Effectiveness of Noise Barriers Installed Adjacent to Transverse Grooved Concrete Pavement

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16. Abstract

In recent years the Ohio Department of Transportation (ODOT) has reconstructed a number of roadways where asphalt pavements were replaced with random transverse grooved concrete pavements. Upon completion, residents living adjacent to the reconstructed roadways have complained of increased noise levels. The Federal Highway Administration (FHWA) Traffic Noise Model (TNM) is used to determine if predicted traffic noise levels warrant abatement and to design the abatement structures. The public perception problem described above suggests that the model does not result in adequate noise barrier abatement designs near random transverse grooved concrete pavements. The overall goal of this project was to provide ODOT with accurate TNM noise predictions when modeling random transverse grooved concrete pavement highways. Three random transverse grooved PCC roadway sites were chosen for study where high quality sound recordings were taken. Sites 1 (Cincinnati I-275) and 2 (Troy I-75) were chosen to represent the noise quality experienced by residents adjacent to the roadway, where the residential areas were separated from the roadway by sound barriers. Site 3 (Madison County I-70) was chosen to study the attenuation of road noise with distance in an easily-characterized environment; an open soybean cropland essentially level on both sides of the roadway with no noise barrier. Through a paired t-test the research findings determined that the sample means of the TNM average pavement and the ODOT random transverse grooved pavement were not equivalent based upon a level of confidence of 95 percent. An examination of the one-third octave band frequency levels indicated that at frequencies greater than 500 Hz, the measured traffic noise levels exceeded both the TNM average pavement type and TNM ODOT random transverse grooved pavement predictions. However, at frequencies less than 500 Hz the predictions tended to exceed the measurements. It is recommended that the experimental version of TNM developed for this project, using the current ODOT random transverse grooved concrete pavement REMEL, should not be used in practice due to its potential to under-predict traffic noise levels. A new surface texture specification should also be developed for concrete pavements to replace the current specification in order to reduce tire/pavement noise levels while maintaining or improving safety and durability characteristics.

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Final Report

Prepared in Cooperation with the
Ohio Department of Transportation,
U.S. Department of Transportation, and
Federal Highway Administration

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NOTATIONS

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

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

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

Exponential time-averaging: A method of stabilizing instrumentation response to signals with changing amplitudes over time using a low-pass filter with a known, electrical time constant. The time constant is defined as the time required for the output level to reach 67 percent of the input, assuming a step-function.

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

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

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

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

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

Octave (frequency) bands: Frequency ranges in which the upper limit of each band is twice the lower limit. An octave band is often subdivided into 1/3 octaves (3 bands per octave) for finer frequency resolution.

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

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

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

NOTE: Unless indicated otherwise, all sound pressure levels referenced in this report are the equivalent continuous, A-frequency weighted, sound pressure levels.

1. INTRODUCTION

In recent years the Ohio Department of Transportation (ODOT) has reconstructed a number of roadways where asphalt pavements were replaced with concrete pavements which were finished with a random transverse grooved surface texture (ODOT specification 451.09). Upon completion of these projects, residents living adjacent to the reconstructed roadways have complained of increased noise levels. Complaints have been received from residents near locations where random transverse grooved concrete pavement replaced asphalt pavement and where no traffic noise barriers were constructed as well as those locations where noise barriers were constructed. In these cases, one might expect that the addition of noise barriers would provide acceptable abatement of the higher traffic noise levels associated with the replacement pavement type. However, the complaints received at these locations suggest that the abatement was not adequate to compensate for the louder source levels. Therefore, this research project was initiated to address the noise barrier design issues associated with the abatement of traffic noise for the ODOT random transverse grooved concrete pavement.

1.1. Problem

The projects described above have one thing in common. They all use concrete pavements with the ODOT specification 451.09 for the random transverse grooved surface texture. Public perception appears to be consistent with the noise producing characteristics of these pavements. It is known with certainty that the interaction of vehicle tires on this pavement produces the highest traffic noise levels of any of the ODOT pavement types [Herman and Ambroziak 2000, p.81].

ODOT does not usually receive complaints from residents in cases where the roadways have been reconstructed with other new pavement types and traffic noise barriers. In these cases the traffic noise barriers are effective and performing as designed.

A traffic noise simulation model is an indispensable tool used in the process of mitigating traffic noise impacts. The Federal Highway Administration (FHWA) Traffic Noise Model (TNM) is used by ODOT during the environmental process to determine if predicted traffic noise levels warrant abatement, and if warranted, the model is used to design the abatement structures. The desired outcome from use of the model can only be attained if the model accurately simulates noise levels. If the model predicts noise levels that are lower than actual, either the abatement will not be designed because it appears not to be warranted or if it is designed, it will not reduce the traffic noise to an acceptable level. The public perception problem described above suggests that the model does not result in adequate barrier designs to abate the traffic noise from the ODOT random transverse grooved concrete pavement type.

TNM, as it is currently configured, simulates the traffic noise source as if the traffic were operating on an “average” pavement. [FHWA 2004]. Since the random transverse grooved concrete pavement is much different than “average” pavement and this difference is not accounted for in the model, the resulting noise level predictions are inherently flawed. Though TNM was designed to account for differences in the traffic noise source, FHWA has been reluctant to take the necessary steps to utilize the full capability of TNM to accurately characterize the traffic noise source for a variety of pavement types. Thus, ODOT traffic noise engineers and analysts are constrained by the use of a traffic noise source characterization that is inappropriate for modeling random transverse grooved concrete pavement. The problem occurs for the projects described above as a result of the increase in the level of the traffic noise source (quieter pavements replaced by louder pavements) while providing barriers designed for a lower

level traffic noise source. The problem tends to be exacerbated for more distant receivers who not only experience the increased level of the tire pavement noise, but receive less benefit from the barriers (barrier attenuation naturally diminishes with increasing receiver distance from the barrier).

1.2. Problem solution

A method is needed to account for the increased traffic noise levels associated with random transverse grooved concrete pavements for traffic noise analysis and abatement design using TNM. Two approaches were considered to solve the problem, as described below.

A. *TNM final level adjustment* – With this approach noise analysis using TNM would continue to be based on the "average pavement" type. The predicted noise levels would then be adjusted to compensate for the inherent error associated with projects involving the random transverse grooved concrete pavement type. As an example, a value of 3 dB might be added to the predicted levels to account for the use of the louder pavement. The specific value for the adjustment would be determined from the mean value of the differences between the actual noise levels (measured) and the predicted noise levels for a sample of receivers.

   This approach, however, is not considered a good choice for a number of reasons. First, it is not an appropriate adjustment, in principle, due to the structure of TNM specifically, and noise models in general. Second, it is an empirical approach that ignores the significant commitment of resources on the National level throughout the 1990s to develop in TNM a deterministic and acoustically correct model with features to accurately characterize different traffic noise sources. Third, it is a regressive approach that at best can only be a temporary solution. Even the FHWA model STAMINA 2.0, which preceded TNM, had the capability to account for special pavement types.

B. *Specific noise source reference level for random transverse grooved concrete pavement* – The correct approach to accounting for the different traffic noise levels associated with random transverse grooved concrete pavements is to configure the source component of TNM with the appropriate reference level information specific to this pavement rather than the "average" pavement.

   This "adjustment factor" is available in the form of the Reference Energy Mean Emission Level (REMEL) developed for the ODOT specification 451.09 random transverse grooved concrete pavement, using methods and equipment approved by the acoustics group of the Volpe National Transportation Systems Center. The proposal for the Effects of Pavement Type on Traffic Noise Levels study anticipated a time when pavement specific REMELs would be seen as the next logical step in model refinement as transportation officials gained increased understanding of the effects of tire/pavement noise. Therefore, the required field data collection, data reduction, etc. were completed for all of the ODOT pavement types as an economical addition to the primary task of ranking the pavements according to their noise producing characteristics using the ISO Statistical Pass-by Method [Herman and Ambroziak 2000].

1.3. Research Need

The significance of the problem to ODOT and other states demanded that this solution be justified quantitatively before implementation. Therefore, an evaluation was needed to close the assessment loop by evaluating the accuracy of the TNM model when using the random transverse grooved concrete pavement REMELs for modeling sites with random transverse

grooved concrete pavement. A comparison of TNM predictions with actual traffic noise levels, determined from field measurements, was required as the basis for this assessment.

1.4. Literature Review

A literature review was conducted to identify the nature and extent of traffic noise problems associated with textured concrete pavements compared to pavements that tend to result in average tire/pavement noise levels. The review also sought to identify any published trends in the use of textured concrete pavements, as well as any published surface textured designs that offer promise as alternatives to the current ODOT concrete surface textures. A short background on the many mechanisms that make up highway noise has been included, as well as some characteristics pertaining to concrete in general.

1.4.1. Vehicle Noise Sources

Efforts to reduce vehicle noise have been concentrated on tire/road noise and drive train noise. Vehicle manufactures have made significant progress in reducing power and drive train noise. If a vehicle is in a good operating condition and has a reasonably good exhaust system, then the effect that power and drive train noise has on the overall noise level will be negligible at moderate to high speeds. There is a "cross-over speed" where tire/road noise begins to dominate the overall noise level of a vehicle. This speed lies in the range of 18.6-31 mi/h (30-50 km/h) for automobiles and 24.9-43.5 mi/h (40-70 km/h) for trucks [Sandberg 1992].

1.4.2. Road Surface Influence on Tire/Road Noise

There are several parameters that affect the amount that the road surface contributes to the generation of tire/road noise. These parameters include the texture, age, thickness, and binder material of the pavement.

The overall texture of the pavement has a significant impact on tire/road noise levels. The texture of a pavement surface can be divided into two subcategories, microtexture and macrotexture. Microtexture can be defined as the small scale roughness or harshness of a road surface, the individual aggregate, and extends down to molecular sizes [Sandberg 1979]. The function of the microtexture is to provide high dry friction on the pavement surface. Macrotexture is the roughness or texture that encompasses the tire tread elements and road aggregate up to the size of the tire/road interface area. The function of the macrotexture is to provide a dry pavement surface creating channels where water can escape to create high friction even on wet roads and at high speeds [Sandberg 1987].

Studies have been performed by the Washington State Department of Transportation to evaluate how tire/road noise changes with pavement age. These studies have shown that asphalt pavements start out quieter than Portland cement concrete pavements, but the asphalt pavements exhibit an increase in noise levels over time [Chalupnik and Anderson 1992]. The reason that the noise levels for asphalt pavements increase over time can be attributed to the pores in the pavement becoming clogged causing the pavement to lose some of its absorptive properties. Another reason for the increase in noise levels is due to an increase in stiffness from traffic loading. Finally, as the asphalt surface wears over time, the coarse aggregate becomes exposed which causes an increase in noise.

The same study by the Washington Department of Transportation has shown that noise levels from Portland cement concrete pavement decrease with age for approximately the first eight years of service for the pavements tested. Traffic volume increases change this eight-year

time period. After eight years have passed, the noise levels generated by the Portland cement concrete pavement have increased. Treatments, such as grooving and tining, are applied to the Portland cement concrete surfaces during the finishing process to enhance surface traction. Over time, the irregularities in this treatment are worn down and smoothed causing a reduction in noise levels. Around the eighth year, the aggregate begins to emerge causing an increase in surface texture and in turn an increase in noise levels.

The effect of pavement thickness has been evaluated for open graded asphalt surfaces and shown to have an influence on tire/road noise. In general, as the thickness of a pavement is increased, the frequency at which the maximum sound level occurs is lowered [Sandberg 1992]. In another study, the use of a double layer open graded asphalt surface instead of a single layer (3.2 in (80 mm) instead of 2 in (50 mm)) reduced traffic noise by 1 dB [Storeheier and Arnevik 1990]. This reduction was accomplished by increasing the voids content in the top layer, while maintaining the same maximum aggregate size in both layers.

Super-thick open graded asphalt pavements with thicknesses up to 27.6 in (700 mm) have been tested in comparison to conventional dense graded asphalt pavements. The results indicated that a total noise reduction of approximately 8 dB was achieved with the thick pavements versus a 4 dB reduction for thin layers [Pipien and Bar 1991].

A number of strategies have been developed to reduce tire/road noise by altering the typical design of a pavement based on an understanding of the mechanisms discussed above. Noise reduction methods have been developed for both asphalt and Portland cement concrete pavements. However, only Portland cement concrete was considered for this study.

In the literature, Portland cement concrete pavements are generally shown to have higher noise levels than asphalt pavements. Efforts to reduce tire/pavement noise levels for Portland cement concrete have focused mainly on strategies involving surface texture. These strategies have included, exposed aggregate, thin overlays or surface dressings, and variations in transverse grooving and longitudinal grooving.

For years, it has been known that the type, method, and direction of texturing Portland cement concrete surfaces must be considered for any strategy to reduce tire/road noise [Sommer 1992-II]. Most of the PCC pavements used on ODOT roadways have been finished with a surface texture composed of transverse grooves. The original groove design specified a constant spacing between adjacent grooves, similar to the design used by most other states. However, the constant spacing tended to promote a tonal quality, or whine, to the noise produced by tires rolling on the pavement. To combat the “whine” problem associated with constant spaced transverse grooved PCC pavements, ODOT, as well as other state DOTs, changed the groove specifications for tined PCC pavements to a random spaced transverse groove pattern. This design change was made to spread the peak sound level over a wider range of frequencies.

Sound level data was collected in Ohio in 1998 using ISO 11891-1, The Statistical Pass-By Method, for the major ODOT pavement types. The sound level data was used to develop the Statistical Pass-By Index (SPBI) values for each pavement type. The SPBI data indicated that random-transverse grooved PCC pavement produced the highest sound levels of the pavement types measured. These levels averaged 3.9 dB higher than the levels for the average pavement, which was one-year old dense graded asphalt, and 6.7 dB higher than the quietest pavement, which was one-year old open-graded asphalt [Herman, Ambroziak, and Pinckney 2000].

Sound level data was also collected in a sub-study, using a single test vehicle to compare tire/road noise levels for six different PCC sites. The six sites included three different groove types: longitudinal (1 site), transverse (2 sites), and random-transverse (3 sites). The site with

the longitudinal grooves produced the lowest sound levels (3.0 dB below the mean of all six sites, for a vehicle speed of 65.2 mi/hr (105 km/hr)), followed by the transverse grooved sites, then the random-transverse grooved sites (as much as 3.2 dB above the mean of all six sites, for a vehicle speed of 65.2 mi/hr (105 km/hr)). However, there was significant variation (almost 2 dB) between the random-transverse grooved sites. The sample size for this sub-study was very small, only one test vehicle was used, only two vehicle speeds were measured, and there was only one site with longitudinal grooves [Herman and Ambroziak 2000].

Subsequent to the "Effects of Pavement Type on Traffic Noise Levels" study described above, ODOT received an increasing number of complaints from residents living near highways that had been reconstructed by replacing asphalt pavements with concrete pavements that were finished with the random transverse grooved pattern. One of these highways was a section of I-76 east of Akron (SUM-76-15.40). ODOT engineers considered these complaints of increased traffic noise and, based on previous research, developed a mitigation strategy for the I-76 project which consisted of changing the random transverse grooved surface texture to a longitudinal grooved surface texture by diamond grinding.

The measurement of traffic noise levels for random transverse grooved concrete pavements compared to longitudinally grooved concrete pavements in the "Effects of Pavement Type on Traffic Noise Levels" study supported the ODOT decision to retexture the random transverse grooved surface to produce longitudinal grooves by the process of diamond grinding. The results of other studies also supported the decision to retexture the surface to longitudinal grooves. A noise level reduction in the range of 0.5 - 3.0 dB was achieved after grinding an old Portland cement concrete surface. [Sandberg 1992]. Also, an Arizona Department of Transportation study, which compared rubberized asphalt to concrete pavements, found improvements of 3.3 - 5.7 dBA over transverse grooved concrete and 0.2 – 1.5 dBA over longitudinally grooved concrete [Henderson and Kalevela 1996]. It could be inferred then, that this study observed a 1.8 – 4.2 dBA difference in noise level between transverse and longitudinally grooved concrete.

The strategy to reduce the tire/pavement noise component of the I-76 traffic noise produced an average noise reduction of 3.5 dB at 7.5 m and 3.1 dB at 15 m from the centerline of the nearest travel lane [Herman et al 2006].

1.4.3. Alternative measures

One method to reduce tire/road noise levels on Portland cement concrete surfaces is to use an exposed aggregate finish. This type of finish can be used on new, reconstructed, or recycled Portland cement concrete pavements. The grain size of the exposed aggregate should preferably be .16 - .28 in (4 - 7 mm) in order to give optimum macrotexture [Descornet and Sandberg 1980]. There are two methods that can be used to expose the aggregate. The first method, which is older and less preferred today, involves simultaneously watering and brushing the fresh concrete surface by means of a rotary brush. The second method involves spraying an appropriate setting retarder on the fresh concrete. After the concrete hardens (24 - 30 hours after laying), the surface is mechanically brushed in order to remove the mortar that has not yet set [Sandberg 1992].

From an economical standpoint, the additional costs for the exposed aggregate procedure cause an increase of approximately 10 % of the total pavement cost [Sommer 1992].

Thin overlays, or surface dressings, can be used to reduce noise on smooth Portland cement concrete surfaces. To obtain the greatest potential reduction in noise, the aggregate size

should be kept as small as possible with respect to wear and drainage. These surfaces have the ability to produce reductions in noise levels equivalent to those of open graded asphalt. However, when the thin overlays are worn, they gradually reach the level similar to a dense graded asphalt pavement [Sandberg 1992].

The Minnesota Department of Transportation (MNDOT) has chosen another alternative, which is a modification of the random transverse grooved pattern. In addition to the random transverse grooves an astro-turf drag is used to impart an additional texture to the concrete surface areas that come in contact with vehicle tires. MNDOT has used this specification since 1999 [Scofield and Smith 2006].

2. RESEARCH OBJECTIVES

The overall goal of supporting the FHWA in its effort to provide ODOT and other states with accurate noise predictions from TNM when modeling highways constructed with random transverse grooved concrete pavement types has led to the specific objectives for the proposed study as follows:

1. Document the experience, regarding traffic noise, of other transportation agencies with textured concrete pavements from a review of published literature on the subject.

2. Review the ODOT traffic noise analysis procedures.

3. Measure actual traffic noise levels at noise barrier sites adjacent to roadways constructed with random transverse grooved concrete pavements (ODOT specification 451.09).

4. Predict traffic noise levels at measurement sites with both average pavement and random transverse grooved pavement source reference levels using TNM.

5. Assess the validity of using TNM with the Reference Energy Mean Emission Levels for the random transverse grooved concrete pavement type.

During the contract period in which work was underway to achieve the objectives listed above, ODOT elected to re-texture the surface of a portion of I-275 in the Cincinnati area (Site 1 for this project) through diamond grinding. The project was initiated in an effort to mitigate tire pavement noise and thus address the complaints of the residents living adjacent to the highway. In order to quantify the effectiveness of the diamond grinding the project scope for this research project was expanded to include three additional objectives:

6. Collect traffic noise level and frequency data, along with traffic and atmospheric data at the locations previously identified to characterize the traffic noise sound field between the roadway and the adjacent noise sensitive areas.

7. Compare the measurement results from objective 6 with the noise measurements made prior to the re-texturing of the pavement surface (objective 3).

8. Identify traffic noise level differences due to the re-texturing of the pavement surface.

3. GENERAL DESCRIPTION OF THE RESEARCH

3.1. ODOT Analysis and Abatement Measures

As part of this study traffic noise analysis and abatement measures used by ODOT for the selected research sites, were examined. The examination was based upon federal regulations, FHWA guidance, and ODOT policies and procedures.

3.1.1. Federal basis for ODOT procedures

As a consequence of the National Environmental Policy Act (NEPA) of 1969, federal regulations were promulgated (23 CFR Part 772) to ensure that the NEPA requirements would be met for major federally funded projects in the environmental area of traffic noise.

The regulations found in 23 CFR Part 772 provide the basis for FHWA policies and guidance [FHWA 1995]. Since transportation projects in individual states involve the use of federal dollars, all policies and procedures developed by the state agencies must be consistent with the federal regulations, policies, and guidance [ODOT 2001].

3.1.2. ODOT procedures

During the project planning process ODOT considers the need for noise mitigation when the predicted noise levels for the design year approach or exceeds the FHWA Noise Abatement Criteria (NAC) or if the predicted noise levels for the design year substantially exceed the existing noise levels. Federal regulations specify that predicted noise levels must be obtained using a method that is both consistent with the FHWA Traffic Noise Model (TNM) and makes use of the National Reference Energy Mean Emission Levels (REMELs). ODOT meets this requirement by using the latest version of TNM (which uses the National REMELs) for noise analyses.

Noise analyses are most often conducted by ODOT for projects involving highway construction designated as Type I projects (Type II projects involve noise analyses for existing highways were no construction is planned). Highways in new locations, modifications to the horizontal and/or vertical alignment, or lane additions to existing highways, are examples of Type I projects. The highway sites with noise barriers that were studied in this project were Type I projects.

The ODOT procedures [ODOT 2008] specify the steps to be taken for a noise analysis, beginning with a noise screening stage, which is to occur early in the project development, to identify potentially impacted areas that require a detailed study. The procedural steps end with a final report that documents the study process and the results. If abatement is warranted the report must include a discussion of abatement alternatives along an analysis of the reasonability and feasibility of the abatement alternatives.

Noise analyses are typically conducted for noise sensitive land uses that are within 600 ft of the edge of the highway pavement. Further, the consideration is limited to exterior areas of frequent human use according to the categories of use specified in the document FHWA Highway Traffic Noise Guidance. By exception, interior noise levels can be considered for non-profit institutions, such as places of worship, schools, libraries, and hospitals. Existing noise level measurements are also made for comparison with predicted levels. The results of a noise study can lead to the decision to provide noise abatement if it is warranted and feasible.

3.1.3. ODOT procedures in review

Based on the examination of the ODOT procedures in general and those followed specifically for the study sites in this project, where abatement has been provided, it was found that the procedures are detailed, comprehensive, and entirely consistent with federal regulations and guidance. Further, the procedures were properly carried out for the noise abatement projects at the highway sites studied in this research. The many successful noise abatement projects that ODOT has completed through the years, beginning with its first projects in the 1970s, provide additional evidence of the suitability of these procedures.

In summary, the cause of the complaints from residents described in the introduction to this report most likely lies with shortcomings in the configuration of the TNM used in the abatement design process rather than the ODOT analysis procedures that are used to study and mitigate traffic noise impacts.

3.2. Site Selection

Through coordination with ODOT, several potential sites were identified within the project limits. The sites were then qualified with reference to criteria established in the U.S. for the measurement of traffic noise reference levels [Lee and Fleming 1996] and for the international standard for the statistical pass-by method of tire/road noise measurement [International Organization for Standardization 1994]. These criteria were developed to enable valid comparisons of noise measurements between different highway sites. They are necessarily more stringent than the requirements for BEFORE and AFTER measurements at the same site. Therefore, every effort was made to find sites that met as many of these criteria as possible, recognizing that the terrain variations and the relatively short project length would preclude meeting all criteria. Further, any criteria that related to the measurement of individual vehicle pass-bys or test lanes were not considered.

1. The roadway test sections extended at least 164 ft (50m) on each side of the microphone locations. This space was free of large reflecting surfaces, such as parked vehicles, signboards, buildings, or hillsides.

2. The roadways were relatively level and straight. It was permissible to have roads with slight bends or with grades less than or equal to 1%.

3. The sites exhibited constant-speed vehicle operating conditions with cruise conditions of at least 54.7 mi/h (88 km/h). Therefore, the site was located away from interchanges, merges, or any other feature that would cause traffic to accelerate or decelerate.

4. The sites had a prevailing ambient noise level that was low enough to enable the measurement of uncontaminated vehicle pass-by sound levels.

5. The road surfaces were in good condition and were homogeneous over the entire measurement sections. The surfaces were free from cracks, bitumen bleeding (asphalt pavements), and excessive stone loss.

6. The traffic volumes for each vehicle category were large enough to permit an adequate numbered sample to be taken to perform the statistical analysis but also low enough to

permit the measurement of individual vehicle pass-bys.

7. The sites were located away from known noise sources such as airports, construction sites, rail yards, and other heavily traveled roadways.

8. The ground surface within the measurement area was essentially level with the road surface, varying by no more than 2 ft (0.6 m) parallel to the plane of the pavement along a line from the microphones to the pavement. The ground was also no more than 2 ft (0.6 m) above or below the roadway elevation at the microphones. Any roadside ditch or other significant depressions were at least 16.4 ft (5 m) from the center of the test lane.

9. At least half of the area between the center of the test lane and the first microphone had acoustical properties similar to the pavement being measured. The ground surface was free from any vegetation that was higher than 2 ft (0.6 m) or could be cut down at any sites that did not meet this requirement.

10. To ensure free field conditions, at least 82 ft (25 m) of space around the microphones was free of any reflecting objects. Also, the line-of-site from the microphones to the roadway was unobscured within an arc of 150 degrees.

3.3. Study Locations

Three random transverse grooved PCC roadway sites were chosen for study from a set of candidates prepared by ODOT technical liaisons. High quality sound recordings were made at carefully documented, recoverable locations within these sites and later analyzed as specified elsewhere in this report. Sites 1 and 2 were chosen to represent the noise quality experienced by residents adjacent to the roadway. Site 3 was chosen to study the attenuation of road noise with distance in an easily-characterized environment.

