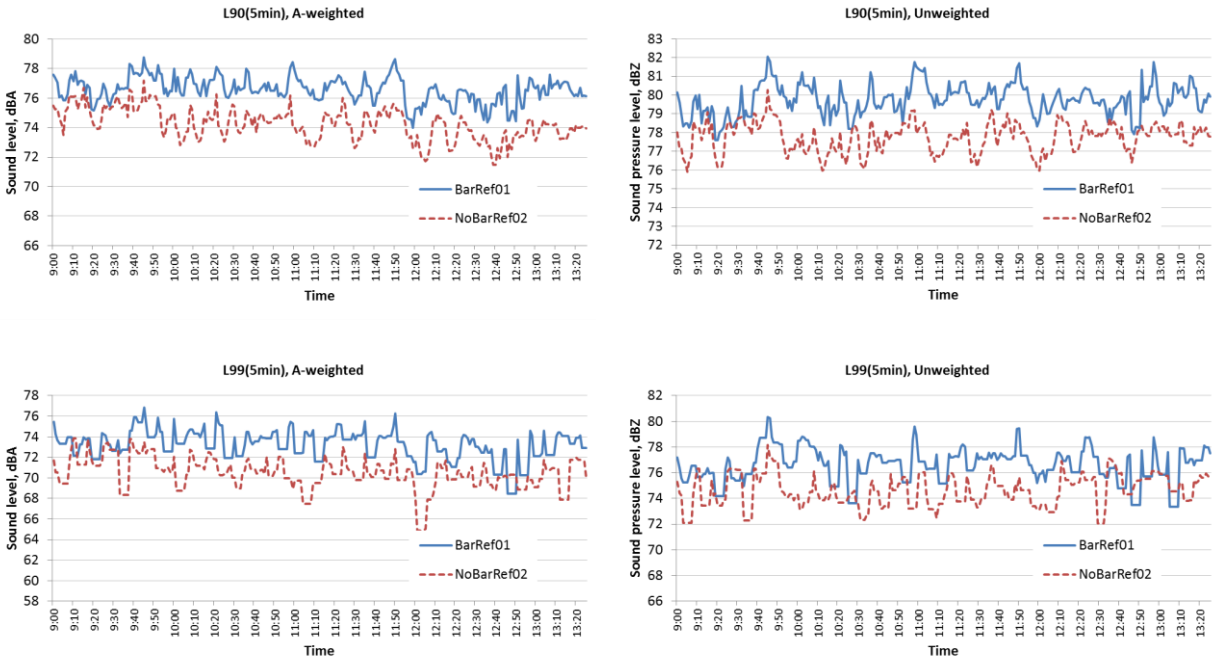


Figure 123. L_{90} (5 min.) and L_{99} (5 min.), SR-71, BarRef01 and NoBarRef02—broadband A-weighted sound level (left) and sound pressure level (right).

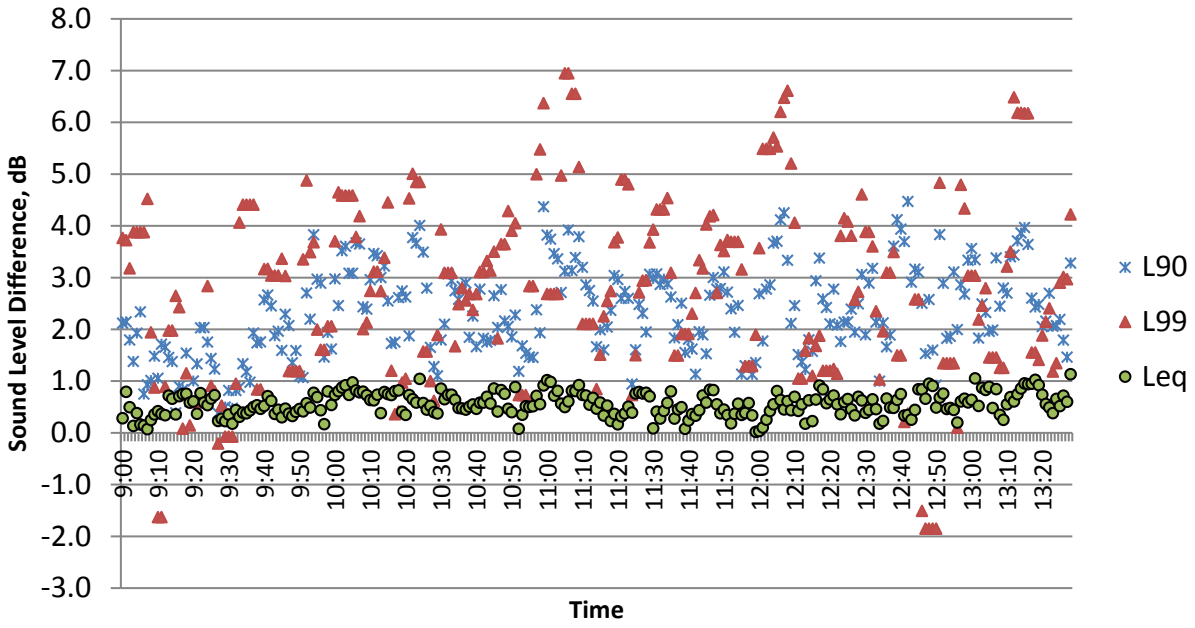


Figure 124. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, SR-71, BarRef01 and NoBarRef02.

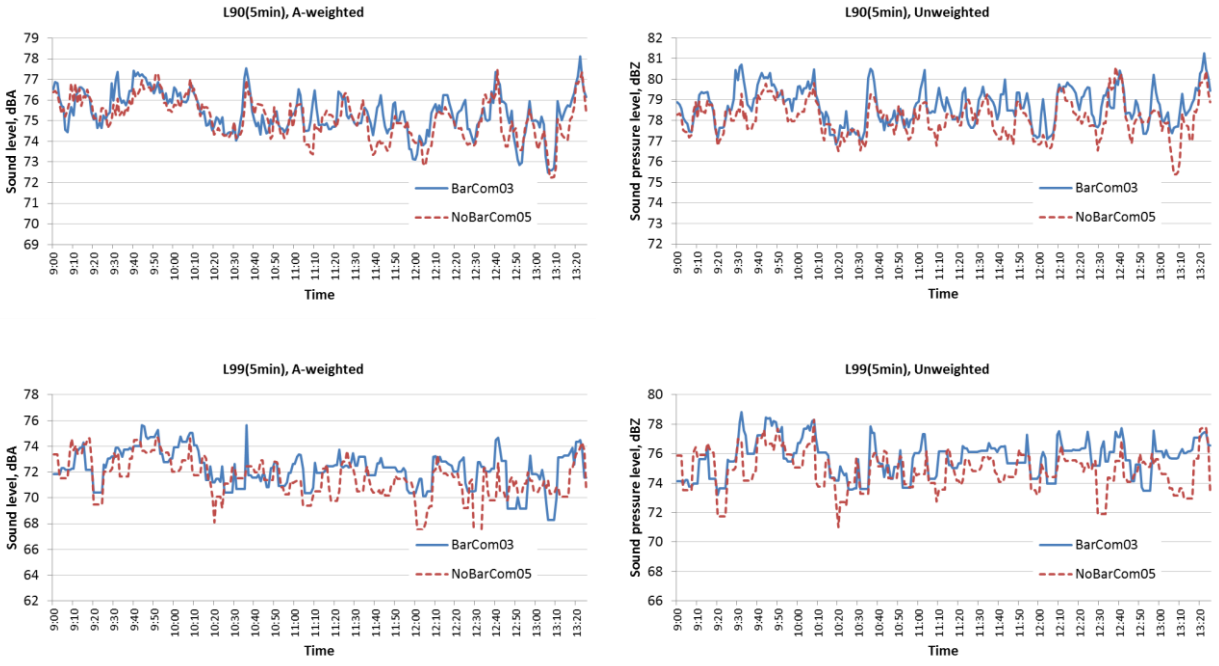


Figure 125. L_{90} (5 min.) and L_{99} (5 min.), SR-71, BarCom03 and NoBarCom05—broadband A-weighted sound level (left) and sound pressure level (right).

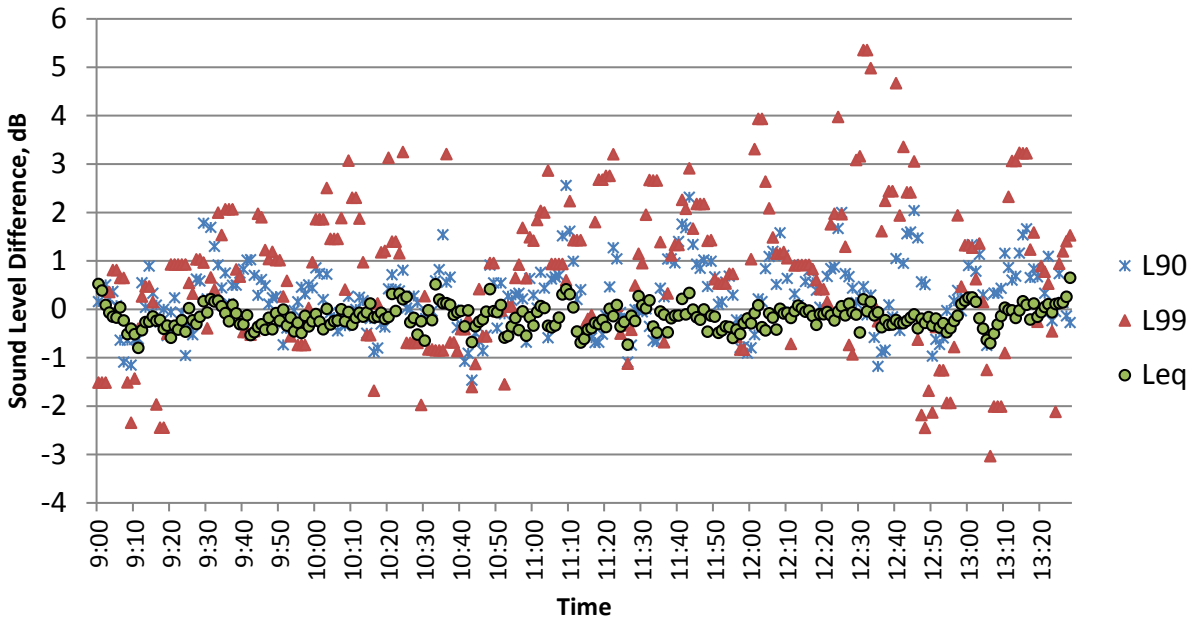


Figure 126. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, SR-71, BarCom03 and NoBarCom05.

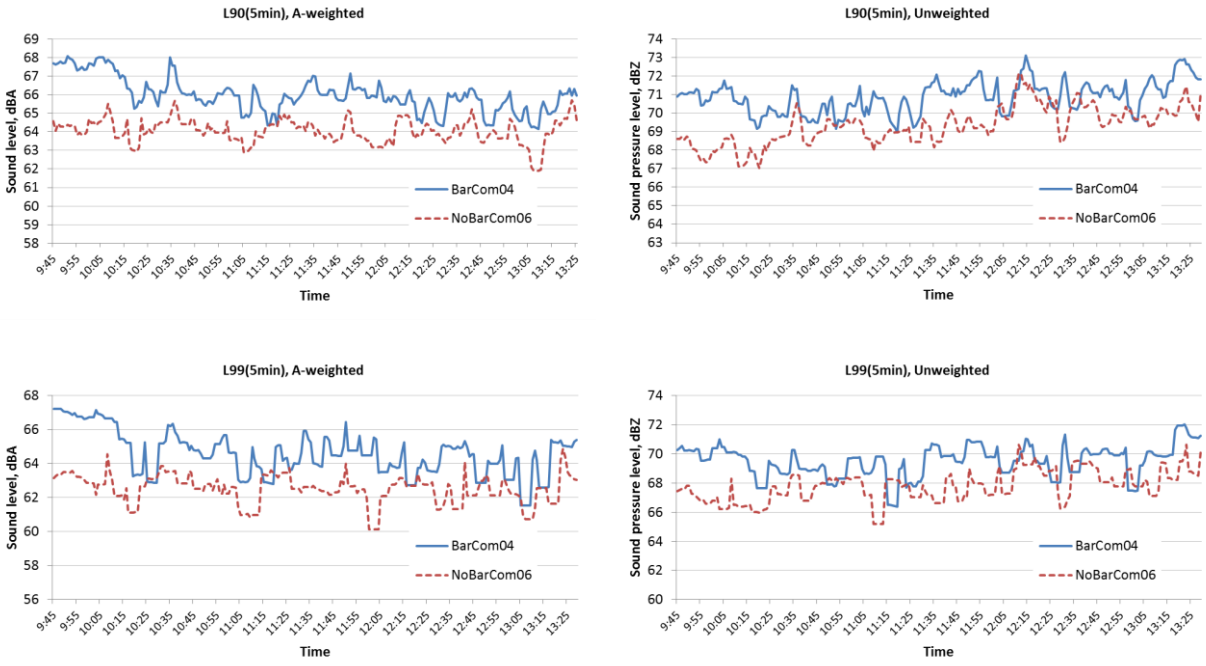


Figure 127. L_{90} (5 min.) and L_{99} (5 min.), SR-71, BarCom04 and NoBarCom06—broadband A-weighted sound level (left) and sound pressure level (right).

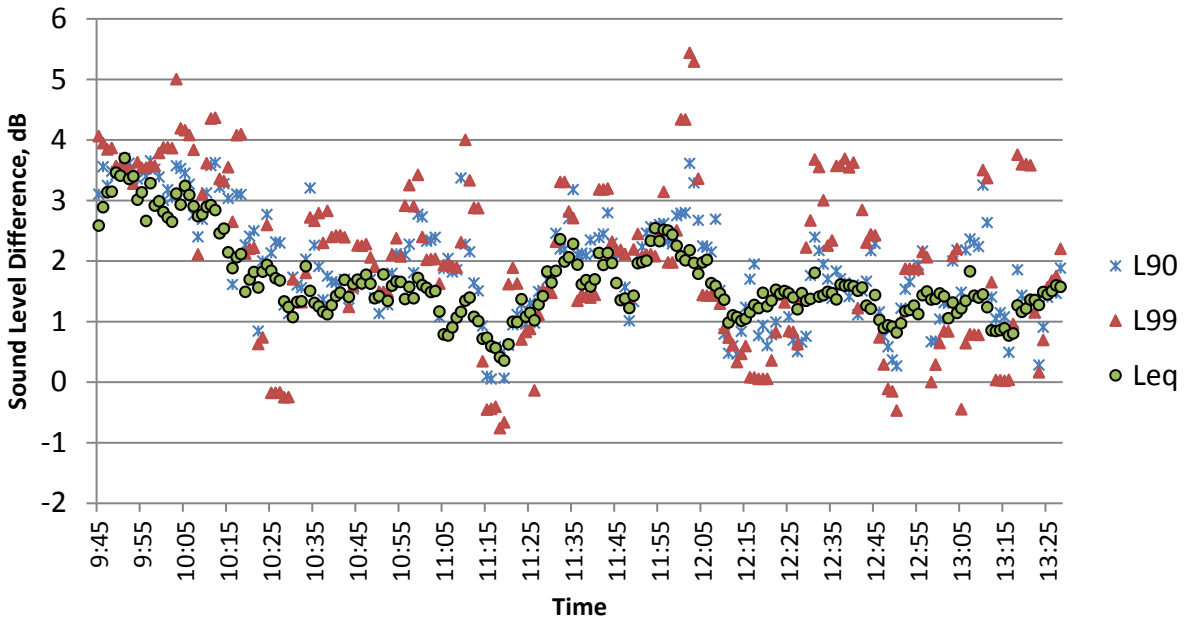


Figure 128. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, SR-71, BarCom04 and NoBarCom06.

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 one-third 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 one-third 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 L_n sound pressure level L_n 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} (5 min.) and L_{99} (5 min.)) in the frequency bands from 500 Hz through 4 kHz for nearly all the sample period, and 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 pass-by noise due to the creation of an image source for each vehicle as the sound reflects off the barrier. This result is like 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 unknown.

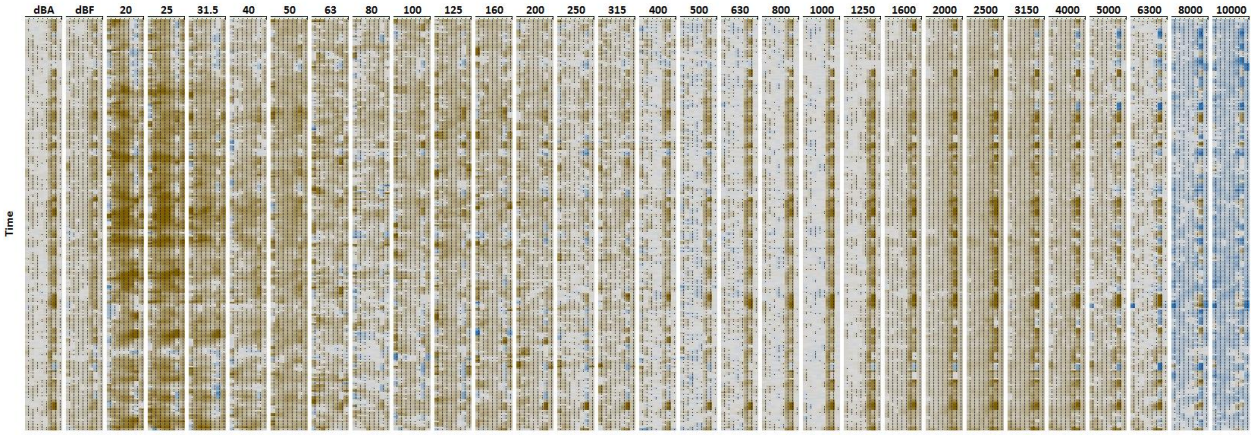


Figure 129. SR-71 Differences in L_n (5 min.) by one-third octave frequency bands: BarRef01 and NoBarRef02.

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 and the highest frequency bands. This pattern applies across most of the L_n descriptors, not just L_{90} (5 min.) and L_{99} (5 min.).

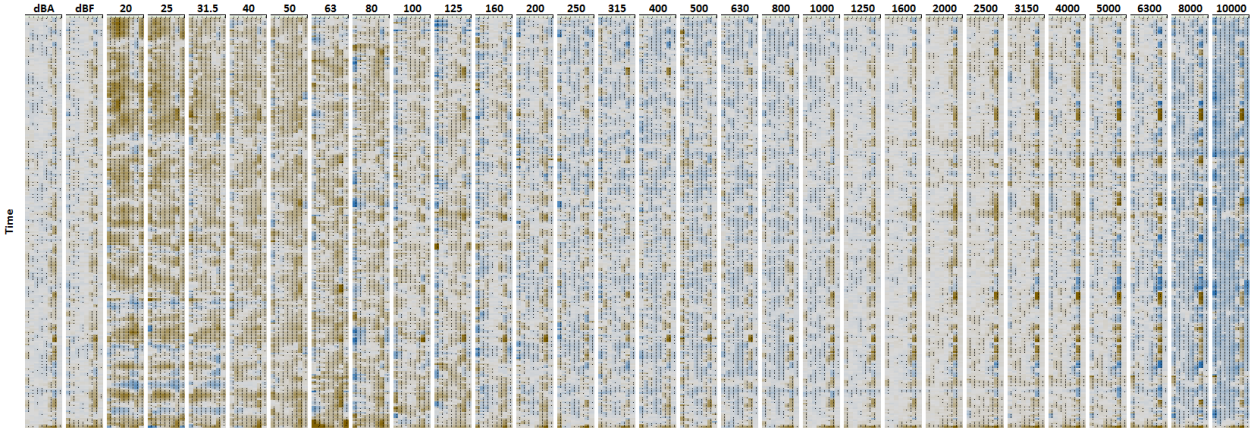


Figure 130. SR-71 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom03 and NoBarCom05.

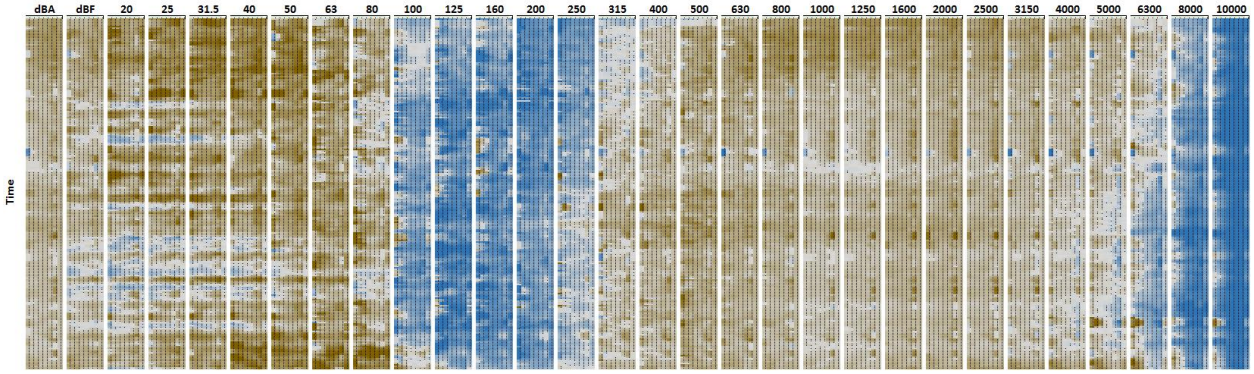


Figure 131. SR-71 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom04 and NoBarCom06.

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 TNM 2.5 analysis was conducted to determine the one-third-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. (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. 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 a technically rigorous modeling since it was not in the work scope, but it was conducted to help determine in what frequency ranges differences between the sites to the barrier reflections could be attributed.

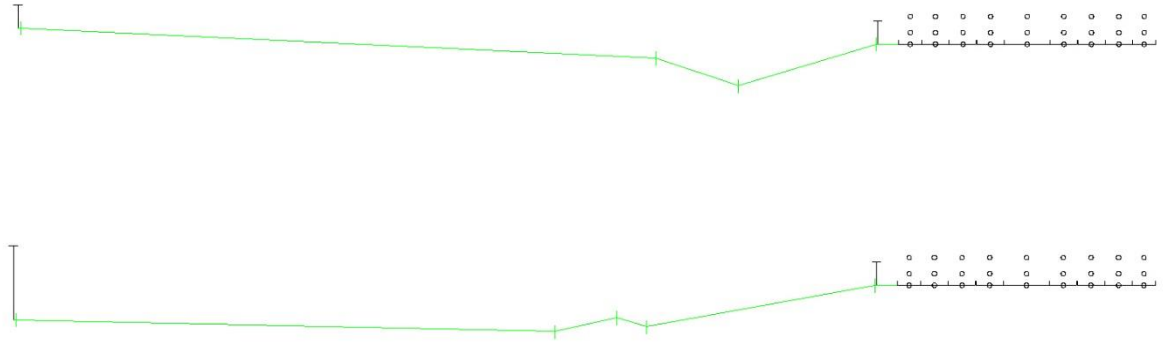


Figure 132. TNM modeling cross-sections: Barrier site (top) and No Barrier site (bottom), SR-71.

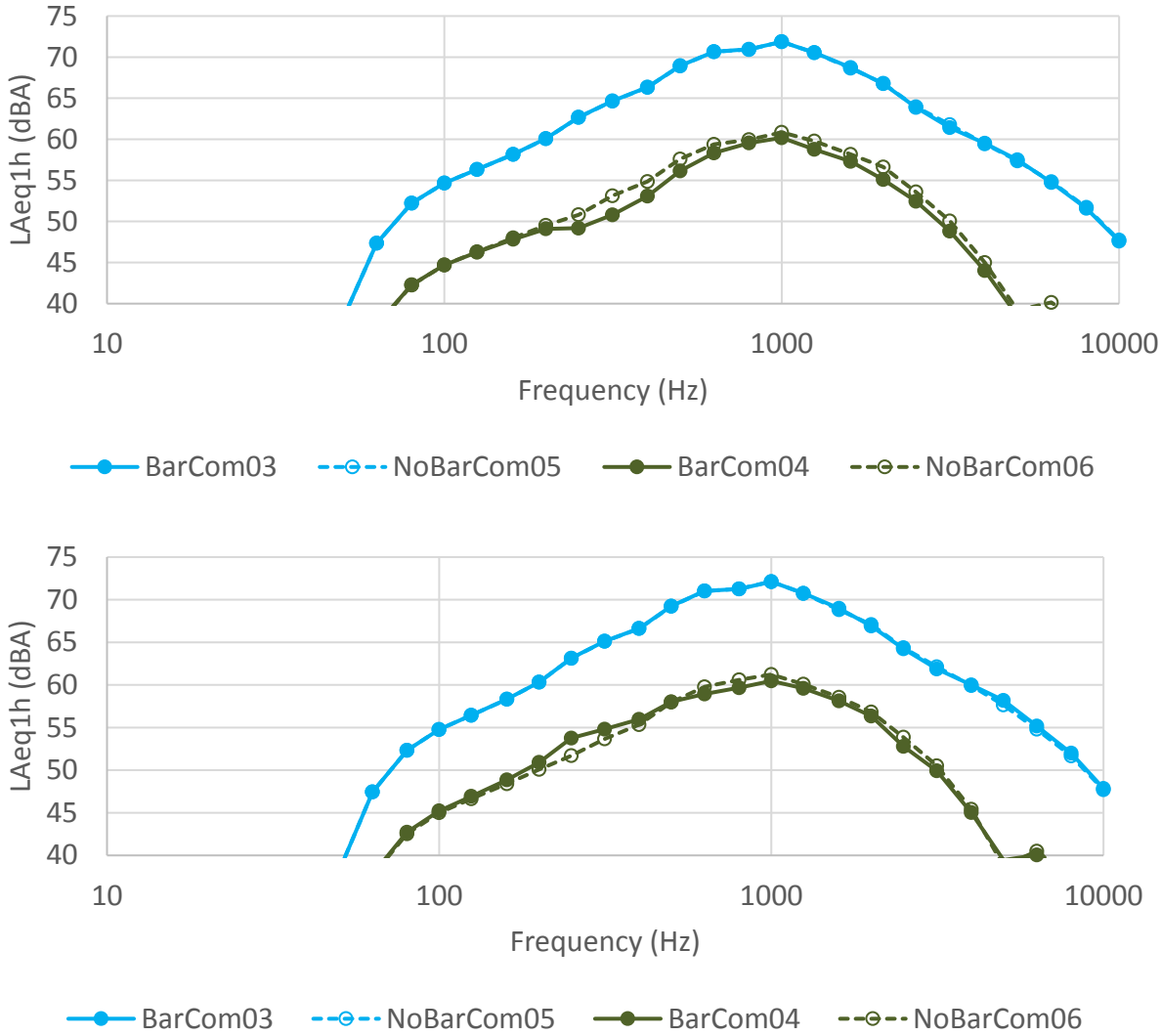


Figure 133. TNM modeling results: TNM soft ground (top) and TNM hard ground (bottom), SR-71.

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 or it is difficult to distinguish differences in levels, since the differences are 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.