Site 1 (Cincinnati I-275) and Site 2 (Troy I-75), were residential areas separated from the roadway by sound barriers. Site 3 (Madison County I-70) was open soybean cropland essentially level on both sides of the roadway with no noise barrier.

Fourteen sound recordings were made at Site 1, organized as Area A (five recordings), Area B (seven recordings) and Area C (two recordings), as shown in Figures 1, 2 and 3, respectively. Areas A and B were adjacent to depressed roadways and Area C was adjacent to elevated roadway. Areas A and B included reference microphones situated above the barrier.

③ Microphone Location and Number

Figure 1. Site 1, Cincinnati, Area A

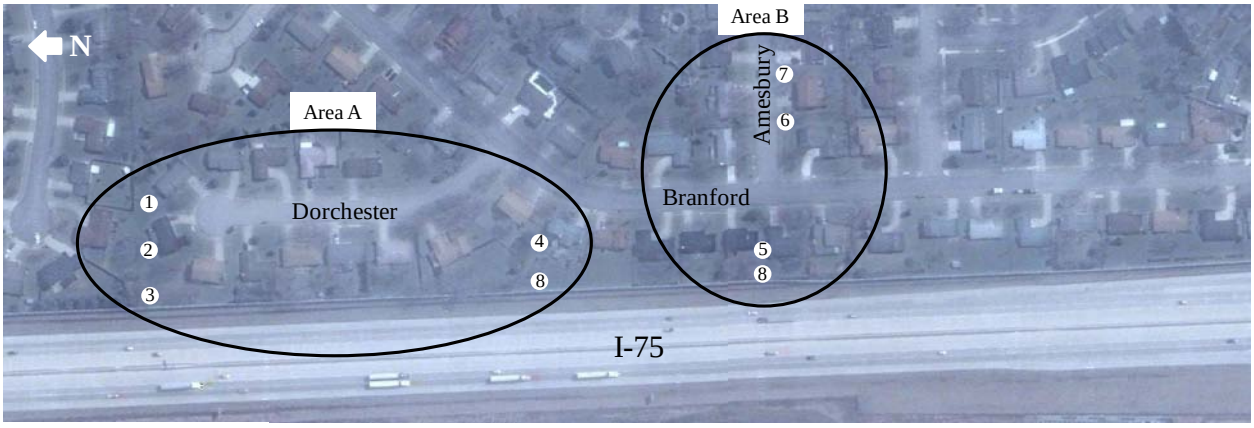
③ Microphone Location and Number

Figure 2. Site 1, Cincinnati, Area B

③ Microphone Location and Number

Figure 3. Site 1, Cincinnati, Area C

Site 2 included five Areas, all of which were practically at-grade with the roadway. A total of sixteen recordings were made at Site 2. Three of the Areas (Area A, five microphones; Area B, four microphones; Area C, four microphones) were behind noise barriers and each included one reference microphone above the barrier. Area D (one microphone) was behind a barrier. Area E (two microphones) was an open area with no noise barrier. Figure 4 depicts the microphone locations in Areas A and B, Figure 5 depicts the microphone locations in Areas C and D while Figure 6 depicts the microphone locations in Area E.



③ Microphone Location and Number

Figure 4. Site 2, Troy, Areas A and B

③ Microphone Location and Number

Figure 5. Site 2, Troy, Areas C and D

③ Microphone Location and Number

Figure 6. Site 2, Troy, Area E

Eight recordings were made at Site 3, which was located between the intersections of SR 29 with I-70 and SR142 with I-70 in Madison County. The recorders were situated on a line perpendicular to the roadway (one side only) at distances that increased by doubling out to 480 meters (1575 feet). One microphone failed, leaving seven good recordings. The approximate locations of the microphones are shown in Figure 7.

The first reconnaissance visits to the sites were made by the researchers with the ODOT liaisons. After letters of introduction and intention were sent by ODOT to homeowners at the proposed test sites, the researchers visited again to secure specific permission from homeowners to set recorders on their property and to develop detailed plans for microphone placement. Locations were established in the horizontal plane using distances to noise barriers and house structures. The elevation of microphones behind noise barriers were given in relation to the top of the barrier. Where there were no barriers, microphone elevations were given in relation to the center of the nearest travelled lane of the roadway.

③ Microphone Location and Number

Figure 7. Site 3, Madison County, Area A

4. INSTRUMENTATION AND SETUP

There were eight recording sets, each consisting of a Larson Davis model 812 sound level meter (SLM) with a ½-inch diameter random incidence condenser microphone (model 2560) and preamplifier (model PRM828) and a Sony TCD-D8 digital audio tape (DAT) recorder, mounted together on an aluminum plate attached to a sturdy tripod. Sound level meters, DATs and mounting plates were marked so that each recording set (number 1 through 8) always contained the same, like-numbered components. All sound data were recorded at a sample rate of 48 KHz and 16 bit resolution. Only one channel of the DAT was used. The DAT has a real-time clock that is recorded continuously with the audio, making it possible to access a recording to the nearest second during playback. The unweighted ac analog output of the SLM was fed to the microphone input of the DAT recorder. The height of the microphone above the ground was 1.5 meter (5 feet). The microphone faced 70 degrees above the horizontal and wore a "foam" wind noise reducing filter.

Traffic noise recordings were analyzed using a Larson Davis 2900B Real Time Analyzer (RTA). During System Normalization (see below) the RTA was used with its microphones (model 2559) and microphone preamplifiers (model 900B) to analyze a sample of traffic noise in real time.

One acoustic calibrator, a B&K type 4231, was used for all calibrations. A backup calibrator, a Larson Davis model CAL200, was available for verification. These calibrators are designed to fit consistently over the ½-inch microphones and to exclude a nominal amount of ambient noise by means of a rubber O-ring seal. Calibration was normally done indoors where it was quiet. A few calibrations had to be performed in the field; in those situations the equipment was taken inside a car or truck to prevent ambient noise from affecting the calibration.

A hand (Abney) level, total station, automatic (self-leveling) level, roll-a-tape and surveyor's tape were used to describe and recover the microphone locations. Recording setups were photographed. A laser "speed gun" was used for collecting traffic characterization data during noise sampling; traffic flow was recorded on video tape as a fail-safe backup.

4.1. Calibration of Instruments

Before field work began, key items in the apparatus were sent to their builders for calibration and certification. They were the Larson Davis model 2900B RTA, a Larson Davis model 3200 RTA, one SLM and its microphone and microphone preamplifier, both microphones and preamplifiers belonging to the RTA, and the two acoustic calibrators mentioned above.

4.2. Preparation for Recording

The recording procedure was, first, to be sure that fresh batteries were in the DATs and SLMs. The time-of-day clocks in the DATs were synchronized to within one second using U.S. official time from the NIST (National Institute of Science and Technology) website and a digital stop watch with time of day mode to transfer the time. The 812 SLM is a very versatile instrument and it was necessary to check its calibration and review all critical operational settings before each recording session. DAT input and data rate switch settings were also checked. Finally, a calibration tone usually lasting one minute was recorded on the tape. An acoustic tone generator with an orifice designed specifically to fit the SLM microphone produced a 94 dB sound pressure level at 1 kHz. This tone was used to calibrate the SLM and to record the calibration tone on the DAT.

Recording the calibration tone required care and judgment. The recorded tone is used to calibrate the Larson Davis 2900B Real Time Analyzer (RTA) before playback of the tape into the RTA. It is important that the recording level of the DAT be carefully set to produce the maximum recorded traffic noise level without exceeding the dynamic range of the digital recording, indicated by the appearance of the word "OVER" on the DAT function display. It was found that too-low settings of the record level control (the only rotary, continuously variable control on the DAT) produced recordings that were deficient in bandwidth. Through experimentation it was found that a certain minimum indicated record level was required to avoid unrecoverable errors in bandwidth. (This is a consequence of the 16-bit recording mode of the DAT recorders used. At the time of this report, digital audio media usually obtain much greater precision using 20 bit words or longer.) Thus, the problem was avoided by careful choice of record level so as to avoid over-and under-recording the traffic noise signal. To achieve reproducible record level settings it was found convenient to monitor the calibration tone sound level during its recording using a digital voltmeter connected to the Line Out jack of the DAT. The voltage level precisely mirrored the level obtained during playback of the same passage. This was far superior to using the record level indicator of the DAT functional display.

A summary of procedures for setup, recording and analysis is given in Appendix A.

4.3. System Normalization

In general, there will be minor response variations among the eight recording sets. It is desirable to normalize all of them to one common response specification. This can be done by comparison of the response of each individual recording set to the response of the 2900B Real Time Analyzer. The RTA and its two microphones and microphone preamplifiers were certified by the maker, so its Channel 1 was used as the norm to which the eight recording sets were calibrated. Recall that each of the eight recording sets always used the same SLM and DAT, so that its response characteristics remained constant throughout the study.

System normalization entailed making a ten- to thirty-minute recording of typical road traffic noise with all eight recording sets while the RTA analyzed the signal from its Channel 1 and Channel 2 microphones. All ten microphones were set up in a row parallel to the roadway and as close together as possible (one foot or less). Afterward the eight recordings were successively analyzed through Channel 1 of the RTA and their respective 1/3-octave frequency bands were compared to the Channel 1 real-time analysis, band by band. Correction factors were calculated for each 1/3-octave band of each recording set to correct it to the Channel 1 response. These factors are small except when the DAT record level is too low. Normalization factors for each of the eight recording sets are embedded in the spreadsheet used to present the acoustic data.

4.4. Field Recording

When weather forecasts indicated acceptable conditions of precipitation, humidity and wind velocity, the researchers traveled to a recording site. Microphone locations were recovered using the drawings prepared during reconnaissance and the recording sets were set up and made ready. Weather monitoring equipment was also prepared.

When the recorders were ready, a data recording start and finish time was given to two researchers posted on a bridge overlooking the roadway where they could record traffic volume, classification and speed by lane. Researchers at both locations used the instant of change of the time of day (minute) displays on their cell phones to mark the start and stop times for data

recording. The instant of change was observed to be synchronous with the NIST website official time display. The recorders were usually started in advance of the data recording time and allowed to run past the stop time. This made it easier to cue the playback of the tapes for input to the RTA.

During the recording two researchers monitored the situation at the microphones, noting wind speed and direction, air and pavement temperatures. They also noted times when extraneous noises occurred that might influence the recording adversely. After the data were reduced to numeric values minute-by-minute, the effects of "bad" minutes could be expunged.

4.5. Data Reduction

Digital audio tape (DAT) recorder/player output (an ac analog signal) from each field recording was input to the 2900B real time analyzer (RTA) using the same DAT that was used to make the recording. The player/recorder Line Out jack was connected by a coaxial jumper cable to Channel 1 of the RTA, which was then calibrated to 94 dB with the calibration tone recorded on the tape. The noise recording was played into the RTA and the RTA analyzed it just as it would analyze a signal from its microphones. During the analysis, a binary data file is created in the RTA memory. The 1/3-octave band analysis and other information are presented on the RTA display, which can be sent to a printer connected to the RTA; but in order to manipulate the data the file must be moved to a computer, either through the RTA serial port or via a floppy disk drive connected to the RTA. As the binary files are not large, the floppy disk was more convenient and served also as a file security backup medium. Once moved to a computer, the binary file was translated using an application distributed by the maker, Larson Davis, called "RTAUtil32," which creates a CSV quasi-spreadsheet file containing all the data elements. It is necessary only to copy the un-weighted 1/3 octave band data to a prepared data reduction/presentation spreadsheet for system normalization (application of correction factors as described above), A-weighting and summation by Site, Area and microphone number.

5. TRAFFIC DATA ANALYSIS

Traffic volume, classification, and speed data were collected and compiled by the research team for this project while traffic noise measurements were being made. Speed data for Sites 1 (Cincinnati), 2 (Troy) and 3 (Madison) was collected manually by laser speed detection while traffic count data was video-taped from an overpass observation location for extraction in the laboratory. The data that corresponded with the collected acoustical data was organized by travel lane in a spreadsheet. Once in the spreadsheet, lane specific values were combined to create total volumes and the corresponding mean speed for each vehicle classification. The tabulated traffic data is shown in Table 1 through 3 for corresponding Sites 1 through 3 with the inside lanes corresponding to the faster lane of traffic and the outside lane being the slower lane of traffic.

Table 1: Traffic count and speed data collected at Site 1

Data Description	Light Vehicles Volume (vph) B(A)*	Light Vehicles Speed (mph) B(A)*	Medium Vehicles Volume (vph) B(A)*	Medium Vehicles Speed (mph) B(A)*	Heavy Trucks Volume (vph) B(A)*	Heavy Trucks Speed (mph) B(A)*	Volume Totals (vph) B(A)*
Site 1, Area A							
Eastbound Outside Lane……..	540 (588)	64.3 (66.0)	72 (47)	60.5 (60.67)	80 (65)	57.9 (61.77)	692 (700)
Eastbound Middle Lane……..	816 (595)	68.2 (68.9)	16 (33)	66.7 (65.25)	36 (17)	N/A (65.0)	868 (645)
Eastbound Inside Lane…….	260 (141)	72.0 (72.3)	0 (4)	N/A (63.0)	4 (4)	N/A (66.5)	264 (149)
Westbound Outside Lane……..	448 (613)	67.8 (65.9)	52 (39)	59.5 (61.1)	128 (53)	59.8 (62.3)	628 (705)
Westbound Middle Lane……..	640 (608)	68.9 (70.3)	52 (16)	61.5 (63.4)	16 (35)	62.0 (64.5)	708 (659)
Westbound Inside Lane…….	176 (181)	81.0 (73.6)	4 (3)	N/A (73.0)	4 (0)	67.0 (N/A)	184 (184)
Site 1, Area B							
Eastbound Outside Lane……..	608 (506)	65.3 (66.3)	36 (64)	64.1 (63.3)	96 (58)	58.9 (61.1)	740 (628)
Eastbound Middle Lane……..	708 (618)	68.2 (69.6)	16 (40)	65.0 (64.7)	24 (10)	63.5 (64.0)	748 (668)
Eastbound Inside Lane…….	184 (126)	71.5 (72.7)	0 (0)	N/A	0 (0)	N/A	184 (126)
Westbound Outside Lane……..	496 (682)	65.8 (66.4)	40 (54)	60.4 (62.5)	96 (52)	58.9 (62.0)	632 (788)
Westbound Middle Lane……..	620 (680)	69.1 (71.3)	16 (30)	67.3 (65.8)	28 (18)	60.7 (62.1)	664 (728)
Westbound Inside Lane…….	108 (194)	71.8 (73.2)	4 (0)	70 (N/A)	0 (0)	N/A (N/A)	112 (108)
Site 1, Area C							
Eastbound Outside Lane……..	504 (672)	62.0 (63.4)	32 (32)	65.0 (63.0)	80 (96)	58.8 (62.5)	604 (800)
Eastbound Middle Lane……..	704 (664)	70.3 (71.3)	32 (32)	65.0 (64.8)	16 (8)	64.0 (61.7)	752 (704)
Eastbound Inside Lane…….	256 (80)	73.3 (69.3)	8 (0)	68.0 (N/A)	0 (0)	N/A	264 (80)
Westbound Outside Lane……..	596 (628)	65.9 (70.0)	8 (40)	62.0 (65.7)	108 (56)	59.1 (62.5)	712 (724)
Westbound Middle Lane……..	660 (660)	69.2 (71.4)	28 (36)	66.0 (64.3)	20 (4)	62.6 (63.0)	708 (700)
Westbound Inside Lane…….	132 (160)	73.9 (74.0)	8 (4)	N/A (70.0)	0 (0)	N/A	140 (164)

*B(A): Before Diamond Grinding (After Diamond Grinding)

Table 2: Traffic count and speed data collected at Site 2

Data Description	Light Vehicles		Medium Vehicles		Heavy Trucks		Volume Totals (vph)
	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)	
Site 2, Area A							
Northbound Outside Lane……..	232	62.5	16	N/A	252	58.95	500
Northbound Middle Lane……..	554	67.76	16	68	104	61.75	674
Northbound Inside Lane…….	360	71.47	2	N/A	2	N/A	364
Southbound Outside Lane……..	412	63.78	14	62	280	59.57	706
Southbound Middle Lane……..	538	68.44	10	61.25	72	61.18	620
Southbound Inside Lane…….	236	73	6	63	0	N/A	242
Site 2, Area B							
Northbound Outside Lane……..	290	66.18	20	60	284	58.42	594
Northbound Middle Lane……..	578	68.55	22	63.6	130	60.23	730
Northbound Inside Lane…….	384	71.7	4	N/A	0	N/A	388
Southbound Outside Lane……..	456	63.7	10	58	252	59.62	718
Southbound Middle Lane……..	676	68.73	20	64.3	46	60.47	742
Southbound Inside Lane…….	244	71.17	4	70	0	N/A	248
Site 2, Areas C and D							
Northbound Outside Lane……..	619	63.33	17	59	253	59.64	889
Northbound Middle Lane……..	670	68.04	19	65	101	62.09	790
Northbound Inside Lane…….	632	71.1	6	70.5	1	63	640
Southbound Outside Lane……..	751	65.91	36	59.5	262	58.79	1049
Southbound Middle Lane……..	718	68.93	22	65.1	95	62.27	834
Southbound Inside Lane…….	414	73.74	8	70.5	1	66	424
Site 2, Area E							
Northbound Outside Lane……..	656	63.33	24	N/A	220	58.83	900
Northbound Middle Lane……..	688	68.07	20	64.6	124	61.67	832
Northbound Inside Lane…….	752	70.56	16	71	0	N/A	832
Southbound Outside Lane……..	684	67.5	28	61.33	216	58.58	928
Southbound Middle Lane……..	820	68.33	20	67	88	62.3	928
Southbound Inside Lane…….	420	72.3	0	N/A	4	75	424

Table 3: Traffic count and speed data collected at Site 3

Data Description	Light Vehicles		Medium Vehicles		Heavy Trucks		Volume Totals (vph)
	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)	
Site 3, Area A							
Eastbound Outside Lane……..	115	66.91	33	60.29	324	59.49	472
Eastbound Middle Lane……..	645	69.05	24	64.33	87	62.97	756
Eastbound Inside Lane…….	372	72.43	5	69	1	N/A	378
Westbound Outside Lane……..	98	65.89	30	59.7	322	59.65	450
Westbound Middle Lane……..	577	68.01	22	63.6	99	62.36	697
Westbound Inside Lane…….	402	71.76	4	72.5	2	65	408

6. TNM MODELING METHODOLOGY

Noise models for this project were prepared using the FHWA Traffic Noise Model (TNM) version 2.5. The United States Department of Transportation (USDOT) Volpe Center Acoustics team provided a specialized version of the TNM that included ODOT specific REMELs for transverse tined PCC pavements (TTPCC) and a 1/3-octave band output function. Due to limitations of the REMEL dataset, this model is only appropriate for use in modeling highway speed traffic. All study areas investigated for this project involve traffic at highway speeds. Models were developed in accordance with the FHWA TNM 2.5 User's Guide and the TNM 2.5 FAQ.

6.1. Study Area Information

The ODOT Office of Environmental Services provided design information for the respective study locations with a combination of geo-referenced tagged image format (tif) and MrSid (sid) aerial photograph files, Microstation (dgn) files, AutoCAD (dwg) files, drawing exchange format (dxf) and project plan sheets. This combination of files provided the layout and design information for the locations under study. The geo-referenced aerials proved very useful because the images showed the built project for each study area rather than limiting project information solely on the project design plans.

6.2. Model Development

Most of the preliminary model development was accomplished using ArcGIS 9.2. The sid, tif and plan files were imported into ArcGIS in the NAD 1983 Connecticut State Plane Coordinate System projection. This approach allowed for use of software available to the modeler and preserved the accuracy of the models. ArcGIS provides functionality similar to computer aided design programs such as capability to overlay project plans and county dgn files over the aerial photographs. Features of the model were drawn onto the aerial photographs as a shapefile representing TNM objects such as buildings, ground zones, terrain lines, receivers, noise barriers, median barriers, and roadways (Figure 8). The completed shapefiles were then converted into dxf format and imported into TNM. The imported dxf files were then converted into TNM objects (Figure 9).

Figure 8. Aerial of HAM-275 Area A with Shapefile Overlay Depicting TNM Objects

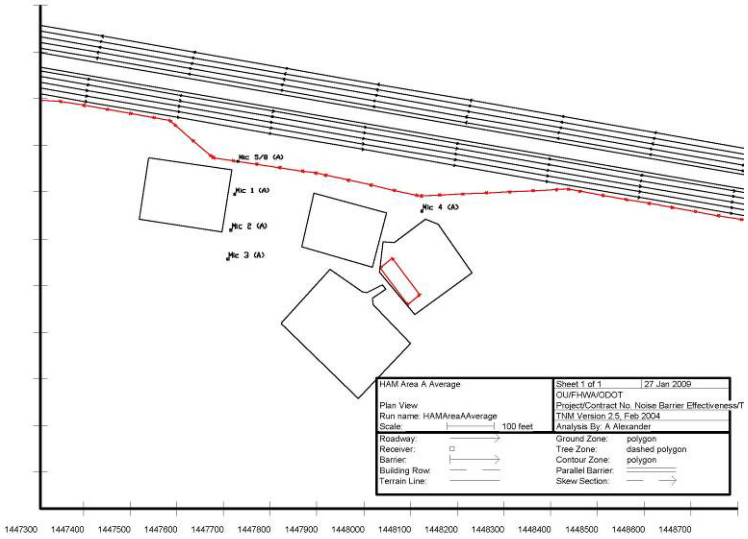


Figure 9. TNM Plan View of HAM-275 Area A

Elevation data was obtained from a combination of the project plans, GIS data and information collected in the field (Figure 10). The plan and GIS data provided the roadway profile elevations and noise barrier top of wall and bottom of wall elevations. The research team collected elevation data relative to microphone locations during the field measurements. Microphone elevations used in the model were calculated based on this data. Stationing for the freeway roadway segments and noise barriers were established as per the design plan. Elevation data from the plan and profile sheets were used as input values in the model. The elevation of

buildings in the model was determined using either ground contour data or extrapolation from the microphone location data.

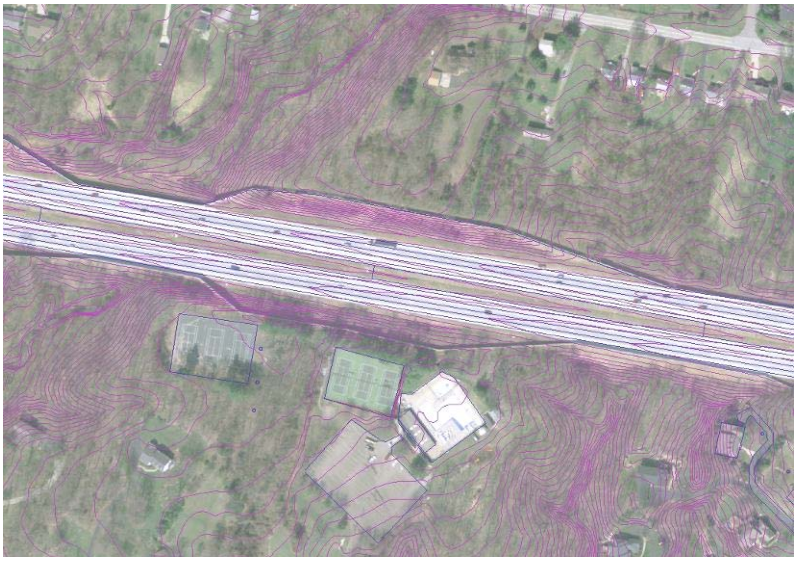


Figure 10. HAM-275 Area A with Elevation Contours

All lanes were modeled as individual TNM roadways and medians were modeled as ground zones (hard ground). Shoulders were modeled as TNM roadways with no traffic assigned. Traffic volumes were determined from the traffic data collected during the measurement periods by vehicle type and average speed per lane. TNM receivers were placed at field measurement microphone locations and models were run for each site using TNM average pavement and TNM PCC pavement for each mainline roadway.

The naming convention used for each model uses the three-letter abbreviation for the county, the area identified in the field data sheets, followed by the pavement type. For example, the run shown in Figure 8 is HAM Area A Average, representing Hamilton County site Area A with Average pavement.

6.3. Calculations

The models were tested using the standard version of the TNM 2.5 using Average and PCC pavements. All final model runs were completed using the same computer (Intel Core 2 Quad Q6700 with 8GB RAM running the Windows Vista Ultimate 64 operating system).

The Volpe Center provided a specialized version of the TNM (ODOT TNM) that included a pavement type based on REMELs collected on Ohio TTPCC pavement. This pavement type is identified as “Custom” in this version of TNM; requiring the user to change the pavement type in the Roadway Input dialogue box from Average to Custom. This version also included capability to obtain output of 1/3-octave band data. All models were recalculated using the ODOT TNM and results were exported to a Microsoft Excel table with the results organized by pavement type for each site to facilitate comparison with the measured data.

7. RESULTS

The field measurement and data reduction procedures yielded the equivalent continuous noise level, A-frequency weighted, in 1/3 octave frequency bands (50 Hz – 10 kHz), as well as the broadband sum over the frequency range, for each microphone location. The TNM modeling procedures yielded two data sets of predicted noise levels for each microphone location, one for average pavement types, and one for the ODOT random transverse grooved pavement type.