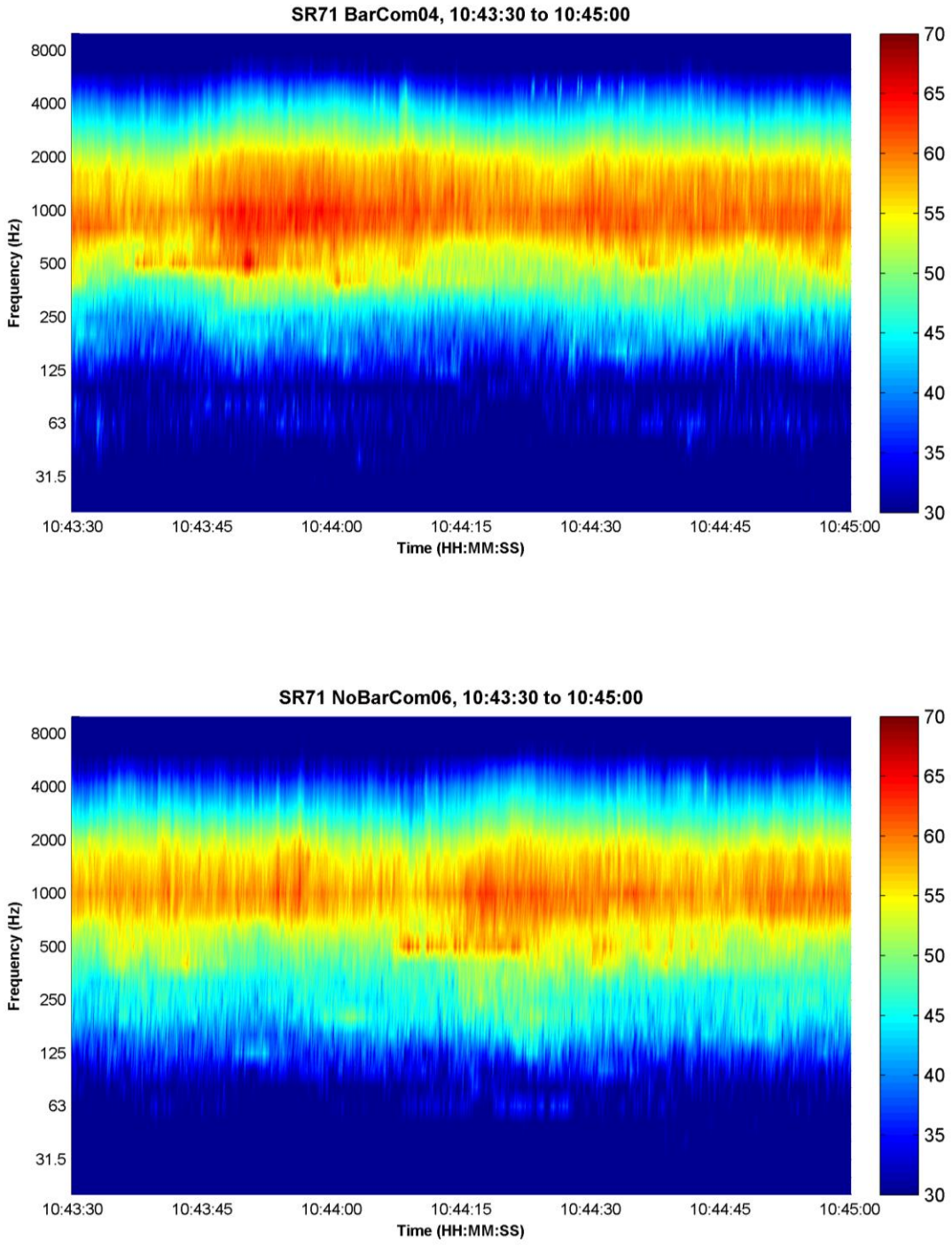


Figure 134. SR-71 spectrograms for heavy trucks on southbound (community) side: top is BarCom04; bottom is NoBarCom06.

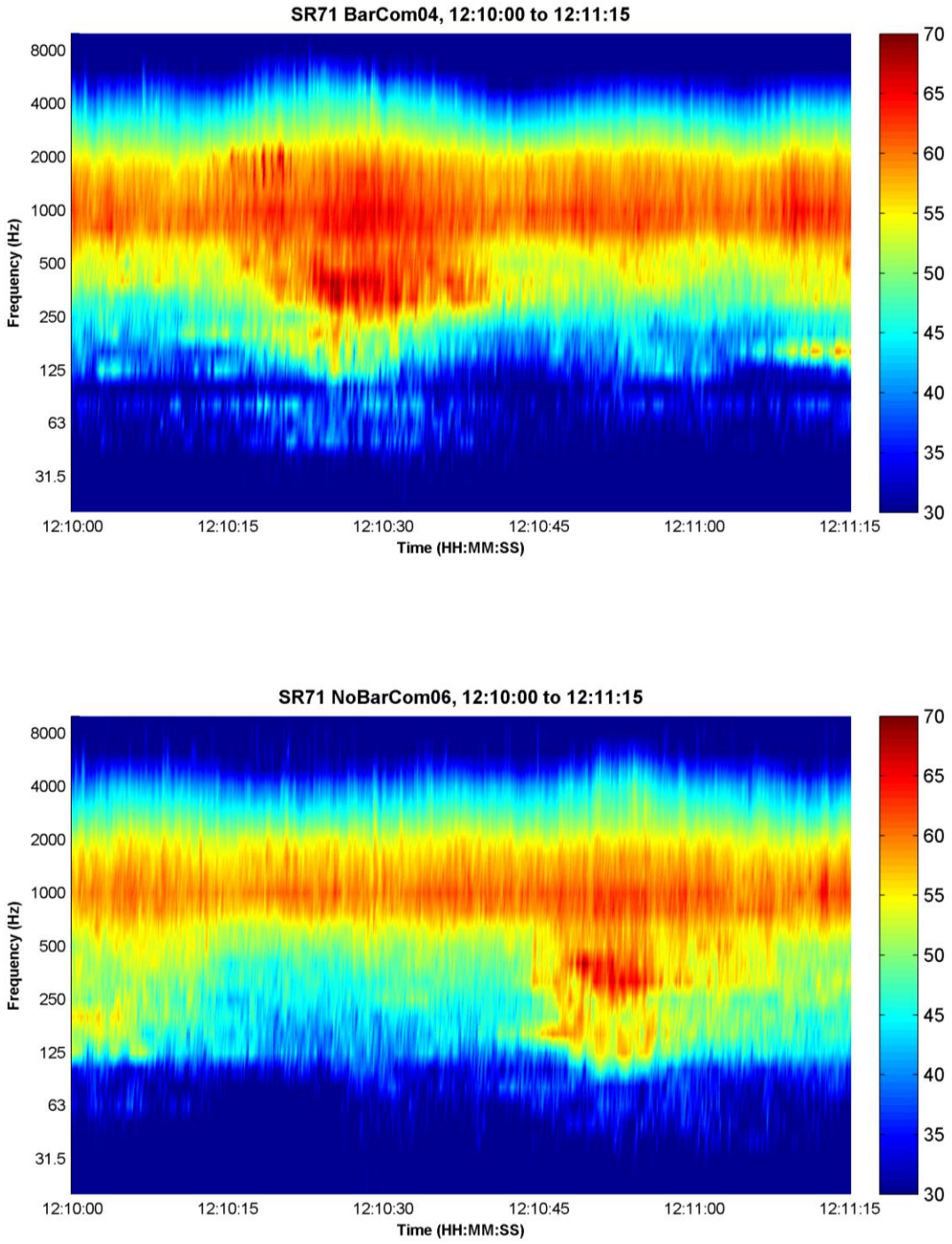


Figure 135. SR-71 spectrograms for motorcycle on southbound (community) side: top is BarCom04; bottom is NoBarCom06.

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, and the second, Figure 137, shows a 5-minute block of clean data in the afternoon at 12:45.

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 the difference between Barrier and No Barrier A-weighted equivalent sound levels ranged from 1.3 dB 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-distance microphones for both vehicle pass-by events and time blocks of data indicates 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 microphones since the path length difference between direct and reflected sound is 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 contribute more to the overall sound level, with the reflected sound contributing little (since it must travel farther than the direct sound).

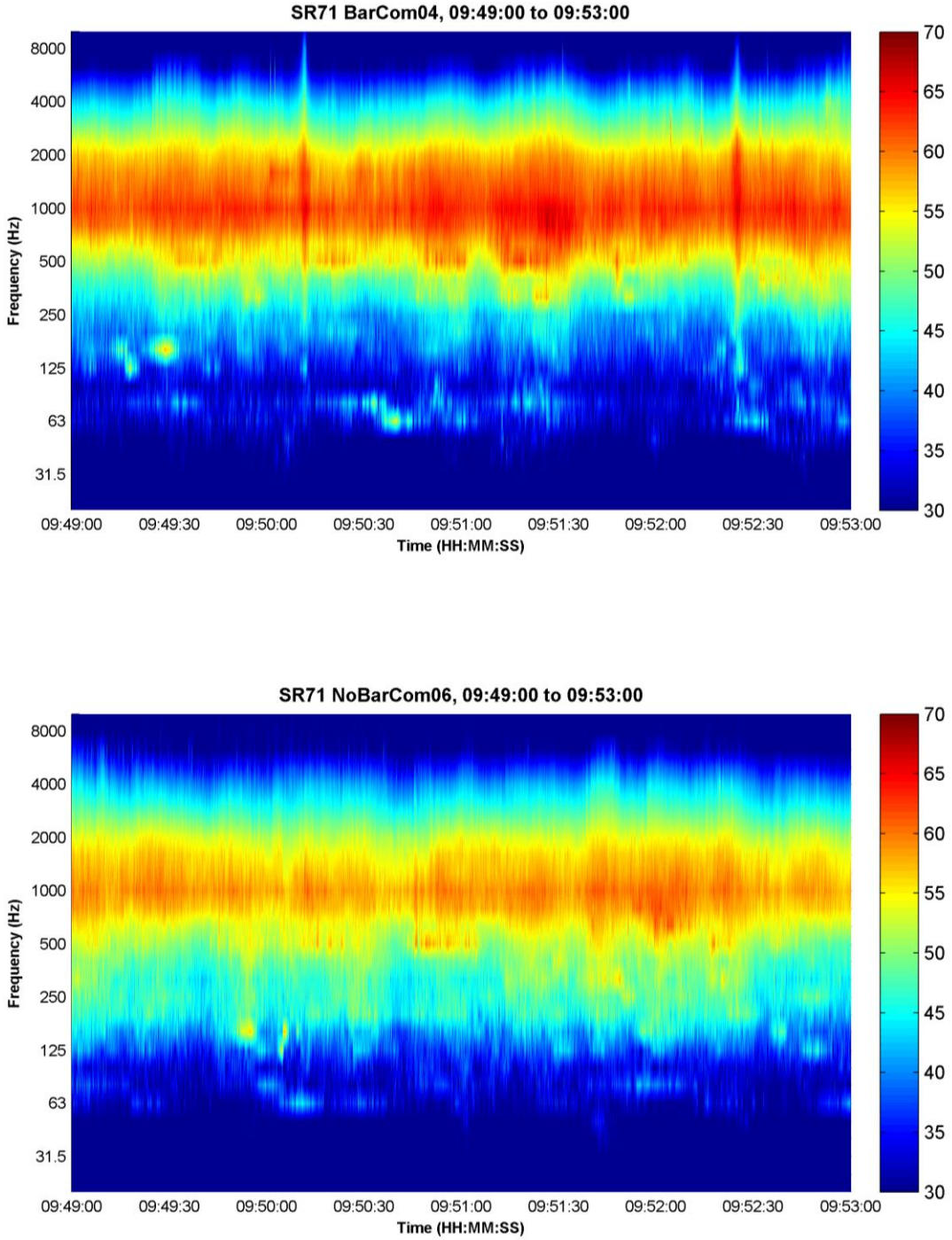


Figure 136. SR-71 spectrograms for 4-minute block of data in the morning at 09:49: top is BarCom04; bottom is NoBarCom06.

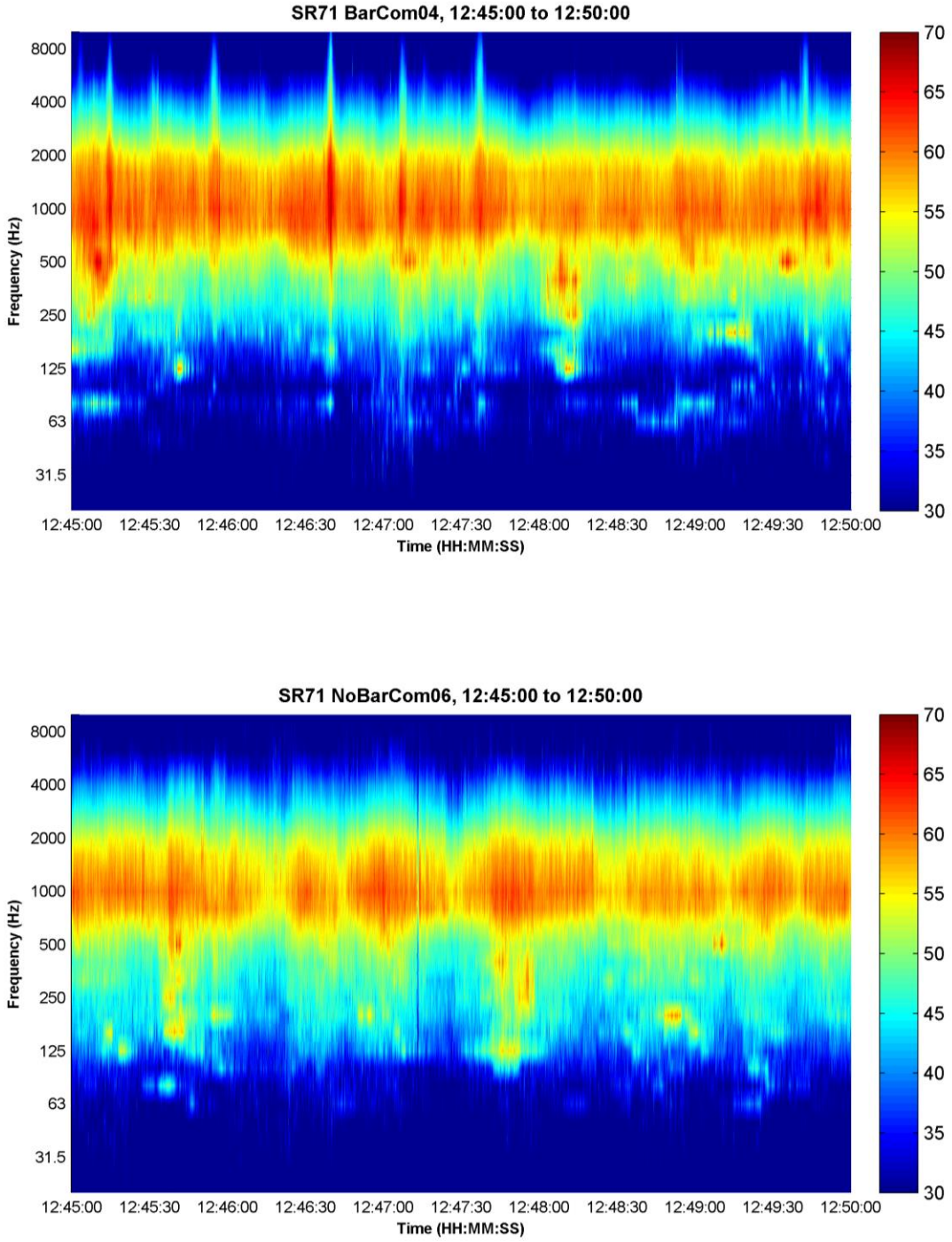


Figure 137. S SR-71 spectrograms for 5-minute block of data in the morning at 12:45: top is BarCom04; bottom is NoBarCom06.

Data Analysis for SR-71 - Psychoacoustics

Table 13 summarizes the descriptive statistics for the computed annoyance metrics at SR-71. 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 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 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 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.

No significant difference exists in the means of the UBA between the Barrier and No Barrier locations for lower microphones. The same is true of the PA. A clear difference exists in the means of the UBA and the PA 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 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.

No significant difference exists in the means of the CSA for either pair of microphones. The linear regression that is the basis of 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	Microphone	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

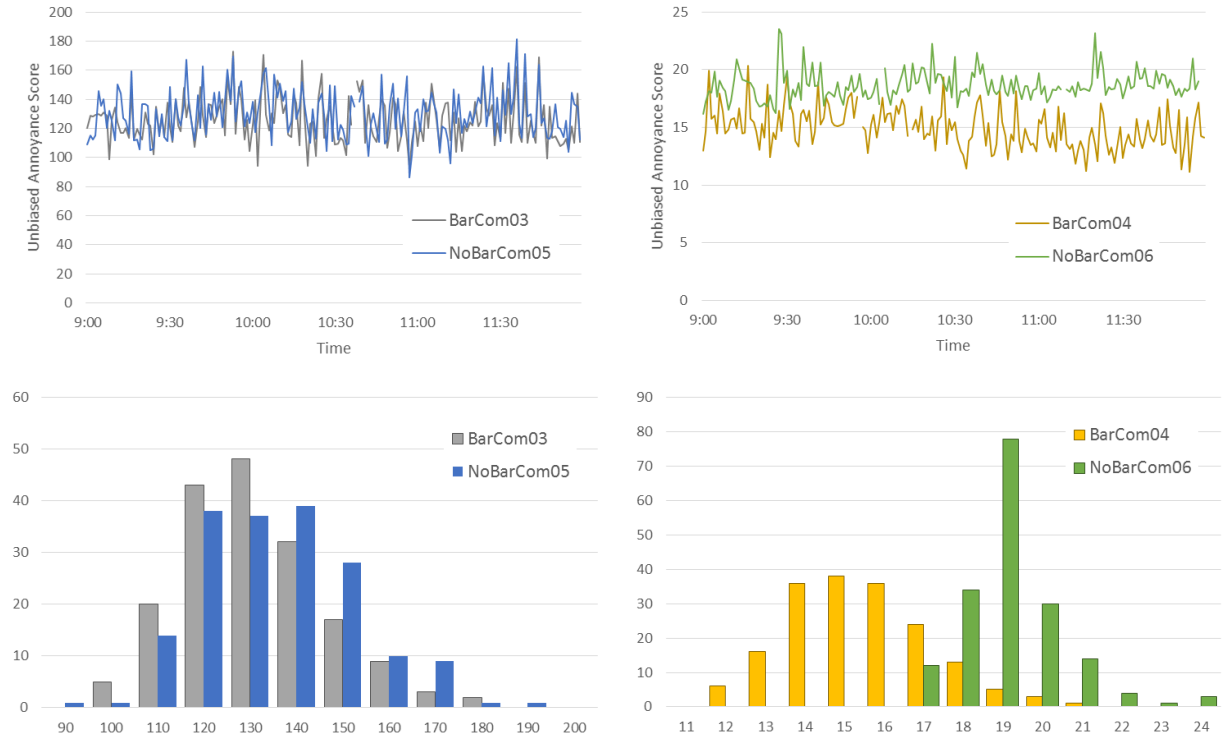


Figure 139. UBA vs. time and histograms, SR-71.

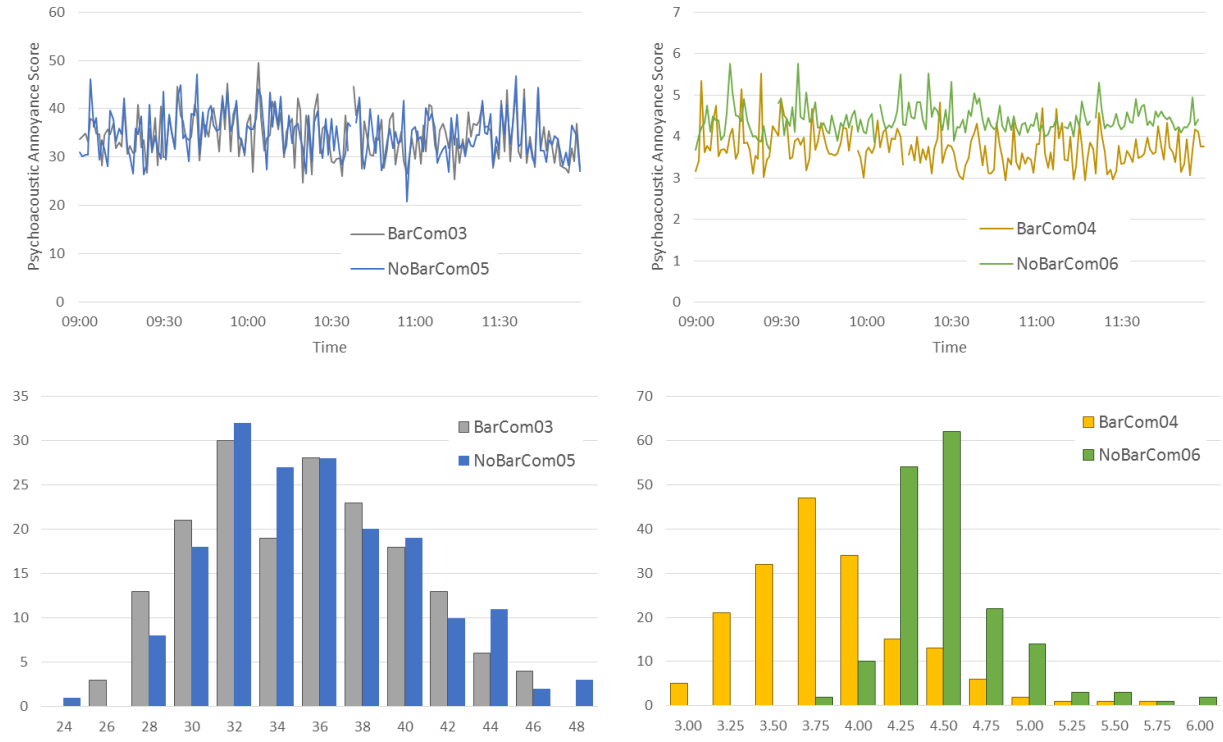


Figure 140. PA vs. time and histograms, SR-71.

Figure 141. CSA vs. time and histograms, SR-71.

CHAPTER E-7

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

The noise measurements at the last location, MD-5 in Hughesville, Maryland, were conducted on June 9, 2015. 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 ft. above the road and 15 ft. from the center of the near travel lane.
- NoBarRef02—A reference microphone placed 17.5 ft. above the road and 18 ft. 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 ft. from the center of the near travel lane. BarCom03 is at a height of 5 ft. and BarCom04 is at a height of 15 ft. above the road.
- NoBarCom05 and 06—The community microphones placed on the same side of the road as BarCom03 and BarCom04, 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 videotaped so 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. Table 14 summarizes the microphone positions. Appendix F (available online) contains site photographs.

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)

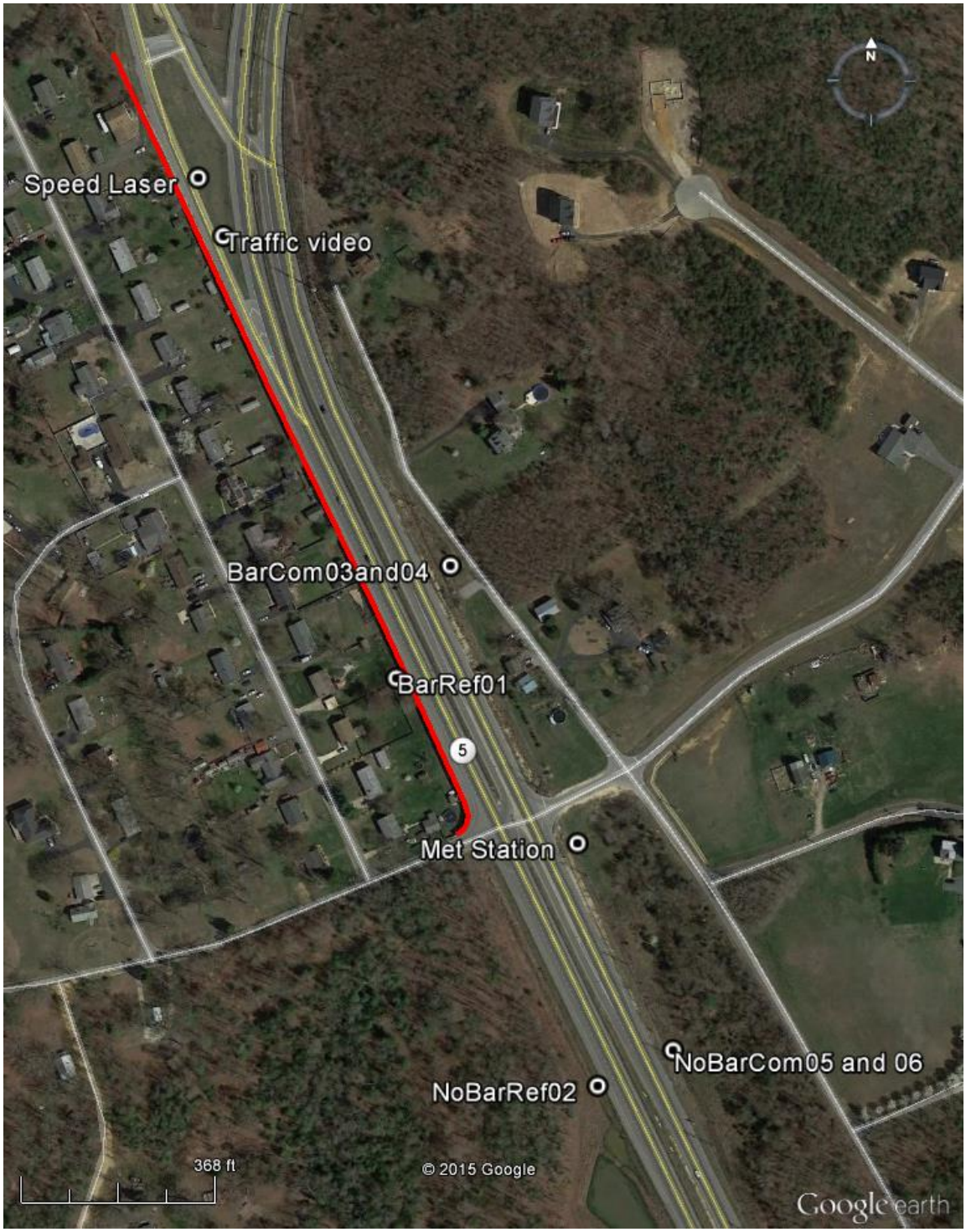


Figure 142. MD-5 microphone positions. (Source: Google Earth.)

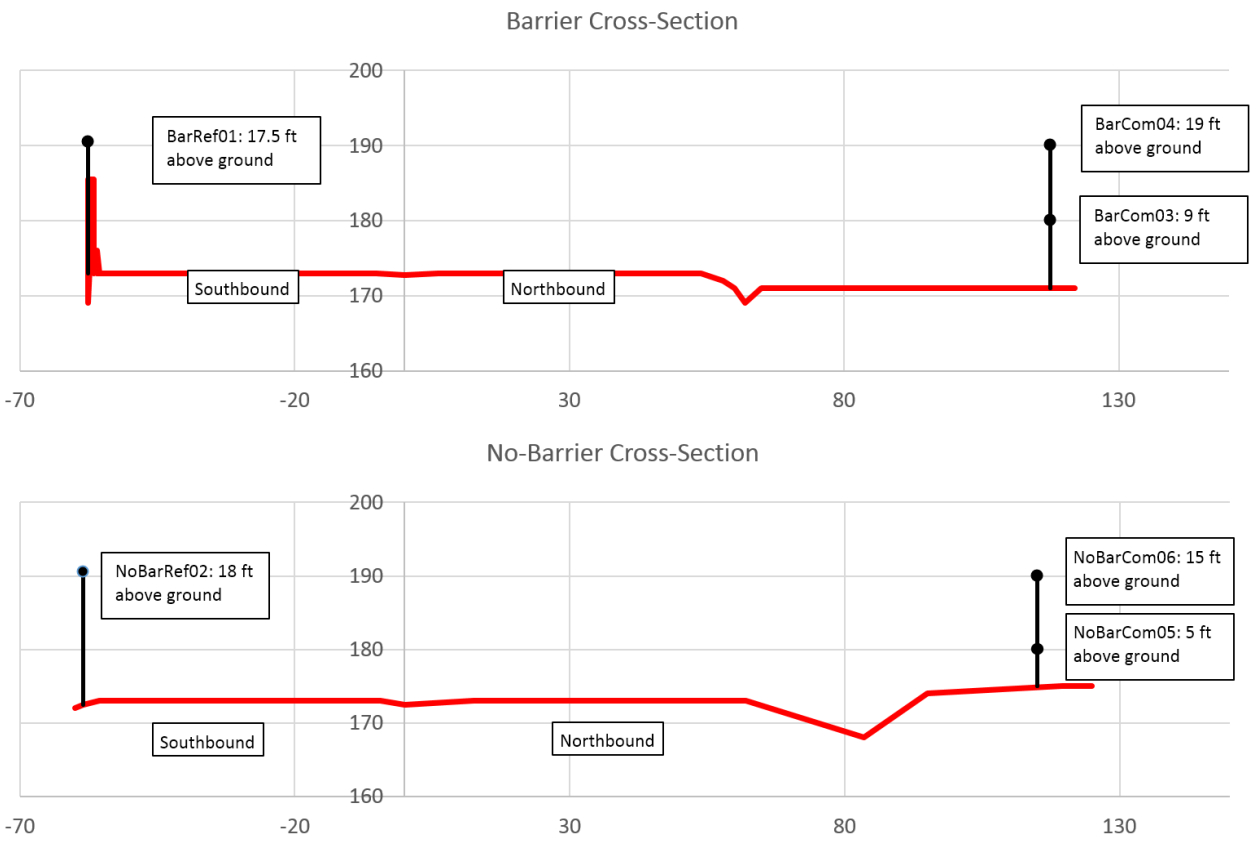


Figure 143. Cross-sections at the MD-5 Barrier (top) and No Barrier (bottom) sites.

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 pass-bys.