The following sections describe the analysis and display the results for the comparison of predicted levels with measured levels. This comparison directly relates to objective 5 for this study: to assess the validity of using TNM with the Reference Energy Mean Emission Levels for the ODOT random transverse grooved concrete pavement type. The analysis of the broadband noise levels is given first, followed by the comparison of predicted levels in 1/3 octave frequency bands.

7.1. Broadband Noise Levels

The measured and predicted noise levels for each study location are shown by microphone designation in Table 4. For example, the designation S1B2 is the abbreviation for Site 1, area B, microphone number 2. Sites 1, 2, and 3 refer to the Cincinnati, Troy, and Madison Co. study areas, respectively. The difference between the measured and predicted levels is shown in the table in the error column. The error is shown as positive or negative to reflect the over-prediction or under-prediction cases.

Table 4. Measured and predicted broadband levels using TNM configured for average pavement types (AVG) and the ODOT random transverse grooved concrete pavement type (ORT).

Study Location	Measured Level (dB)	TNM Average Pavement Prediction (dB)	TNM ORT Pavement Prediction (dB)	TNM Error Average Pavement (dB)	TNM Error ORT Pavement (dB)
S1A1	67.7	61.1	61.9	-6.6	-5.8
S1A2	65.9	59.9	60.5	-6.0	-5.5
S1A3	63.6	58.3	59.0	-5.2	-4.6
S1A4	66.9	60.8	61.6	-6.1	-5.3
S1A5	80.3	75.0	76.7	-5.3	-3.6
S1B1	65.7	60.8	61.5	-5.0	-4.2
S1B2	63.3	59.1	60.0	-4.2	-3.3
S1B3	66.7	60.8	61.8	-5.9	-4.9
S1B4	66.0	60.3	61.5	-5.7	-4.6
S1B5	58.6	55.5	56.6	-3.1	-1.9
S1B6	65.3	61.2	62.5	-4.1	-2.8
S1B7	79.6	75.0	76.9	-4.6	-2.7
S1C6	58.9	55.3	56.2	-3.6	-2.7
S1C7	59.2	56.2	57.0	-3.0	-2.2
S2A1	60.6	57.0	58.0	-3.6	-2.6
S2A2	64.8	59.5	60.3	-5.3	-4.5
S2A3	66.3	60.4	61.1	-6.0	-5.3
S2A4	65.6	61.5	62.2	-4.1	-3.4
S2A8	83.2	77.3	78.7	-5.9	-4.5
S2B5	66.1	61.8	62.5	-4.3	-3.7
S2B6	56.6	55.2	56.0	-1.4	-0.7
S2B7	54.1	52.4	53.1	-1.7	-1.0
S2B8	82.7	77.7	79.2	-5.0	-3.5
S2C1	67.6	63.1	63.8	-4.5	-3.8
S2C2	56.3	58.0	59.1	1.7	2.8
S2C3	57.6	56.0	57.0	-1.6	-0.6
S2C8	84.4	78.4	79.9	-6.0	-4.5
S2D4	66.5	61.9	62.9	-4.6	-3.5
S2E5	72.3	69.5	70.4	-2.9	-1.9
S2E6	69.3	68.6	69.4	-0.7	0.0
S3A1	88.1	80.8	82.3	-7.3	-5.8
S3A2	84.7	78.6	80.0	-6.1	-4.7
S3A3	85.3	78.7	80.2	-6.6	-5.1
S3A4	77.3	75.9	77.2	-1.4	-0.1
S3A5	73.3	72.0	73.2	-1.3	-0.1
S3A6 (failed)	NA	67.5	68.5	NA	NA
S3A7	64.1	62.4	63.2	-1.7	-0.9
S3A8	59.9	55.0	55.4	-4.9	-4.6
			MEAN	-4.1	-3.1

The nature of field experiments with the attending complexities involved in the system generally produces a large amount of scatter in the results. This scatter was anticipated. Therefore the research plan called for the final comparison of the TNM predictions by pavement type to be based upon the means of the errors for all measurement sites.

The error for the prediction based on the average pavement type ranged from an under-prediction of –7.3 dB to an over-prediction of +1.7 dB with a mean value of –4.1 dB. By contrast the error for the prediction based on the ODOT random transverse grooved pavement type ranged from an under-prediction of –5.8 dB to an over-prediction of +2.8 dB with a mean value of –3.1 dB. On the average, for the sites tested, the prediction based on the ODOT random transverse grooved concrete pavement type reduced the error present with the average pavement type prediction by over 1.0 dB. This difference is due solely to the use of the ODOT random transverse grooved pavement type REMEL to characterize the traffic noise source in TNM. All other factors influencing the prediction were held constant. The statistical analysis of the means and mean errors will be described in the two sections that follow.

Figures 11 and 12 present the results from Table 4 graphically. In both figures, the diagonal line represents the ideal condition where the points would fall if the predicted levels exactly matched the measured levels. While there is obvious scatter in both figures, the under-prediction in Figure 11, which is based on the average pavement type, is slightly reduced in Figure 12, which is based on for the ODOT random transverse grooved concrete pavement type.

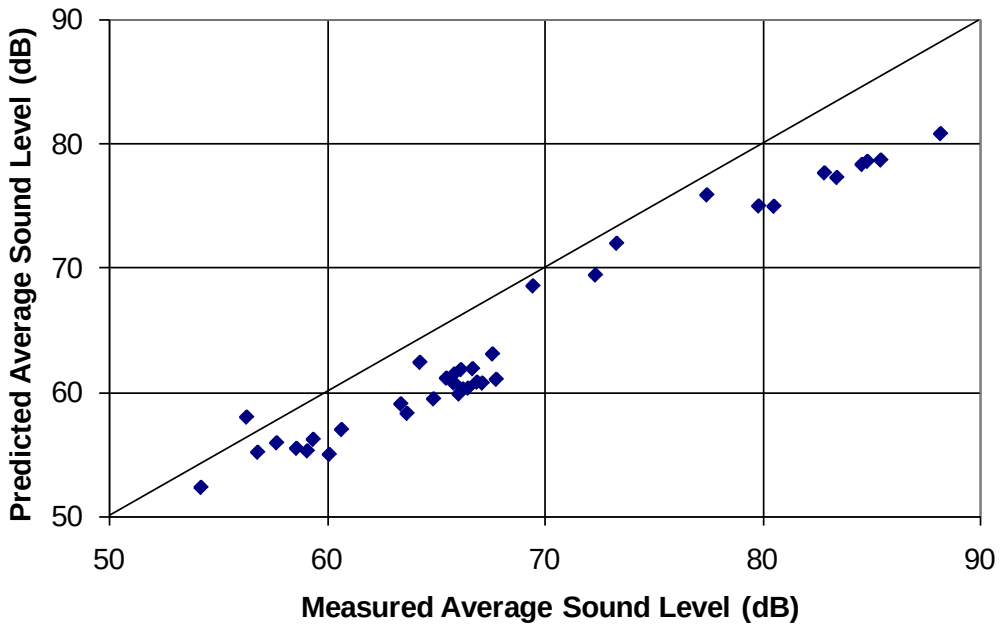


Figure 11. TNM predicted levels vs. measured levels for the average pavement type.

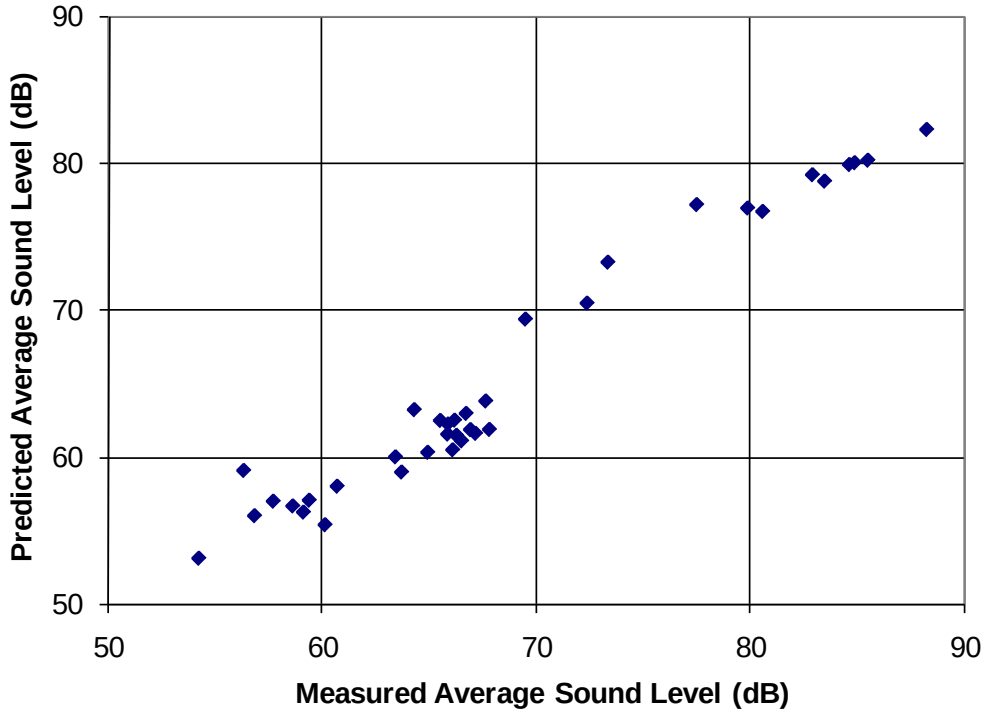


Figure 12. TNM predicted levels vs. measured levels for the ODOT random transverse grooved concrete pavement type.

7.2. Statistical Analysis of Mean Error

The difference in the mean errors between the two TNM predictions was given in the previous section. This section will present an analysis of the difference in the means. While it is obvious that the means are different, the issue is whether they statistically significant in their difference. The criterion used in the statistical comparisons is the 0.05 level of significance, which corresponds to the 95% confidence interval. The statistical test used to analyze the sample means from the results of TNM configured for the average pavement type and TNM configured for the ODOT random transverse grooved concrete pavement type is the paired t-test. This test is used since the comparison for each model is done by measurement site. The test is conducted on the differences between the paired samples in the prediction columns of Table 4. The mean of these differences is represented by μ_{DIFF}. If the differences in the models are not significant, the mean will be essentially zero, μ_0

This hypothesis test is described by:

$H_O : \mu_{DIFF} = \mu_0$

$H_1 : \mu_{DIFF} \neq \mu_0$

Reject H_0 at the 0.05 level of significance if:

$$P_t = \frac{\overline{X}_B - \overline{X}_A}{\frac{s_D}{\sqrt{n}}} \qquad \text{Equation 1}$$

$$s_D^2 = s_B^2 + s_A^2 - 2\left[\frac{1}{N-1}\sum_{i=1}^{N}\left(X_{Bi} - \overline{X}_B\right)\left(X_{Ai} - \overline{X}_A\right)\right] \qquad \text{Equation 2}$$

Where:

$\overline{X}_B$ = sample mean of the ORT pavement prediction
$\overline{X}_A$ = sample mean of the average pavement prediction
N = number of microphone readings
S_B = standard deviation for ORT pavement prediction
S_A = standard deviation of average pavement prediction

The null hypothesis for this test states that the two sample means are equivalent. That is, any apparent difference in the means is only due to the size of the sample. If the samples were increased in size to include all possible test sites, they would appear to be the same. The alternative hypothesis is that TNM configured for the ODOT random transverse grooved concrete pavement type is statistically different than TNM configured for the average pavement type. The test statistic is calculated to be -19.196, which is greater than $\pm$2.021, the critical value based upon the degrees of freedom for the sample (N-1). The evidence is large enough to overturn the null hypothesis and support acceptance of the alternative hypothesis.

In summary, the statistical analysis used to compare the two TNM predictions indicates that a statistically significant improvement is to be realized with TNM configured for the ODOT random transverse grooved concrete pavement type over TNM configured for the average pavement type. It is emphasized that this improvement is to be expected on the mean result for a large number of sites and not necessarily for an isolated site.

7.3. Statistical Error Analysis

The comparison of the performance of TNM configured for the ODOT random transverse grooved concrete pavement type versus TNM configured for the average pavement type is extended in this section to include an error analysis.

The errors given in Table 4 for both predictions are shown plotted according to the corresponding predicted levels in Figures 13 and 14.

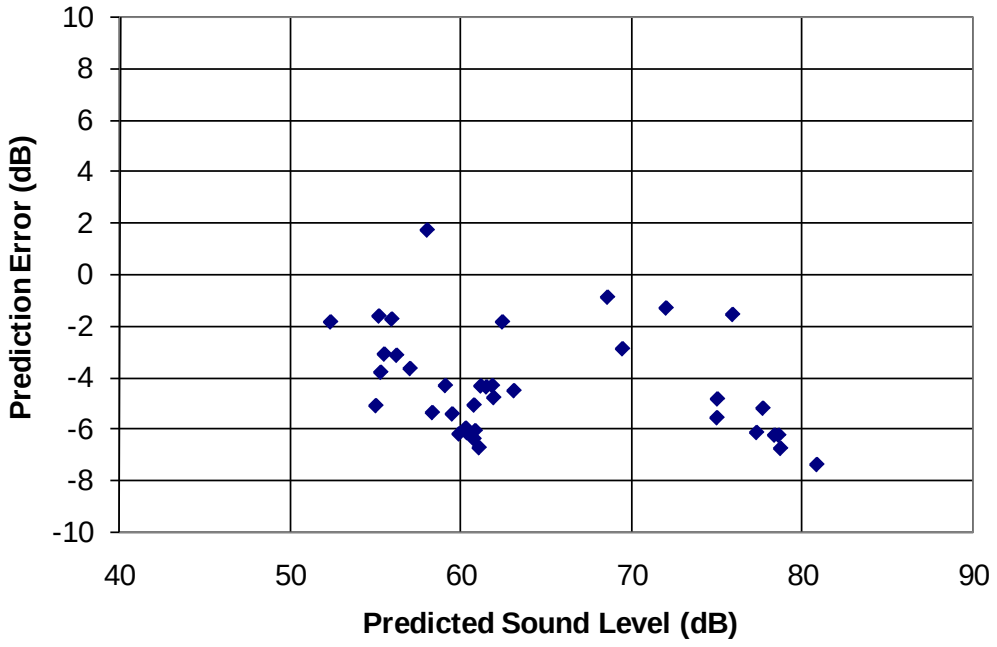


Figure 13. Prediction errors versus predicted level for TNM configured for the average pavement type.

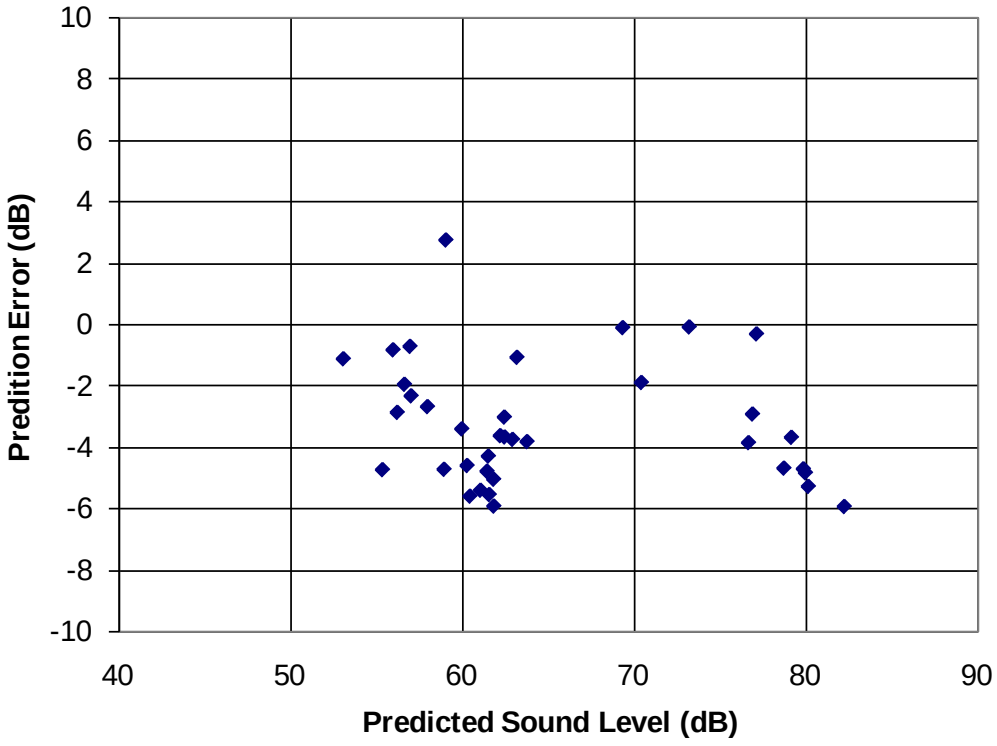


Figure 14. Prediction errors versus predicted level for TNM configured for the ODOT random transverse grooved concrete pavement type.

A good prediction model should produce a mean error close to zero. In addition, a good prediction model should satisfy three basic conditions. The first of these conditions is linearity, which refers to the lack of a bias trend throughout the prediction range. That is, the mean error should not drift appreciably throughout the prediction range. The second condition, homoscedasticity, refers to the dispersion of the errors. It is desirable that the spread of the errors should not change appreciably throughout the predicted range. The third condition is independence or randomness. The individual error terms should be independent of the prediction level. That is, a given error should be just as likely to be positive or negative about the mean error level regardless of the predicted level [Kenkel 1989, 610]. The data acquired in this study was evaluated for these conditions.

Figures 13 and 14 display the under-prediction of TNM configured for both the average pavement type and the ODOT random transverse grooved concrete pavement type. While the mean errors are not shown in the figures, the means of the errors are obviously below zero in both cases.

The condition of linearity is evaluated subjectively by observing the error plots in Figures 13 and 14. The prediction errors appear to be about the same regardless of the predicted noise level. Therefore, no serious violation of linearity is suggested by either figure

The condition of equal dispersion or homoscedasticity is also evaluated subjectively. In both Figure 13 and Figure 14 the errors, while showing a bias below zero, have an approximately equal dispersion of errors throughout the predicted range. The quantitative comparison of this overall spread in errors will be addressed below.

The condition of independence or randomness can be evaluated quantitatively by means of the RUNS test which provides an inference of randomness in the prediction error at a selected level of significance. The RUNS test examines the sign (+ or -) of the errors about the error mean, throughout the prediction range, in order of increasing predicted level. A "run" is a string of errors with the same sign. For a given set of data, an expected number of "runs" is calculated for the assumption of randomness at the given level of significance. The actual number of “runs” is then compared with this expected number to produce an estimate of randomness [Kenkel 1989, 921].

The RUNS test was applied to both the errors for TNM configured for the average pavement type and the errors for TNM configured for the ODOT random transverse grooved concrete pavement type. The observed runs for TNM configured for the average pavement type was 15, while the observed runs for TNM configured for the ODOT random transverse grooved concrete pavement type was 11. The average pavement type errors were determined to be random while the random transverse grooved pavement was determined not to be random at an alpha level of 0.05. When the errors about the median for the average pavement type were compared with the errors about the median for the random transverse grooved pavement type, the results of the RUNS test were slightly different. For the average pavement type, the median error was -4.6 dB and for the random transverse grooved pavement type the median error was -3.5 dB. The observed runs for the average pavement type and the random transverse grooved concrete pavement was 15. The average pavement errors and the random transverse grooved pavement errors were both found to be random.

From the observations described above, the errors of both TNM configured for the average pavement type and TNM configured for the ODOT random transverse grooved concrete

pavement type, the approximations of linearity, homoscedasticity, and independence were judged to be satisfied by the data.

In subsection 7.2, the means for the two predictions were compared. The test indicated that the mean for the prediction with TNM configured for the ODOT random transverse grooved concrete pavement type was indeed statistically different from the mean for the prediction with TNM configured for the average pavement type. In this subsection, the data is analyzed to determine if either of the mean errors is statistically different from zero. While the means are different numerically, the difference may be due to the sample size. Given a large enough sample, the means might be assumed to converge to the same number, that number being zero.

The null hypothesis for each test is that the mean error is zero. The statement of the first hypothesis test is:

$$H_0: \mu_{AVG} = \mu_0$$
$$H_1: \mu_{AVG} \neq \mu_0$$

where μ_{AVG} is the mean error for the predictions with TNM configured for the average pavement type and μ_0 is zero. Equation 1 describes the test statistic for which H_0 is to be rejected at the 0.05 level of significance. In this equation μ_{AVG} (-4.1) is substituted for μ and 2.00 is the standard deviation for the prediction errors with TNM configured for the average pavement type. The result, -13.105, is greater than $\pm$2.021; therefore the null hypothesis is rejected. The mean prediction error with TNM configured for the average pavement type is statistically different than zero at the 0.05 level of significance.

The statement of the second hypothesis test is:

$$H_0: \mu_{ORT} = \mu_0$$
$$H_1: \mu_{ORT} \neq \mu_0$$

where $\mu_0 = 0$ and μ_{ORT} = the mean error for TNM configured for the ODOT random transverse grooved concrete pavement type. Again, Equation 1 describes the test statistic for which H_0 is to be rejected at the 0.05 level of significance. In this equation μ_{ORT} (-3.1) is substituted for μ and the standard deviation for the prediction errors with TNM configured for the ODOT random transverse grooved concrete pavement type is 1.96. The result, -10.09, is greater than $\pm$2.021; therefore, the null hypothesis is rejected. The mean prediction error for TNM configured for the ODOT random transverse grooved concrete pavement type is statistically different from zero at the 0.05 level of significance.

The spread in the prediction errors was also analyzed. The underlying premise for this study is that if the predictions with TNM configured for the ODOT random transverse grooved concrete pavement type is indeed a better model it ought to produce a reduced mean difference between predicted and measured levels compared to TNM configured for the average pavement type, without increasing the error spread.

The variances for the two data sets were compared to determine whether the variances, and thus the standard deviations, are statistically different from each other. Statistical inferences concerning variance are typically made with the F-test. However, the two predictions for the 37 study locations are paired data sets and not two independent samples as required for the F-test.

The standard deviation of the prediction errors with TNM configured for the average pavement type was 2.00, while the standard deviation TNM configured for the ODOT random transverse grooved concrete pavement type was 1.96. The standard deviations are close to each other numerically; however, the standard deviation of the prediction errors with TNM configured for the ODOT random transverse grooved concrete pavement type is slightly less than the standard deviation for the predictions with TNM configured for the average pavement type.

Therefore, the improvement in mean error, gained by using the TNM configured for the ODOT random transverse grooved concrete pavement type was obtained while maintaining or slightly decreasing the error spread.

The results of the statistical error analysis indicate that TNM configured for the ODOT random transverse grooved concrete pavement type is a slightly more accurate and a more consistent predictor of noise levels on a large sample than TNM configured for the average pavement type.

7.4. One-third octave band frequency levels

The traffic noise data that was acquired at each study location was also post-processed to yield noise levels in one-third octave frequency bands. The TNM modeling procedure also produced predicted noise levels for both the average pavement type and the ODOT random transverse grooved pavement type in one-third octave frequency bands for each study location. The predicted levels and the measured levels were plotted for each study location. The results for one study location, S1A1, are given in Figures 15, 16, and 17, as an example. It should be noted that the one-third octave band frequency levels were not adjusted for traffic conditions due to the limitations of the TNM model. While the broadband results shown in Table 4 provide the amount of over or under-prediction by the models for each study location, the one-third octave band analysis provides insight to the frequency-dependence of the over or under-prediction. At site 1 (Cincinnati), Area 1, Microphone 1, TNM, configured for the average pavement type, produced a net under-prediction of the measured levels of 6.6 dB, and when configured for the ODOT random transverse grooved pavement type it produced a net under-prediction of the measured levels of 5.8 dB (refer to Table 4). However, from the one-third octave band results for this microphone location, shown in Figure 15, the under-prediction was not present throughout the frequency range. While there is a net under-prediction, both models over-predicted the levels in the lower frequencies and under-predicted the levels in the higher frequencies.

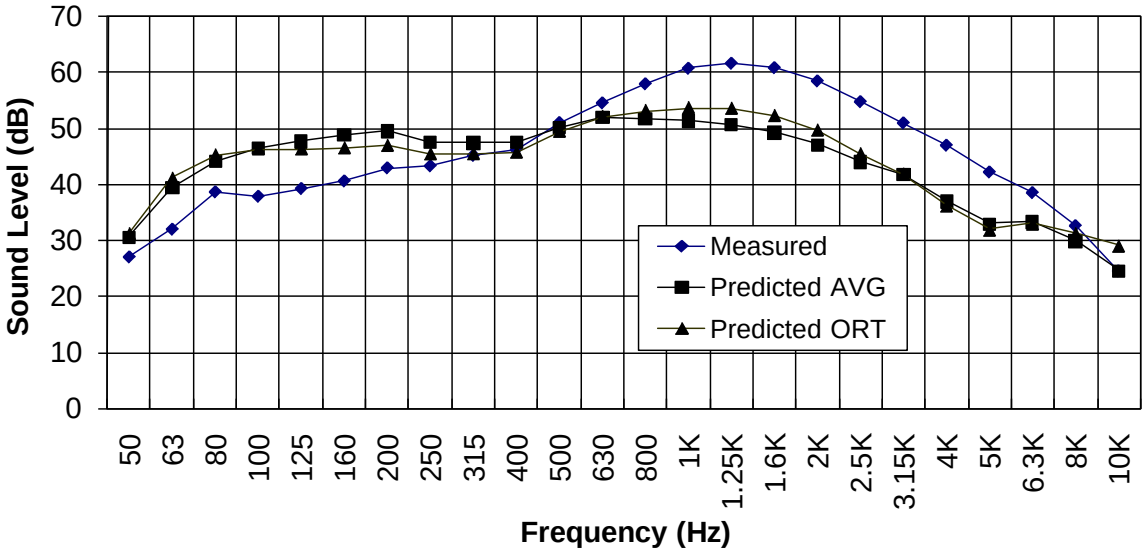


Figure 15. Measured and predicted one-third octave sound levels for site S1A1.