During the first hour of measurements of the daytime session, the winds were generally 4 mph 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 except 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 ft. 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, sound levels varied but were 65 dB to 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 pass-by” event. There were 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. 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 21:00, 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 several 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 pass-bys 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, ranging from 65 dB to 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 pass-bys 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} (5 min.) 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.
- 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} (5 min.) 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} (5 min.) periods during both the afternoon and evening, the BarCom04 levels were higher than the NoBarCom06 levels. The unweighted L_{eq} (5 min.) 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.

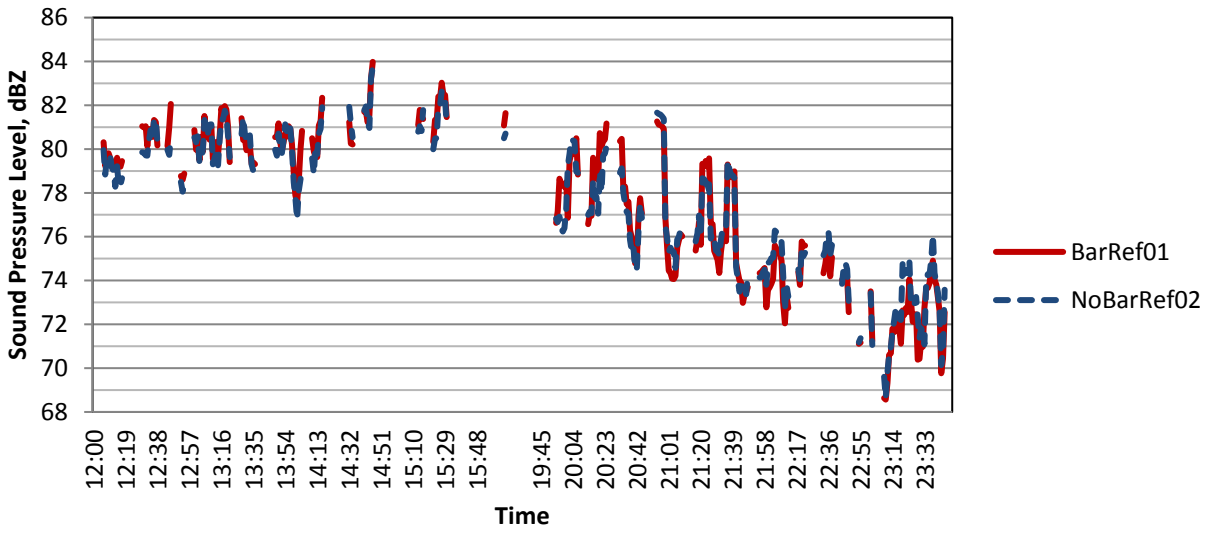


Figure 144. Running L_{eq} (5 min.), MD-5, unweighted sound pressure level, dBZ, BarRef01 and NoBarRef02.

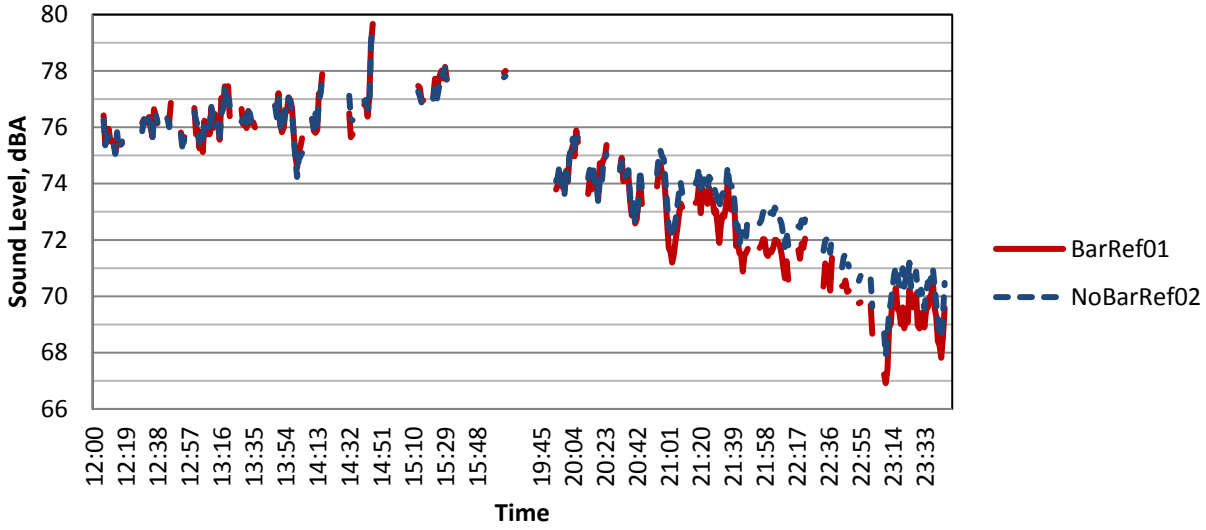


Figure 145. Running L_{eq} (5 min.), MD-5, A-weighted sound level, dBA, BarRef01 and NoBarRef02.

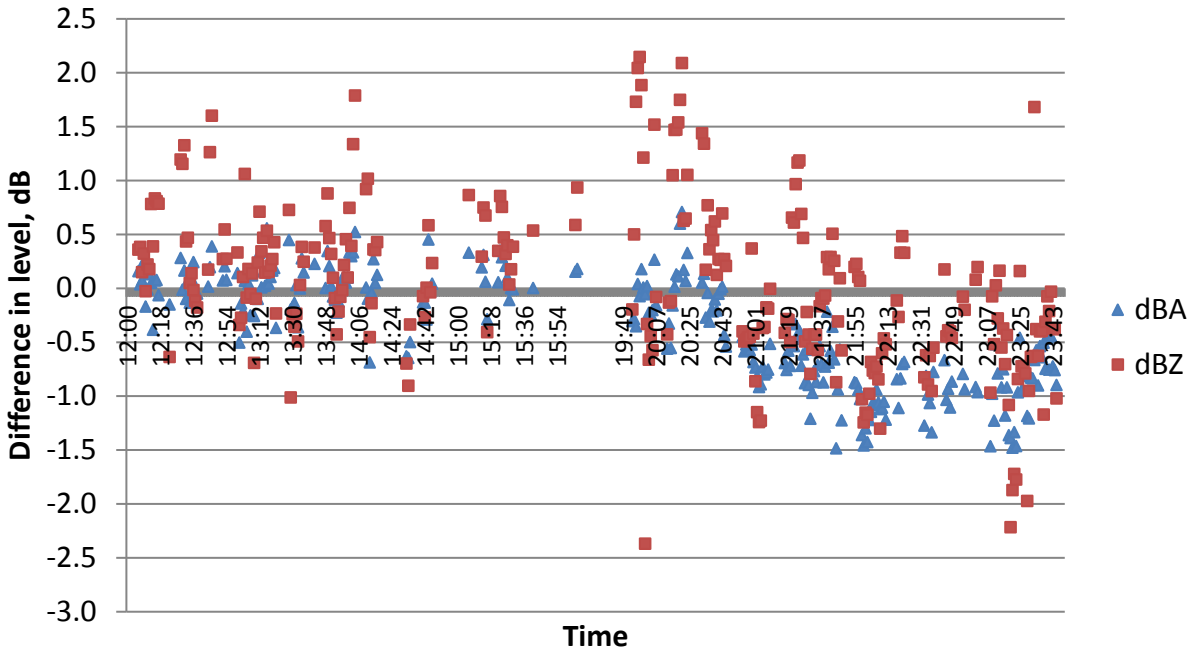


Figure 146. Differences in running L_{eq} (5 min.), MD-5, BarRef01 minus NoBarRef02.

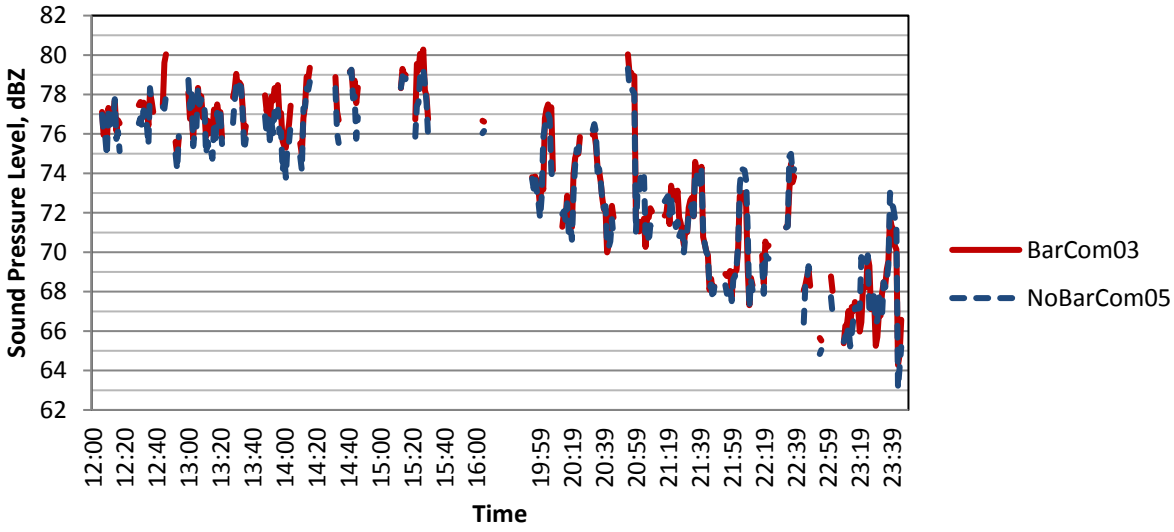


Figure 147. Running L_{eq} (5 min.), MD-5, unweighted sound pressure level, dBZ, BarCom03 and NoBarCom05.

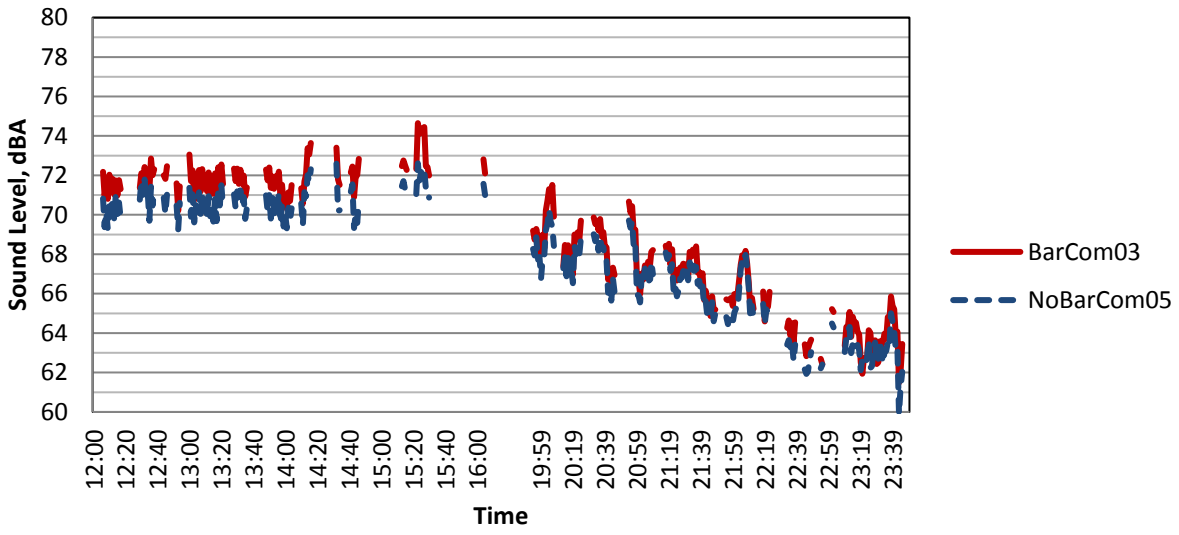


Figure 148. Running L_{eq} (5 min.), MD-5, A-weighted sound level, dBA, BarCom03 and NoBarCom05.

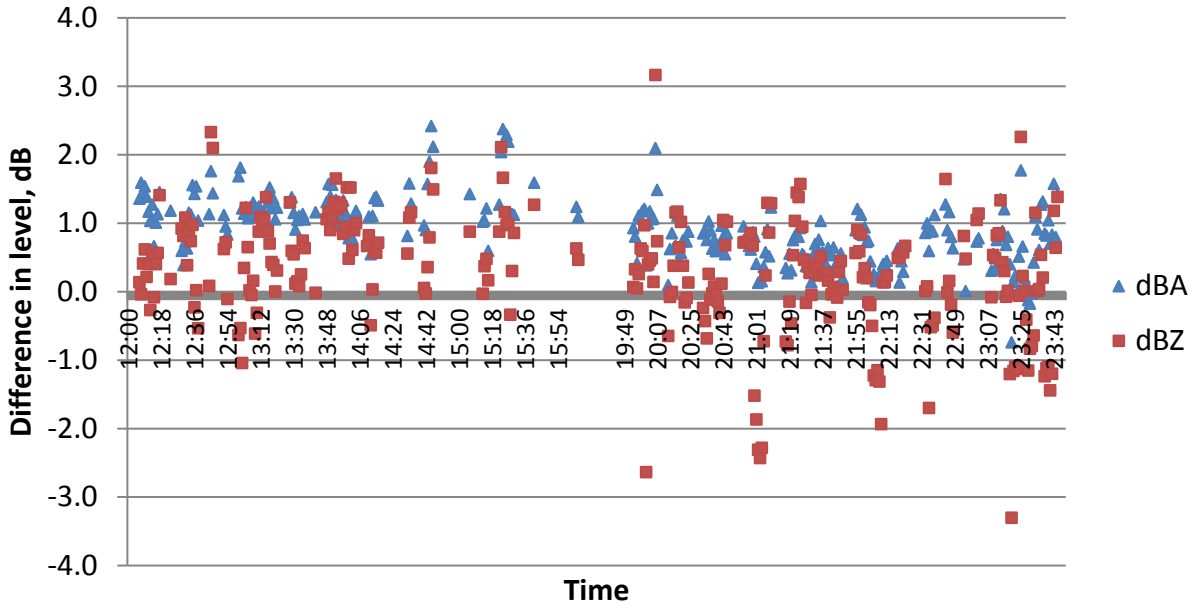


Figure 149. Differences in running L_{eq} (5 min.), MD-5, BarCom03 minus NoBarCom05.

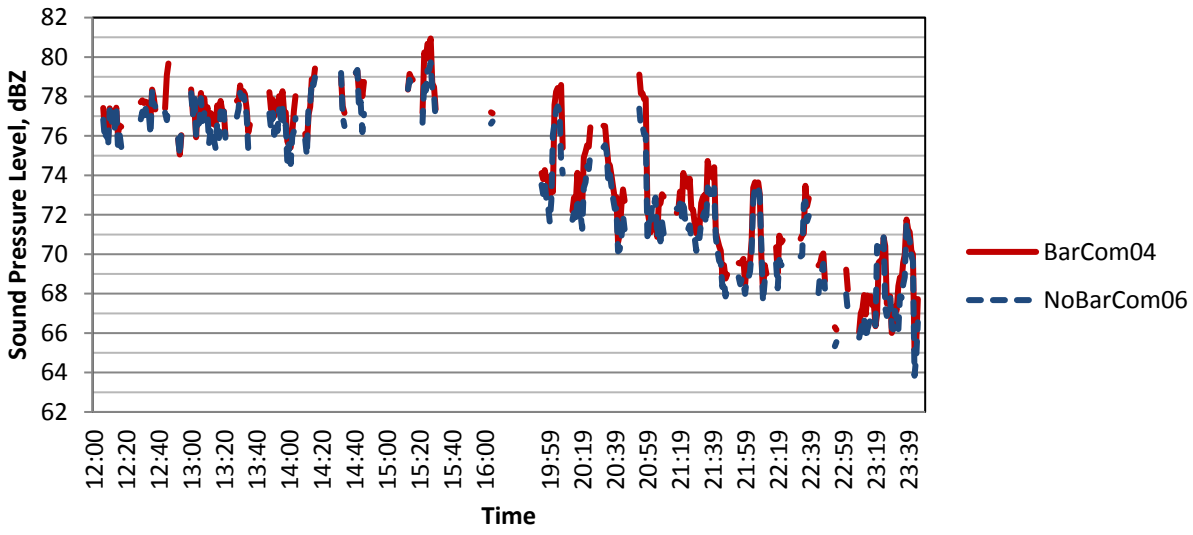


Figure 150. Running L_{eq} (5 min.), MD-5, unweighted sound pressure level, dBZ, BarCom04 and NoBarCom06.

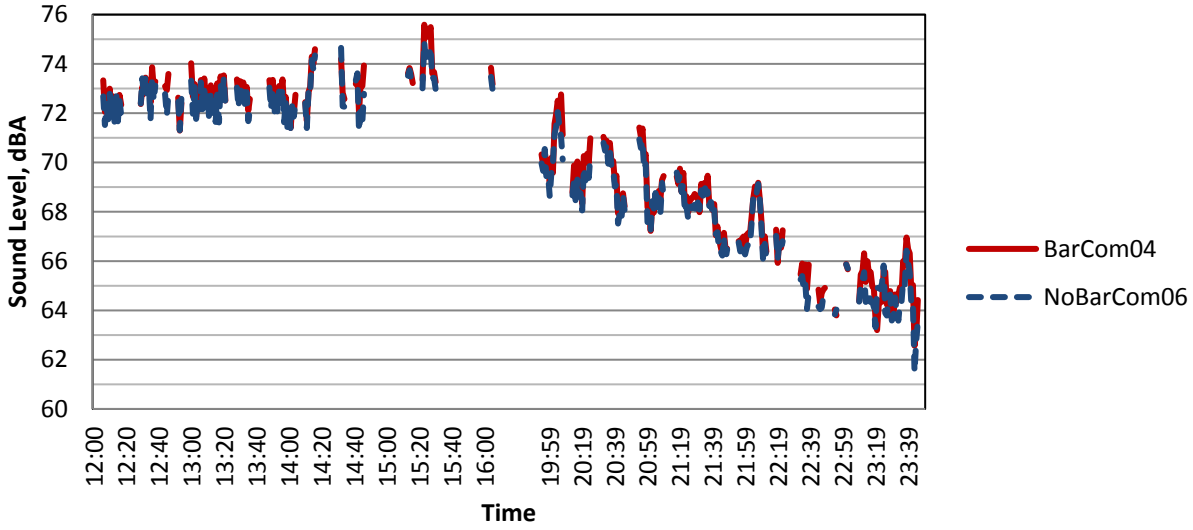


Figure 151. Running L_{eq} (5 min.), MD-5, A-weighted sound level, dBA, BarCom04 and NoBarCom06.

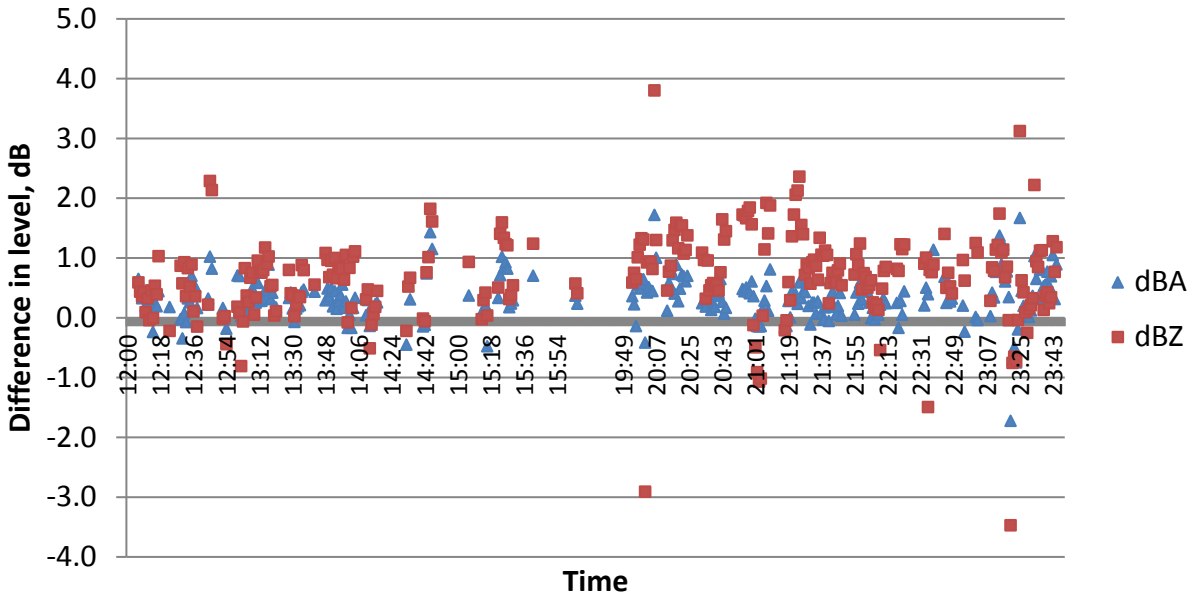


Figure 152. Differences in running L_{eq} (5 min.), MD-5, BarCom04 minus NoBarCom06.

Data Analysis for MD-5—FHWA Method

Equivalent Groups

All 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 visually depicted in Figure 153.
- Downwind Neutral: 7 groupings each with three to five 5-minute equivalent periods ("DNG-"), with the starting times visually depicted in Figure 154
- Downwind Lapse: 15 groupings each with three to five 5-minute equivalent periods ("DLG-"), with the starting times visually depicted in Figure 155
- Calm Inversion: 15 groupings each with three to five 5-minute equivalent periods ("CIG-"), with the starting times visually depicted in Figure 156

While all 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 shown 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.

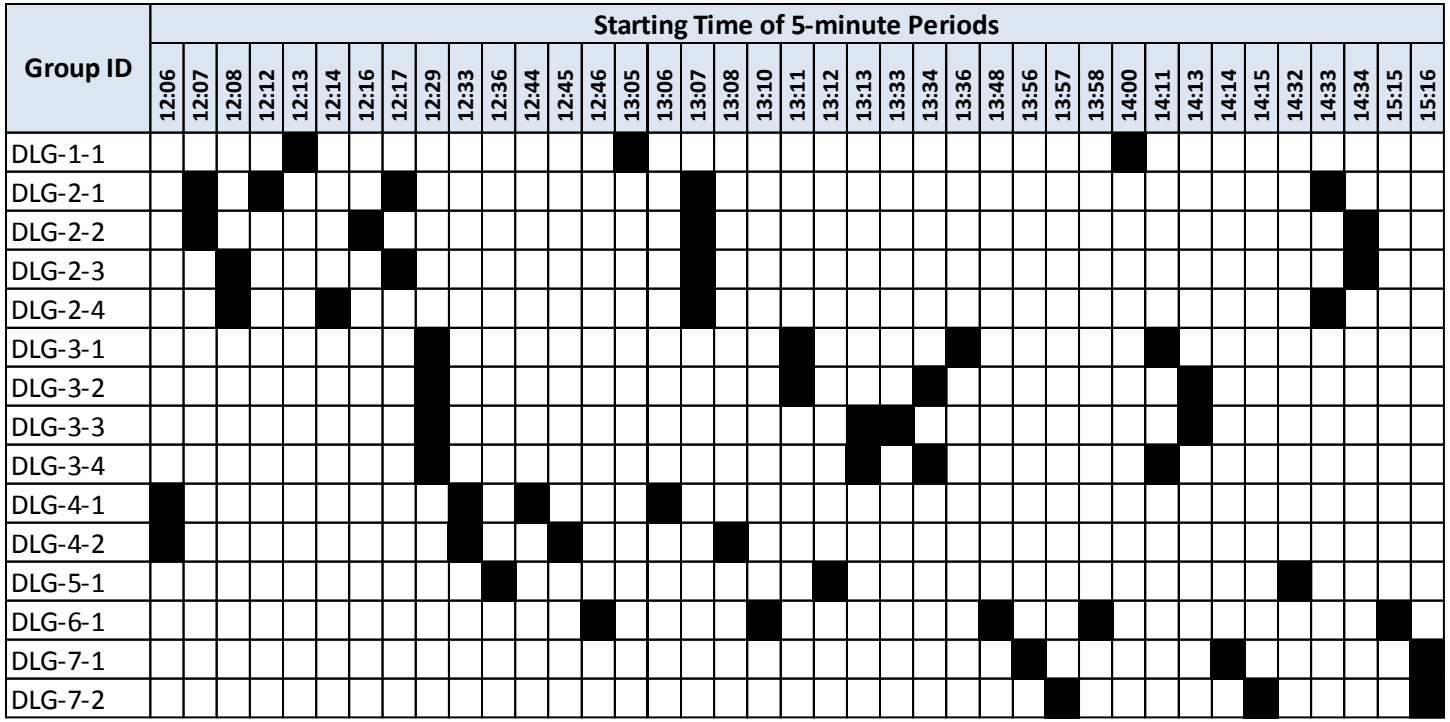


Figure 155. Equivalent 5-minute periods for Downwind Lapse groups at MD-5.

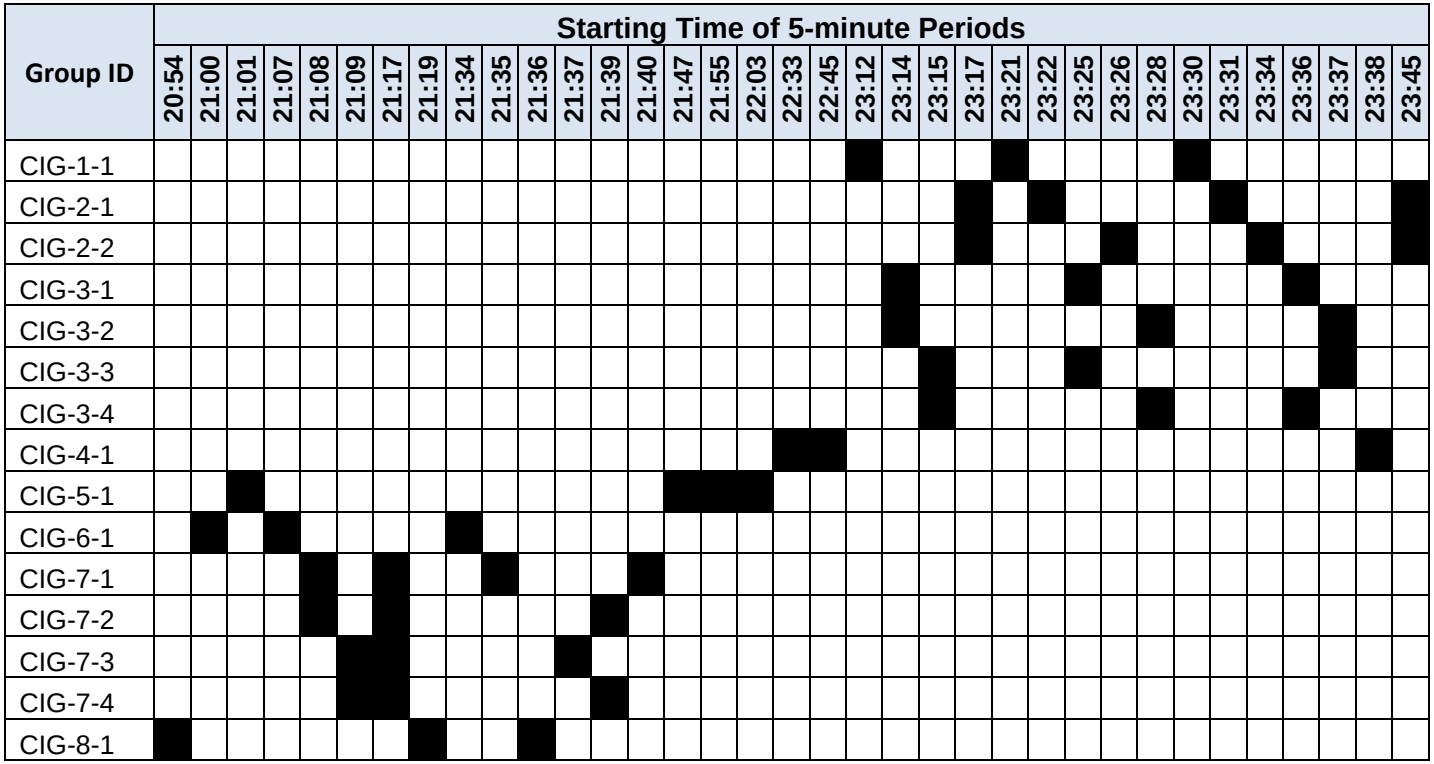


Figure 156. Equivalent 5-minute periods for Calm Inversion groups at MD-5.

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

Group	Two-Way Traffic Volumes (5 minutes)					Factored Hourly Volume (vph)
	Period 1	Period 2	Period 3	Period 4	Period 5	
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 as follows:

- 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.