The specific differences between predicted and measured noise levels in one-third octave frequency bands for TNM configured for the average pavement type are quantified and shown in Figure 16, and the differences for TNM configured for the ODOT random transverse grooved pavement type (ORT) are shown in Figure 17. As an example, it can be seen that the maximum difference between predicted and measured levels for TNM configured for the ODOT random transverse grooved pavement type (ORT) is an under-prediction of 10.8 dB which occurred in the 4000 Hz frequency band (Figure 17). While these figures for location S1A1 are representative of the general trend for all locations, there are differences in this pattern at other study locations. The one-third octave band results for all other study locations, corresponding to Figures 15,16, and 17, are provided in Appendix C.

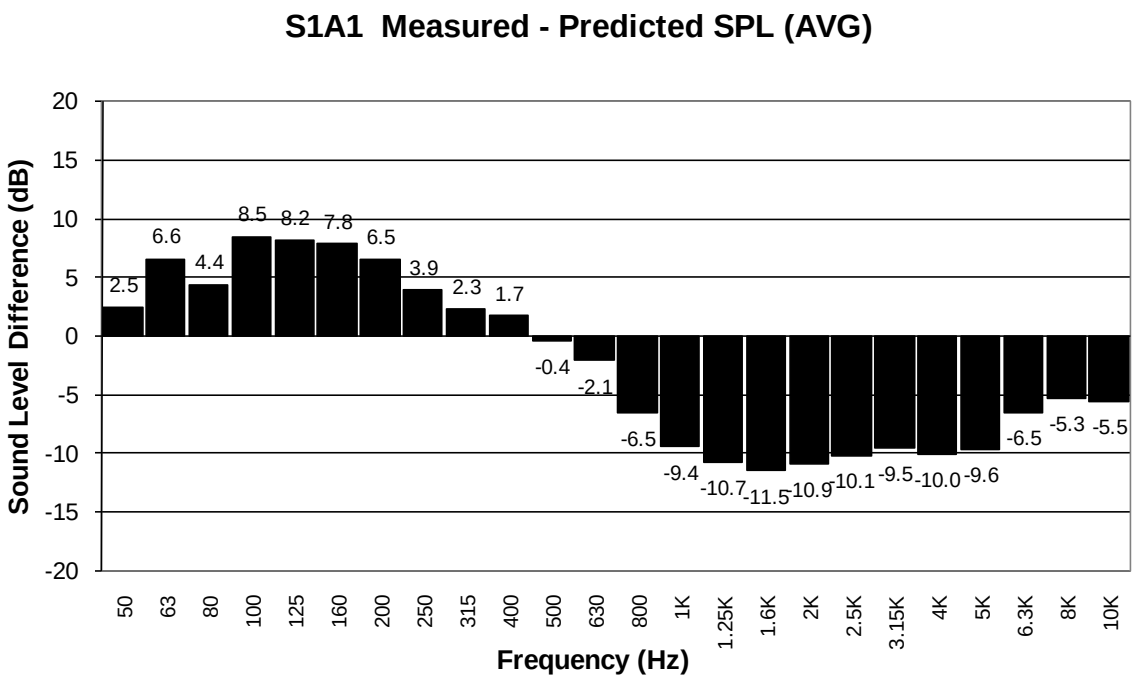


Figure 16. The differences between noise levels predicted for average pavement types and measured levels.

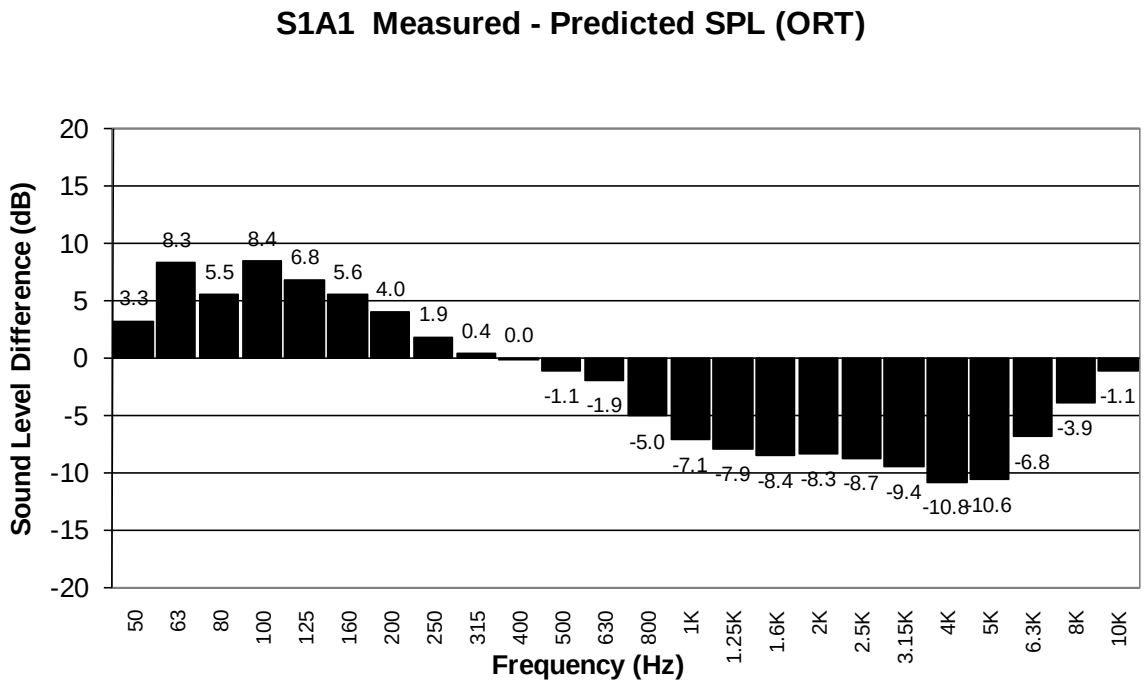


Figure 17. The differences between noise levels predicted for the ODOT random transverse grooved pavement type and measured levels.

7.5. Effectiveness of surface re-texturing through diamond grinding – Comparison of BEFORE/AFTER measurements

The determination of the effectiveness of the diamond grinding project was to be based on a comparison of the traffic noise measurements made before and after the diamond grinding, as stated in Objective 7. To be valid, conditions for the before and after measurements, ideally, should be identical, so that only the changed pavement surface has an effect on the "after" measured levels. However, conditions are never truly identical for such a comparison. Atmospheric and traffic conditions are two of the most common conditions that can affect measured levels. To minimize the atmospheric differences the traffic noise measurements were made after the diamond grinding during the summer season under similar conditions. To quantify these conditions atmospheric data was collected during the noise measurement periods, as shown in Table 5.

Table 5. Atmospheric Conditions

Location/ Data Description	Average Ambient Temp. (°F)	Average Pavement Temp. (°F)	Average Relative Humidity (%)	Average Wind Speed (mph)	Average Wind Direction	Sky Cover
Area A						
Before	71	85	60	<2	NW	Clear
After	72	84	61	0	N/A	Partly Sunny
Area B						
Before	67	75	67	<2	Variable	Clear
After	69	84	68	<1	S	Overcast
Area C						
Before	80	108	57	2	NW	Clear
After	83	89	50	1	S	Overcast

There were minor atmospheric differences between "before" and "after" measurements as shown in Table 5. The significance of these differences can be realized by referring to criteria established in the international standard for the statistical pass-by method of tire/road noise measurement [International Organization for Standardization 1994]. These criteria were developed for the measurement of absolute noise levels and are therefore necessarily more stringent than the criteria needed for a study such as this one where the differences in noise levels are of primary interest. This standard requires that the wind speed be less than 11.2 mi/h (5 m/sec), the atmospheric temperature between 41 and 86 °F (5 and 30 °C), and the pavement temperature be between 41 and 122 °F (5 and 50 °C) during the measurements. Based on this standard the differences in atmospheric conditions for the before/after comparison are negligible.

To minimize the traffic differences, the traffic noise measurements were made after the diamond grinding during the mid-week and between the AM and PM peaks near the same times as the measurements made before diamond grinding. In addition, TNM was used to model the difference in noise levels that would occur due to any differences between the before and after traffic volumes or speeds, as shown in Table 1. The modeled differences were then applied to the measured noise levels to remove the effect of traffic differences on the noise measurement results.

7.5.1. Noise level reduction

The comparison of the broadband traffic noise levels made after diamond grinding with the levels made before diamond grinding are shown in Table 6.

Table 6. Measured Broadband Noise Levels Before and After Diamond Grinding on (CLE-HAM)-275 NOTE: Area C was unchanged.

Study Location (Area)	BEFORE Measured Level (dB)	AFTER Measured Level (dB)	DIFFERENCE (dB)	TNM Average Pavement Prediction (dB)	TNM Average Pavement Prediction CORRECTED for Traffic (dB)	CORRECTIONS for Traffic (dB)	CORRECTED DIFFERENCE (dB)
A1	67.7	61.6	-6.1	61.1	60.3	-0.8	-5.3
A2	65.9	59.6	-6.3	59.9	59.0	-0.9	-5.4
A3	63.6	56.6	-7.0	58.3	57.5	-0.8	-6.2
A4	66.9	62.9	-4.0	60.8	60.0	-0.8	-3.2
A5	80.3	75.0	-5.3	75.0	74.4	-0.6	-4.7
B1	65.7	60.6	-5.1	60.8	59.9	-0.9	-4.2
B2	63.3	58.2	-5.1	59.1	58.3	-0.8	-4.3
B3	66.7	61.3	-5.4	60.8	60.3	-0.5	-4.9
B4	66.0	61.1	-4.9	60.3	60.0	-0.3	-4.6
B5	58.6	53.5	-5.1	55.5	55.0	-0.5	-4.6
B6	65.3	60.1	-5.2	61.2	60.9	-0.3	-4.9
B7	79.6	75.4	-4.2	75.0	75.0	0.0	-4.2
C6	58.9	58.0	-0.9	55.3	55.3	0.0	-0.9
C7	59.2	59.6	0.4	56.2	56.3	0.1	0.3
Average for A and B locations:			-5.3				-4.7

The diamond grinding was effective in that it reduced the broadband noise levels for every microphone location in Area A and Area B. The reduction ranged from a minimum of -4.1 dB to a maximum of -7.0 dB with a mean value of -5.3 dB. Note, Area C (S1C6 and S1C7) is located adjacent to I-275 in a section that was not part of the diamond grinding project. However, traffic noise measurements were repeated at the two microphone locations in Area C as a control to verify that all procedures and conditions for the before and after diamond grinding measurements were essentially equivalent.

7.5.2. One-third octave band noise level reduction

As a result of the diamond grinding project, the broadband traffic noise levels for microphone S1A1 were reduced by -6.0 dB, as shown in Table 6. The frequency-dependant characteristics of the noise reduction were determined by one-third octave band analysis. The differences in one-third octave band noise levels between the measurements made before and after the diamond grinding at microphone S1A1 are shown in Figures 18 and 19.

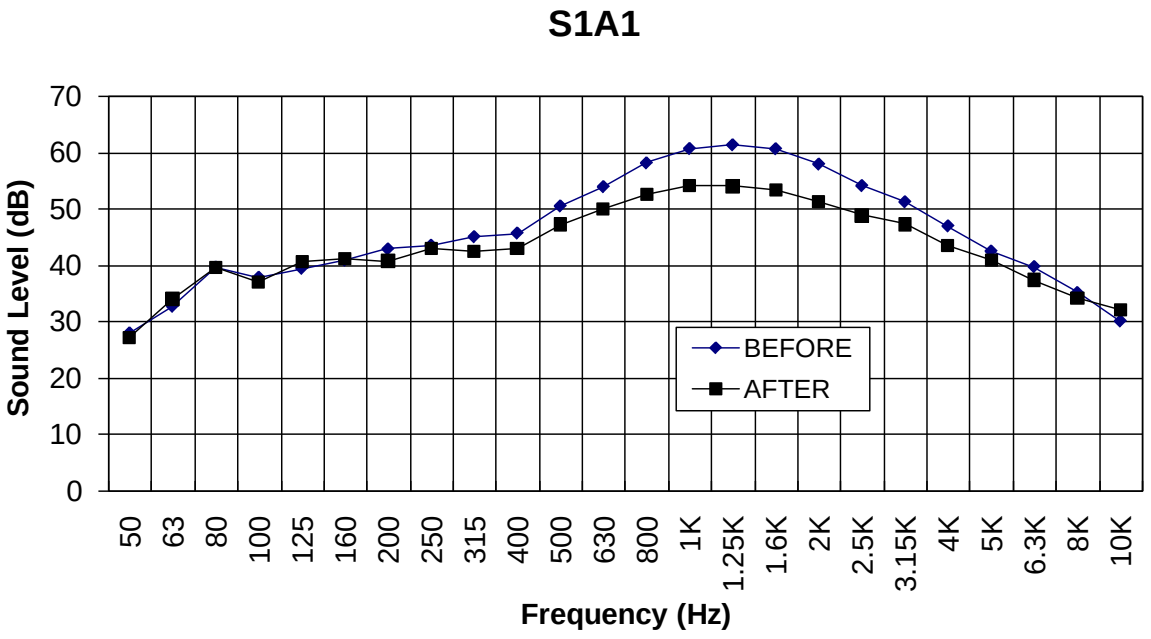


Figure 18. Before and after one-third octave sound levels for site S1A1.

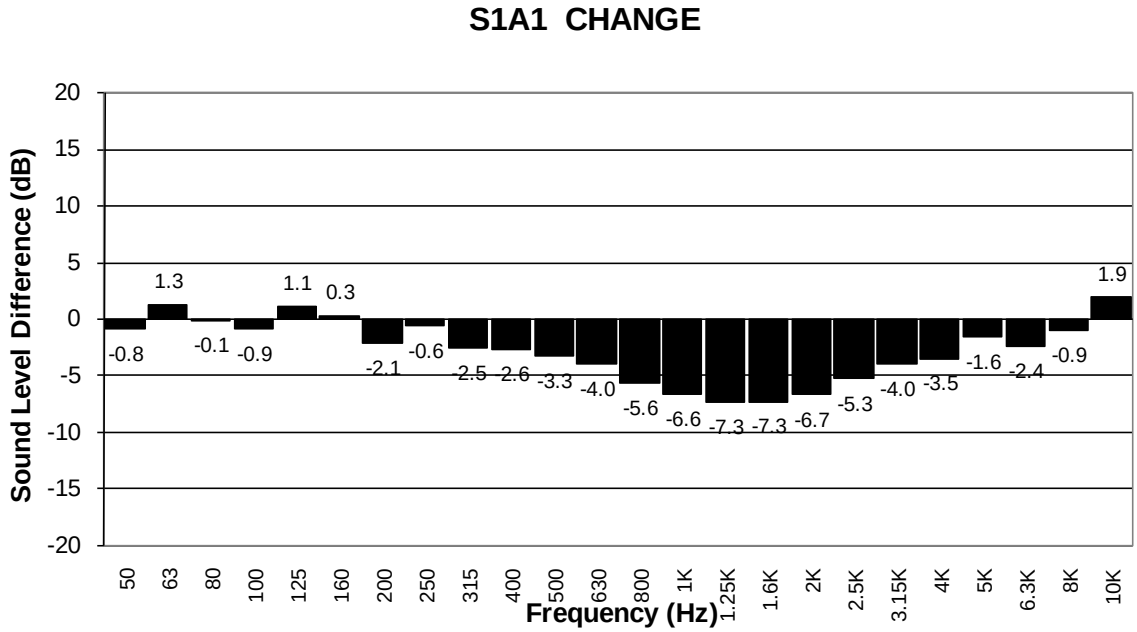


Figure 19. The differences between the before and after noise levels.

While the diamond grinding did not significantly affect the noise level below 200 Hz, the levels in the frequency bands from 200 Hz to 8 kHz were all reduced. The specific amounts of noise reduction are shown in Figure 19 where the maximum reduction of 7.3 dB occurs in the 1 kHz to 2 kHz range. While these figures for location S1A1 are representative of the general trend for all locations, there are differences in this pattern at other study locations. For example, a number of microphone locations in Area B experienced a reduction in levels in the frequency bands below 200 Hz. The one-third octave band results, corresponding to Figures 18, and 19, for

all other study locations, including Area C (where no diamond grinding occurred) are provided in Appendix D.

7.6. Discussion of Results

The research described in this report was initiated to support the FHWA in its effort to provide ODOT and other states with accurate noise predictions from TNM when modeling highways constructed with random transverse grooved concrete pavement types. The achievement of this goal was progressively guided by the completion of four specific objectives that would in turn provide the basis for the completion of the fifth objective: assess the validity of using TNM with the Reference Energy Mean Emission Levels (REMELs) for the random transverse grooved concrete pavement type. It was realized at the outset that the concrete pavement type REMEL may or may not be valid for use in TNM. Either way, the information would support the FHWA program to obtain better predictions.

The primary basis for the assessment of using the ODOT random transverse grooved concrete pavement type REMEL in TNM was to be the mean error value for the modeled noise levels. The mean error value was 3.1 dB (refer to Table 4). While some error was expected, 3 dB is a value too large to claim validity for the model. While a 3 dB or greater error could occur at one more locations within the test sample the mean value of all locations should not be this large. As a point of reference, the current TNM modeling practice for U.S. highway noise studies is to use the average pavement type for modeling the random transverse grooved pavement. Following this practice for the sites on this research project yielded an error of 4 dB. A 1 dB improvement in a 4 dB error is not sufficient to validate the use of the ODOT random transverse grooved concrete pavement type REMEL.

During the course of this project several lines of evidence have emerged that suggest a reason for the failure of the ODOT random transverse grooved concrete pavement type REMEL to reduce the TNM modeling error by more than 1 dB.

7.6.1. In-vehicle human perceptions

The ODOT random transverse grooved concrete pavement type REMEL was developed from data acquired in 1998 for a section of pavement constructed in 1997 in Noble County [Herman and Ambroziak 2000]. The pavement was one first to be constructed under the ODOT specification 451.09. Since that time the researchers and technical liaisons associated with this project had experienced interior vehicle noise levels while driving on other roadways within the state that were constructed under the same specification. During the site selection portion of this project the interior vehicle noise levels for the sites selected were perceived to be louder than some of the levels experienced at other locations within the state.

7.6.2. Noise level differences within one project

While various microphone locations were being considered for the site located adjacent to I-70 in Madison County it was perceived that the traffic noise was louder for the western portion of the site compared to the eastern portion. In order to determine the validity of the perceptions microphones were located on the shoulder adjacent to the eastbound outside travel lane at the same distance from the center of the lane. Data was collected simultaneously to determine

whether there were differences in noise levels for the same traffic that passed by both of the microphones. All conditions were equivalent including the roadways cross-section geometries throughout the length of the test section. Further, there were no reflecting surfaces to affect the condition of equivalence. Analysis of the results indicated a 2 dB difference in broadband noise levels. The comparison of the noise levels in one-third octave bands is shown in Figure 20.

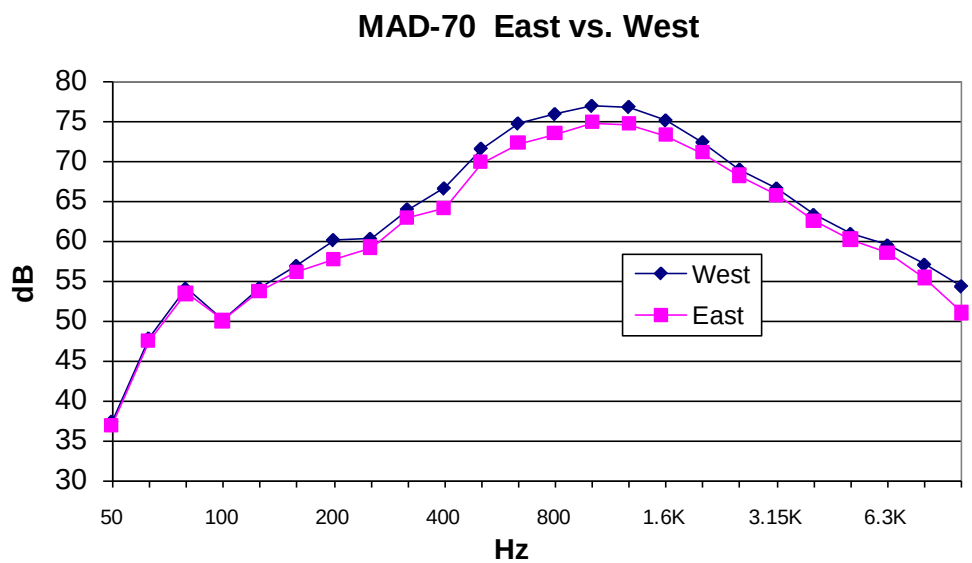


Figure 20. The differences between the eastern and western portions of the Madison County sites.

7.6.3. Differences in diamond grinding results

The average broadband noise level reduction due to diamond grinding for a section of I-76 east of Akron, OH was found to be 3 dB for microphone locations at 15 m or greater from the roadway [Herman et al 2006]. By contrast the average broadband noise level reduction due to diamond grinding at the Cincinnati site was -5.3 dB. Assuming that the diamond ground textures for both pavements are similar, this results suggests that random transverse grooved Cincinnati pavement produced higher traffic noise levels than the I-76 random transverse grooved pavement.

7.6.4. Discussion Summary

The observations discussed in this section suggest that the noise producing properties of the random transverse grooved concrete pavements vary throughout the state even though they were all constructed under the same specification. Not only do they vary by construction project, but also within a construction project. This variation could account for the fact that the ODOT REMEL developed from the I-77 data, when used in TNM, does not provide an accurate prediction of traffic noise levels for the random transverse grooved pavements studied in this research project.

8. CONCLUSIONS

Traffic noise predictions, using the Federal Highway Administration Traffic Noise Model (TNM) configured for both the average pavement type and the ODOT random transverse grooved concrete pavement type, were compared with noise level measurements at 37 microphone positions at three sites in Ohio where the roadways were constructed with concrete pavement having a random transverse grooved surface texture. The analysis of the data resulted in the following findings:

1. The error for the prediction based on the average pavement type ranged from an under-prediction of -7.3 dB to an over-prediction of +1.7 dB with a mean value of -4.1 dB. By contrast the error for the prediction based on the ODOT random transverse grooved pavement type ranged from an under-prediction of -5.8 dB to an over-prediction of +2.8 dB with a mean value of -3.1 dB. The over and under-prediction of the TMN configurations were based upon the Model with REMELs for "average" pavement type and the model with the REMELs for the ODOT transverse grooved pavement type.

2. The paired t-test determined that the sample means of the TNM average pavement and the ODOT random transverse grooved pavement were not equivalent based upon a level of confidence of 95 percent.

3. The mean errors for the predictions of the TNM configured for the average pavement type and of the TNM configured for the ODOT random transverse grooved pavement are statistically different than zero.

4. An examination of the one-third octave band frequency levels indicates that at frequencies greater than 500 Hz, the measured traffic noise levels exceeded both the TNM average pavement type and TNM ODOT random transverse grooved pavement predictions for the majority of microphone positions. However, at frequencies less than 500 Hz the predictions tended to exceed the measurements.

5. The TNM configured for the ODOT random transverse grooved concrete pavement type is slightly more accurate and a slightly more consistent predictor of noise levels than the TNM configured for the average pavement type.

6. The ODOT construction project to re-texture the surface of a portion of I-275 in the Cincinnati area (Site 1) by diamond grinding was effective in reducing broadband traffic noise levels at the microphone locations by an average of -5.3 dB. One-third octave band analysis indicated that most of the noise level reduction was in the frequency range of 200 Hz to 8 kHz.

8.1. Recommendations

1. The experimental version of TNM developed for this project, using the current ODOT random transverse grooved concrete pavement REMEL, should not be used in practice due to its potential to under-predict traffic noise levels.

2. The experimental version of TNM developed for this project should be refined to eliminate the tendency to under-predict noise levels. This development should be accomplished by implementing a REMEL developed from traffic noise data acquired from those random transverse grooved concrete pavements that exhibit noise producing characteristics in the higher end of the typical range. The data collection for the REMEL development should be made in accordance with the standard USDOT/FHWA REMEL data collection procedure [Lee and Fleming 1996].

3. Diamond grinding should be considered as a mitigation measure for locations where ODOT is concerned about traffic noise levels at sites with random transverse grooved concrete pavement.

4. A new surface texture specification should be developed for concrete pavements to replace the current specification (451.09) in order to reduce tire/pavement noise levels while maintaining or improving safety and durability characteristics.

8.2. Implementation

None.