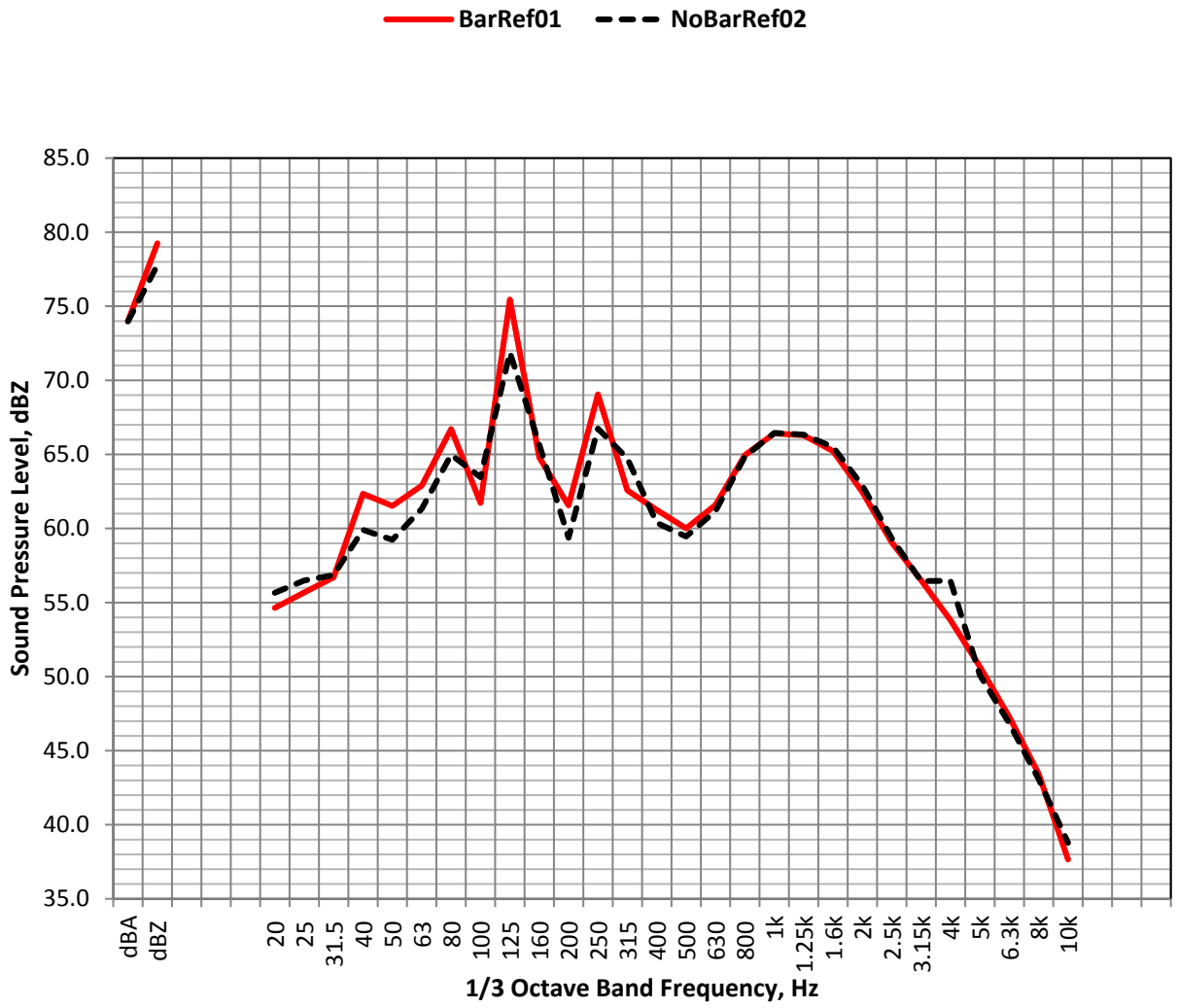


Figure 157. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Calm Neutral group CNG-3-4, 20:17 (L_{eq} (5 min.), dBZ).

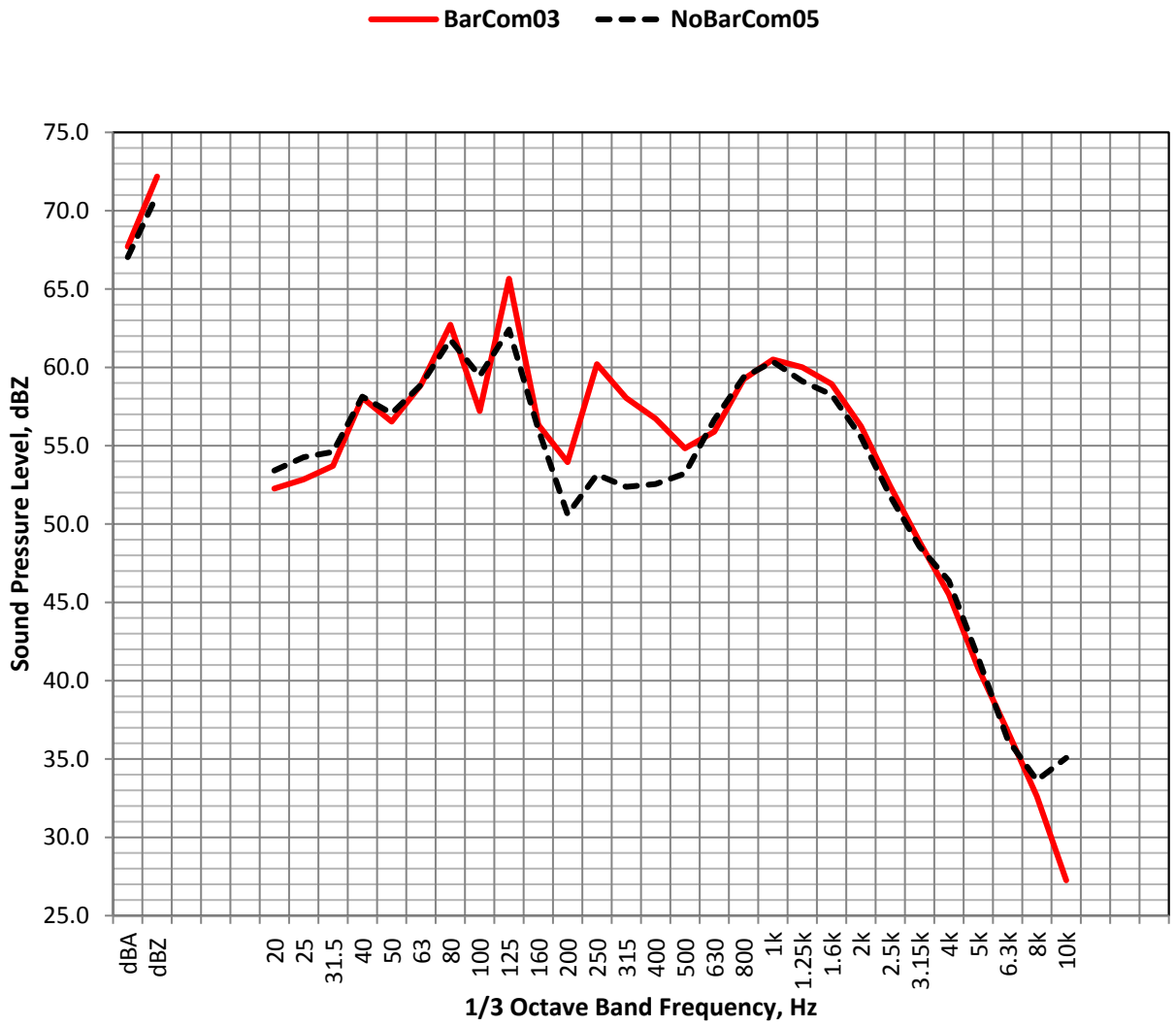


Figure 158. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Calm Neutral group CNG-3-4, 20:17 (L_{eq} (5 min.), dBZ).

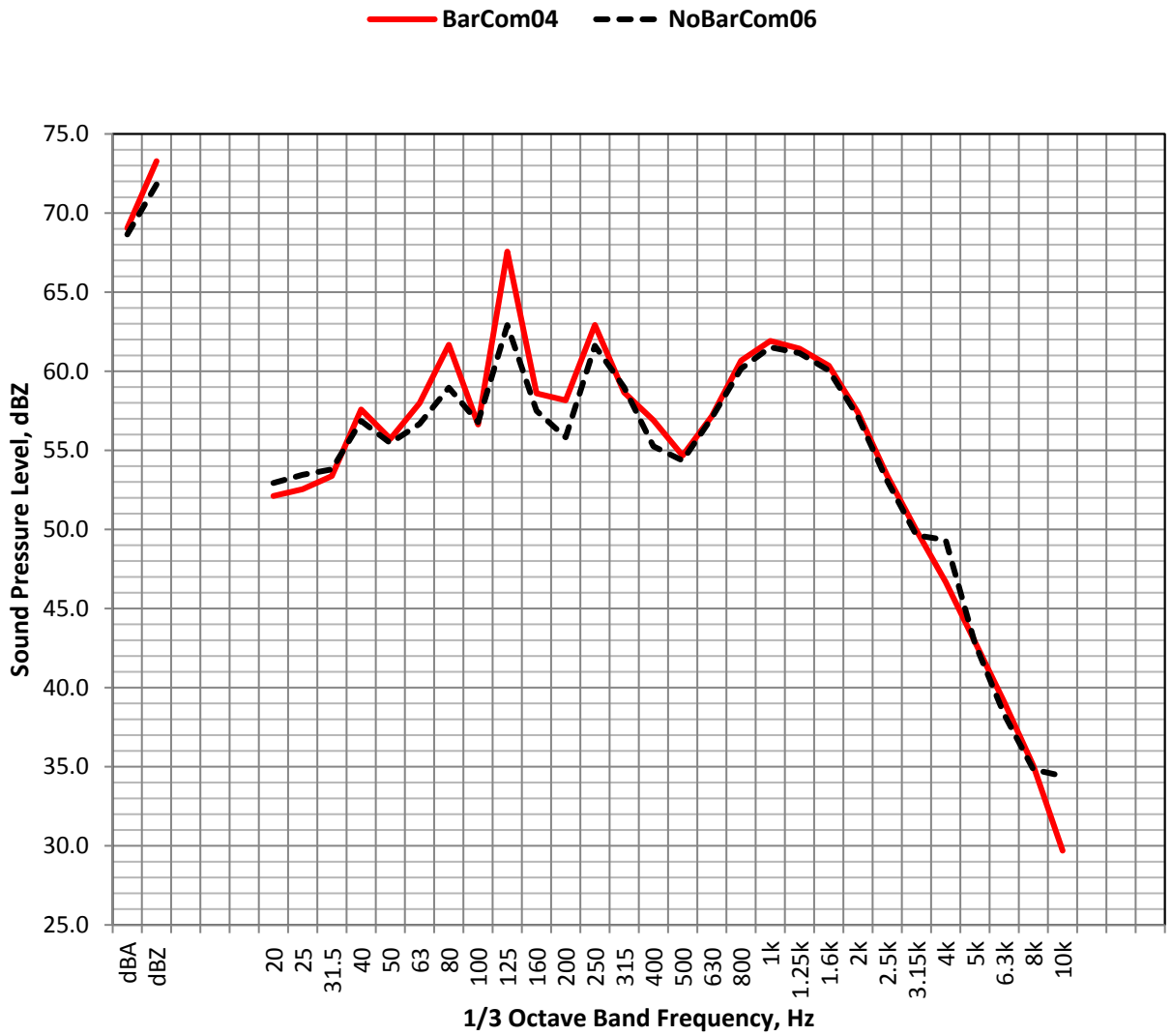


Figure 159. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Calm Neutral group CNG-3-4, 20:17 (L_{eq} (5 min.), dBZ).

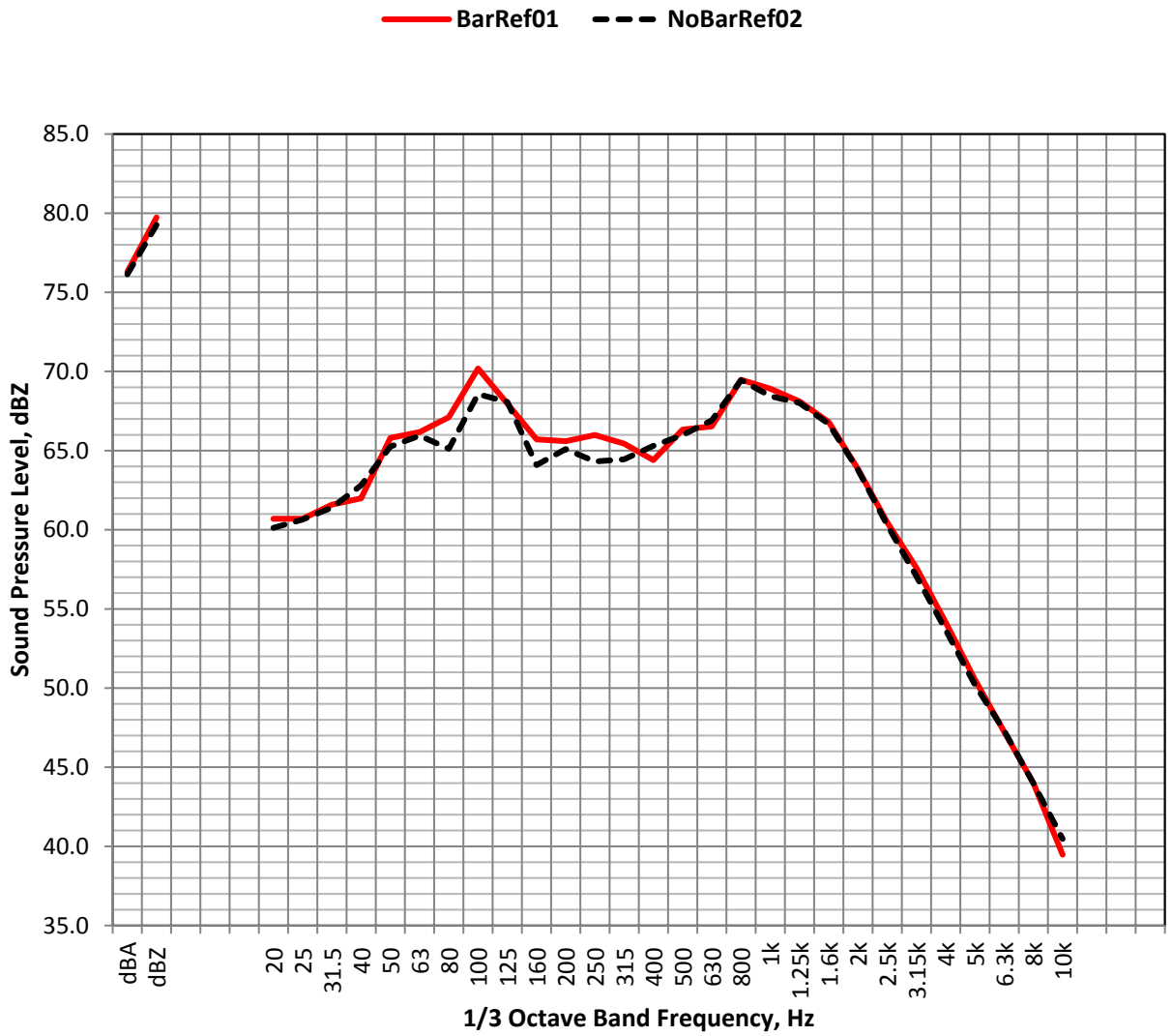


Figure 160. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Downwind Neutral Group DNG-2-2, 13:14 (L_{eq} (5 min.), dBZ).

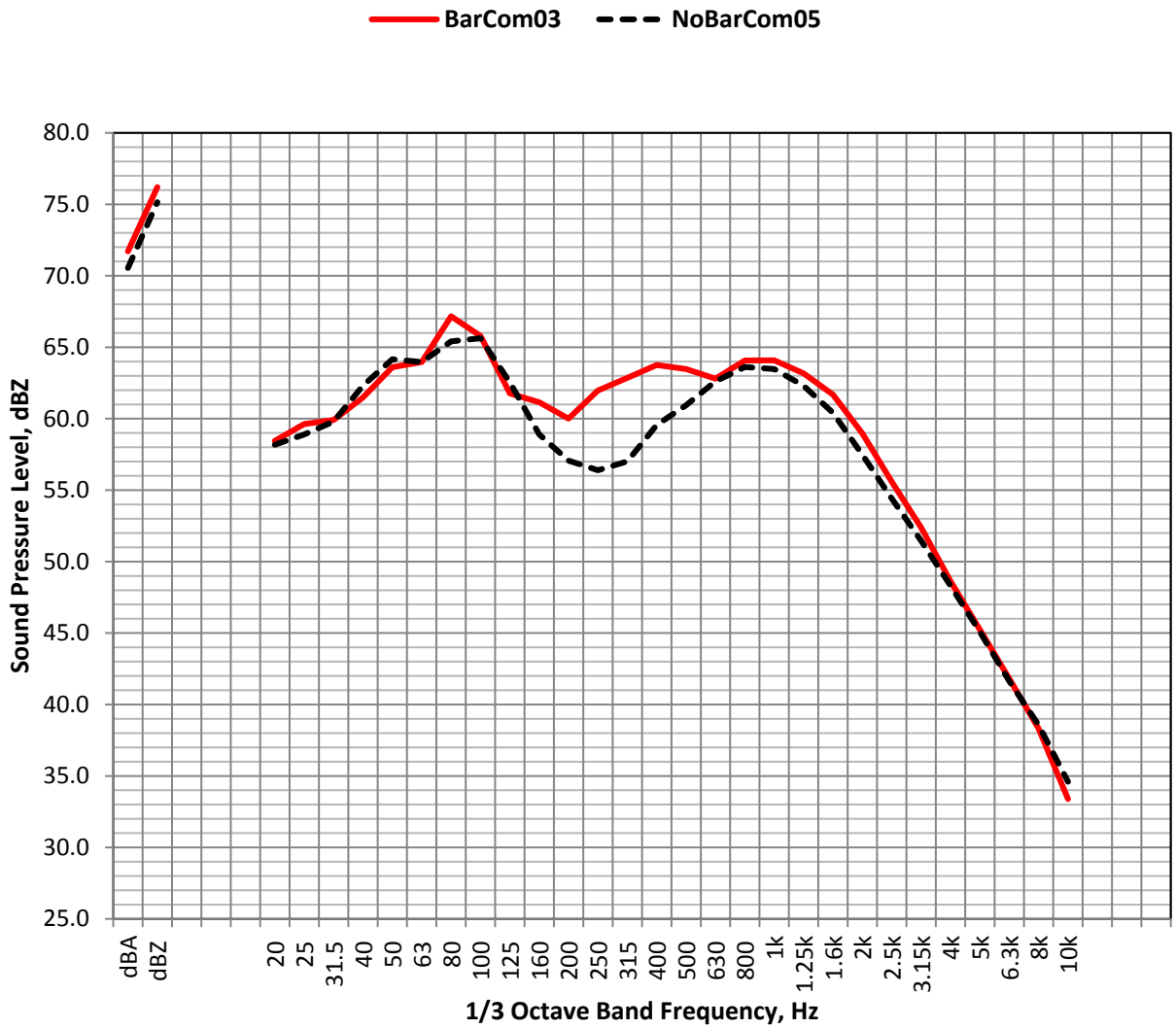


Figure 161. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Downwind Neutral Group DNG-2-2, 13:14 (L_{eq} (5 min.), dBZ).

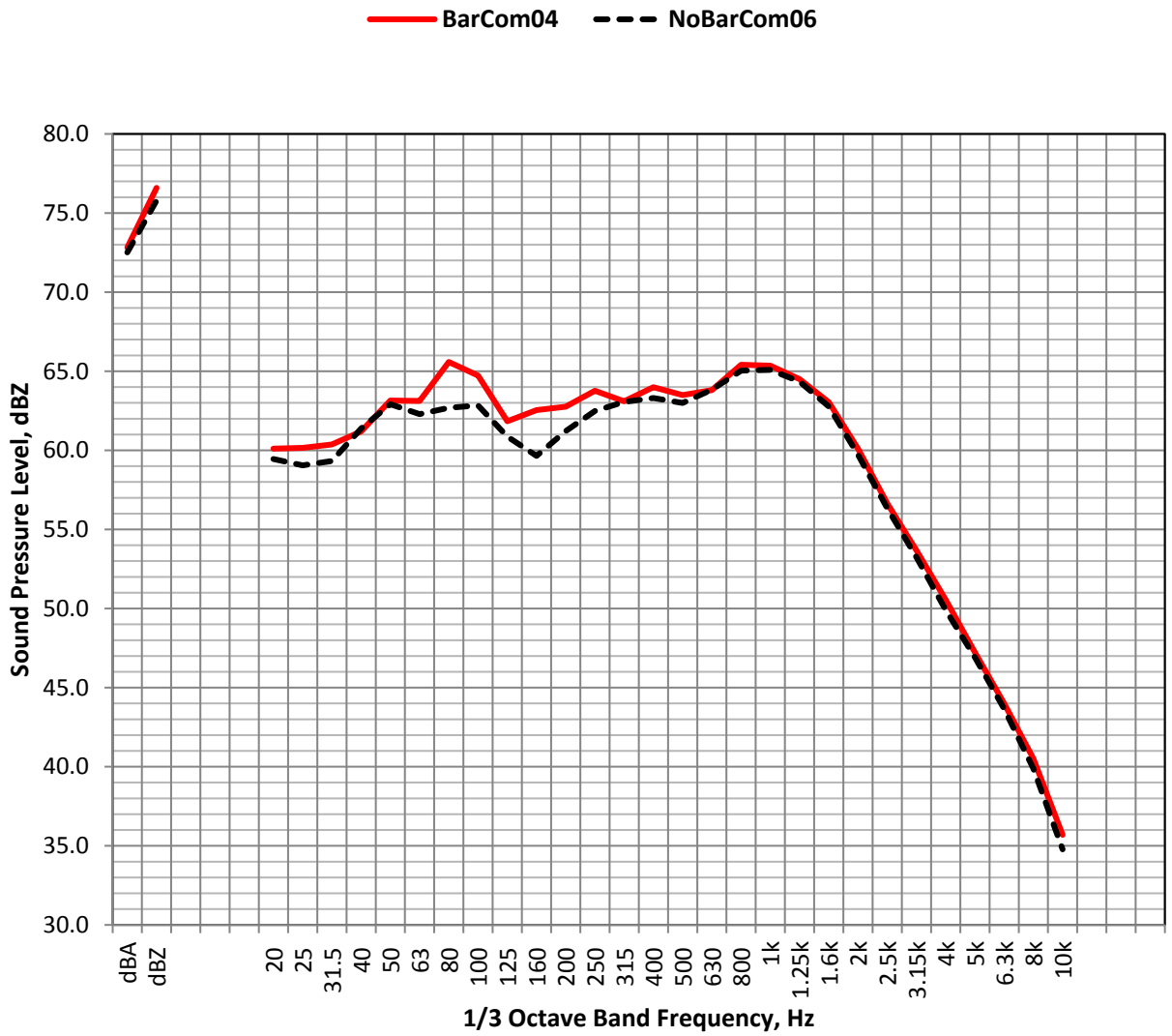


Figure 162. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Downwind Neutral Group DNG-2-2, 13:14 (L_{eq} (5 min.), dBZ).

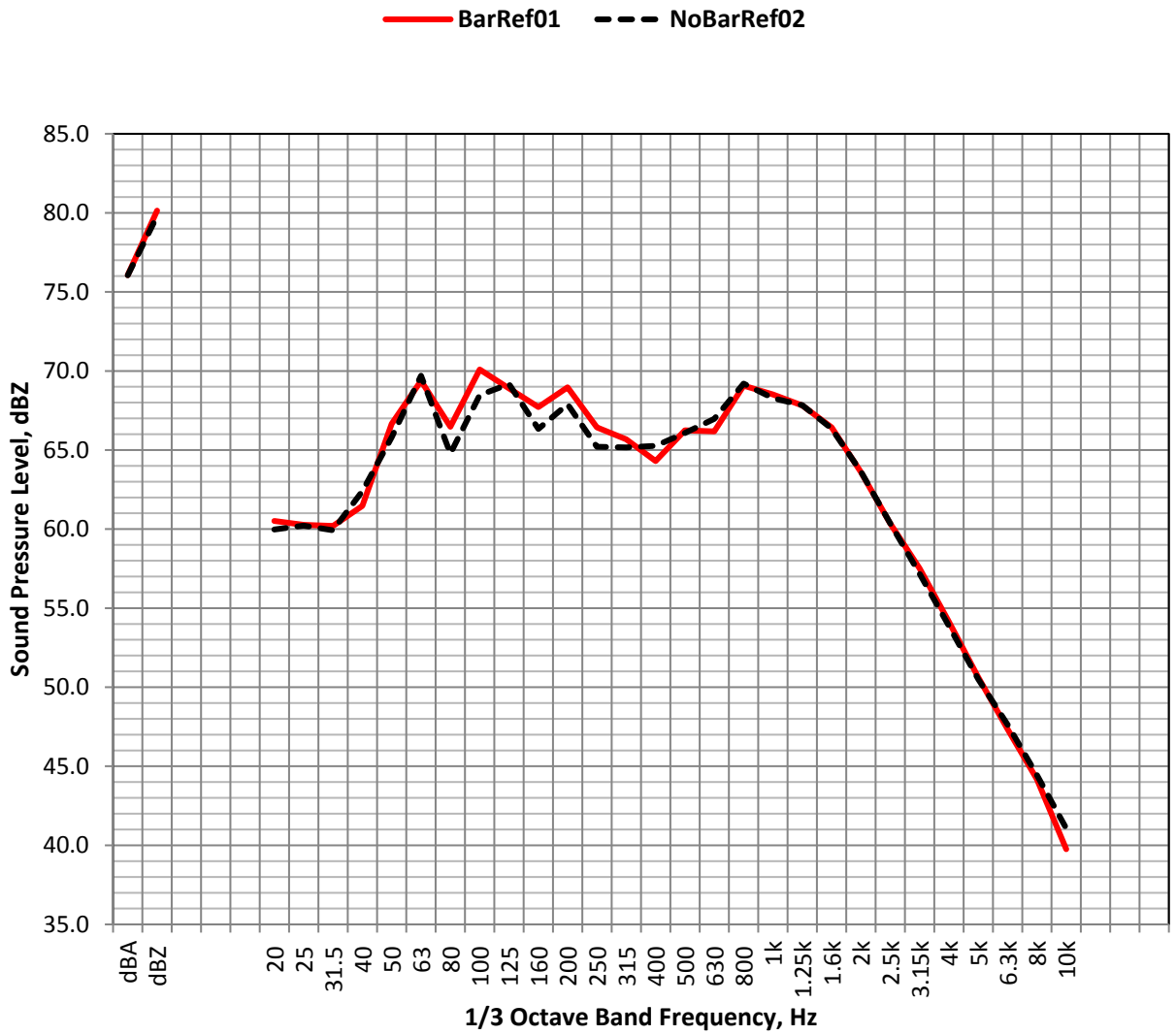


Figure 163. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Downwind Lapse Group DLG-3-4, 13:13 (L_{eq} (5 min.), dBZ).

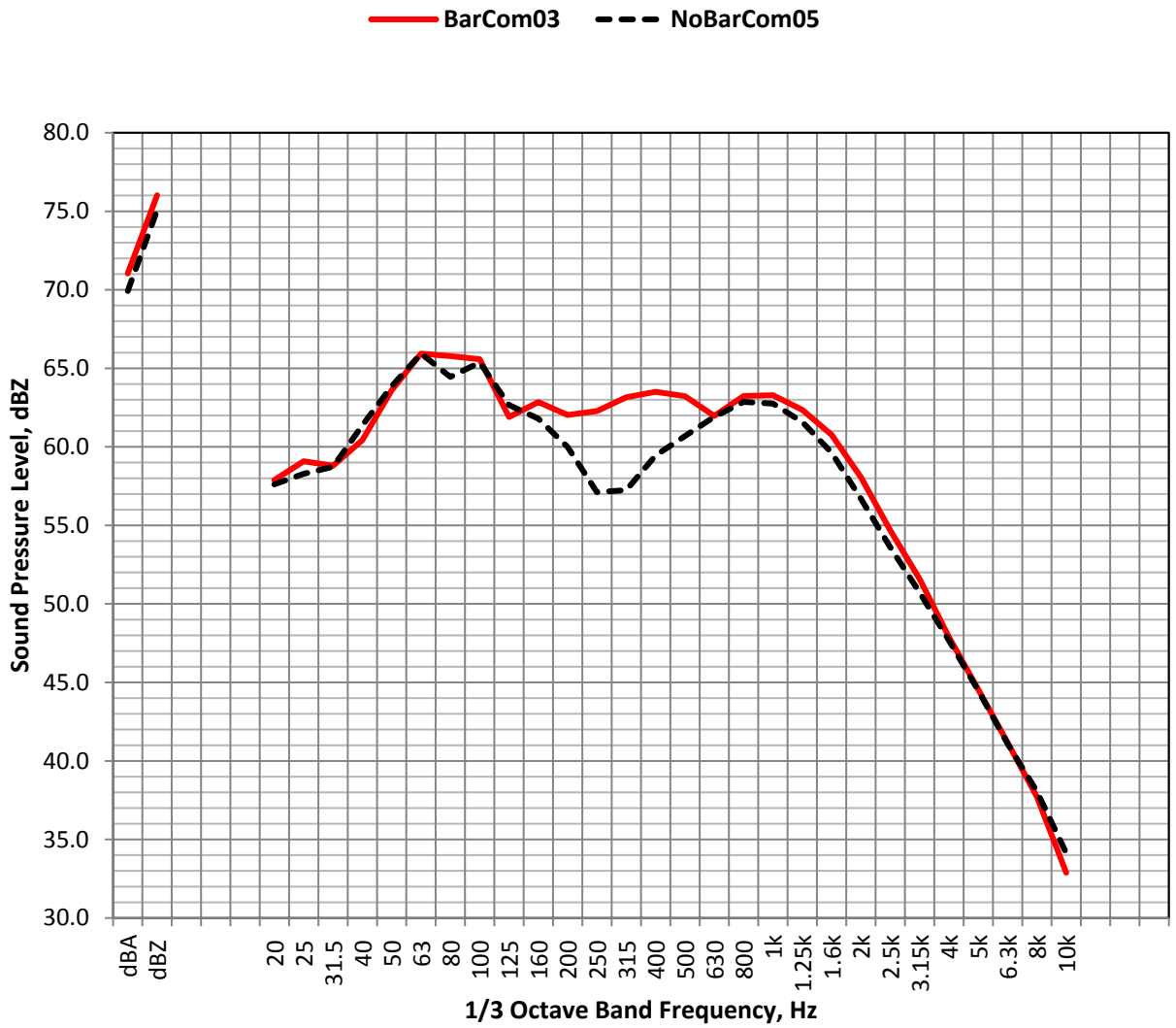


Figure 164. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Downwind Lapse Group DLG-3-4, 13:13 (L_{eq} (5 min.), dBZ).

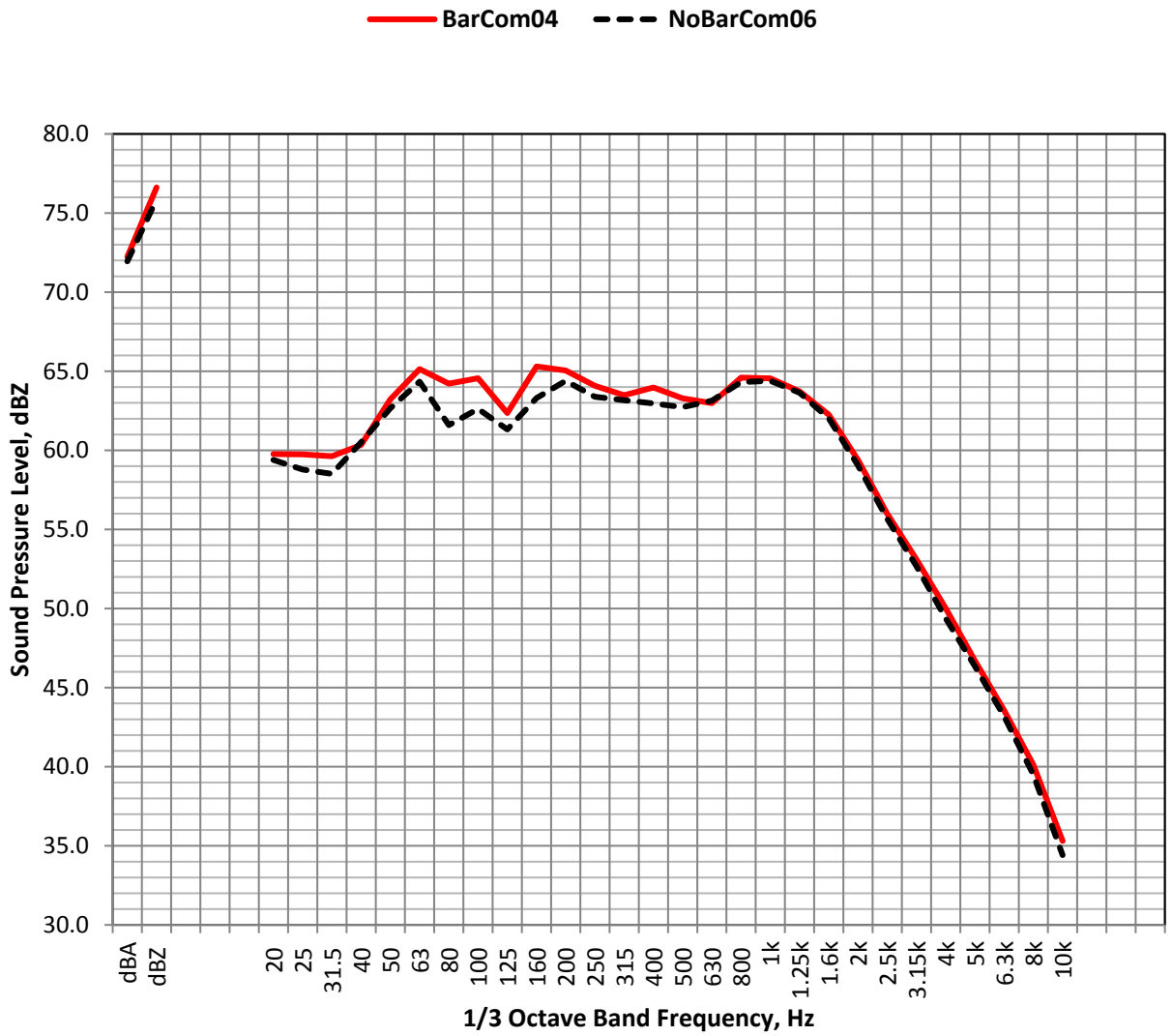


Figure 165. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Downwind Lapse Group DLG-3-4, 13:13 (L_{eq} (5 min.), dBZ).

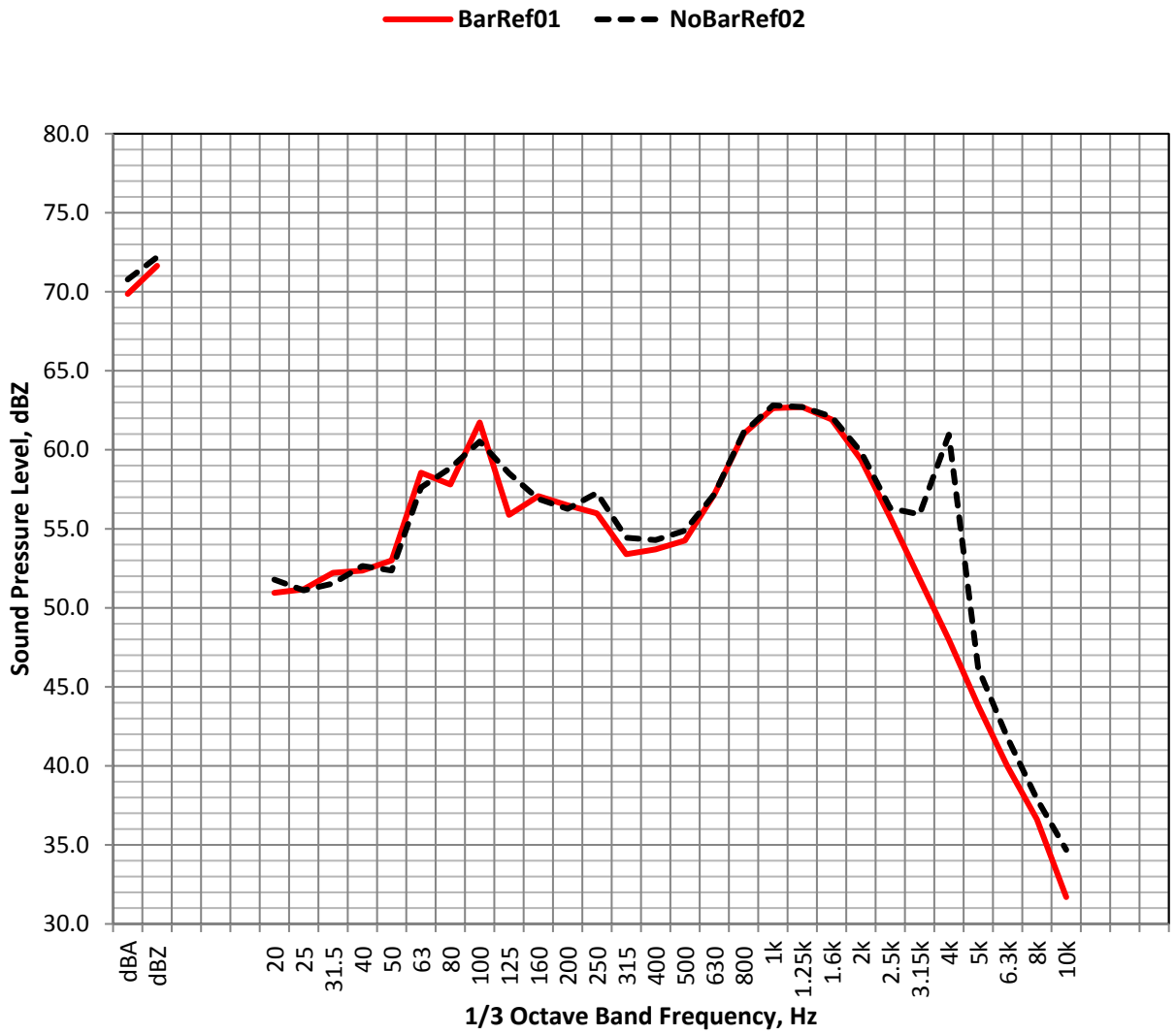


Figure 166. Sample sound pressure level spectra for BarRef01 and NoBarRef02, MD-5, Calm Inversion group CIG-3-4, 23:15 L_{eq} (5 min.), dBZ).

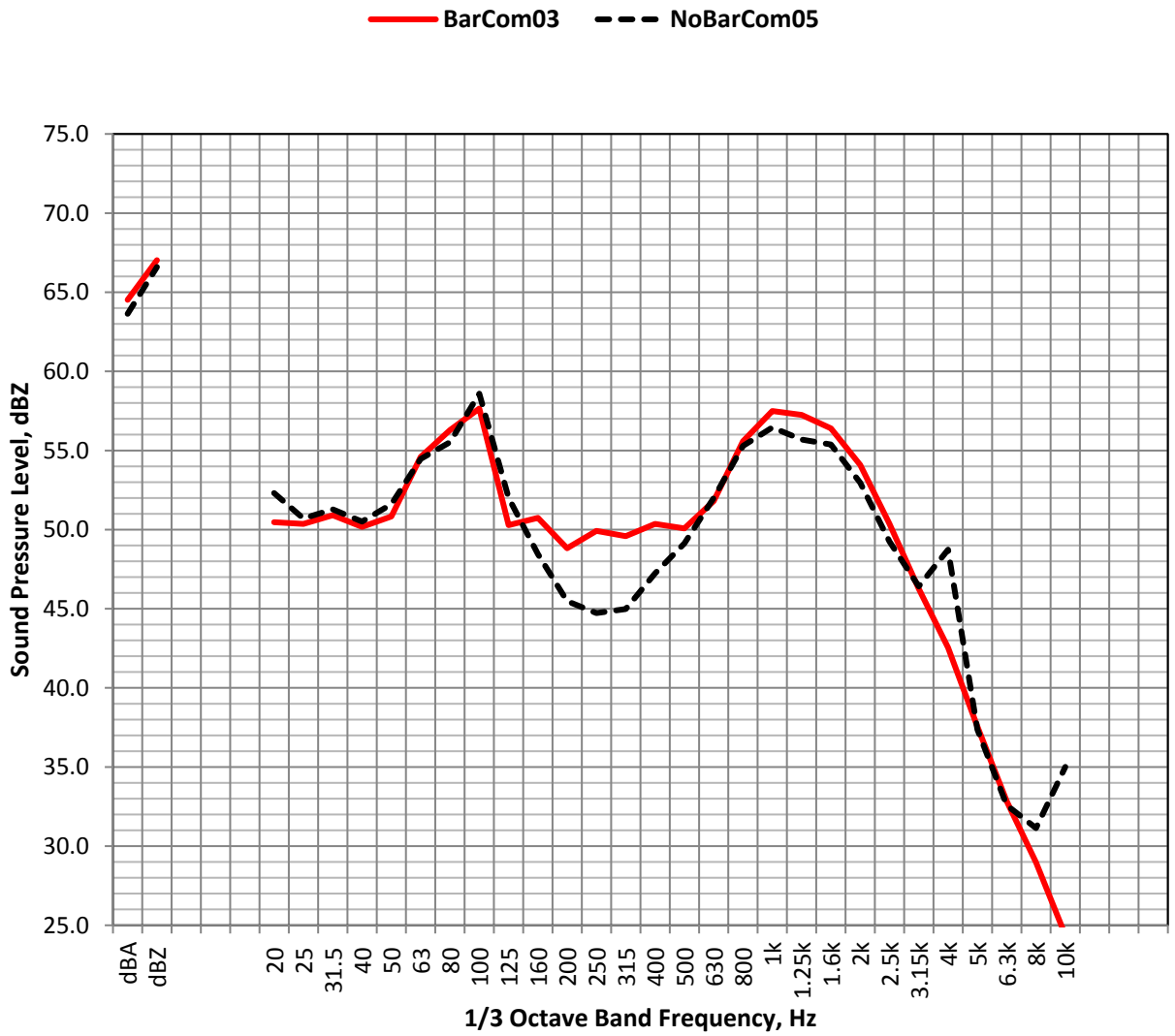


Figure 167. Sample sound pressure level spectra for BarCom03 and NoBarCom05, MD-5, Calm Inversion group CIG-3-4, 23:15 (L_{eq} (5 min.), dBZ).

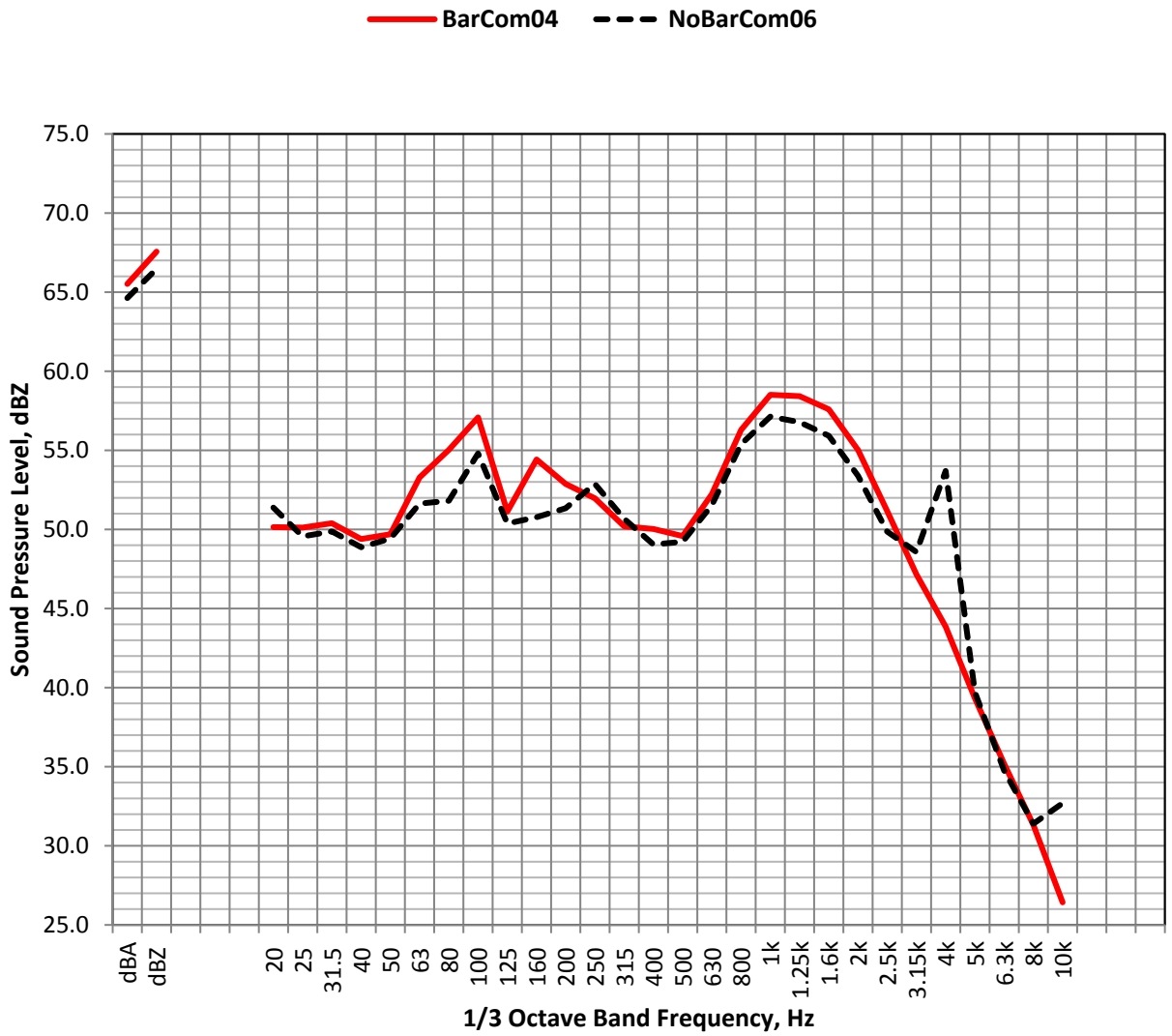


Figure 168. Sample sound pressure level spectra for BarCom04 and NoBarCom06, MD-5, Calm Inversion group CIG-3-4, 23:15 L_{eq} (5 min.), dBZ).

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.
- 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 one-third octave band sound pressure levels from 20 Hz to 10 kHz. Graphs for all the groups in all the meteorological classes are in spreadsheet files in the project record. The trends across the one-third 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 Hz to 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 Hz to 500 Hz range would be nonexistent or diminished. Exactly this effect is seen for all four of the meteorological classes in the sample spectra presented in Figure 158, Figure 161, Figure 164, and Figure 167. As a result, the barrier effect is pronounced in the 250 Hz to 500 Hz range.

Calm Neutral Class

Figure 169 shows the results for the Calm Neutral class. The upper graph shows that, in general, the BarRef01 levels vary little compared to NoBarRef02 across most of the frequency range from 20 Hz to 2.5 kHz, except for 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 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 like 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 through 2.5 kHz; and a 4 dB higher level at NoBarCom06 due to frog and insect noise.

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

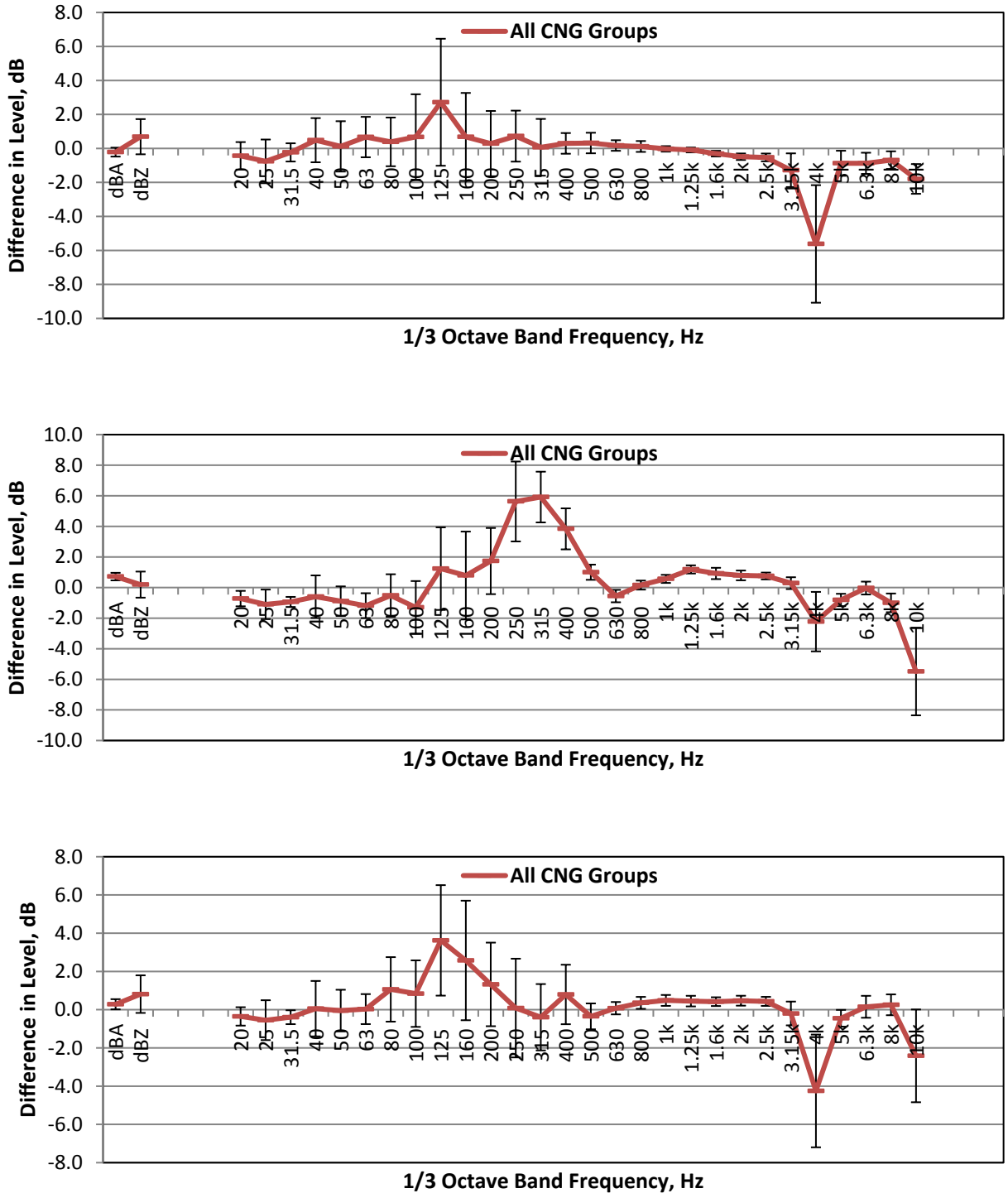


Figure 169. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Neutral groups, MD-5.

Downwind Neutral Class

Figure 170 shows the results for the Downwind Neutral class. The upper graph shows 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 1 dB 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 like 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 1 dB 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 the 5-minute periods in all the Downwind Neutral groups were not equivalent in traffic volume and speed across all the equivalent groups, these averages of the average differences generally show consistency with the results in the individual groups.

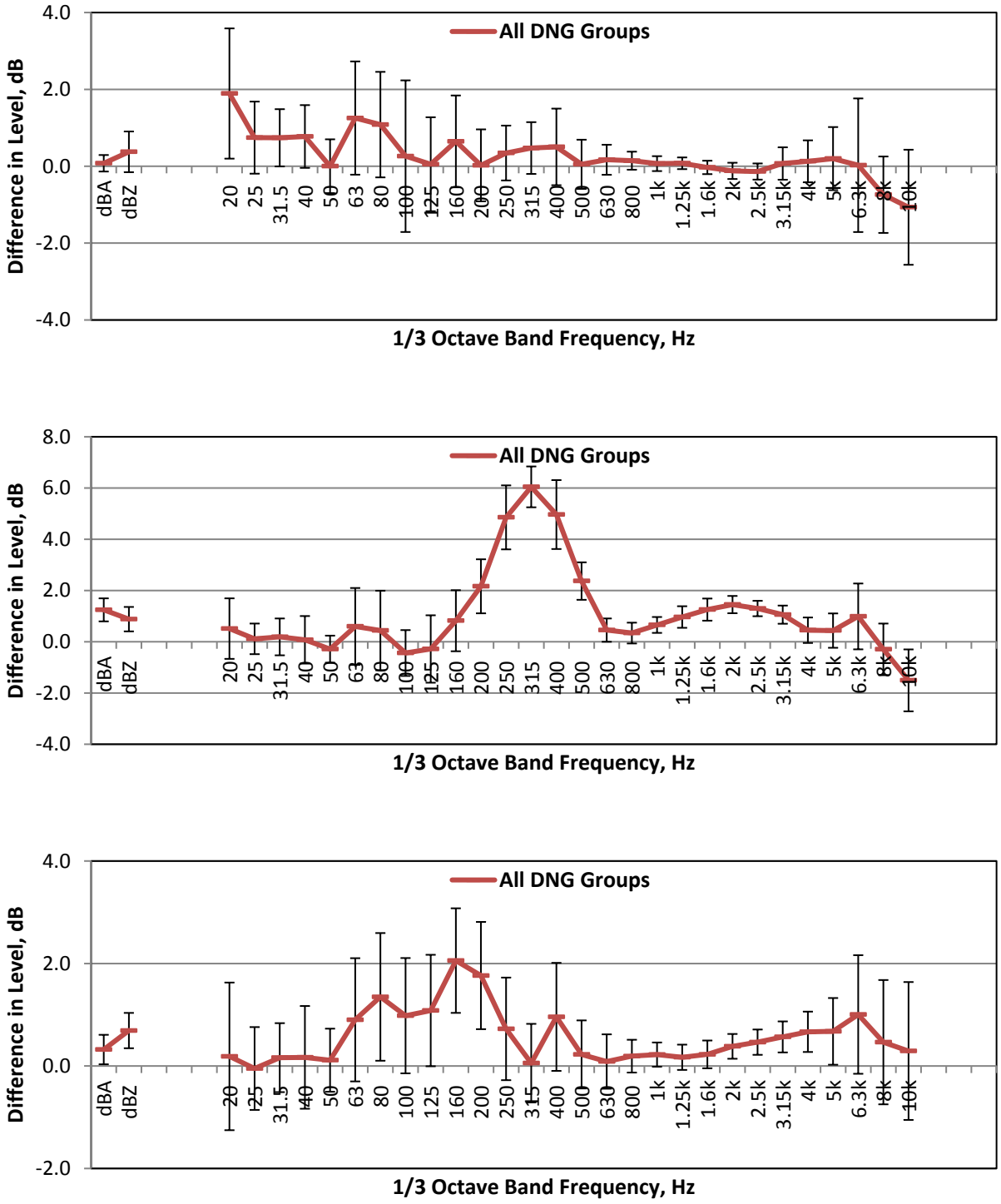


Figure 170. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Downwind Neutral groups, MD-5.

Downwind Lapse Class

Figure 171 shows the results for the Downwind Lapse class. The results for these daytime periods are like those for the daytime Downwind Neutral class. In the upper graph, there are few differences at the reference microphones above 160 Hz and minor differences of up to 1 dB (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 like 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 the 5-minute periods in all the Downwind Lapse groups were not equivalent in traffic volume and speed across all the equivalent groups, these averages of the average differences generally show consistency with the results in the individual groups.