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APPENDIX A

Equipment	Model	Serial Number
Larson-Davis Real Time Analyzer	3200	0459
Larson-Davis Preamplifier	PRM900B	0317
Larson-Davis Preamplifier	PRM900B	0320
Larson-Davis Microphone	2559	1264
Larson-Davis Microphone	2559	1261
Larson-Davis Sound Level Meter	812	0336
Larson-Davis Sound Level Meter	812	0337
Larson-Davis Sound Level Meter	812	0338
Bruel and Kjaer Acoustic Calibrator	4231	2241909
Sony DAT Player/Recorder	TCD-D8	548971
Sony DAT Player/Recorder	TCD-D8	548631
Sony DAT Player/Recorder	TCD-D8	548973
Sony DAT Player/Recorder	TCD-D8	548974
Sony DAT Player/Recorder	TCD-D8	548975
Davis Instruments Weather Wizard	III	WC80224A51
Hygrocheck Digital Hygrometer	NA	5851
Omegascope Hand Held Infrared Thermometer	OS520	7012794
Larson-Davis "Dummy" Microphone	ADP005	74868 UG-1094/U

APPENDIX B

Equipment Procedures for REMEL Project

LD 812 SLM setup:

1. install battery (a good 9V battery will last a long time in the SLM)
2. turn on

NOTE: steps 3-6 can be done while SLM is self-testing

3. battery check: Shift>battery>cancel
4. polarization (**200**V): Setup>modify>**43**>enter (to change use [>|] > enter) > cancel
5. calibration level (**94.0** dB): Setup>modify>**35**>enter (ditto above paren.)>cancel
6. AC output (**FLAT**): Setup>modify>**41**>enter (ditto above paren.)>cancel
7. DATA RESET (must do this before steps 8-10): Shift>reset>reset to affirm "YES" Wait--SLM will go to start menu when finished.
8. Detector speed (**FAST**): Setup>modify>**39**>enter (ditto above paren.)>cancel
9. Set input filter (**A** weighted): Setup>modify>**40**>enter (ditto above paren.)>cancel
10. Calibrate Mic. (**94** dB): Place calibrator over microphone, turn on @ 94 dB level. Shift>cal/SLM>(up arrow to check cal., <u>down arrow to set level to 94.0 dB</u>). Wait--SLM will say "done" when finished. You may have to repeat if message is "can't calibrate." Exit with Enter or Cancel.
11. Press the SLM button and R/S, else the SLM unit will go to sleep.

DAT setup:

1. Check batteries; don't risk losing a recording. Batteries showing a "1/2" or "3/4" indication may sink fast.
2. Switch: SP 48.kHz (switch to left)
3. Switch: Line Out (output not controlled by +/- level buttons) (switch to right)
4. Switch: Manual Record Mode (switch to left)
5. Switch: Low Mic Sens (switch to left)
6. Synchronize Dates and Clocks.
7. Reset tape counter at TOP (beginning) of tape, nowhere else.
8. Perform steps 1 and 2 of the section "Recording session" below, then lightly place a knob on the record level control shaft. In a quiet place, set the sound level calibrator, producing a 94 dB tone, fully on the microphone. The mic signal will go to the DAT Right Channel. Press Pause/Record on the DAT and adjust the control for the desired deflection of the record level indicator. When finished, press the Stop button and carefully remove the record level knob without disturbing the adjustment.

Some judgment is required in the setting, which must finally be verified in the field by observing the effect of traffic noise to be recorded. There are two conditions that must be satisfied. First, the noise to be recorded should maintain at least a "three bar" deflection of the record level indicator and must not cause the "OVER" warning to be shown by the record level indicator. Second, the calibration tone must be somewhere in the same range. Those conditions are satisfied by the adjustment of the record level control. If they can not be satisfied, there are two options: use a 114 dB calibrator on the microphone or, as a last resort, accept a less than "three bar" level for the noise.

Here are suggested starting points for adjustment of the record level control. When the noise is expected to be very high, set a 94 dB calibration tone at the "circle 12" indication on the meter and in the field check to be sure that the noise does not drive the meter to the "OVER" indication. For extremely high noise levels, set the 94 dB tone lower than the "12" mark (but no lower than a four-bar meter indication) or use a 114 dB calibrator. Where low noise levels are expected, set the 94 dB calibration tone at the high end of the record level indicator, staying clear of the "OVER" indication.

Incidentally, plugging the AC power supply into a DAT disconnects the batteries and, if the power supply is not active, the date and time clock will reset in a few seconds.

Recording session:

1. Perform SLM and DAT setups as described above. Assemble the SLM and DAT to a mounting plate. Push 1/8" mini plugs of the short jumper cable into output jack of SLM (red sleeve end in SLM) and Mic input of DAT. Double check DAT switch settings.
2. In a quiet place plug headphones into DAT Line Out jack to check sound quality of the mic, SLM and DAT assembly. Press Pause/Record (press and hold Pause button on DAT and "roll over" onto Record button). You will only hear sound from the Right headphone. Wiggle the connectors. There should be no hum or static and you should be able to hear yourself speak. Press Stop.
3. In a quiet place, record a 60 second calibration tone: Set the sound level calibrator to 94 dB, turn it on and place it fully on mic. The mic signal will go to the DAT Right Channel. Press Pause/Record on DAT to monitor the record level. The 94 dB signal should produce the expected Right Channel sound level meter indication. (See "DAT setup" step 8.) If the signal appears steady, re-start the calibrator to be sure it will run for the whole minute and press Pause to begin recording. Do not disturb the equipment or undesired noise may be recorded with the calibration tone. Press Stop at the end of the minute.
4. Before collecting sound data, verify that the DAT clocks are still synchronized.
5. If the clocks are synchronized it is *not good practice* to start and stop the data collection recording at exactly the beginning and ending of the data period. Start the recording a little early and stop it a little late, to avoid trying to play the tape into the RTA when the RTA endstor value is the same duration as the recorded noise.
6. Use the preprinted form to note times when extraneous noises void the recording. The bad noise data can then be purged from the analysis.
7. At the end of a recording, slide the cassette write-protect tab "open" to prevent erasure.
8. If you are using a DAT or some other instrument to record from the AC output of the RTA, note that changing the scale factor of the RTA changes the RTA output level. A calibration tone recorded on the DAT through the RTA will be voided if the RTA scale factor is changed after the calibration.

LD 2900B RTA setup

Procedure summary: you will create a new RAM data file, key-in setups for READ and CAL, store each in turn to a user setup soft key so named, copy the file to floppy disk.

It is not necessary to have separate "mic" and "DAT" versions of these setups because the 200 Volt microphone polarization voltage can not reach the DAT, only the mic.

To create a user setup routine:
User setups can be renamed and redefined but sometimes a wholesale "R.SETUP" (step 2) is easier.
1. Turn ON, wait for main menu. Display should show "Dual" in line 3 and "Channel 1 of 2" in line 6. If not, fix with SYSTEM>#chanls and CH1 and CH2 keys, followed by EXIT.
2. If desired, to clear all existing user setups at once, SYSTEM>SETUP>R.SETUP.

If you clear all the old user setups, you must create new sites to hold new setups. If you are not in the SETUP menu, go there from the main menu and press the "name" key. You are prompted to select one of the "undef" (undefined) or named keys ('J' through 'P') to hold the new setup and then to enter the name. Press EXIT. Repeat to create sites for additional user setups, then define them in the following steps.

For a READ (analysis) setup:
3. DISPLAY>Dig.WGT>NO WGT>1/3>EXIT
4. DETECTR>LIN.R>AV.TIME>0.25>EXIT>EXIT
5. SYSTEM>INPUT>20-10kHz>200V>EXIT>UNITS>SPL>EXIT>EXIT>Leq
On the second pass, skip step 6.
6. Change the input channel (press the CH2 or CH1 hard key) and start over at step 3.
7. AUTOSTR>byTIME>delta>60.0>EXIT> endstor>3600.0>EXIT>EXIT
8. Store the setup in a prepared user setup site using the steps given below the CALIB setup.

For a CALIB (calibration) setup:
3. DISPLAY>Dig.WGT>NO WGT>1/3>EXIT
4. DETECTR>EXP>EXIT
5. SYSTEM>INPUT>20-10kHz>200V>EXIT>UNITS>SPL>EXIT>EXIT>NORMAL
On the second pass, skip step 6.
6. Change the input channel (press the CH2 or CH1 hard key) and start over at step 3.
7. AUTOSTR>OFF>EXIT
8. Store the setup in a prepared user setup site using the steps given below.

To store a setup: SETUP>STORE(the 'E' key)>press the soft key displaying the desired setup name>EXIT. To make the 2900B boot directly to a user setup: SETUP>BOOT>press soft key of desired boot setup>EXIT.
To import stored setups if they are not in a file already stored in RAM, load a floppy file containing the setups, move it to memory, highlight the file on the left side of the FILES screen, EXIT to the main screen. The file name that was highlighted appears in the lower left hand corner of the screen and any user setups stored in that file are available from the keyboard.

Sound analysis session:

Calibration
To run a calibration (CALIB) setup, boot system>SYSTEM>user setup soft key>EXIT. Place calibrator carefully on the mic or play the DAT calibration signal track. Press R/S key. It may be necessary to adjust the display scale using the up and down arrows. If "OVER" is displayed,

use the up arrow to increase the scale factor until “OVER” does not appear. **Move dotted line cursor to 1000Hz filter using the < and > arrows.** If the “d=” reading is steady but not 94.0: SYSTEM>UNITS> level>[type in the calibrator setting (+094.0 or +114.0)]>EXIT. Use a cable with the mic because pushing buttons can be “heard.” Note the + sign. If a minus sign is shown it is necessary to change it with SHIFT>+. To halt: R/S>EXIT. If analyzing both channels simultaneously, it is necessary to calibrate both. After calibrating one channel, press R/S>exit and change the channel with the CH 1 or CH 2 button. Calibrate the other channel using R/S to start and R/S>EXIT to quit.

Data collection

To run a data collection (READ) setup: boot system>SYSTEM>user setup soft key>EXIT. The delta and endstor parameters can now be changed to suit without disturbing the other settings, using EXIT to return to main menu. If you change any SYSTEM parameter, e.g. #chanls, be sure to press EXIT>Leq after the change, else it defaults to and stores another measure.

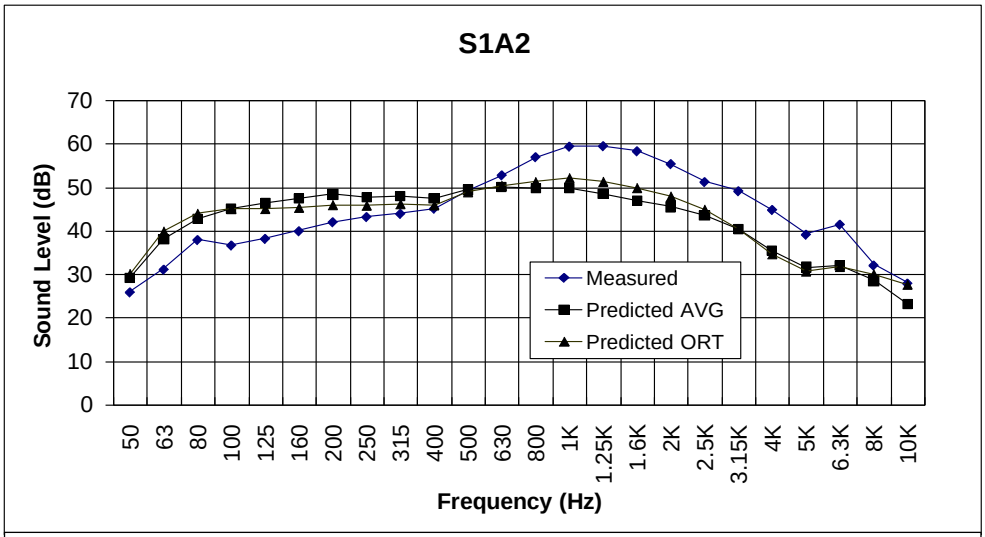
Two DAT recordings can be collected and analyzed at once, using Channel 1 and Channel 2 simultaneously. Both DAT-to-RTA cables are wired to connect the DAT Right Channel to the RTA. Connect the mini plug to the Line Out jack on the DAT and the other plug to a mic input of the RTA. Preview mic or DAT signals with earphones (via RTA AC output jacks) to check for unwanted system noise. Press R/S key to begin analysis. Start DAT a little before hitting R/S and be sure there is data on the DAT a little past the endstor RTA setting to avoid recording void data at the end. If “OVER” is displayed, the RTA input is overloaded. Use the up arrow to increase the scale factor until “OVER” does not appear, and start over. Elapsed time of the session is displayed in seconds on the top line of the display. The RTA will halt at the endstor value, and tape(s) can then be stopped. Data are stored automatically at the end of each “delta” time interval. The RTA can be stopped using the R/S key before endstor is reached and as many observations will have been recorded as there were “delta” periods before R/S was pressed. If using a microphone with the RTA, use a mic cable to physically isolate the mic from mechanical vibrations due to pushing buttons on the RTA.

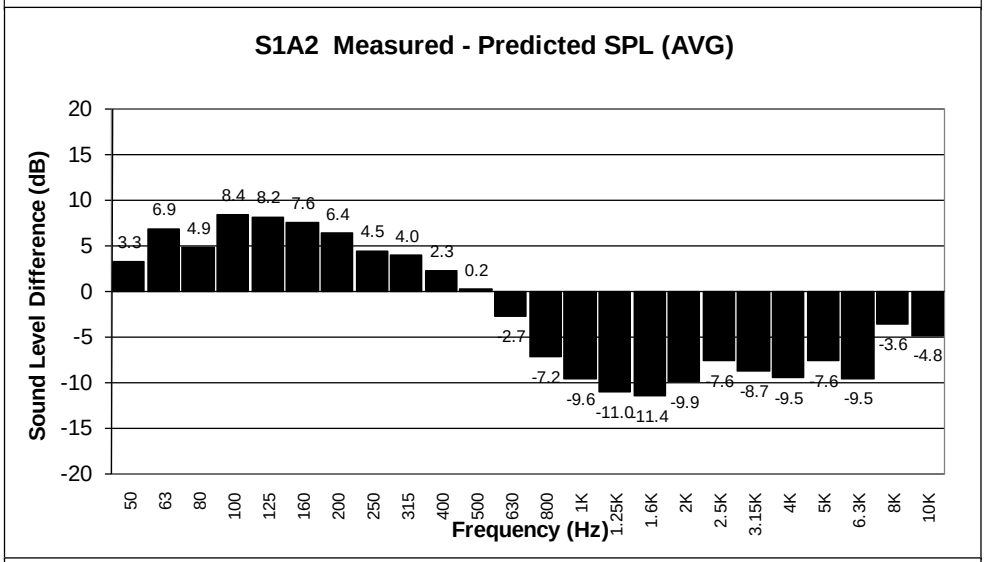
A file created in the FILES menu will contain data created, and the user setups present in RAM, while that file name appears in the lower left hand corner of the main menu. Each data set stored with the STORE key or automatically by AUTOSTR adds a “record” under the file name that can be confirmed by pressing the “RECORDS” soft key in the FILES menu. Individual records can be deleted from the RAM file. Copying a RAM file to the floppy moves all the records to the floppy as well as the user settings. Floppy files can be copied to RAM. The floppy files are binary; there is no “unerase,” and they can not be edited. Data can be transferred to the translation program RTAUtil32 via the floppy or by using a null modem. If the latter, set the 2900B and the computer to 9600 Baud. Develop a systematic procedure for moving data from the RTA to secure storage without losing the identity of the data because of ambiguous or duplicate file naming.

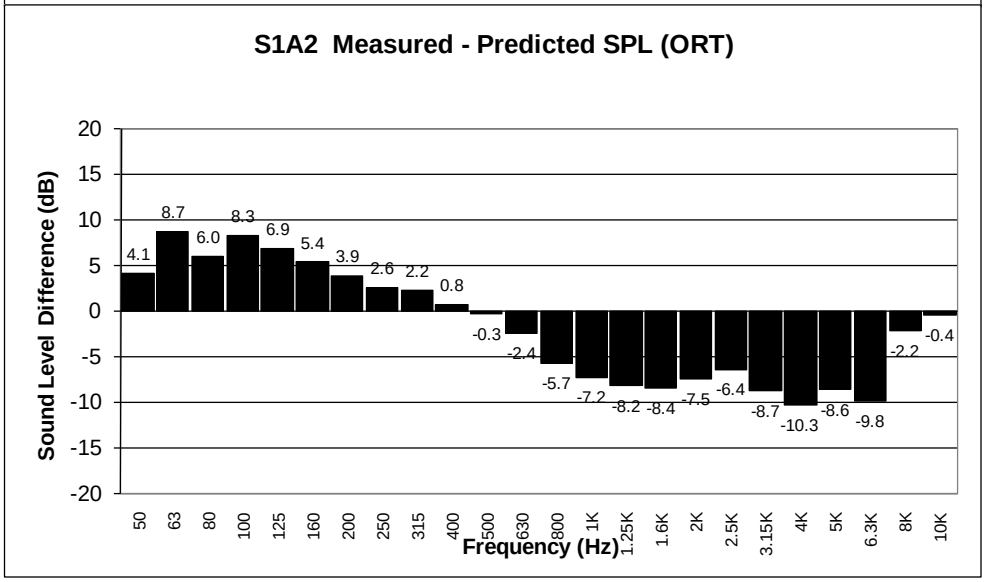
Note on DAT AC power supplies. Plugging the power supply cable into the DAT disconnects the internal battery. If the power supply isn’t live, the DAT time-of-day clock will reset after a few seconds.

APPENDIX C

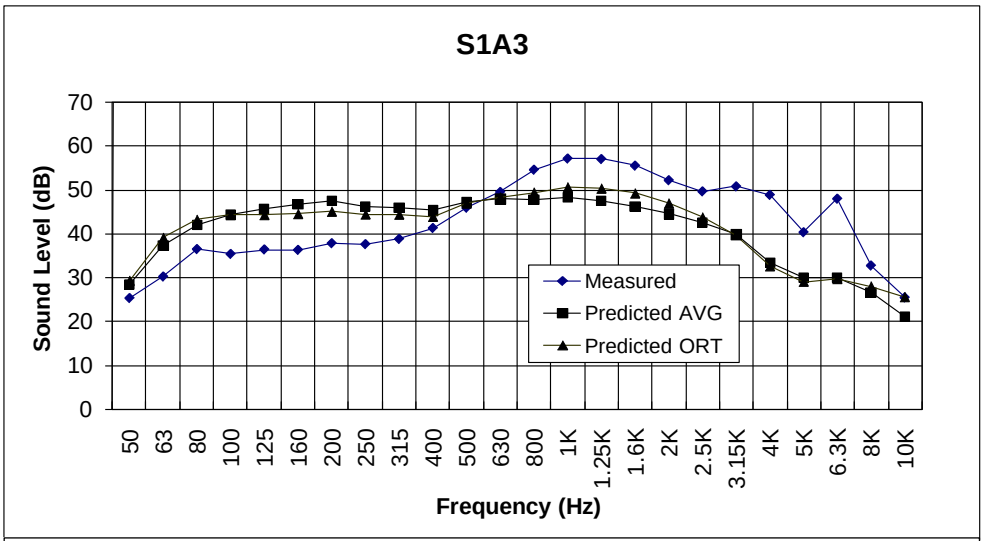
Site 1, Area A, Microphone 2

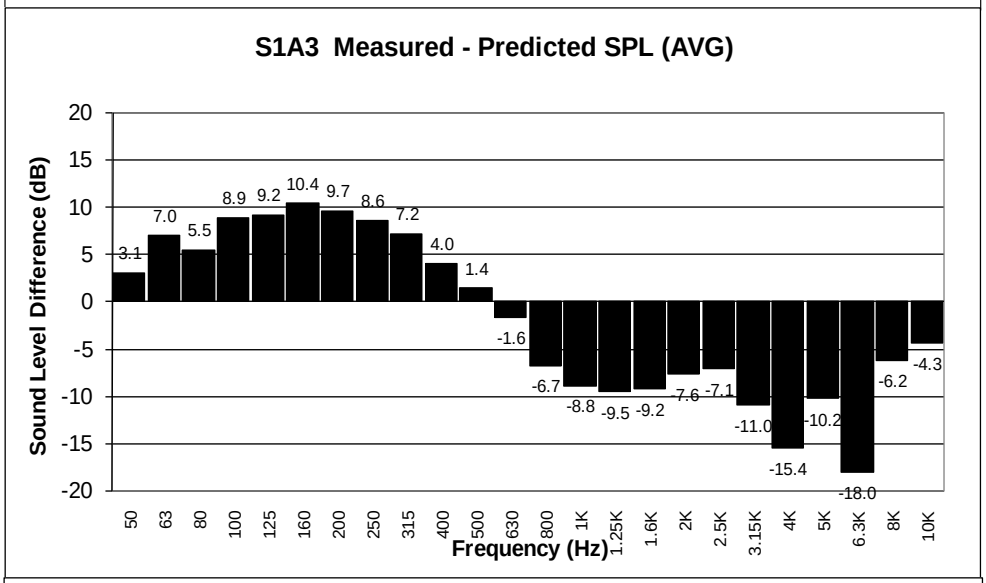


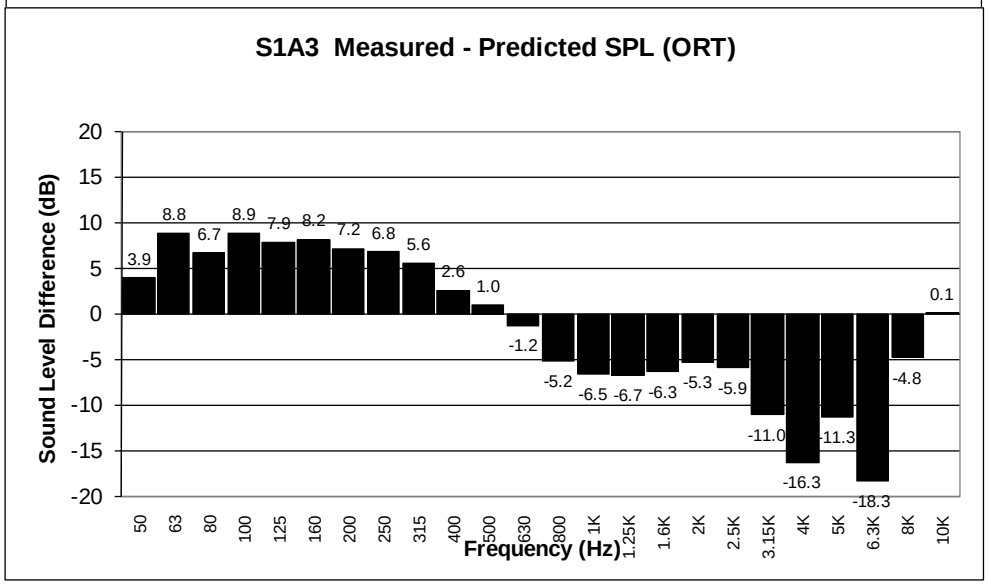




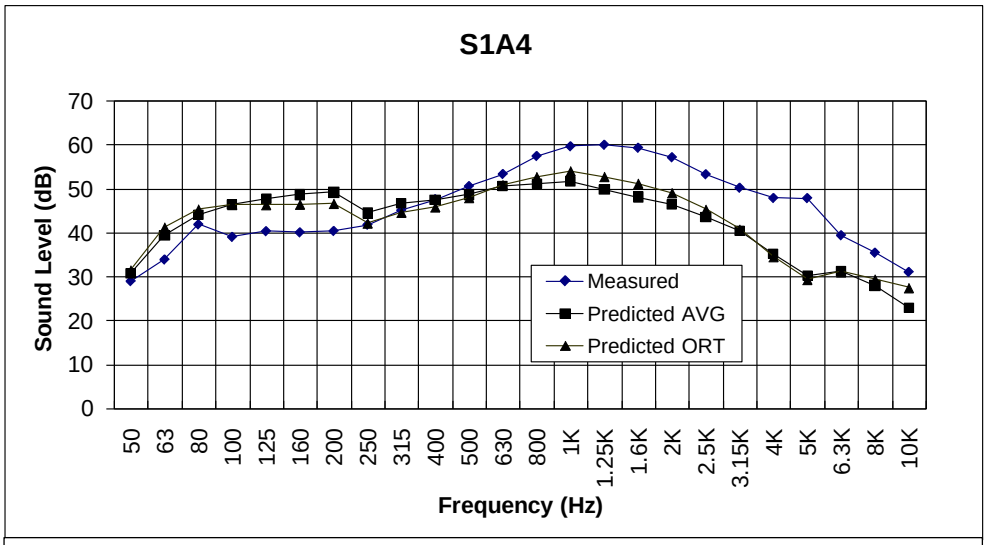
Site 1, Area A, Microphone 3

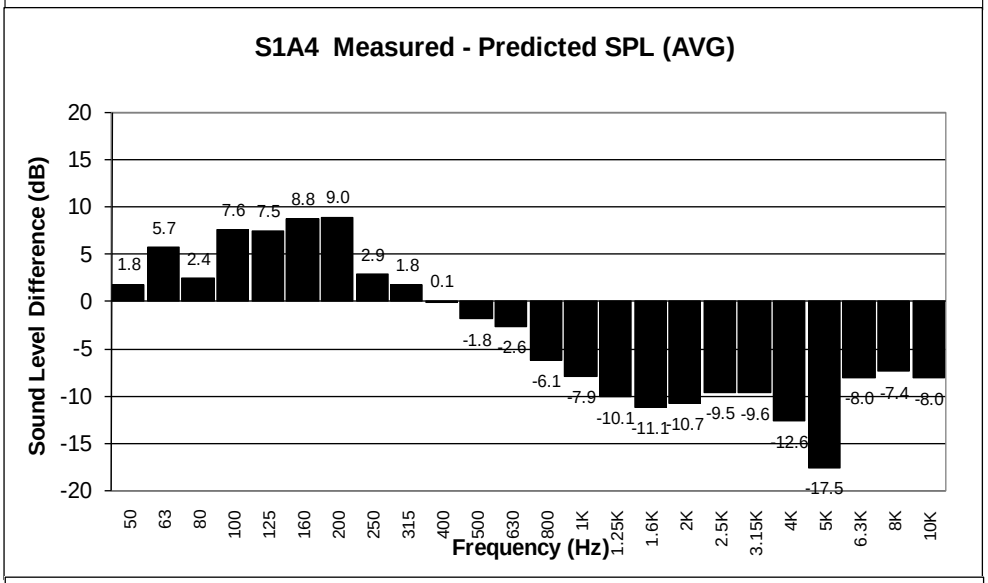


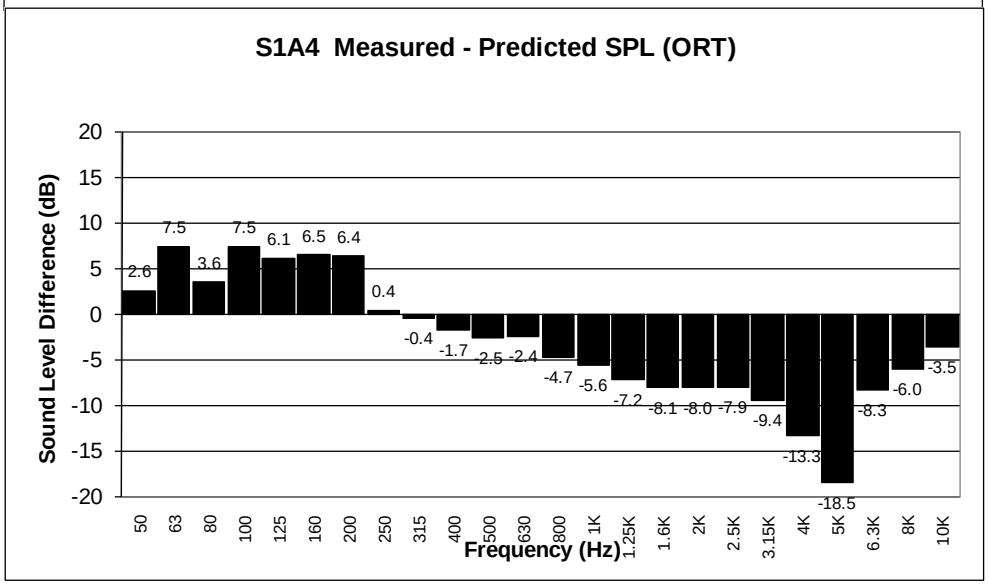




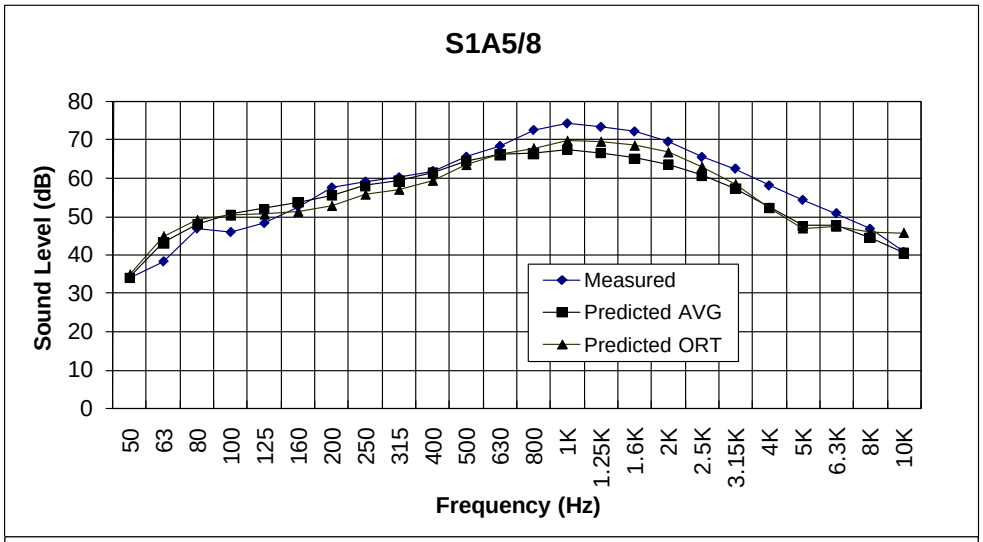
Site 1, Area A, Microphone 4

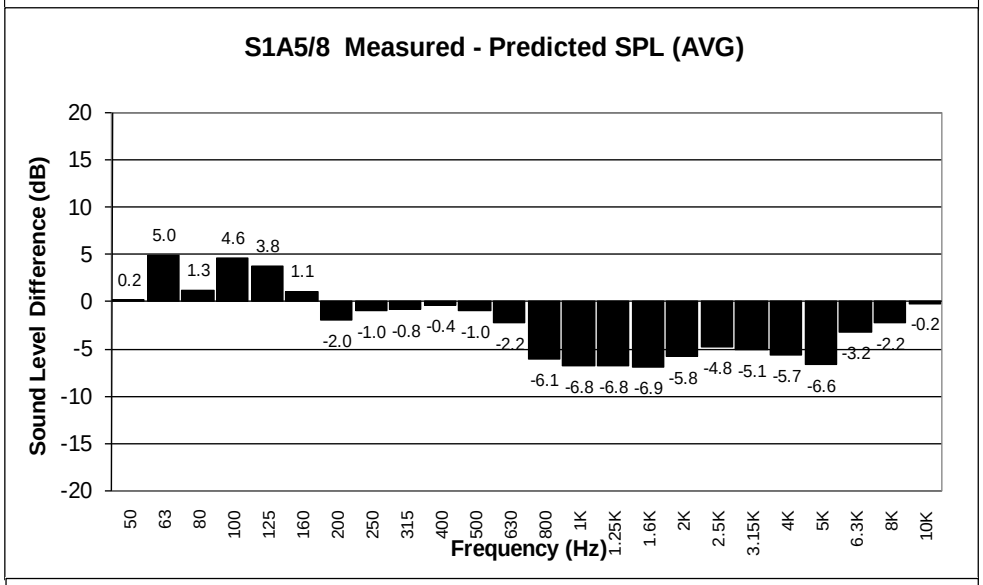


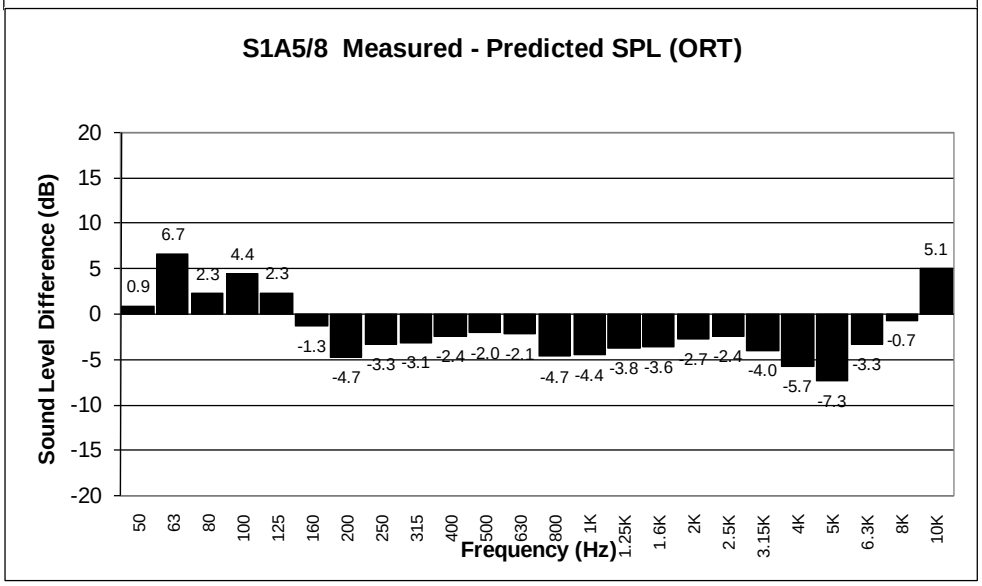




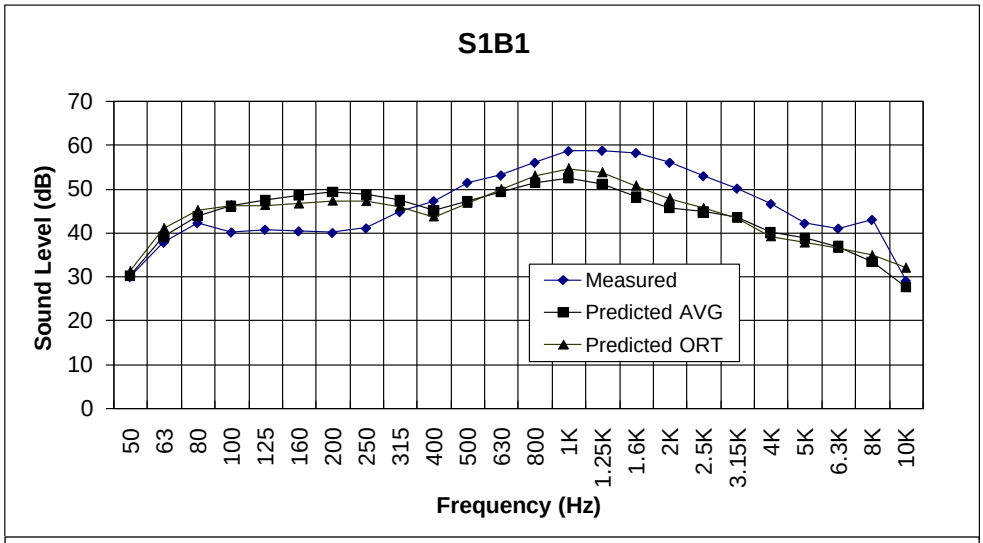
Site 1, Area A, Microphone 5/8

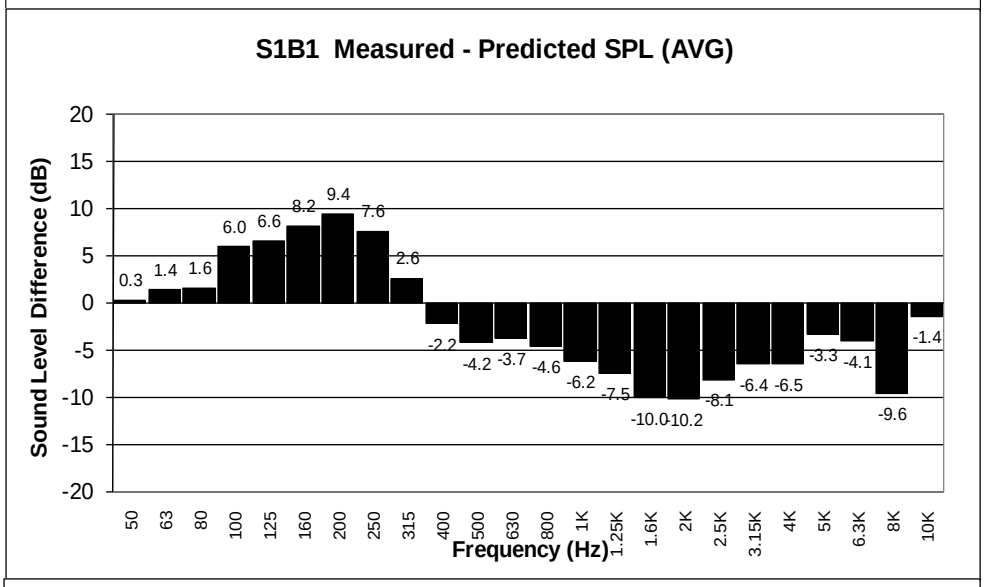


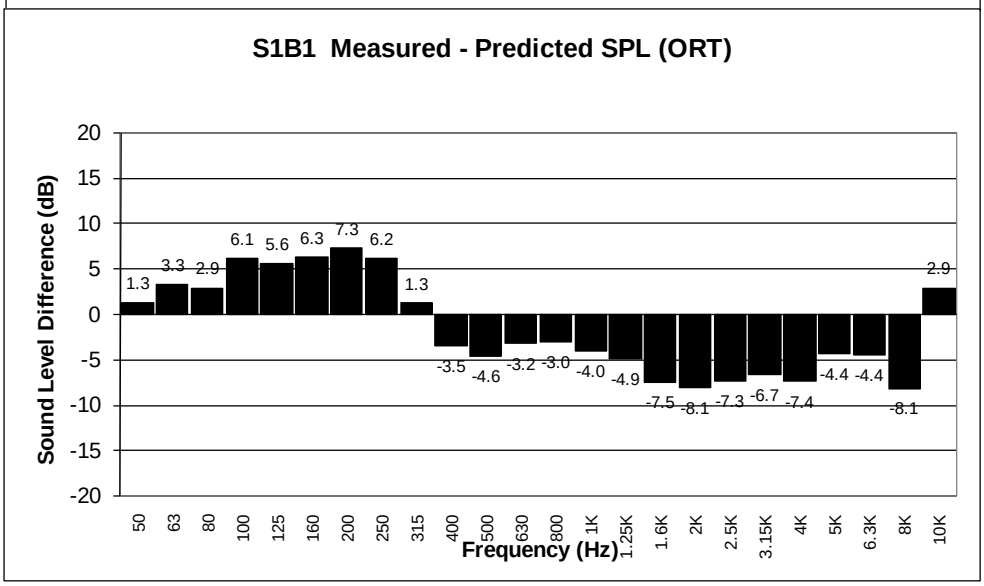




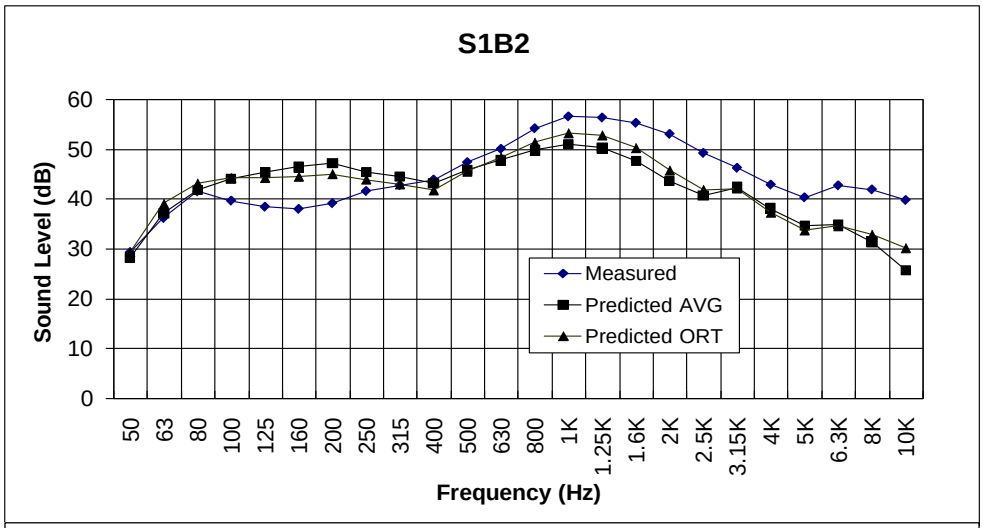
Site 1, Area B, Microphone 1

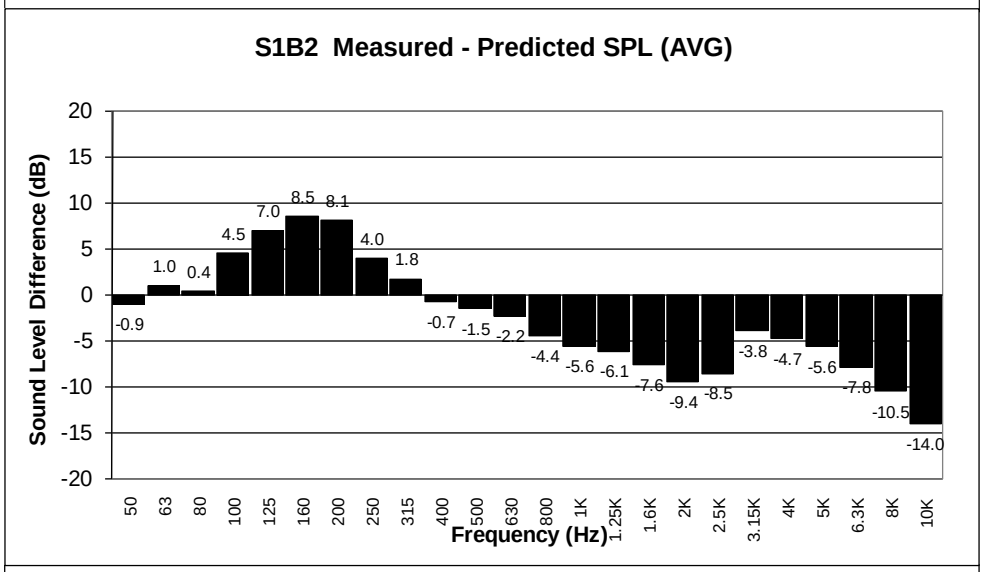


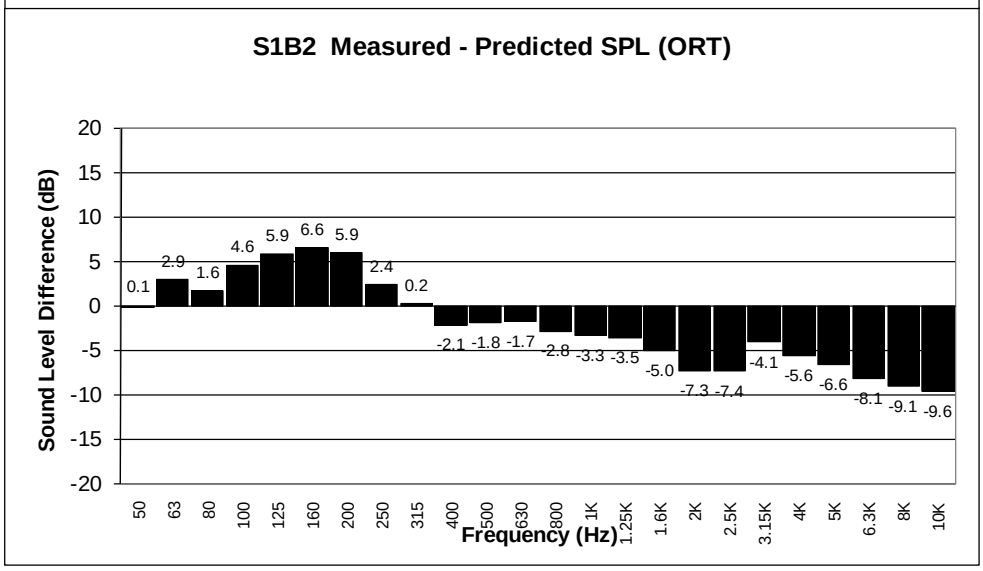