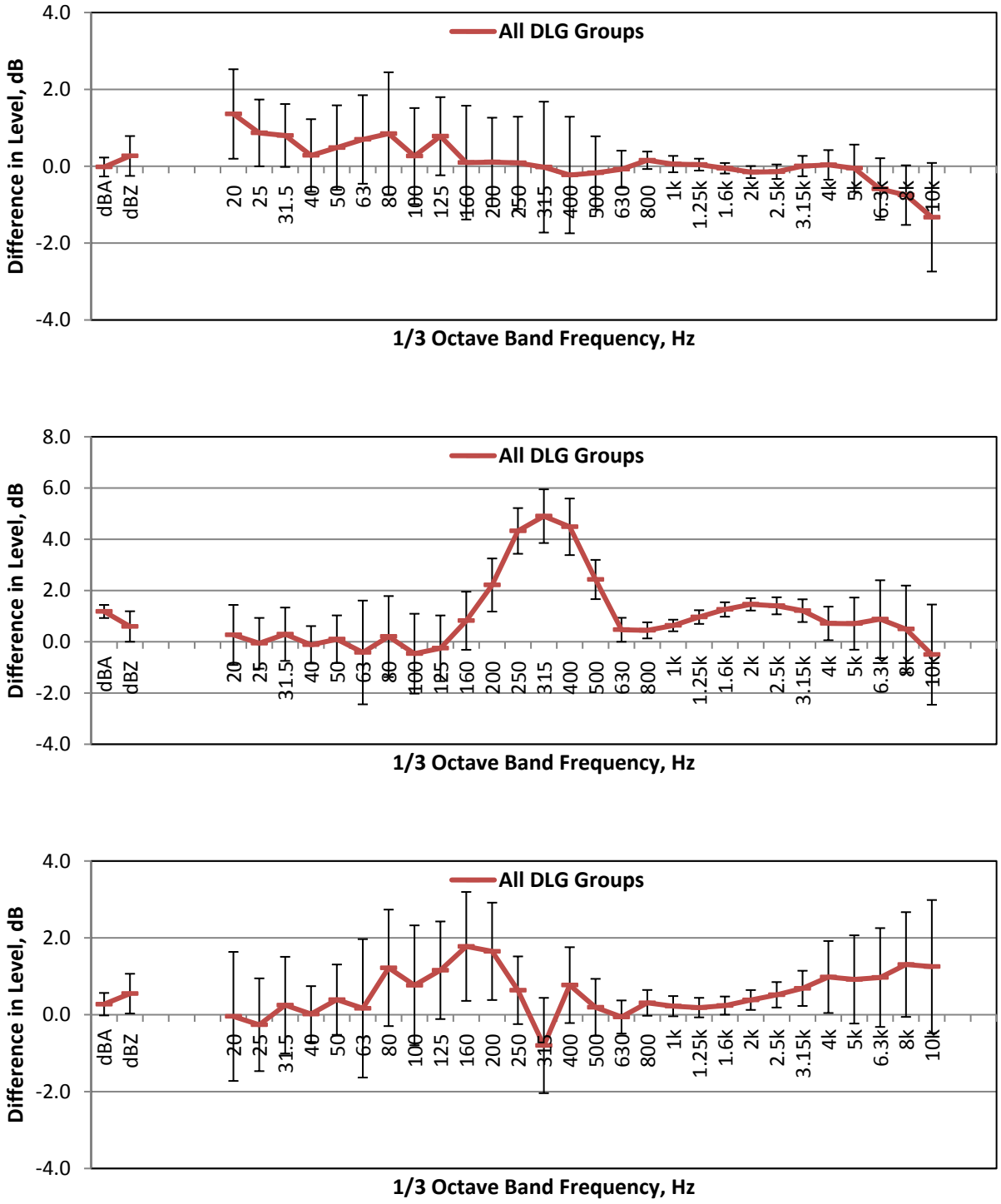


Figure 171. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Downwind Lapse groups, MD-5.

Calm Inversion Class

Figure 172 shows the results for the Calm Inversion class. The results for these later evening periods are like those for the Calm Neutral class. In the upper graph, there are few differences at the reference microphones across the entire spectrum, except for 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 are again like 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 like 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 the 5-minute periods in all the Calm Inversion groups were not equivalent in traffic volume and speed across all the equivalent groups, these averages of the average differences generally show consistency with the results in the individual groups. Although, the Calm Inversion group showed a roughly 300% change in factored hourly traffic volume across all the equivalent groups, meaningful conclusions about any correlations between traffic volumes and the differences in L_{eq} (5 min.) could not be established.

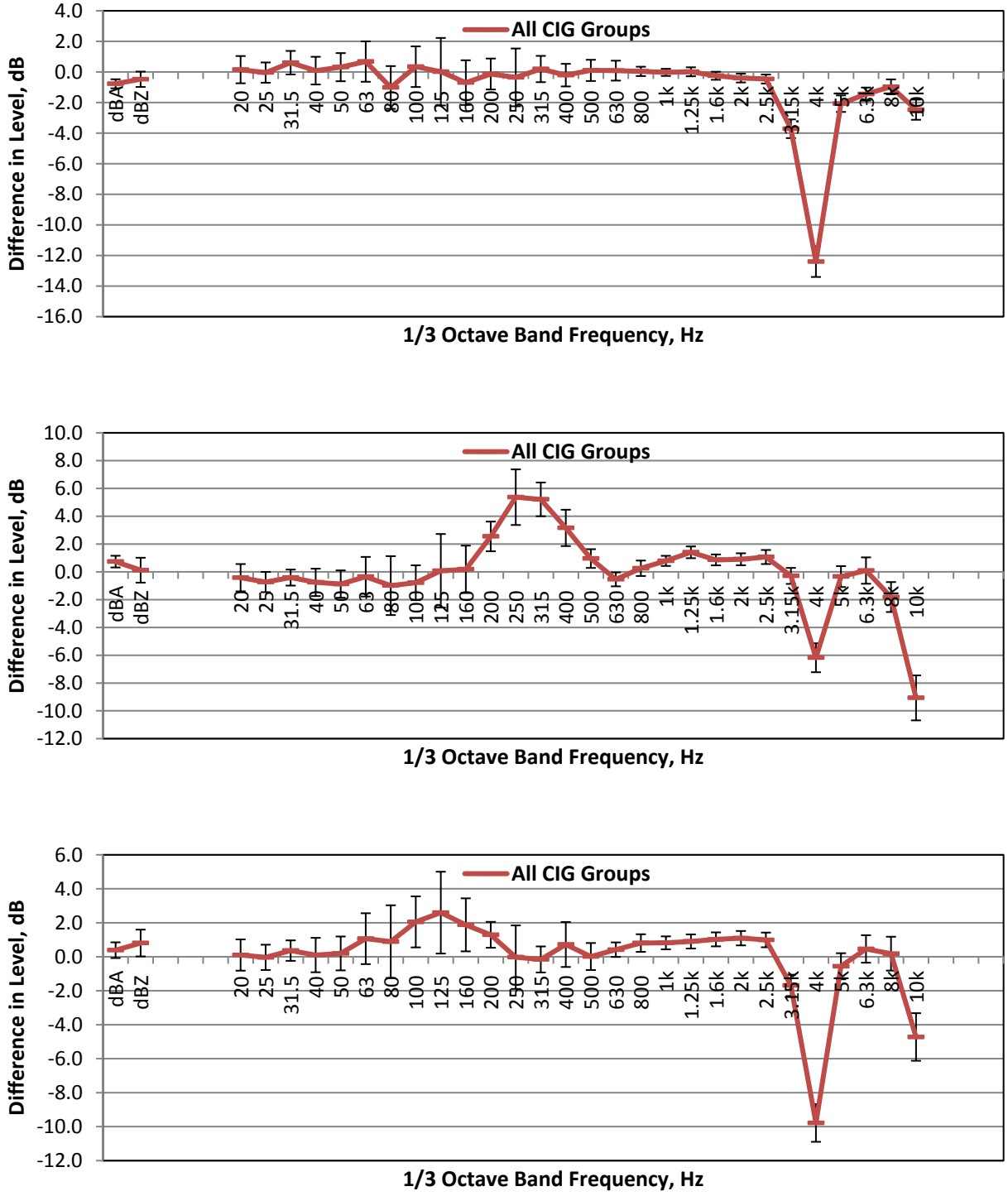


Figure 172. Averages of the differences in L_{eq} (5 min.) +/- one standard deviation (dB), all microphones, for all Calm Inversion groups, MD-5.

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. 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 compares 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. Except for 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 0.5 dB or less.

For the lower community microphones (BarCom03 and NoBarCom05), ignoring the frog noise at 4 kHz, the Calm Neutral differences are as follows:

- 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 0.5 dB 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 as follows:

- 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.
- 0.5 dB 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.

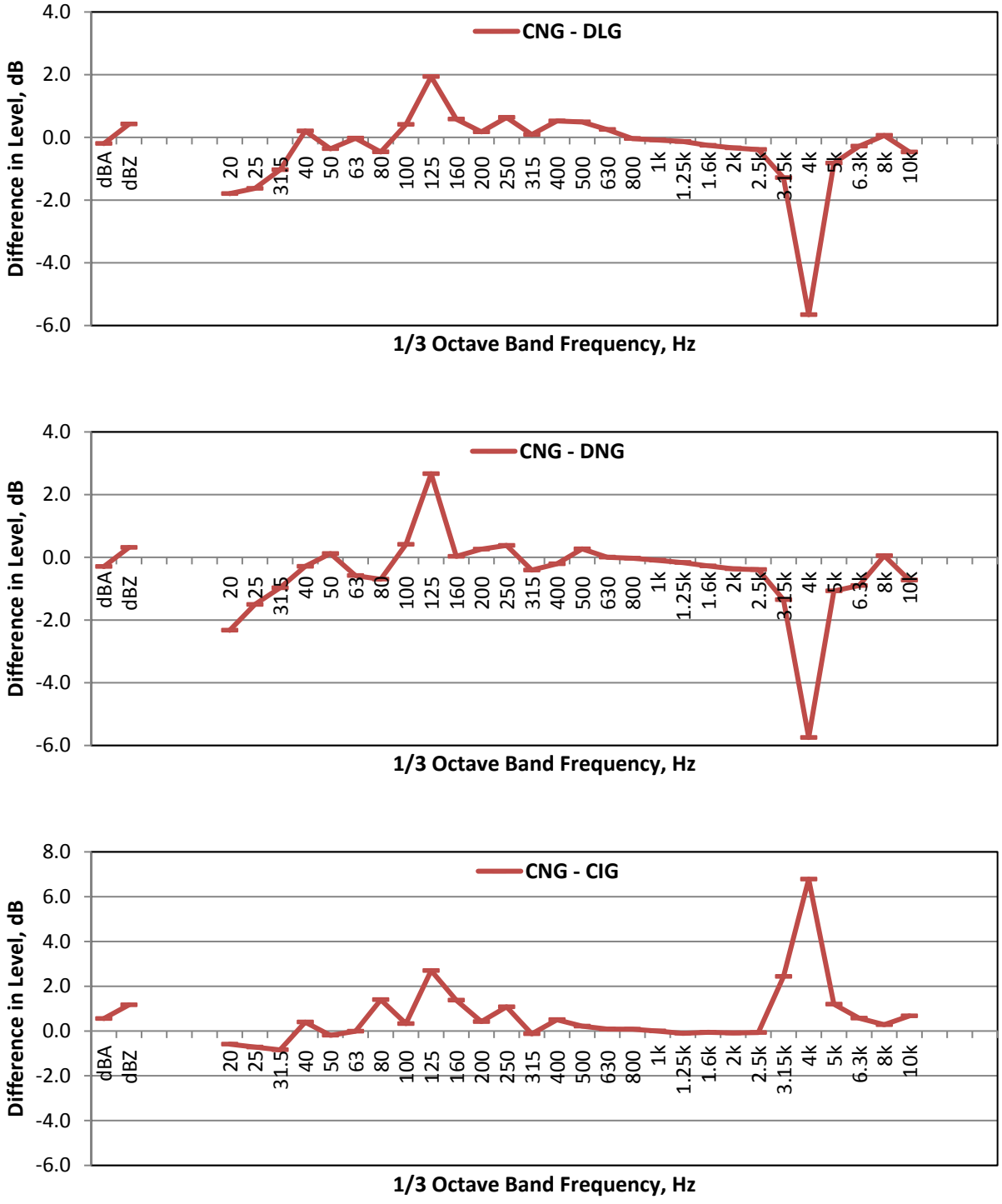


Figure 173. Differences in the Calm Neutral average differences and Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq} (5 min.)), BarRef01 minus NoBarRef02, MD-5.

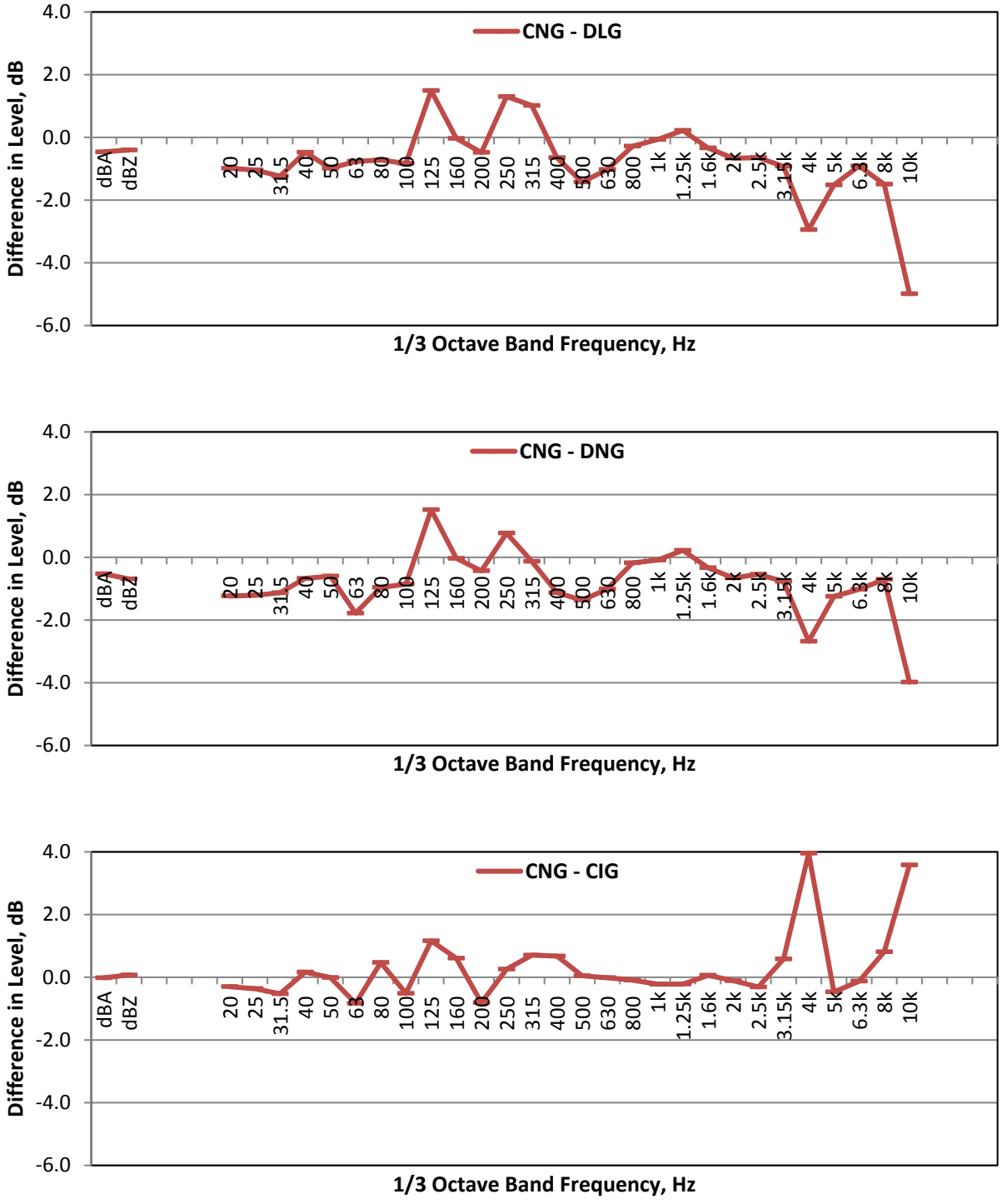
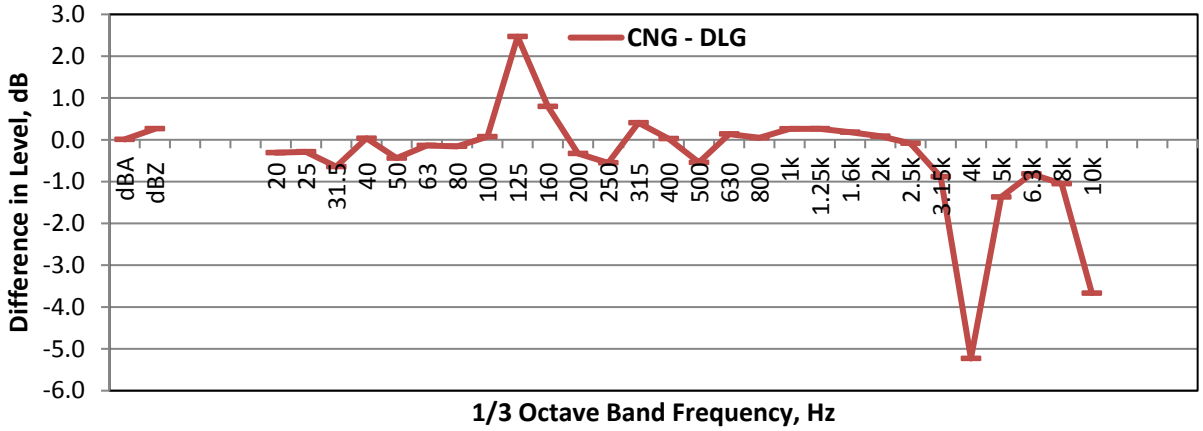
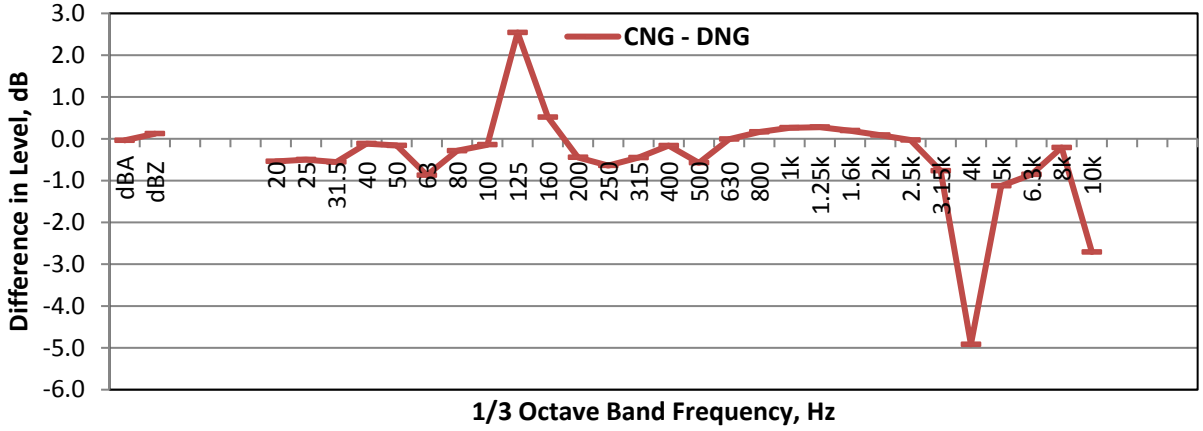


Figure 174. Differences in the Calm Neutral average differences and Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq} (5 min.)), NoBarCom05 minus NoBarCom05, MD-5.





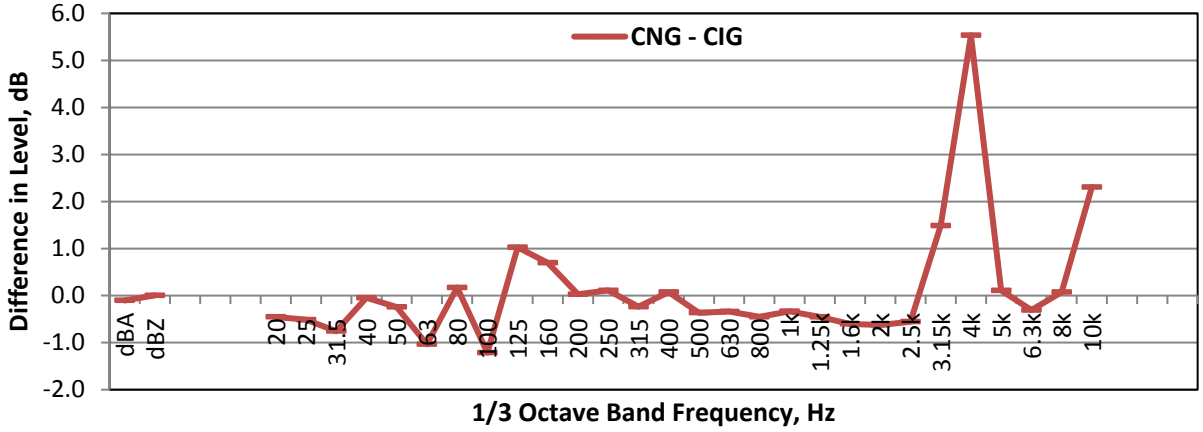


Figure 175. Differences in the Calm Neutral average differences and Downwind Lapse, Downwind Neutral and Calm Inversion average differences (L_{eq} (5 min.)), BarCom04 minus NoBarCom06, MD-5.

Additional Sound Level Analysis—L_n Descriptors

Figure 176 presents the L_{90} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.), computed as BarRef01 minus NoBarRef2 for the A-weighted sound levels.

The results show that while there is little difference in the L_{eq} (5 min.) 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 suggests 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} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom03 minus NoBarCom05.

Evidence exists of the elevated background level at BarCom03 during the daytime hours. While the L_{eq} (5 min.) averages about 0.5 dB to 1 dB higher than NoBarCom05, the L_{90} (5 min.) at BarCom03 range from 9 dB lower to 10 dB higher than NoBarCom05, averaging approximately 2 dB higher. Almost all the daytime L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) 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} (5 min.) and L_{99} (5 min.) along with L_{eq} (5 min.) for the A-weighted sound levels, computed as BarCom04 minus NoBarCom06.

Mixed evidence exists 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, strong evidence exists of elevated background level at NoBarCom06 due to frog and insect noise in the No Barrier area.

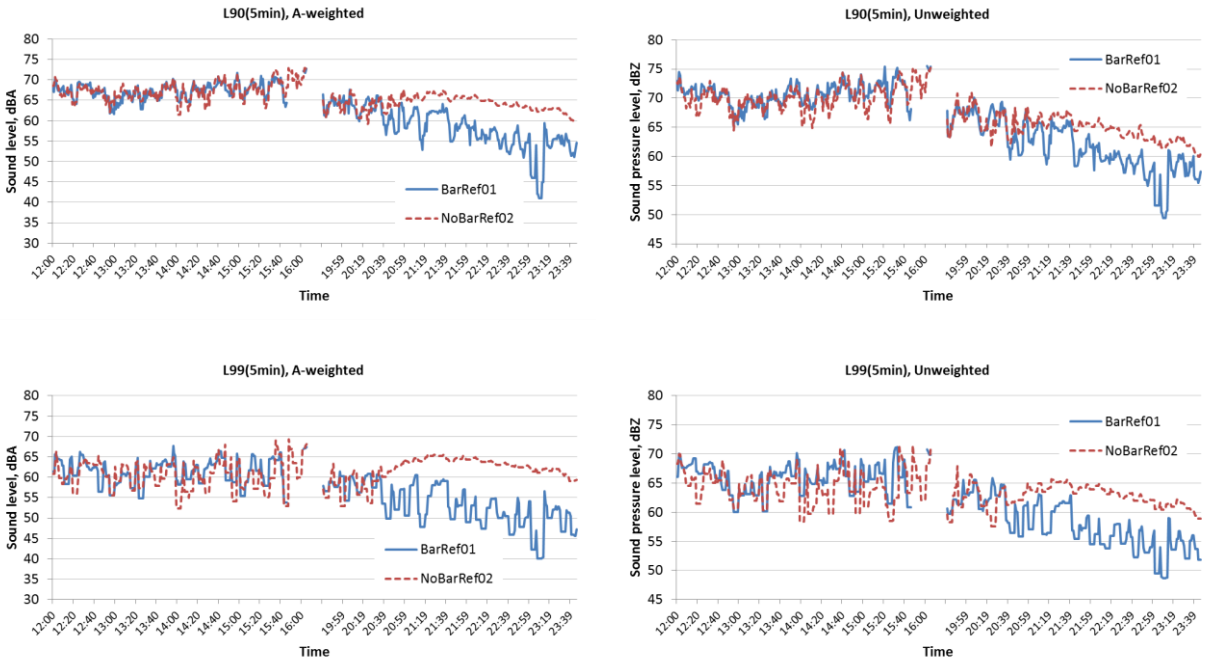


Figure 176. L_{90} (5 min.) and L_{99} (5 min.), MD-5, BarRef01 and NoBarRef02—broadband A-weighted sound level (left) and sound pressure level (right).

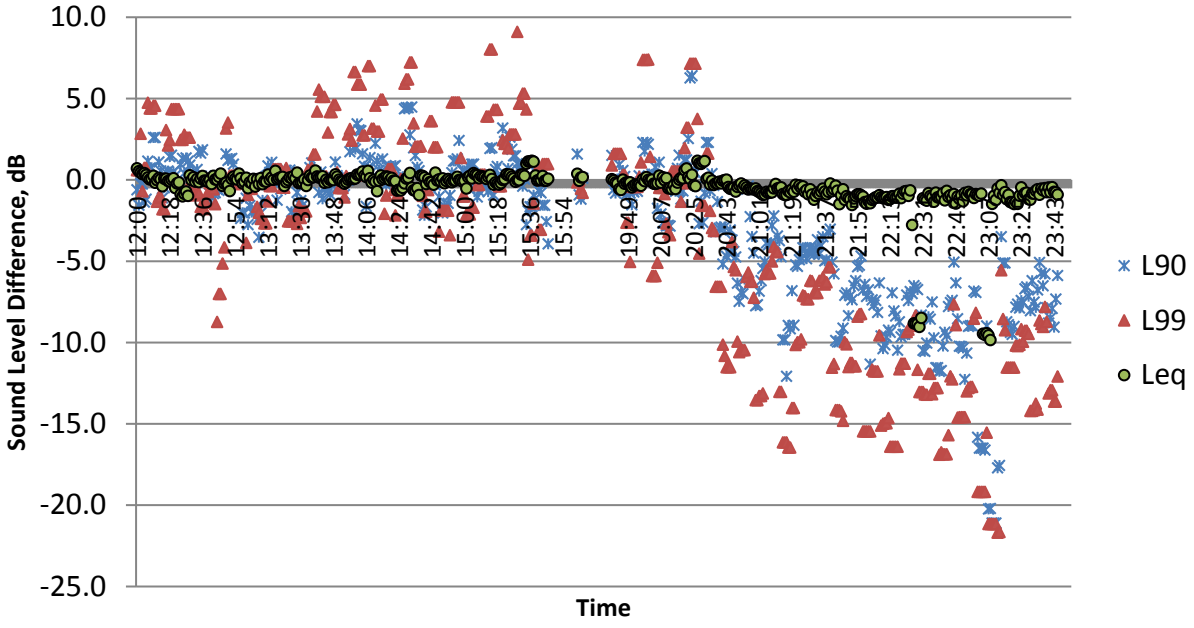


Figure 177. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, MD-5, BarRef01 and NoBarRef02.

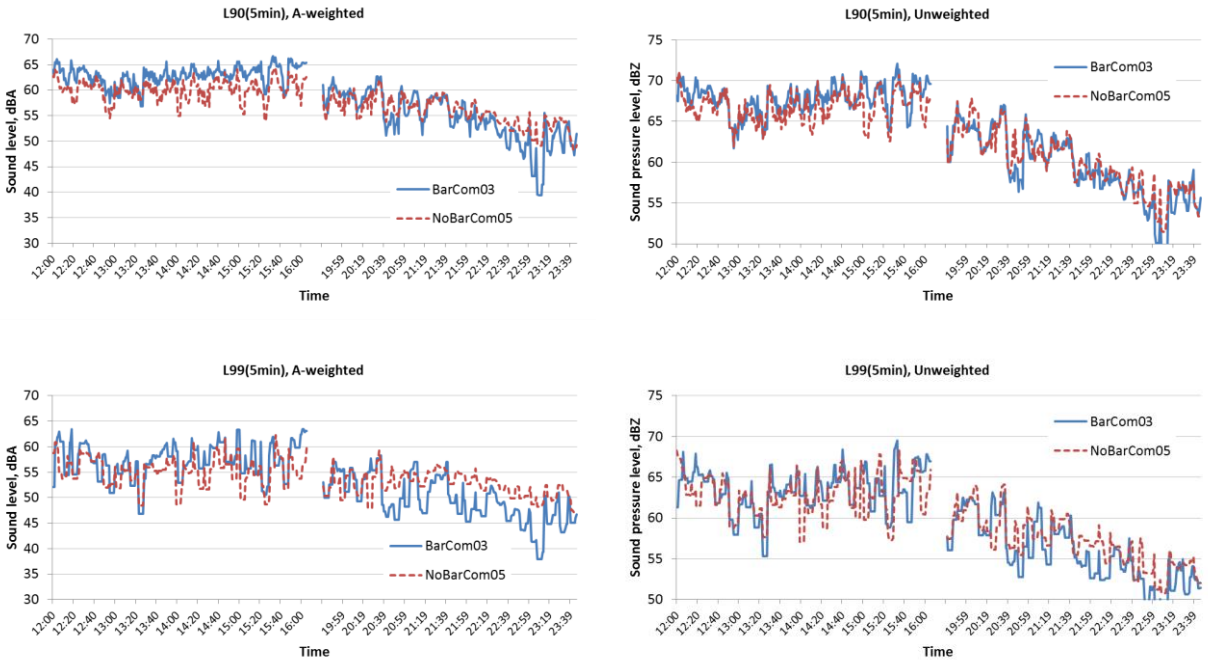


Figure 178. L_{90} (5 min.) and L_{99} (5 min.), MD-5, BarCom03 and NoBarCom05—broadband A-weighted sound level (left) and sound pressure level (right).