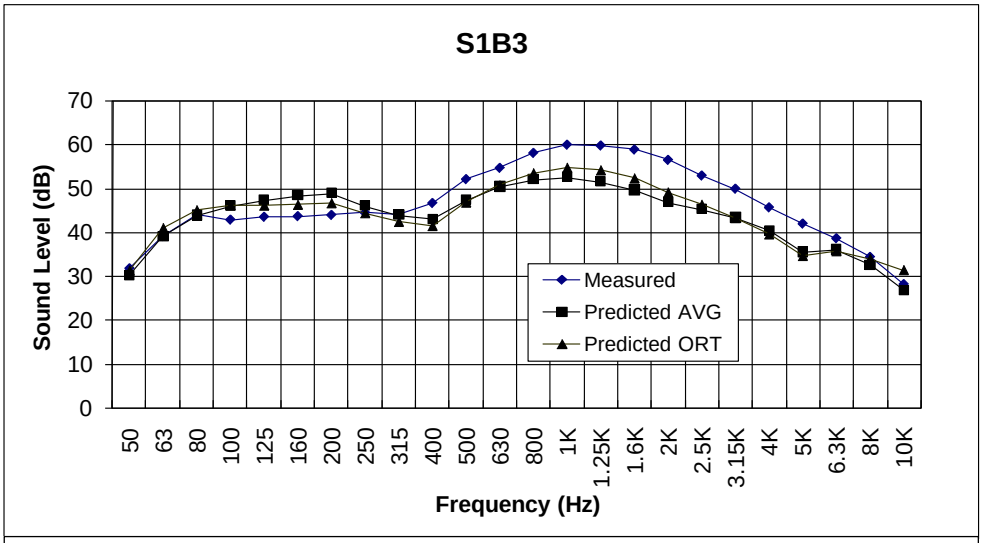
Site 1, Area B, Microphone 2

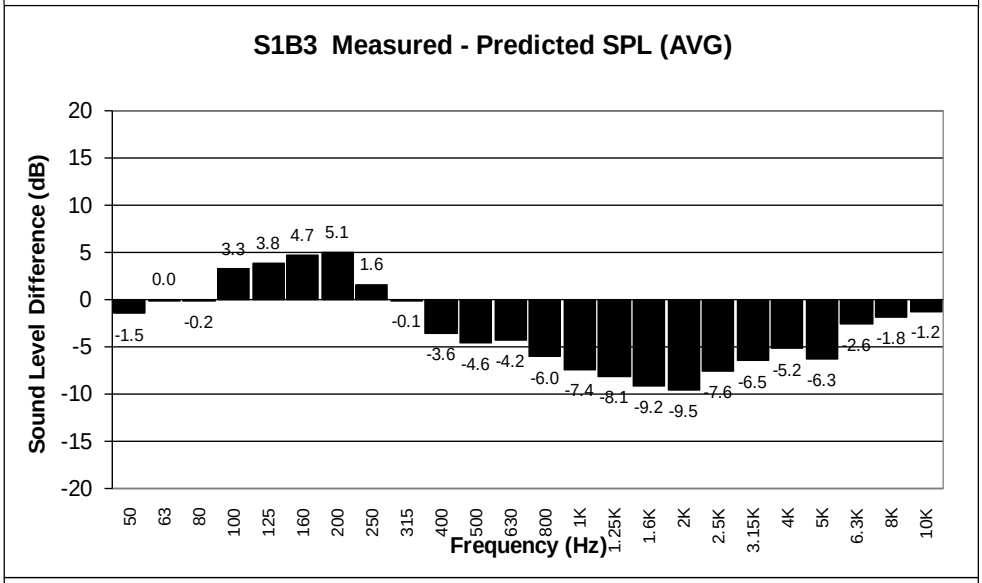


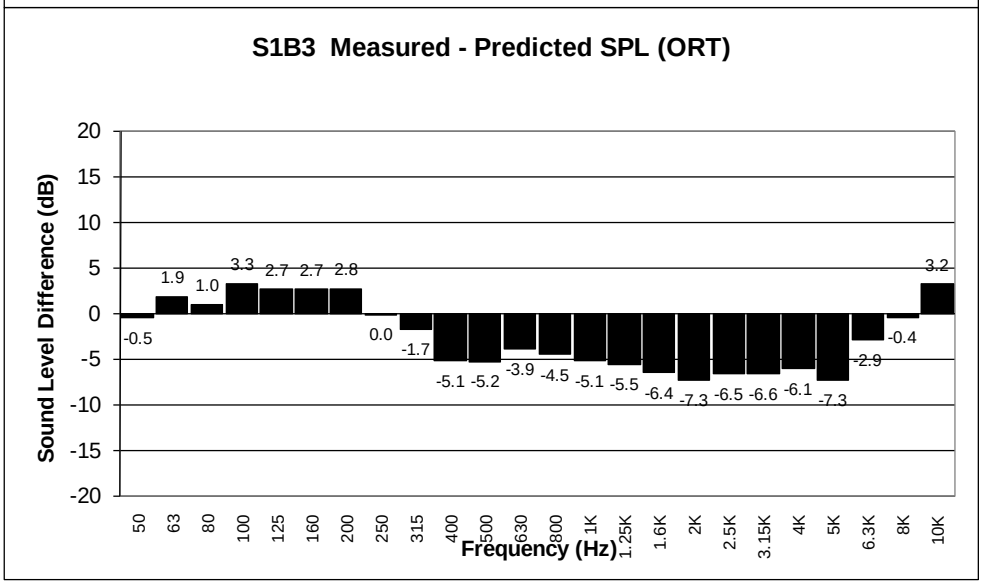




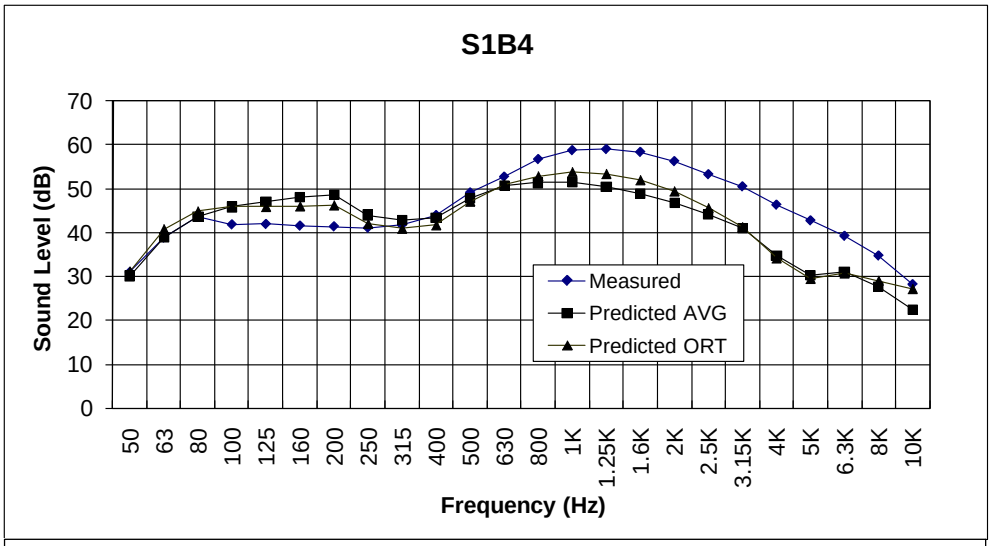
Site 1, Area B, Microphone 3

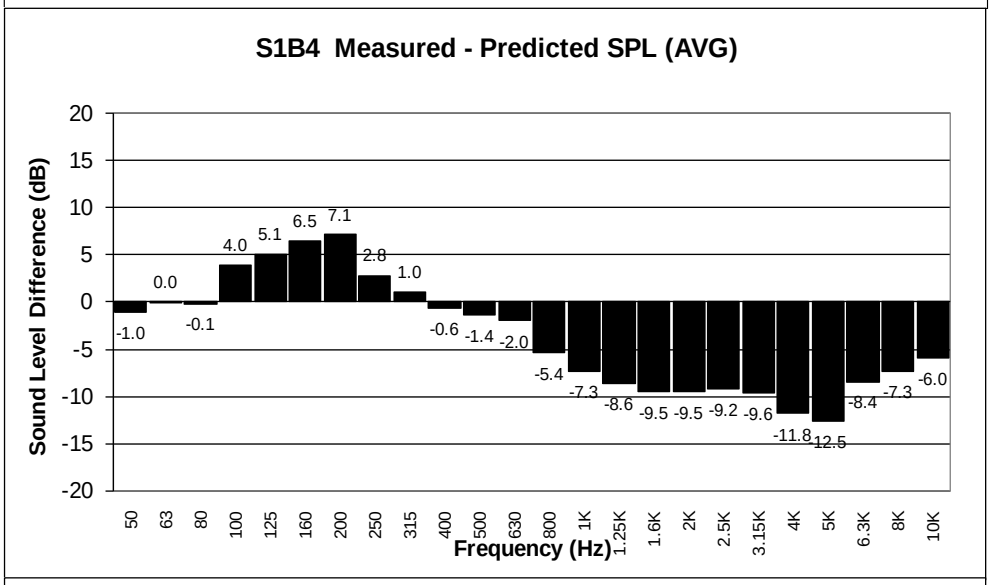


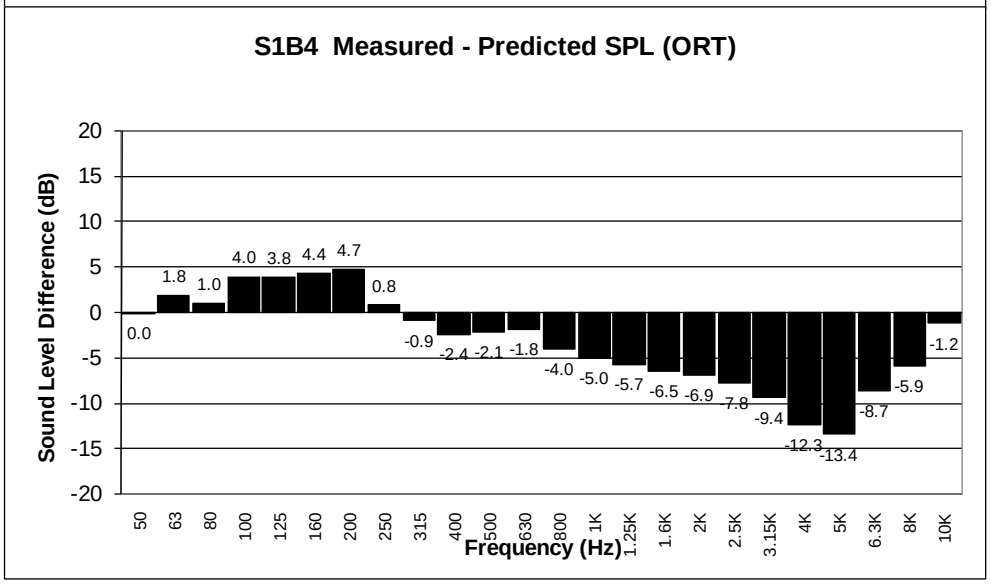




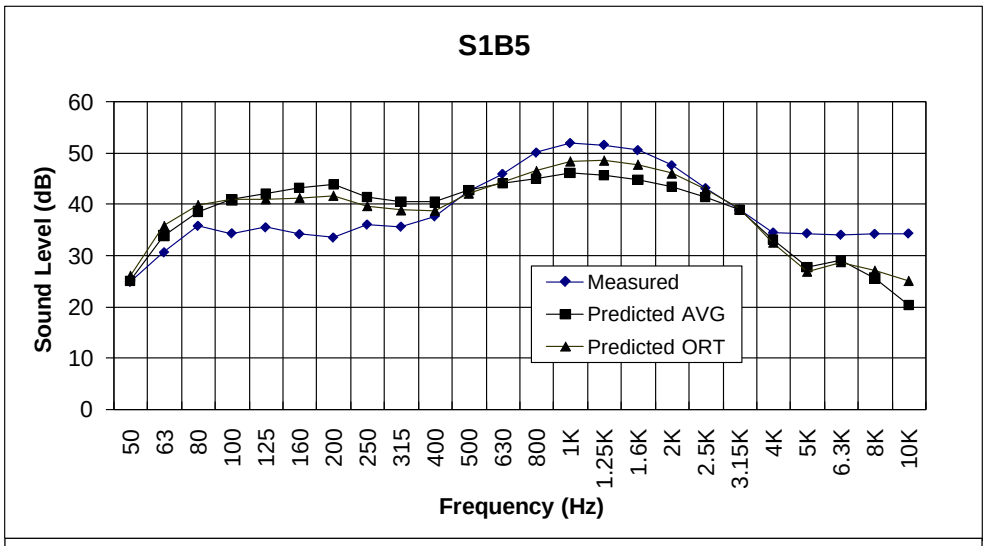
Site 1, Area B, Microphone 4

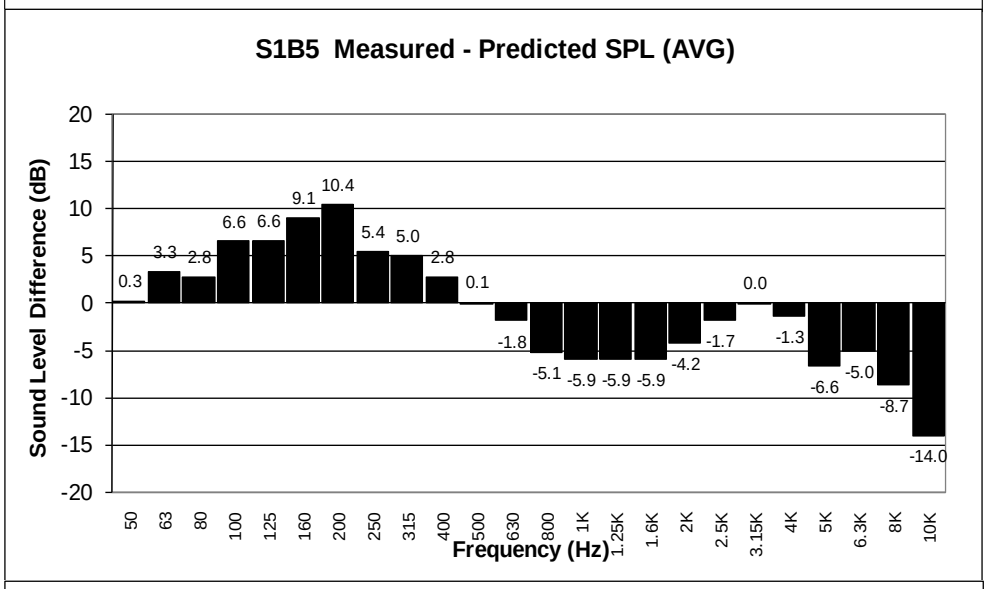


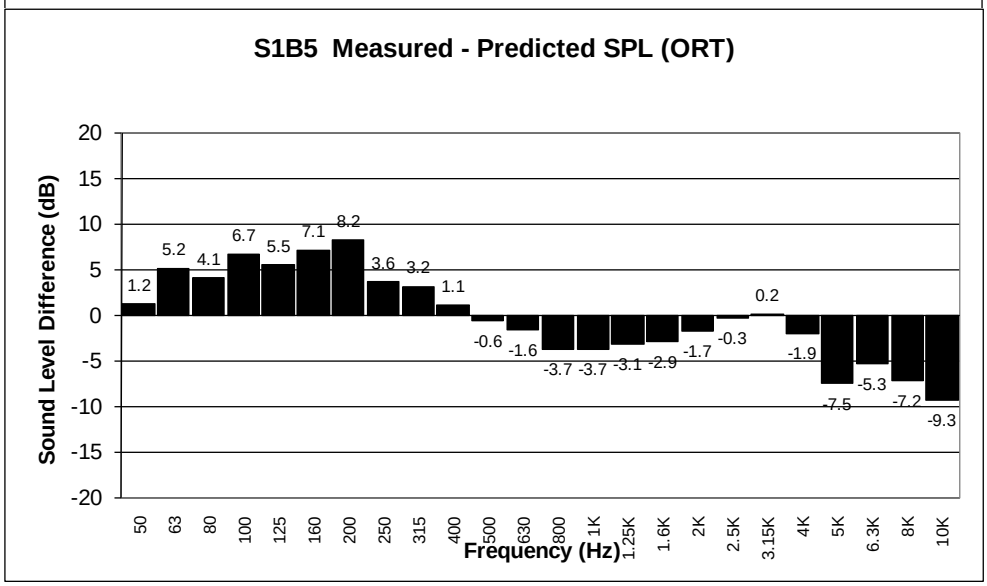




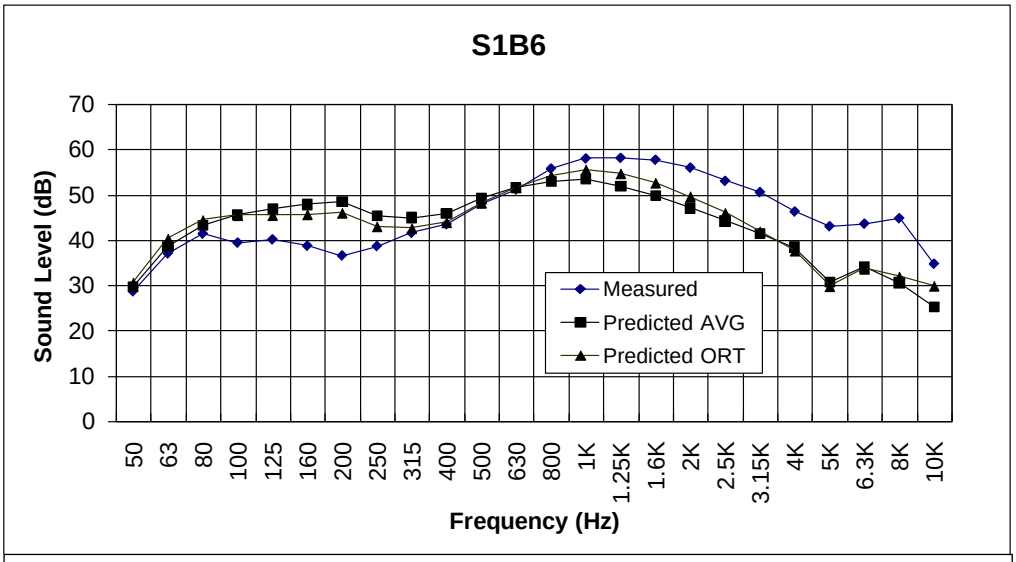
Site 1, Area B, Microphone 5

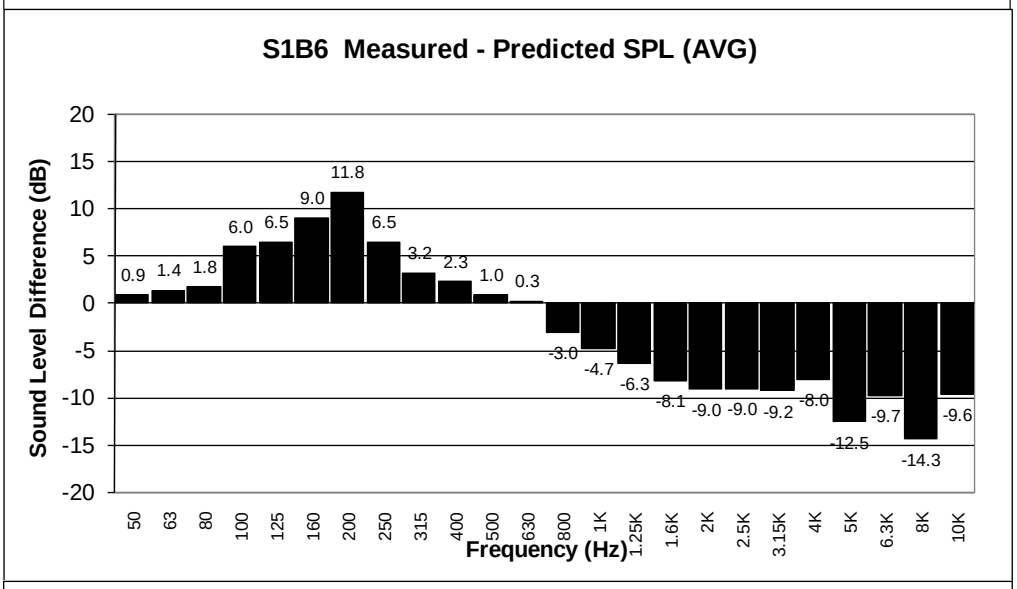


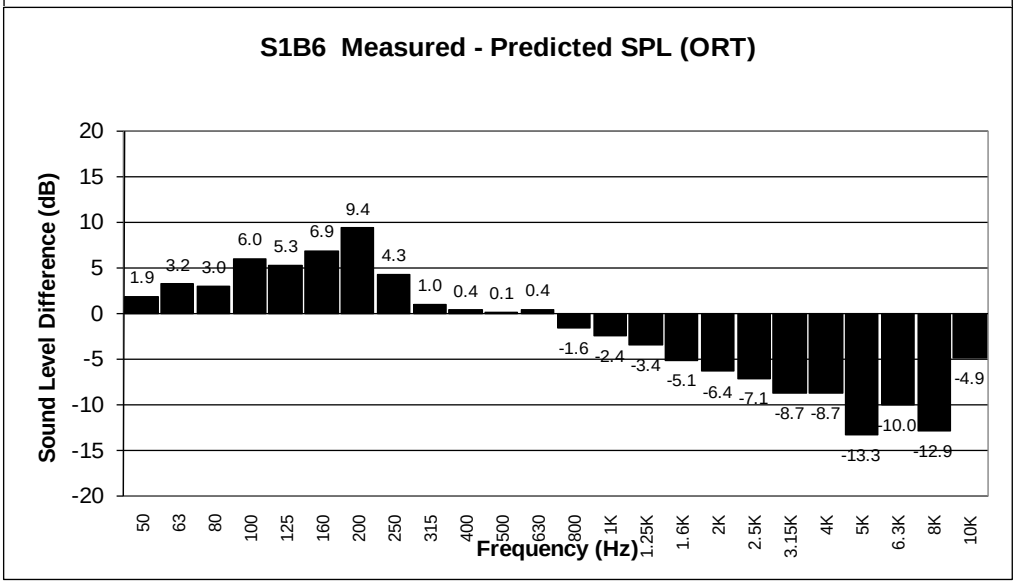




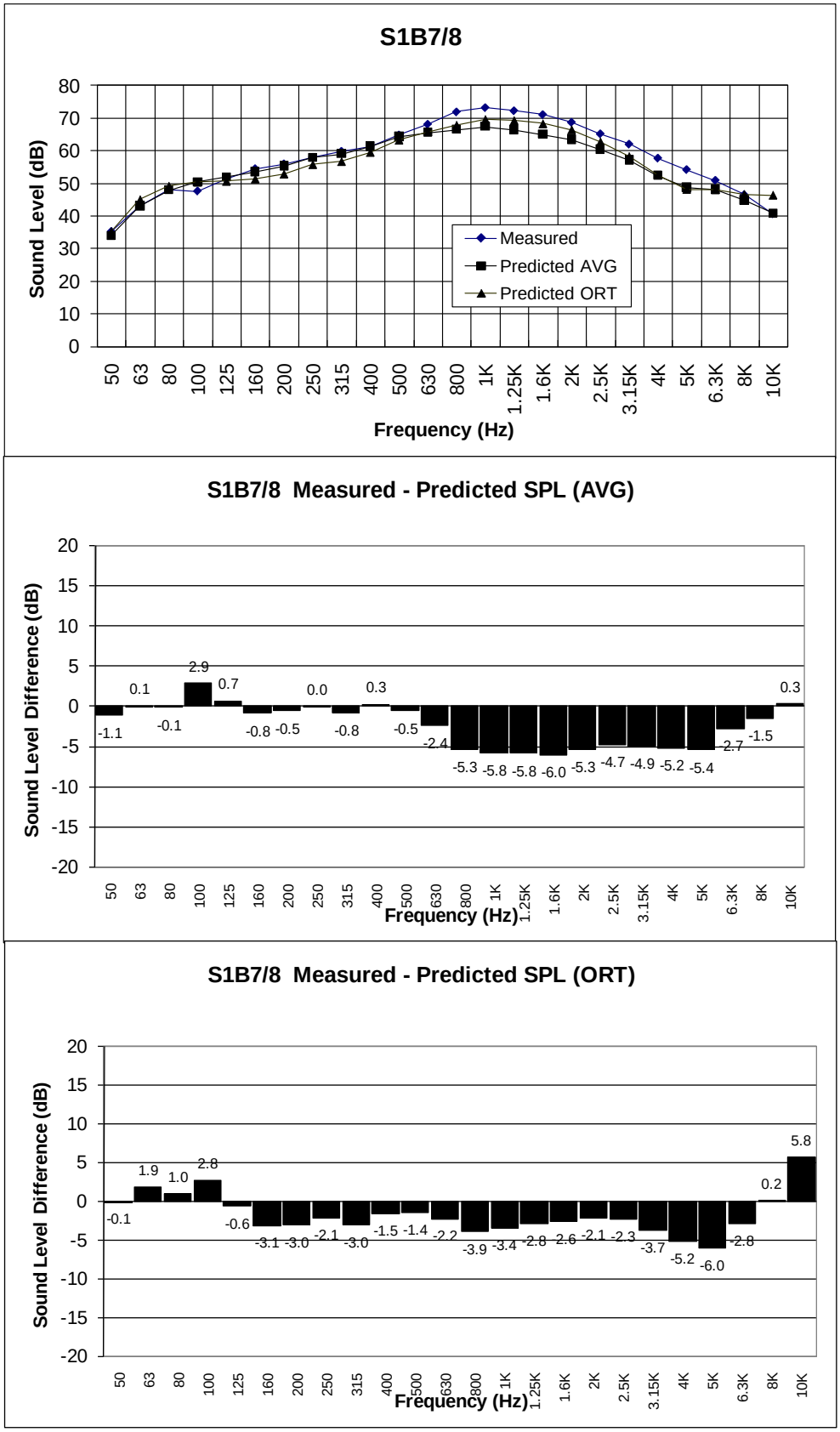
Site 1, Area B, Microphone 6



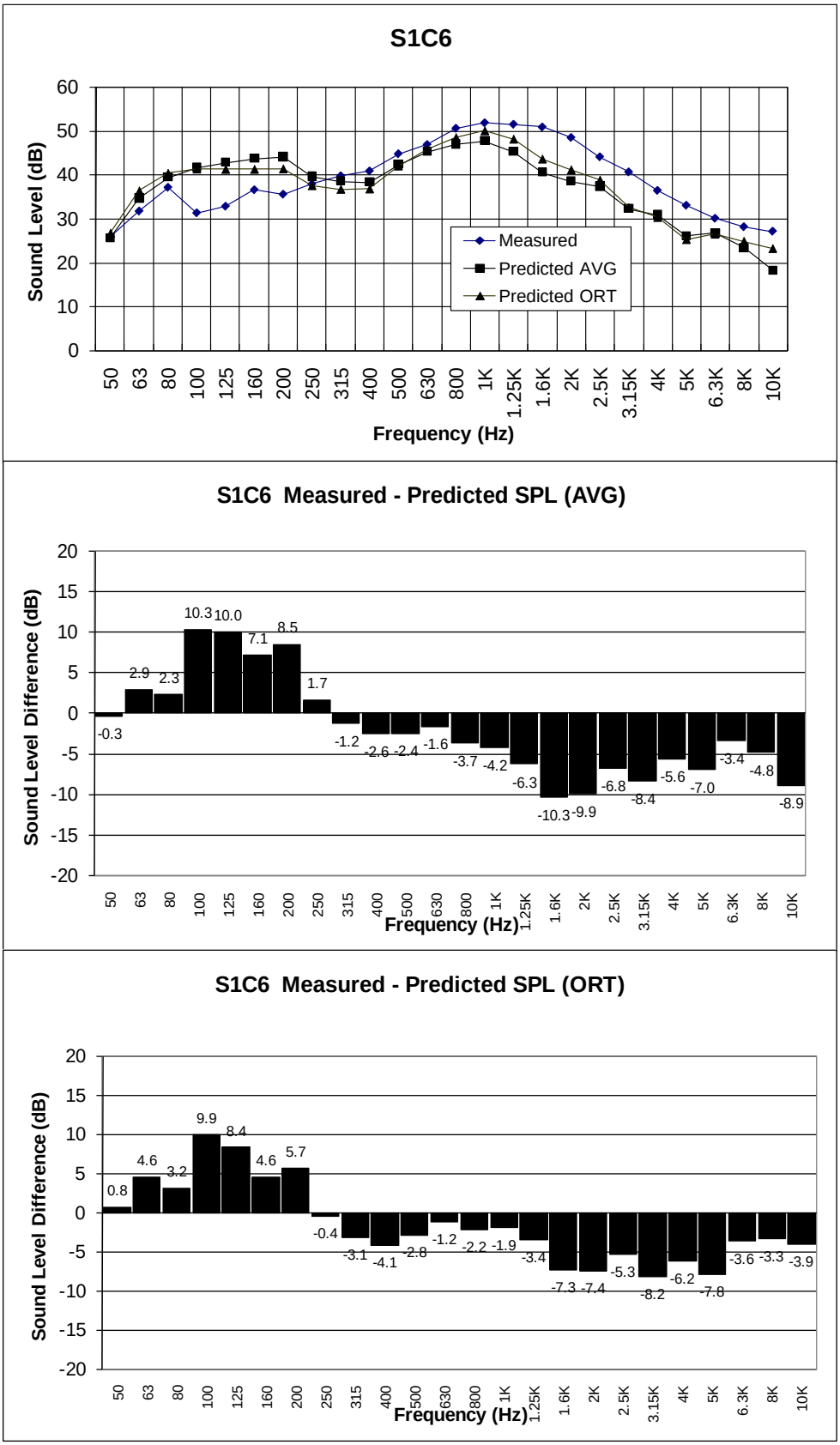