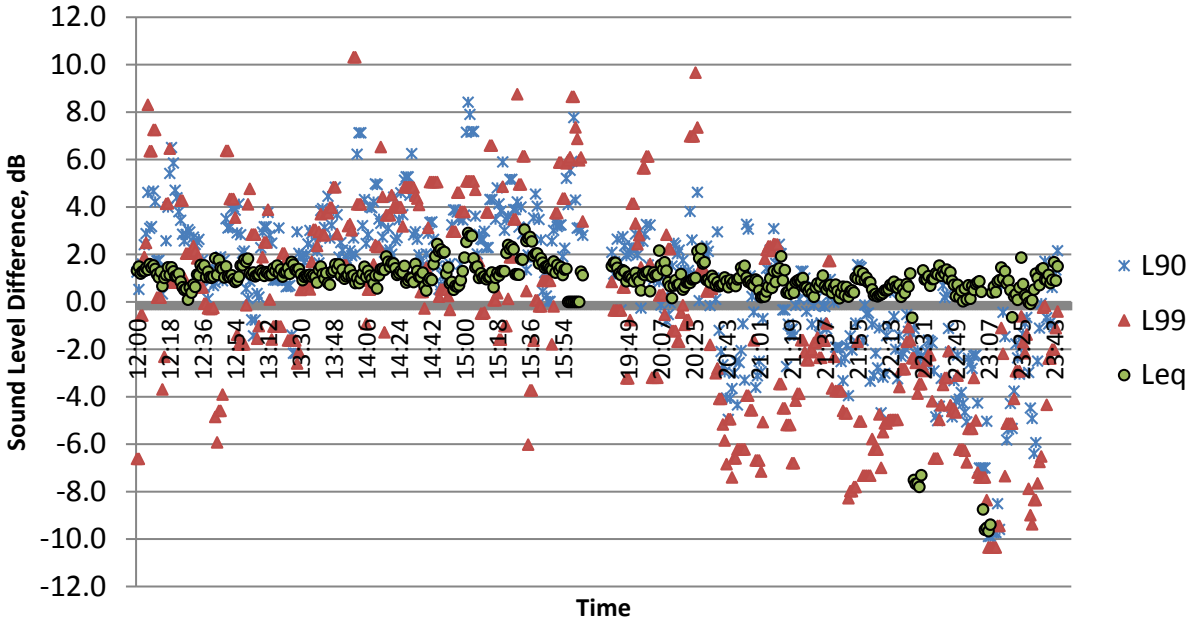


Figure 179. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, MD-5, BarCom03 and NoBarCom05.

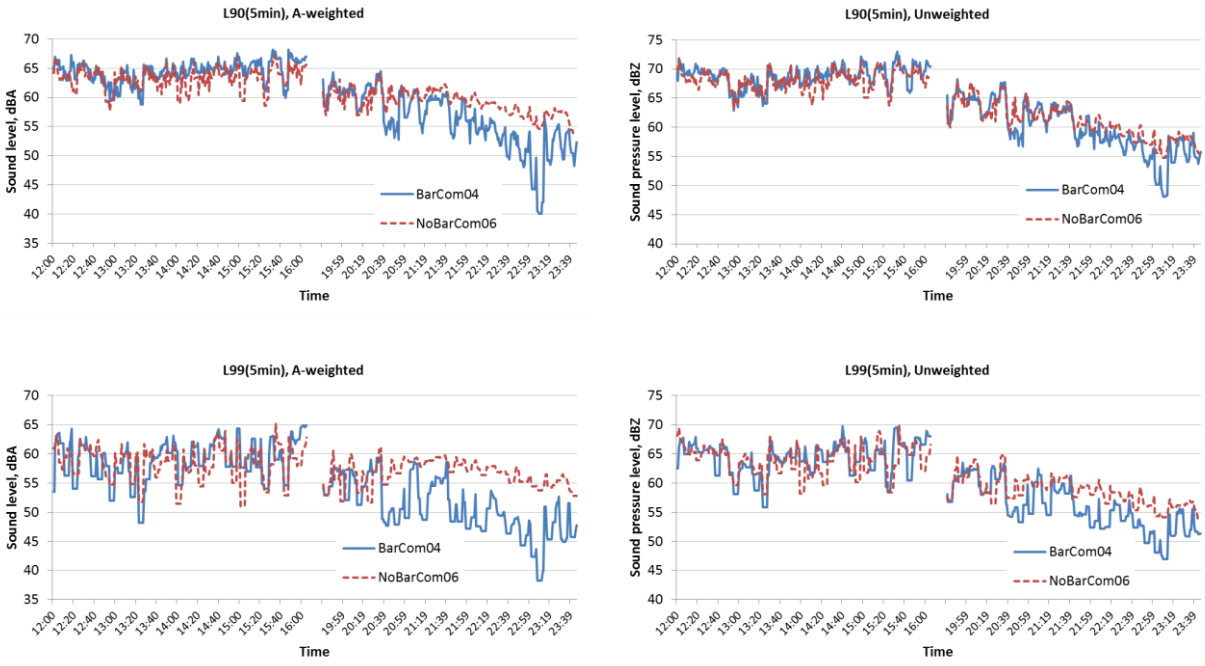


Figure 180. L_{90} (5 min.) and L_{99} (5 min.), MD-5, BarCom04 and NoBarCom06—broadband A-weighted sound level (left) and sound pressure level (right).

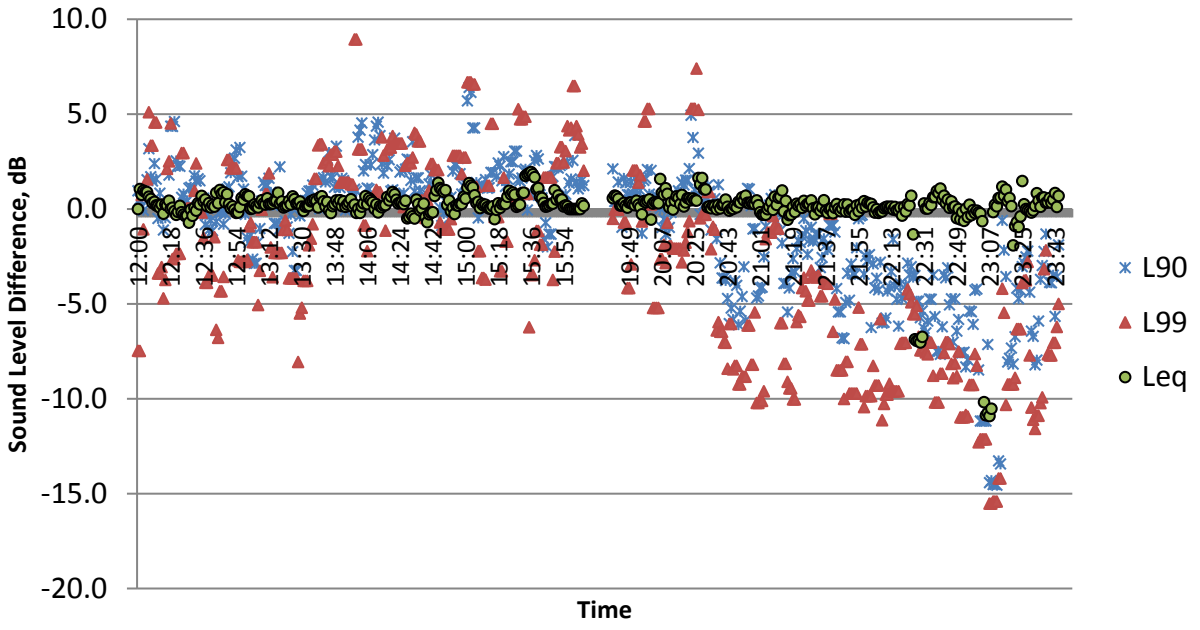


Figure 181. Differences in broadband A-weighted 5-minute L_{90}, L_{99} and L_{eq}, MD-5, BarCom04 and NoBarCom06.

The preceding graphs were for the broadband A-weighted sound levels and unweighted sound pressure levels. The next graphs broaden the analysis to include the individual one-third 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 one-third 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. Some evidence exists of higher background levels at BarRef01 in the afternoon session in the bands from 630 Hz through 2.5 kHz, as evidenced by the brown streaks on the right side of the one-third octave band columns of data.

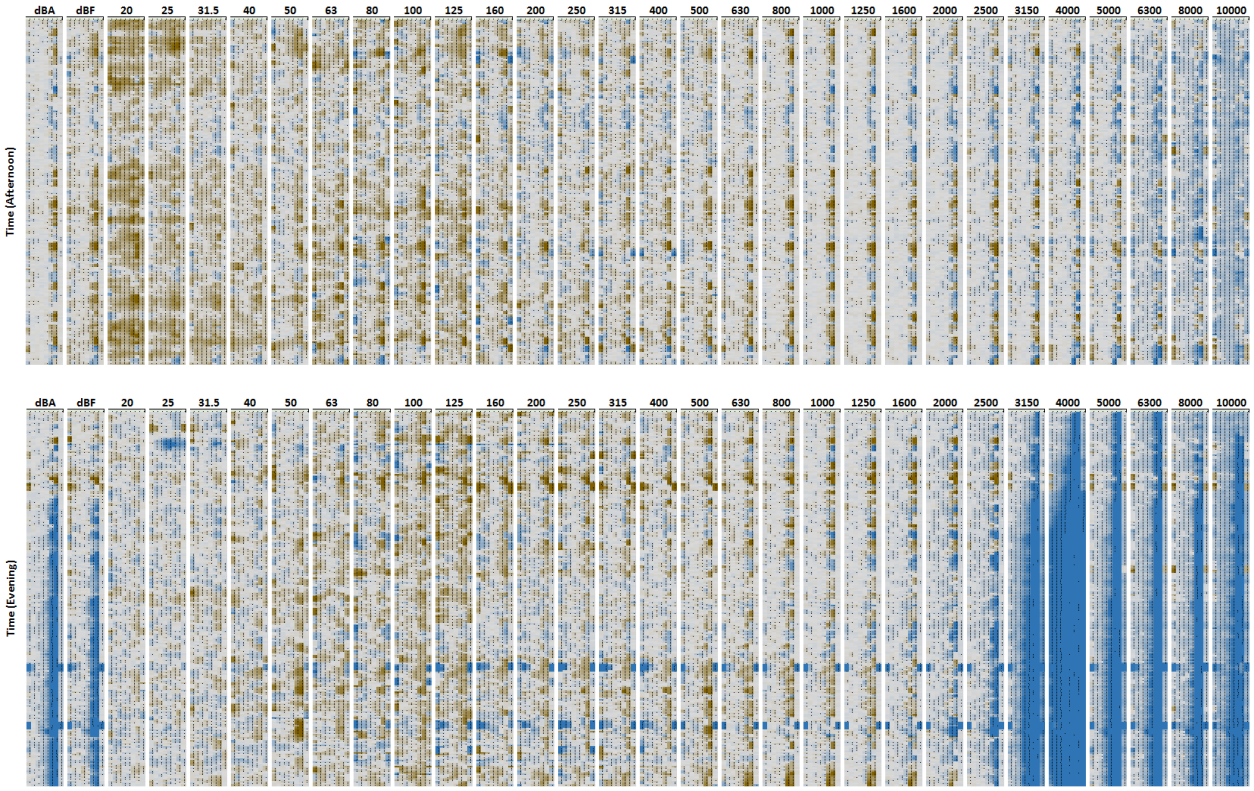


Figure 182. MD-5 Differences in L_n (5 min.) by one-third octave frequency bands: BarRef01 and NoBarRef02.

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 Hz 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 pass-by 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.

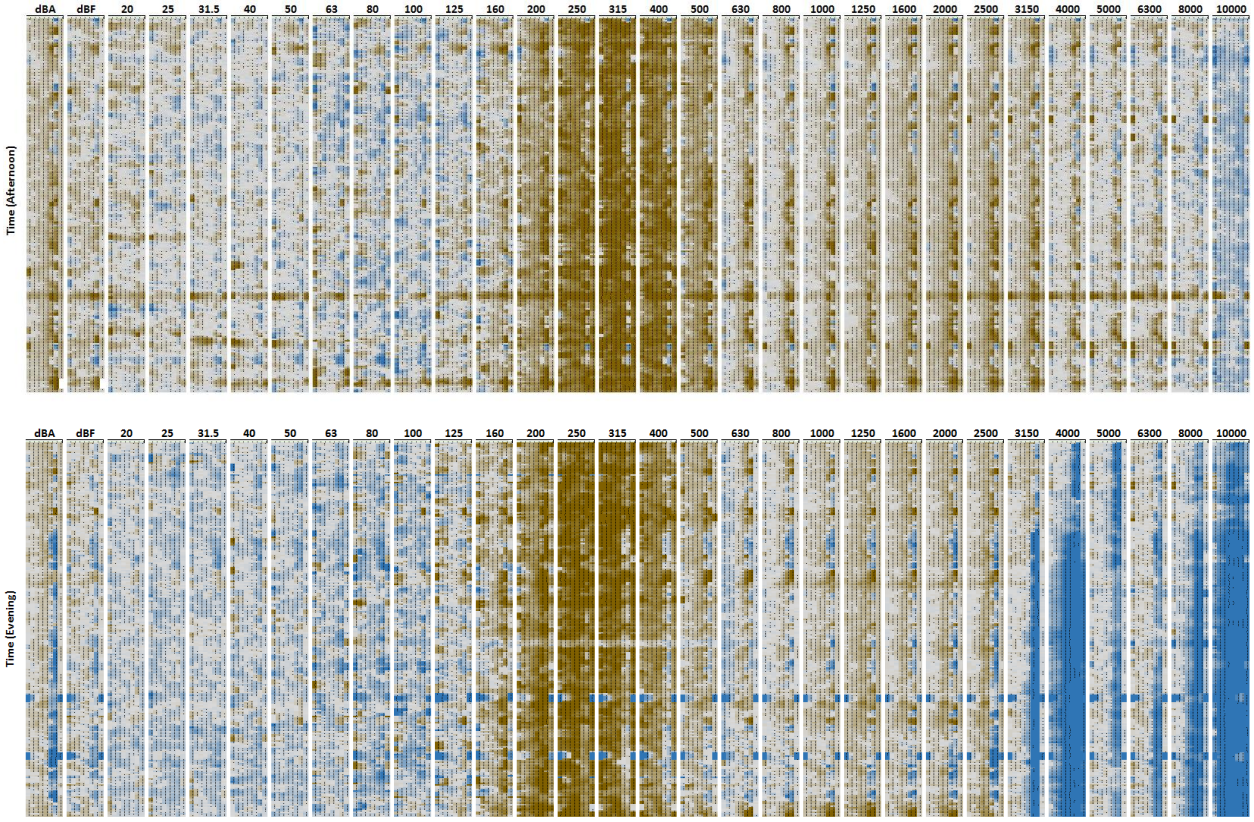


Figure 183. MD-5 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom03 and NoBarCom05.

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 Hz 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 pass-by 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. Two horizontal lines of blue shading appear 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.

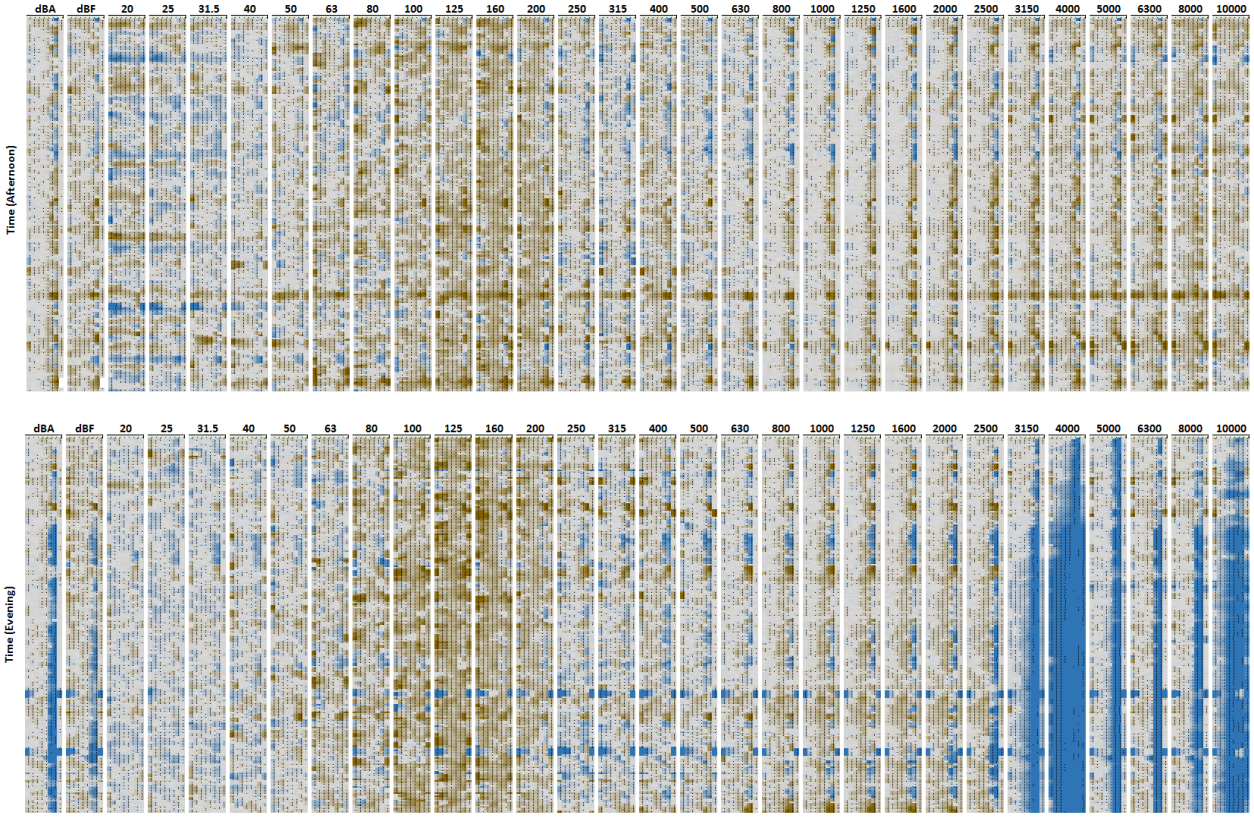


Figure 184. MD-5 Differences in L_n (5 min.) by one-third octave frequency bands: BarCom04 and NoBarCom06.

Data Analysis for MD-5 - Spectrograms

Refer to Table 14 for the MD-5 location six microphone positions.

Two equivalent microphones compare 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 following figures. 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 that contribute most to the overall sound level and causing these levels to be sustained for a longer period for each vehicle pass-by event.

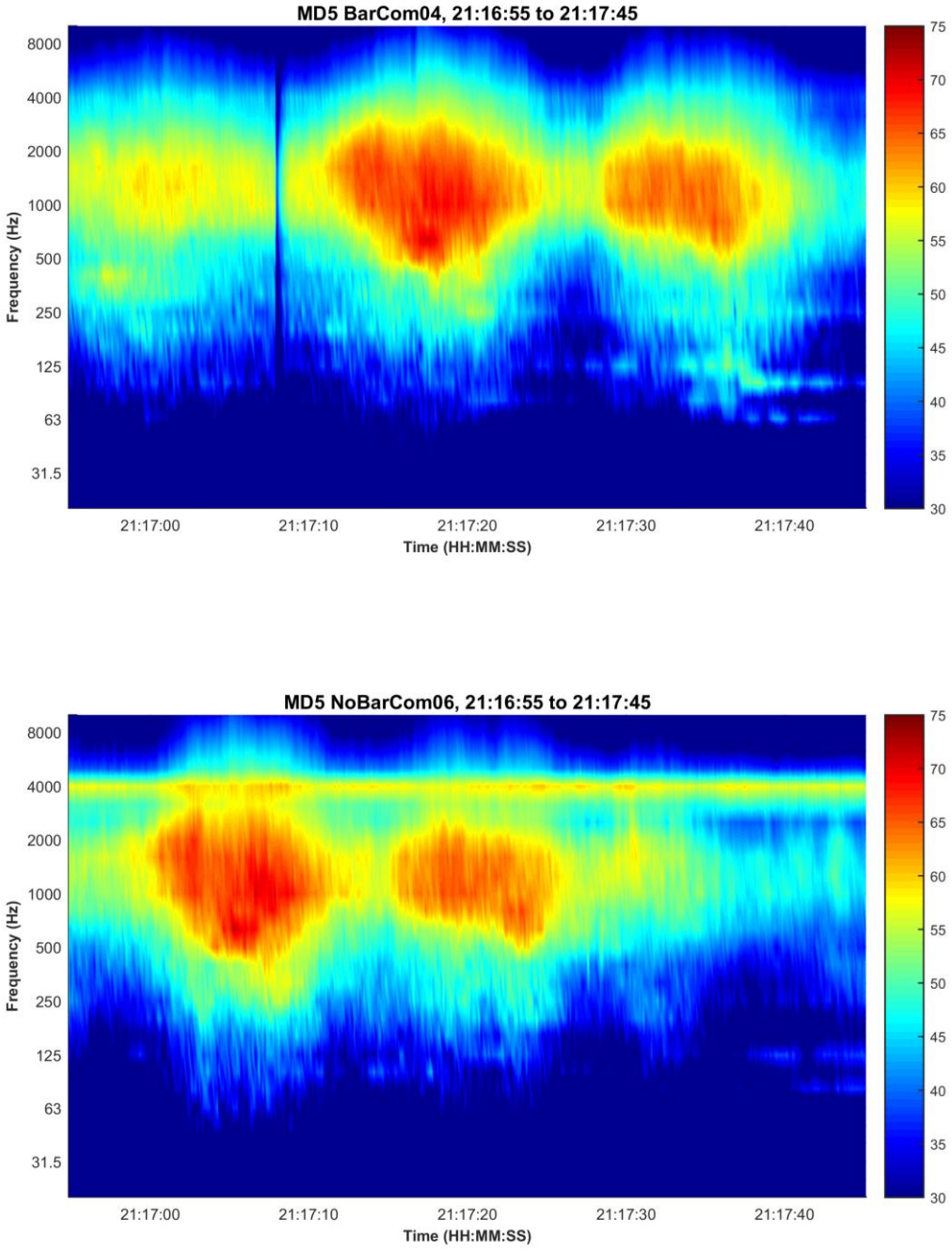


Figure 185. MD-5 spectrograms for heavy truck on northbound (community) side (approximate event times: Barrier site 21:17:20, No Barrier site 21:17:05.) Additional vehicle follows the heavy truck: top is BarCom04; bottom is NoBarCom06.

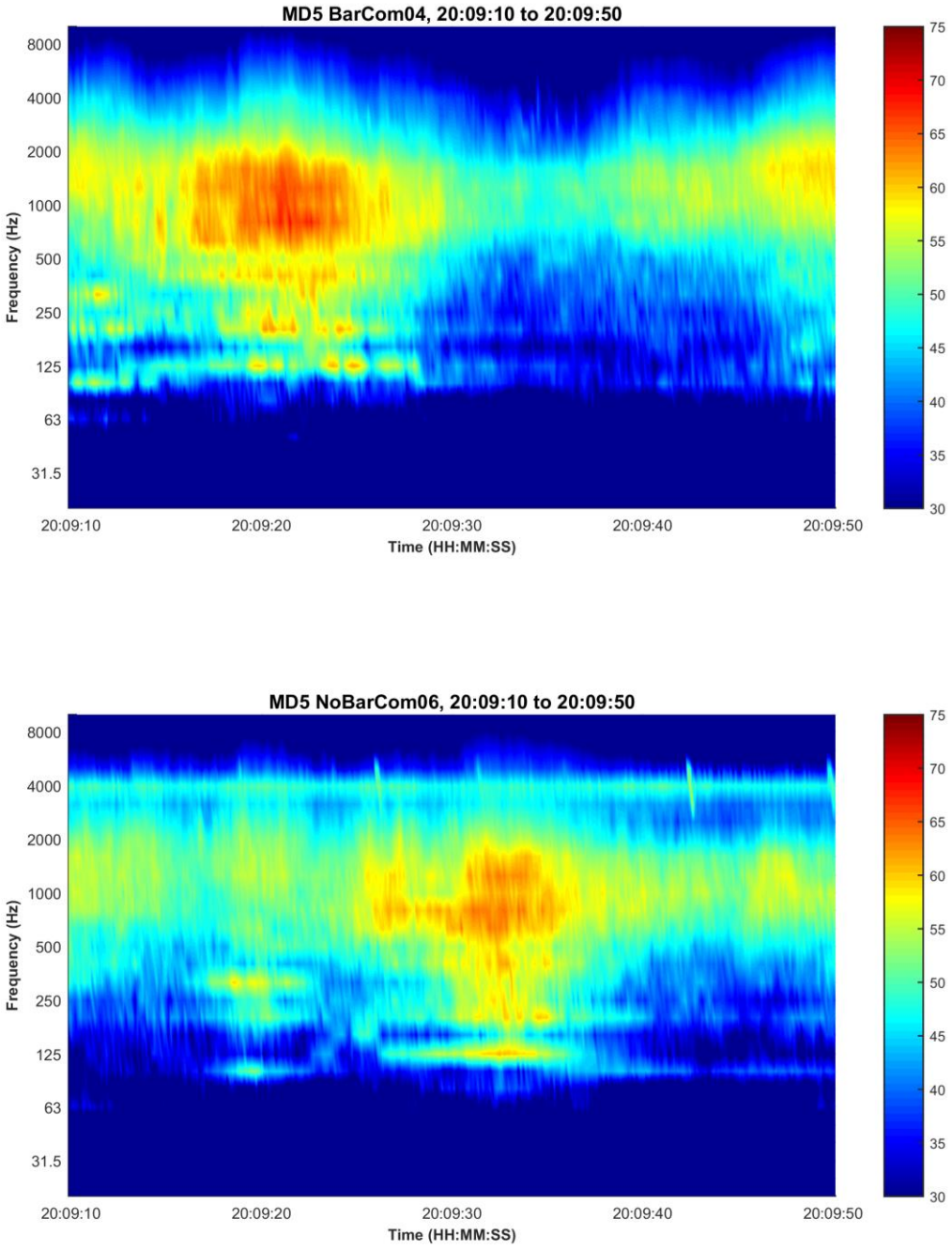


Figure 186. MD-5 spectrograms for a pickup truck on southbound (barrier) side (approximate event times: Barrier site 20:09:20, No Barrier site 20:09:35.) Additional vehicle follows the heavy truck: top is BarCom04; bottom is NoBarCom06.

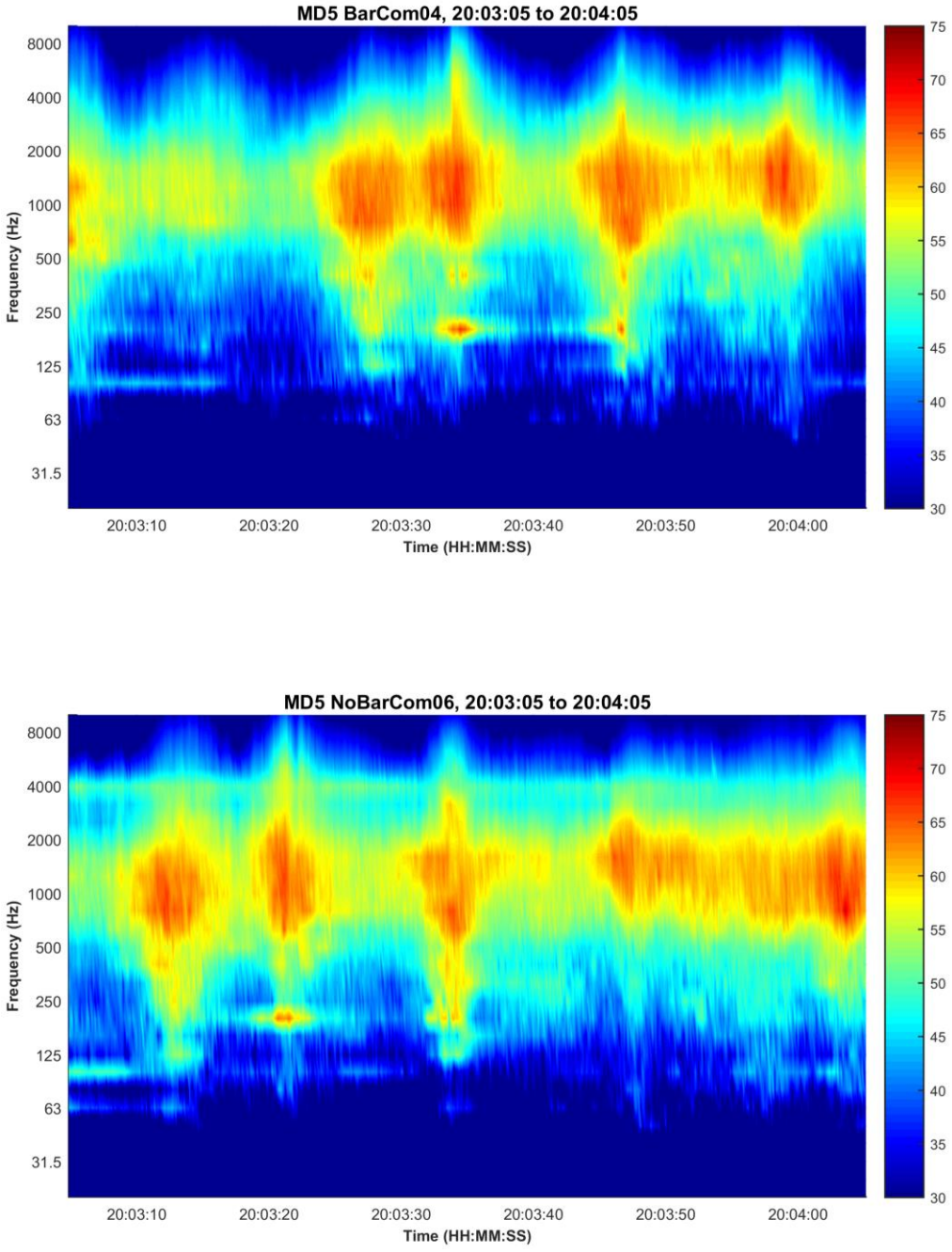


Figure 187. MD-5 spectrograms for Motorcycle on northbound (community) side. (Approximate event times: Barrier site 20:03:35, No Barrier site 20:03:22.) Additional vehicles come before and after the motorcycle: top is BarCom04; bottom is NoBarCom06.

In addition to examining vehicle pass-by events, spectrograms for blocks of data also were examined. An example is provided in Figure 188 for the high microphones at a distance of 75 ft. (BarCom04/NoBarCom06) for a 41-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 sparse. However, upon careful examination, 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 that contribute most to the overall sound level and cause these levels to be sustained for a longer period for each vehicle pass-by event.

The spectrogram data include a band of light blue at 4 kHz at the No Barrier site, which is due to frogs and insects.

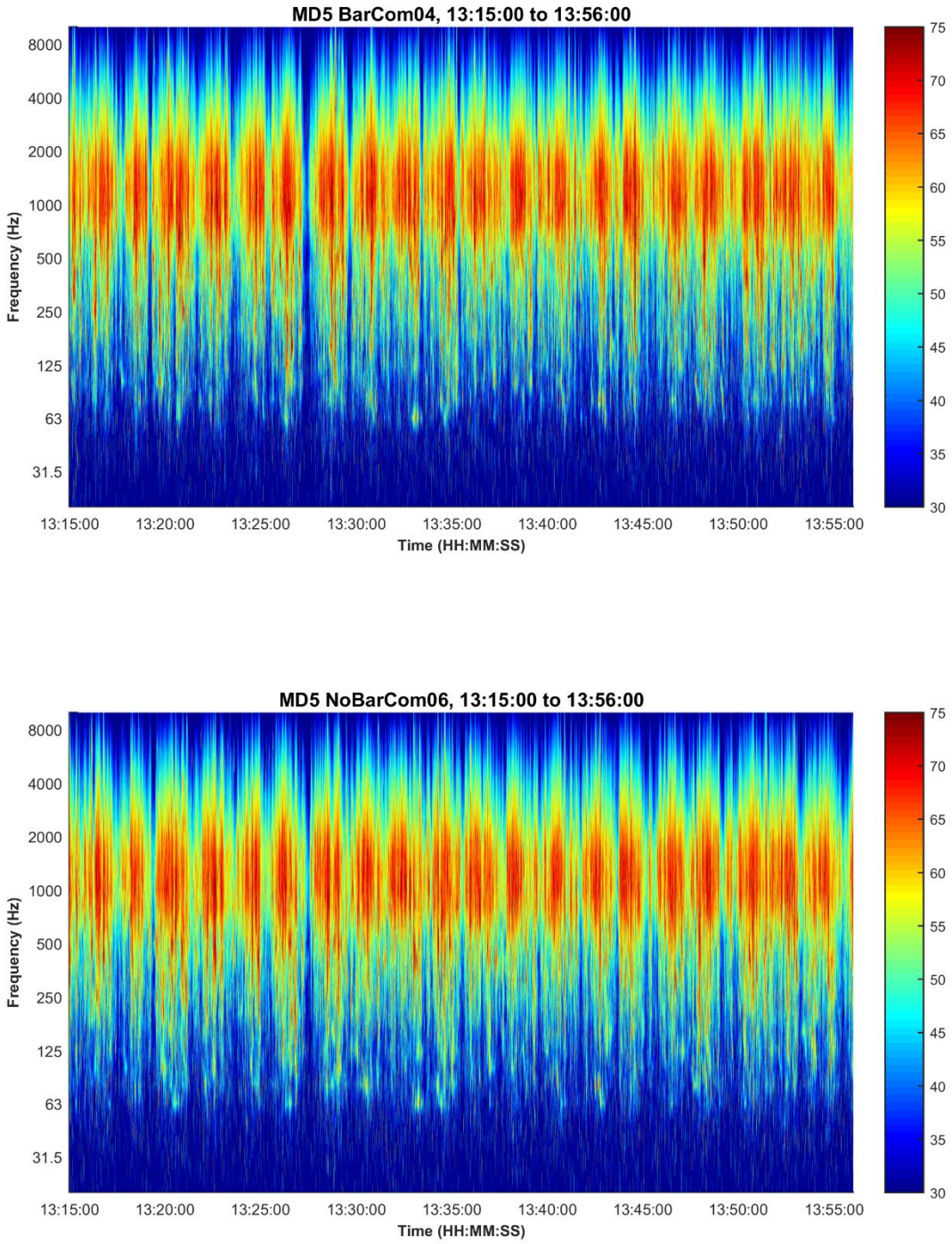


Figure 188. MD-5 spectrograms for 41 minutes of clean data (no contamination from other noise sources): top is BarCom04; bottom is NoBarCom06.

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 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 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 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 UBA and UBA between the Barrier and No Barrier locations, for both the higher and lower microphones, are much different from 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 "bimodal." 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, neither the UBA nor the PA substantiate an assumption of increased annoyance due to the presence of the barrier at this site.

No significant difference exists in the means of CSA for either pair of microphones. The simple linear regression that is the basis of 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	Microphone	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

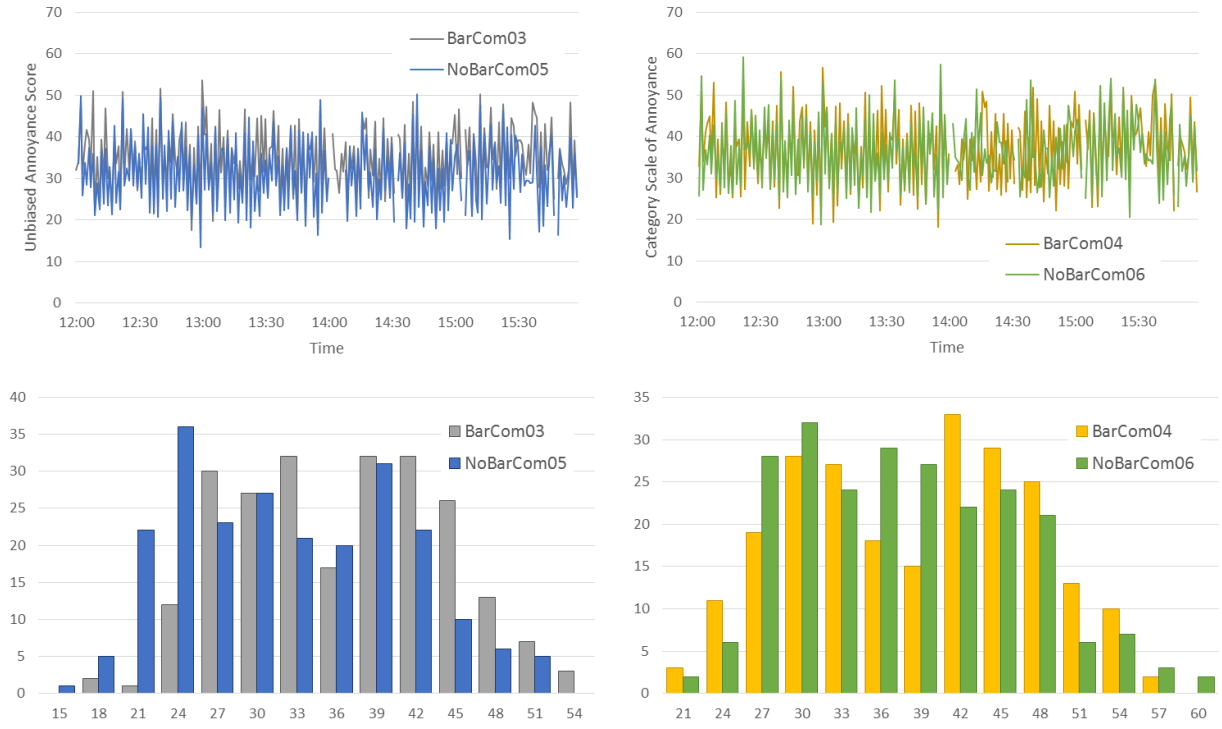


Figure 190. UBA vs. time and histograms, MD-5, afternoon.

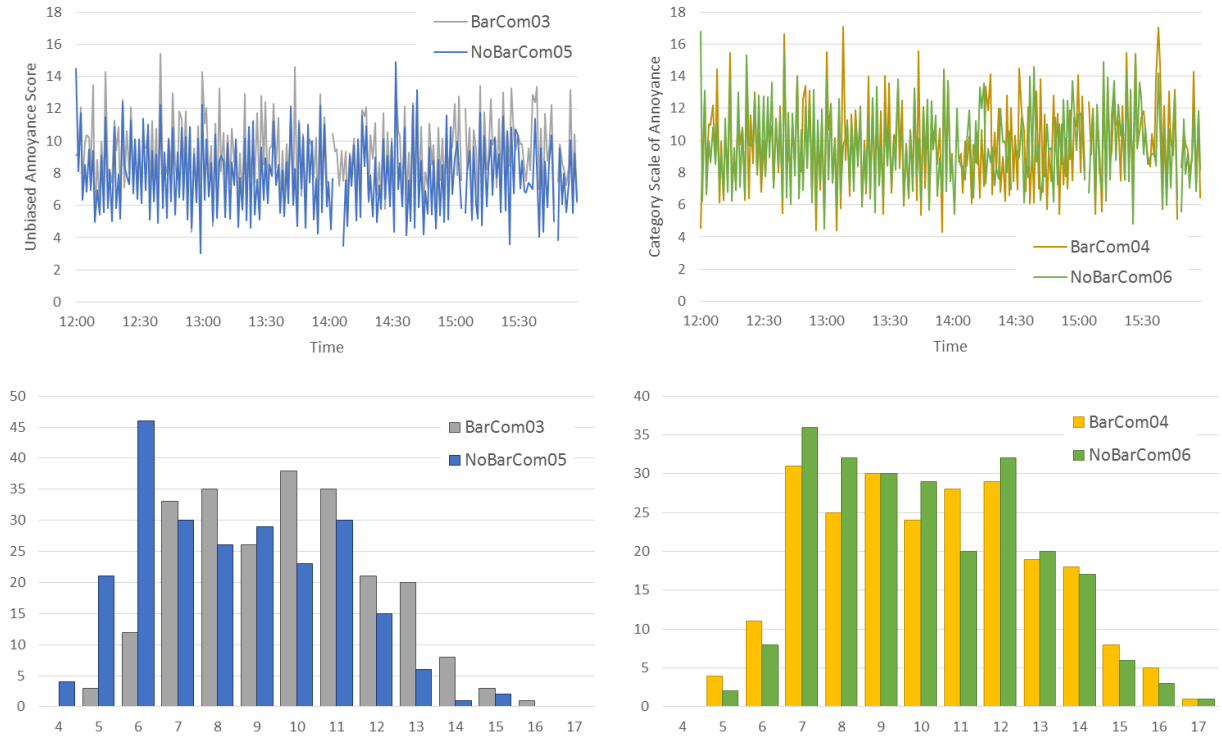


Figure 191. PA vs. time and histograms, MD-5, afternoon.

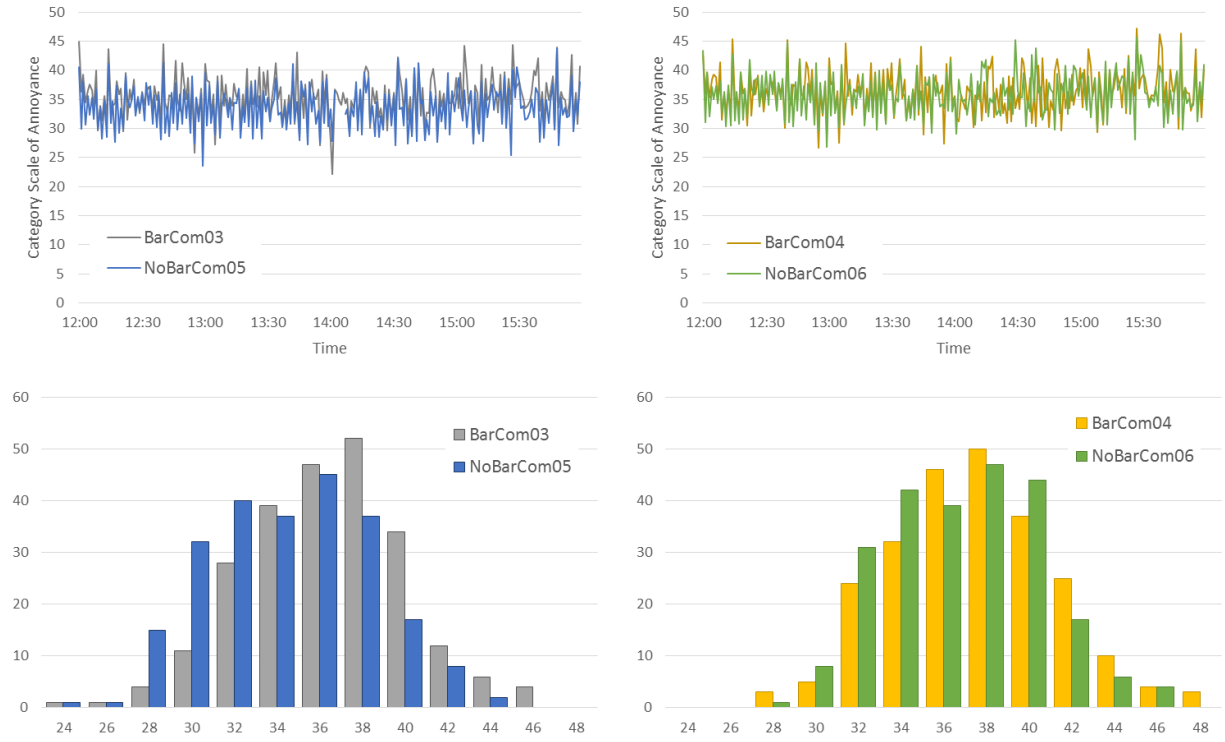


Figure 192. CSA vs. time and histograms, MD-5, afternoon.

Psychoacoustical Annoyance Metrics, Night

The audio recordings from nighttime monitoring at MD-5 were contaminated with very high frequency sound from frogs. Therefore, significant high-frequency filtering was applied to the recordings prior to analysis. The one-third 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 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 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 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 UBA and PA between the Barrier and No Barrier locations at the lower microphones do not show a significant difference. This trend is also seen at SR-71 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 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 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.

No significant difference exists in the means of the CSA 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.

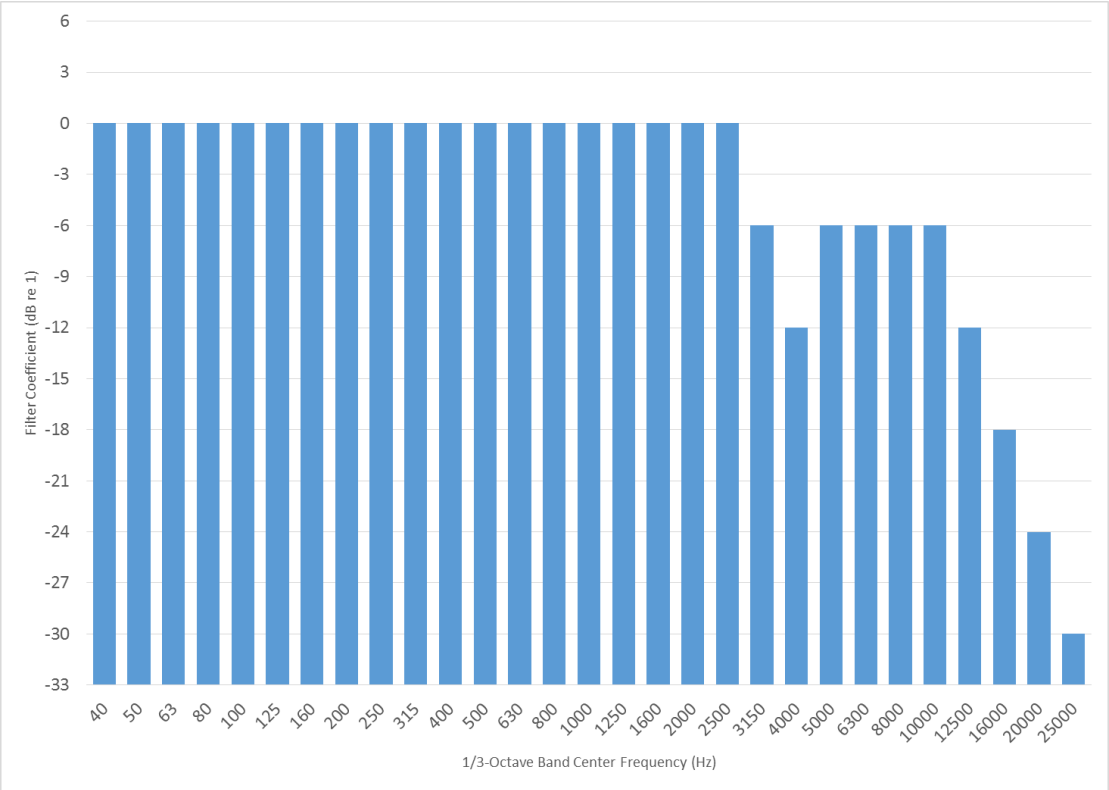


Figure 193. One-third-octave band graphic equalization applied to nighttime audio.

Table 17. Descriptive statistics of annoyance metrics, MD-5, night.

Metric	Microphone	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

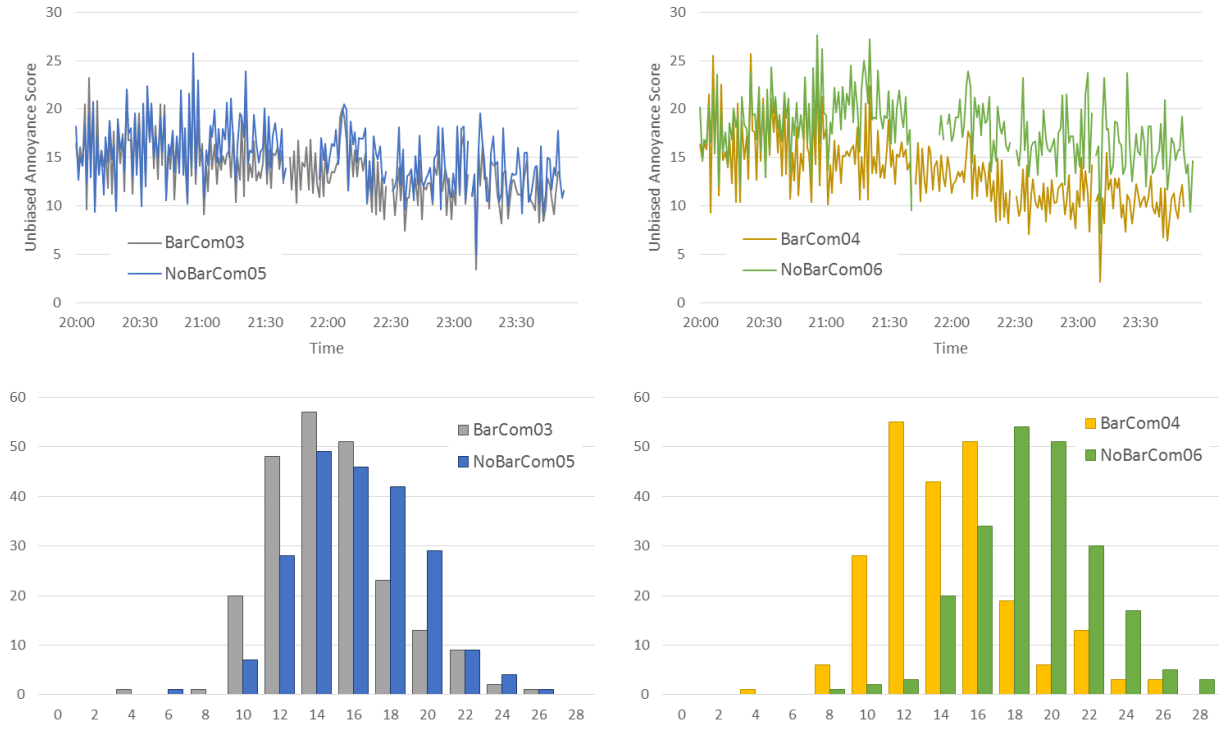


Figure 194. UBA vs. time and histograms, MD-5, night.

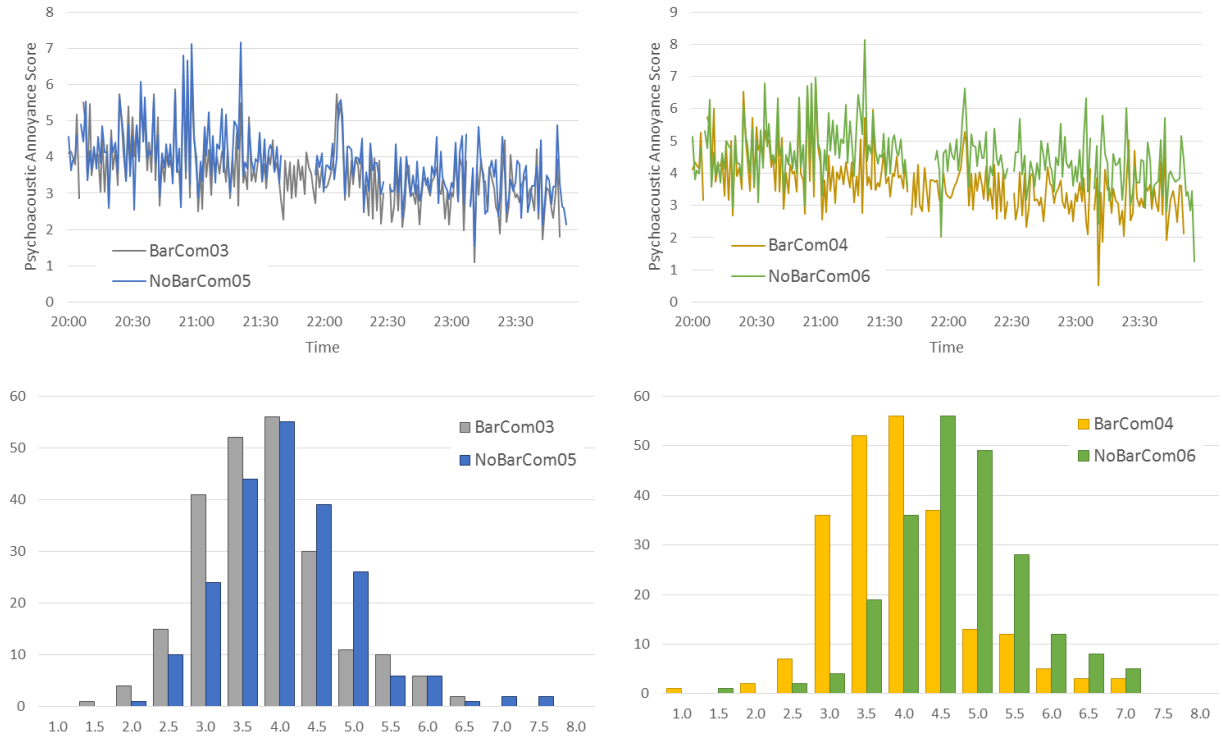


Figure 195. PA vs. time and histograms, MD-5, night.

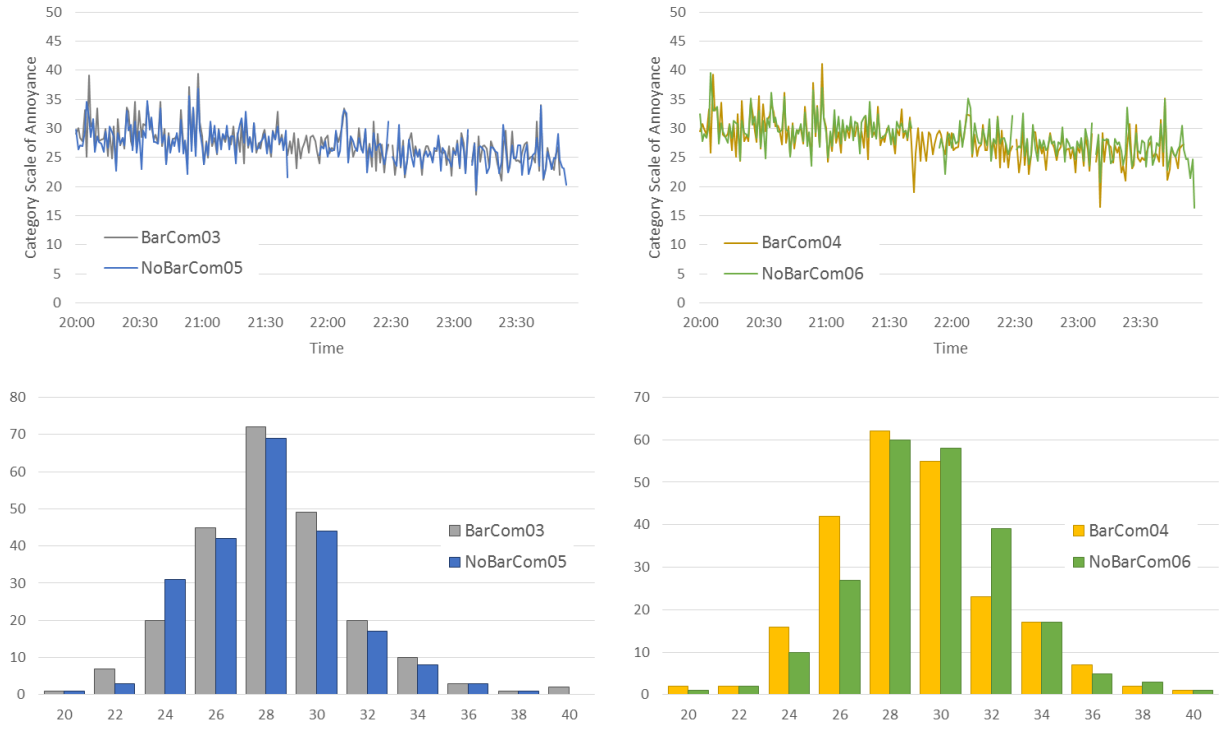


Figure 196. CSA vs. time and histograms, MD-5, night.

CHAPTER E-8

Summary

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 an 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 FS 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 data, 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 1-second data were collected at each location, processed 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 and the sound level differences were examined. Evening measurements at two of the locations were scheduled to study individual vehicle pass-by events.

Overall findings, applications, recommendations, and suggested future research are topics covered in the main report.

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