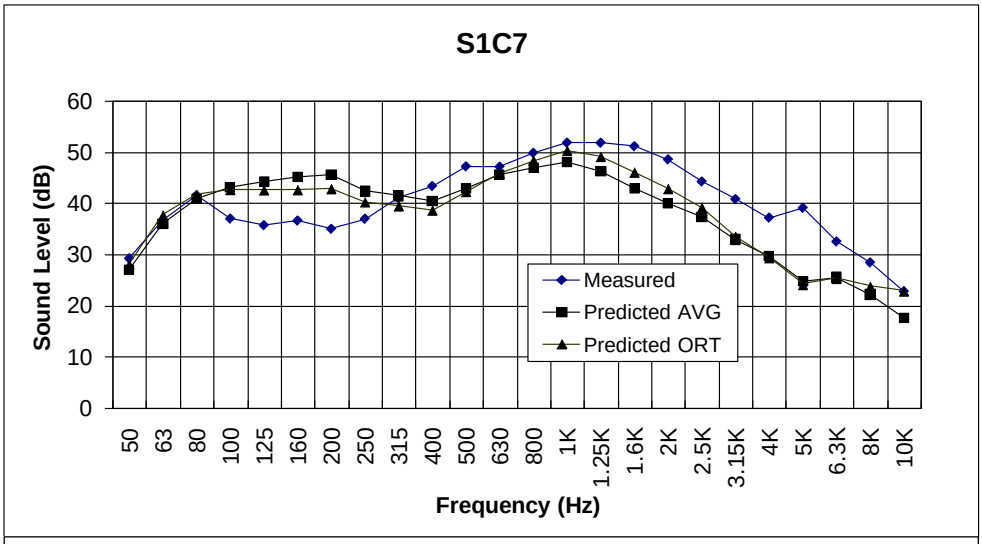
Site 1, Area B, Microphone 7/8

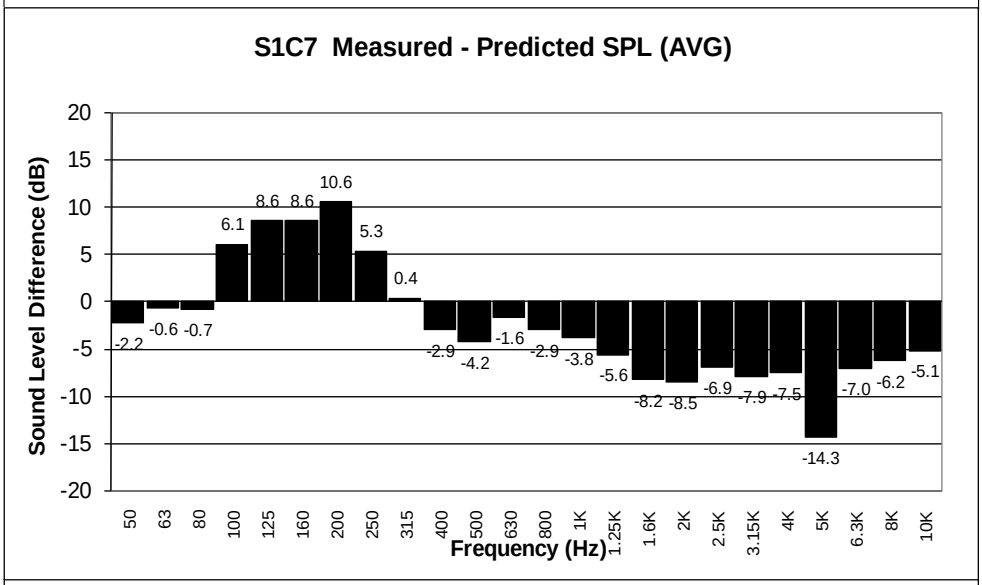


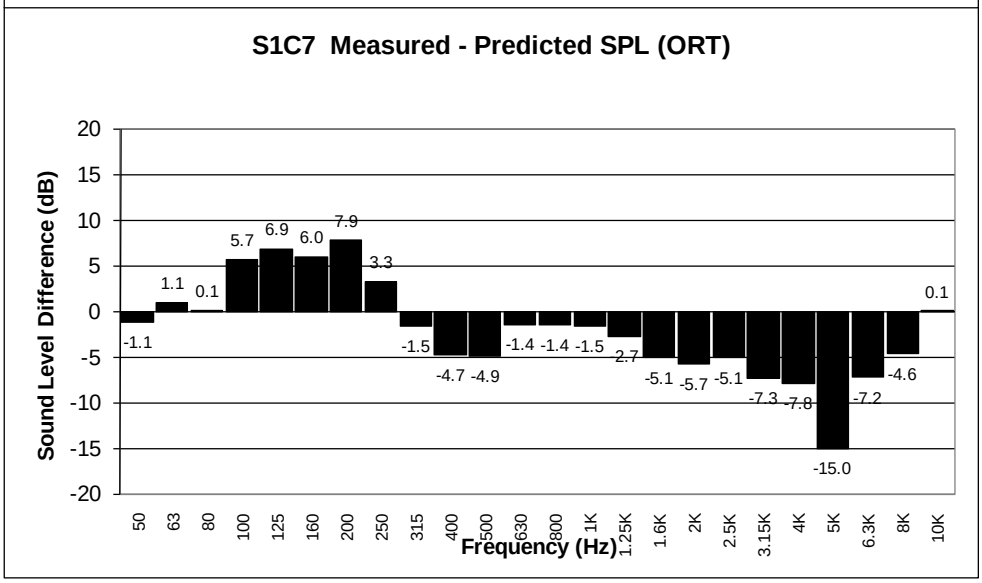
Site 1, Area C, Microphone 6



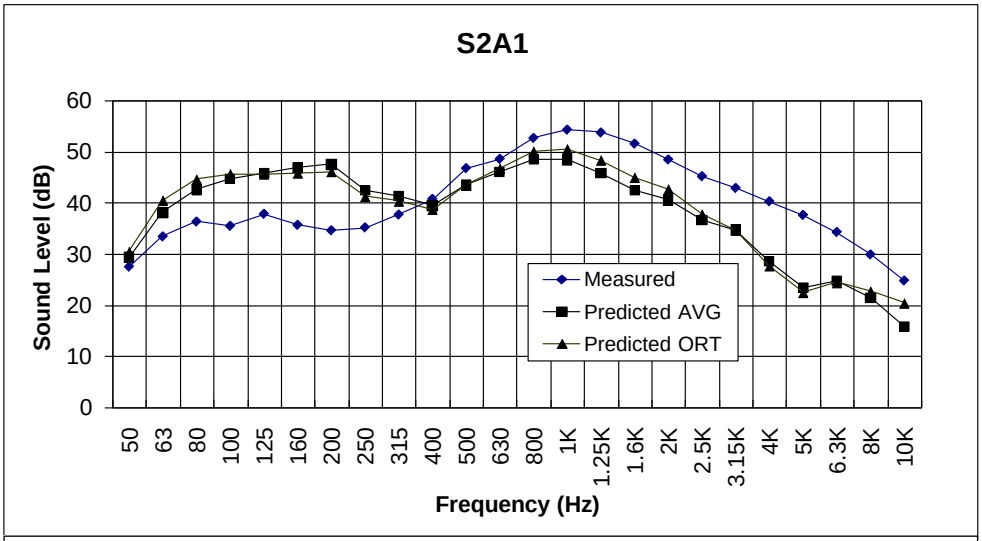
Site 1, Area C, Microphone 7

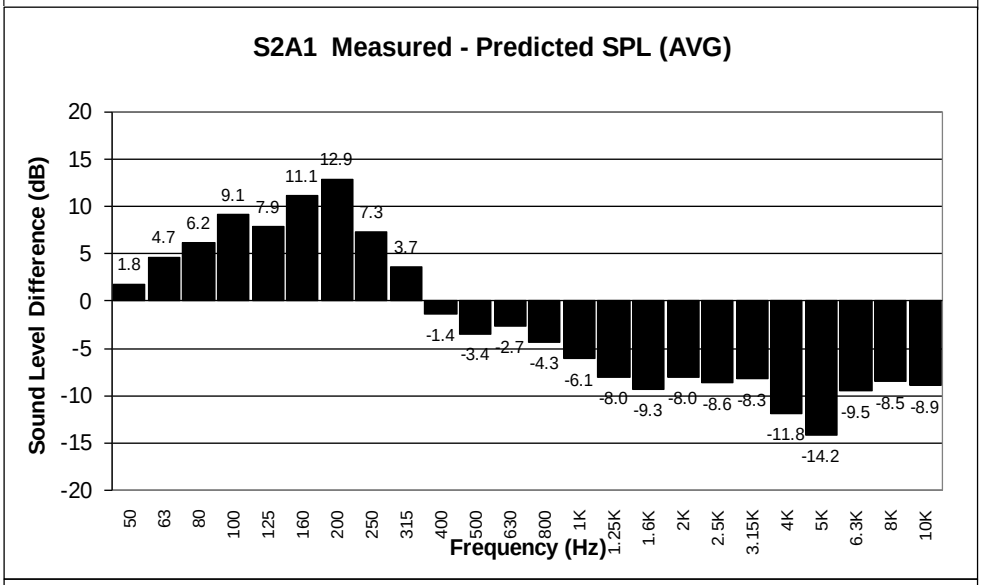


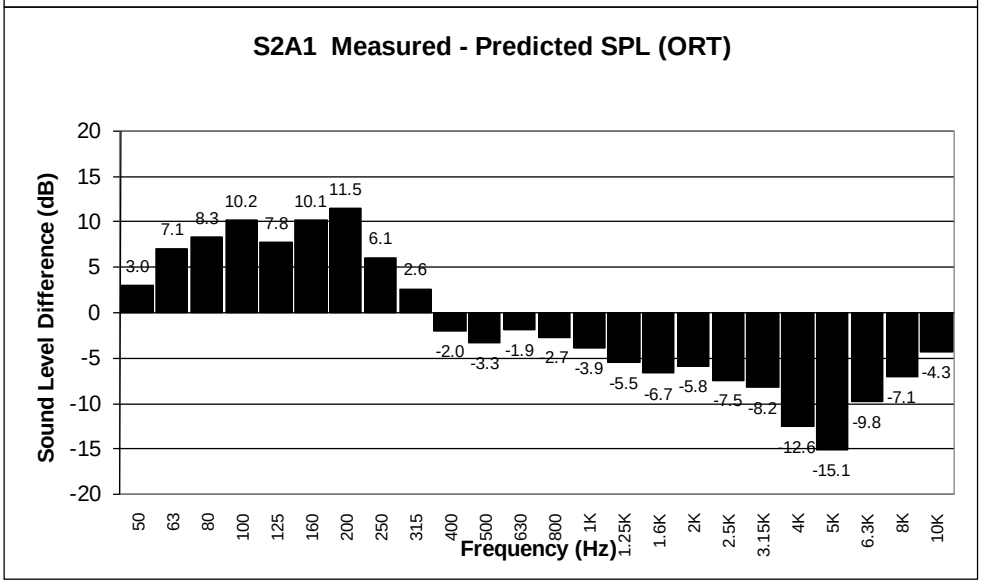




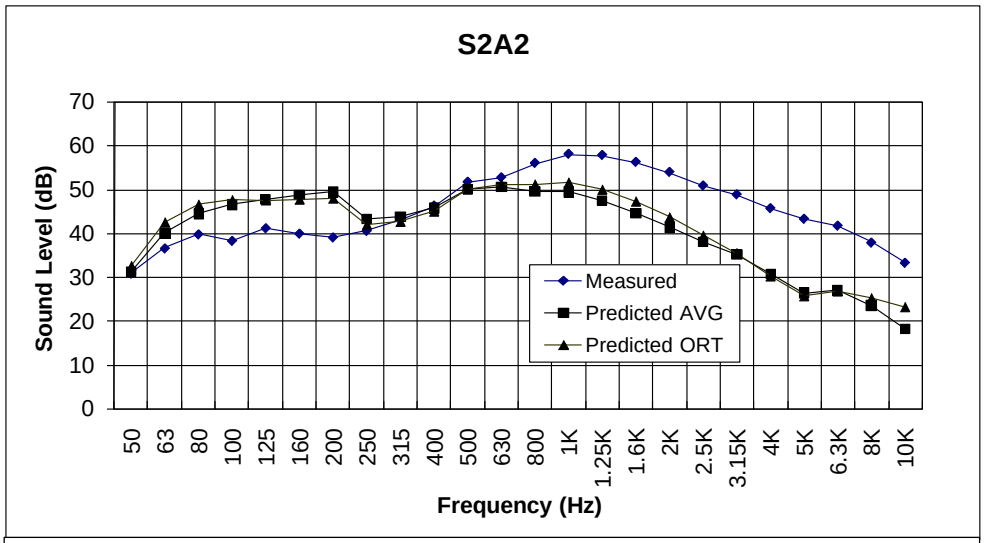
Site 2, Area A, Microphone 1

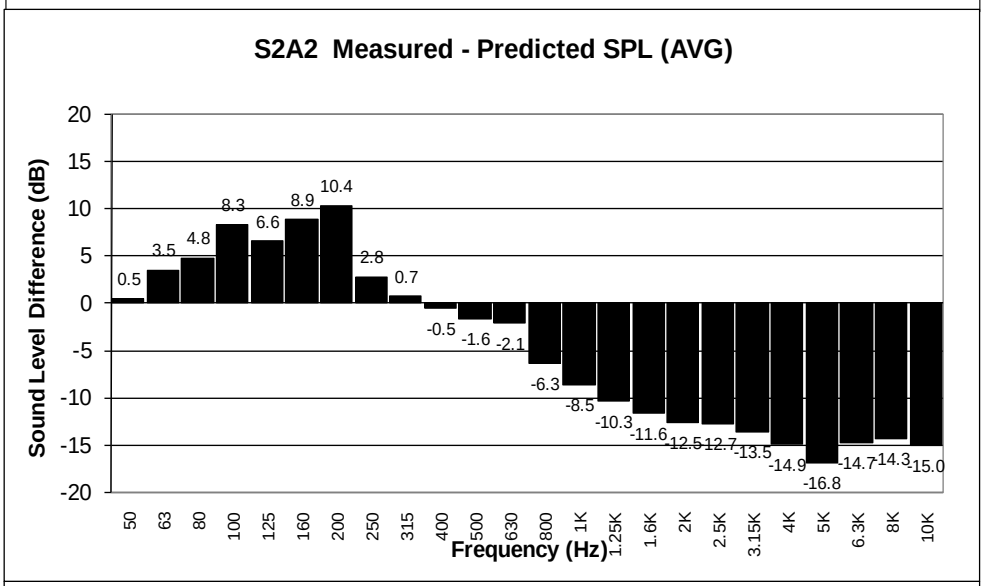


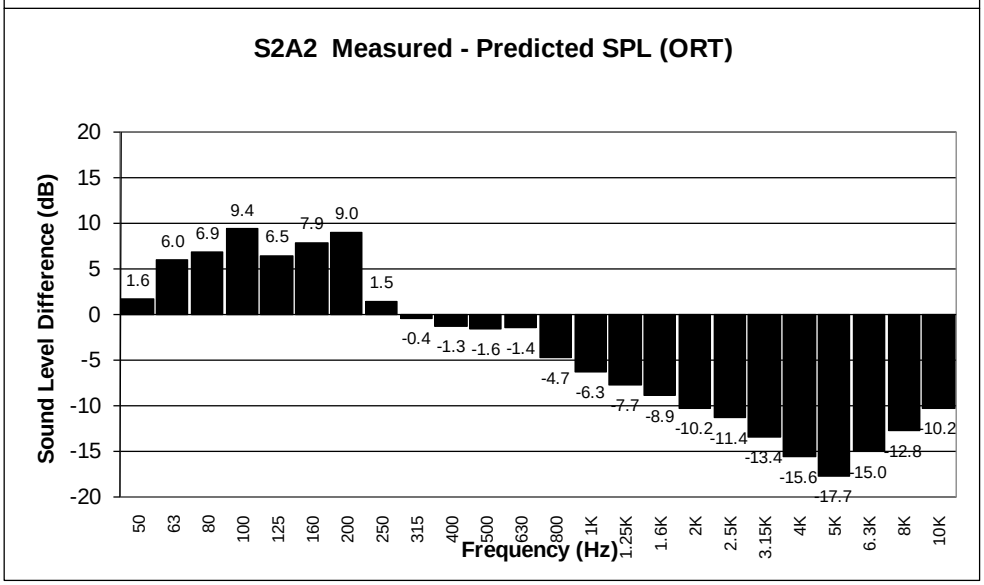




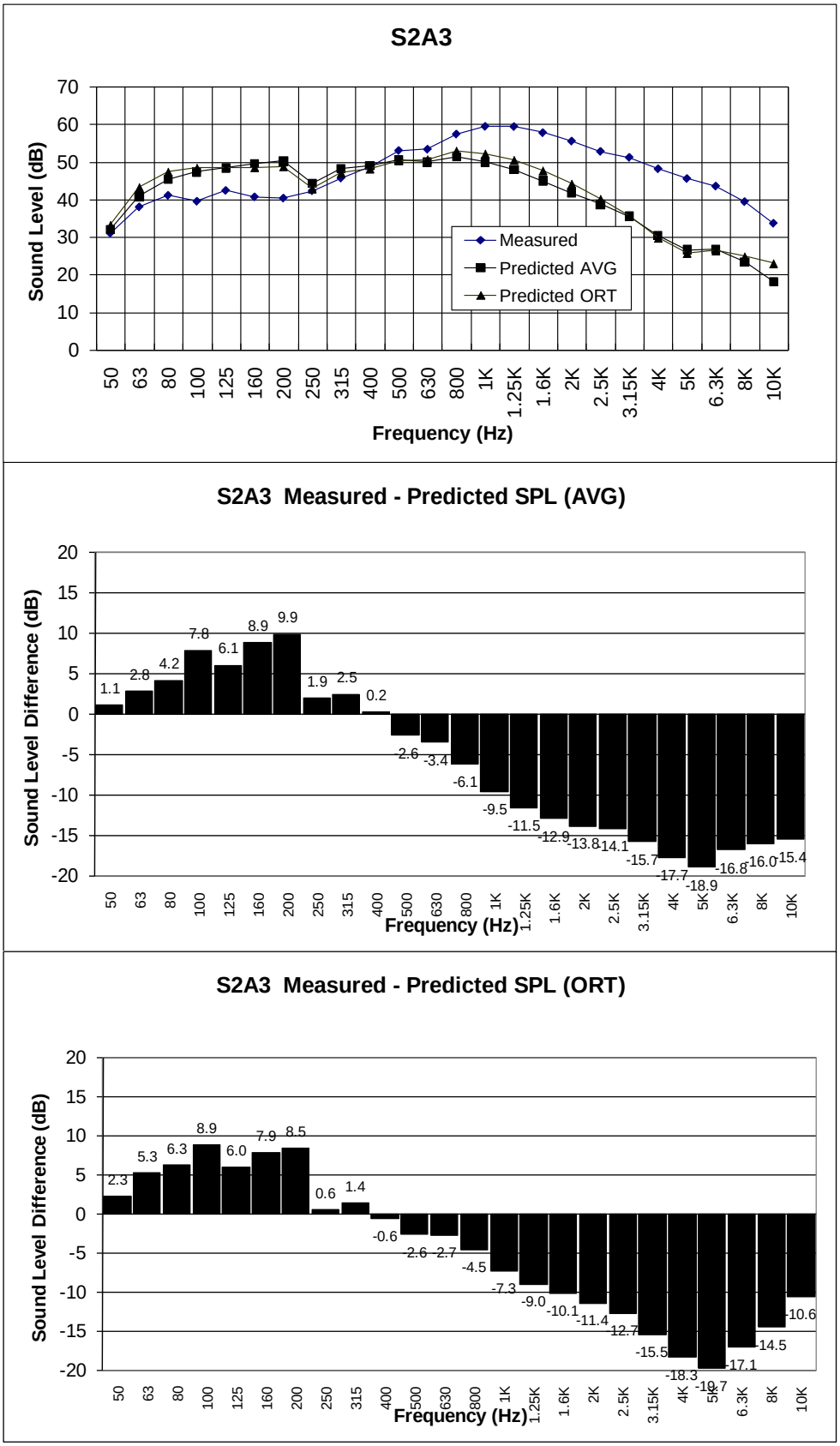
Site 2, Area A, Microphone 2



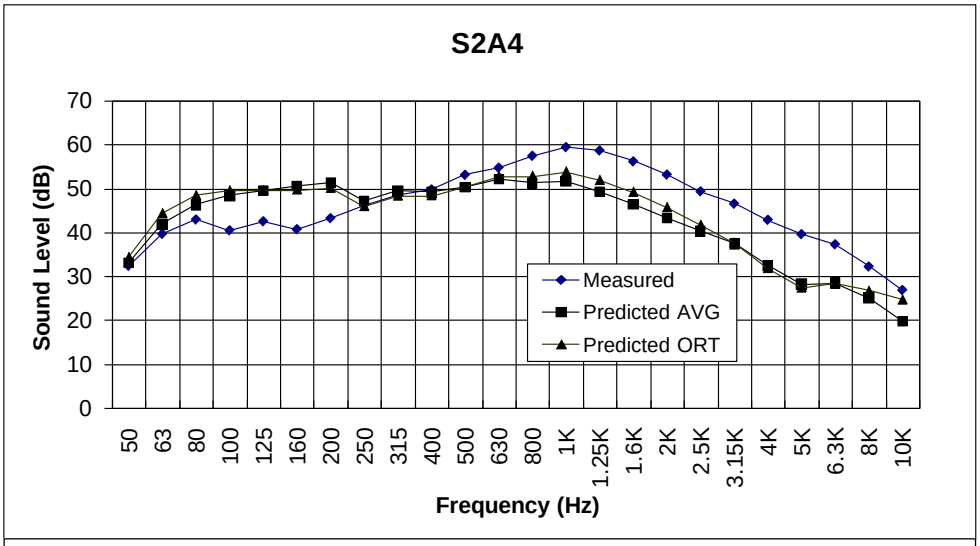


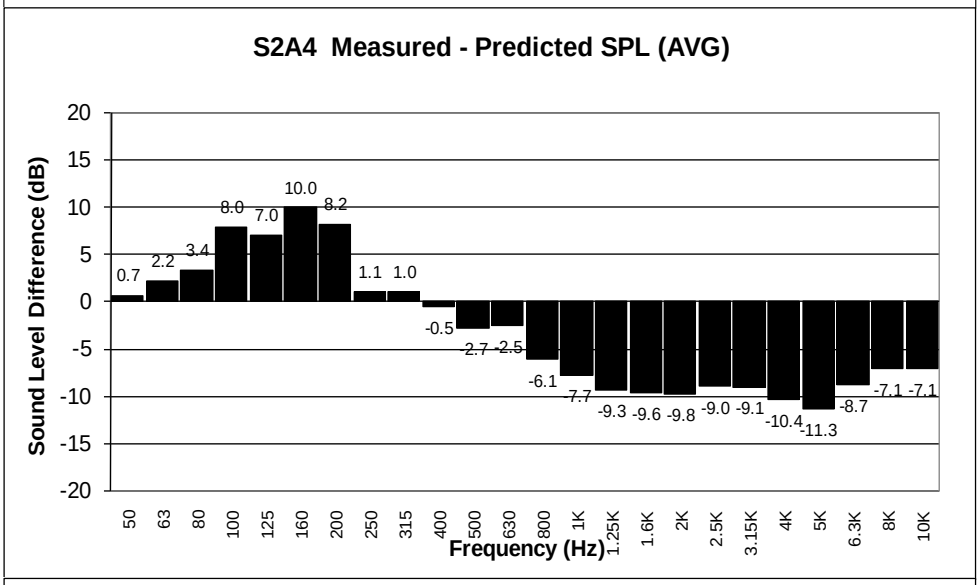


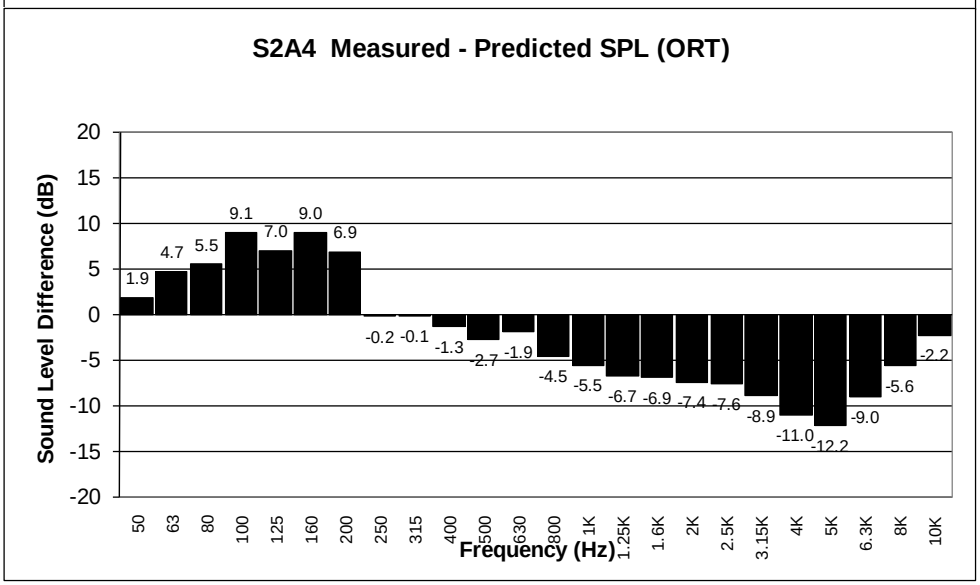
Site 2, Area A, Microphone 3



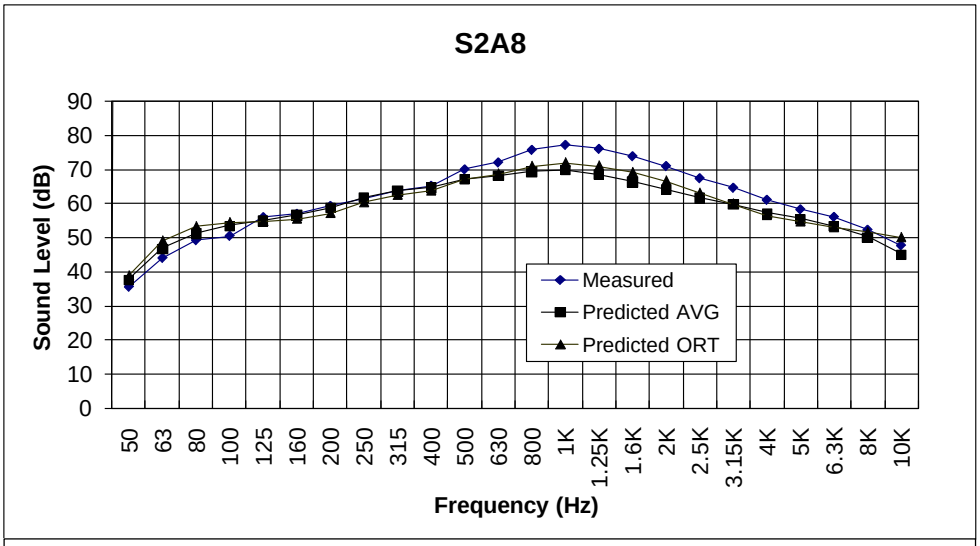
Site 2, Area A, Microphone 4

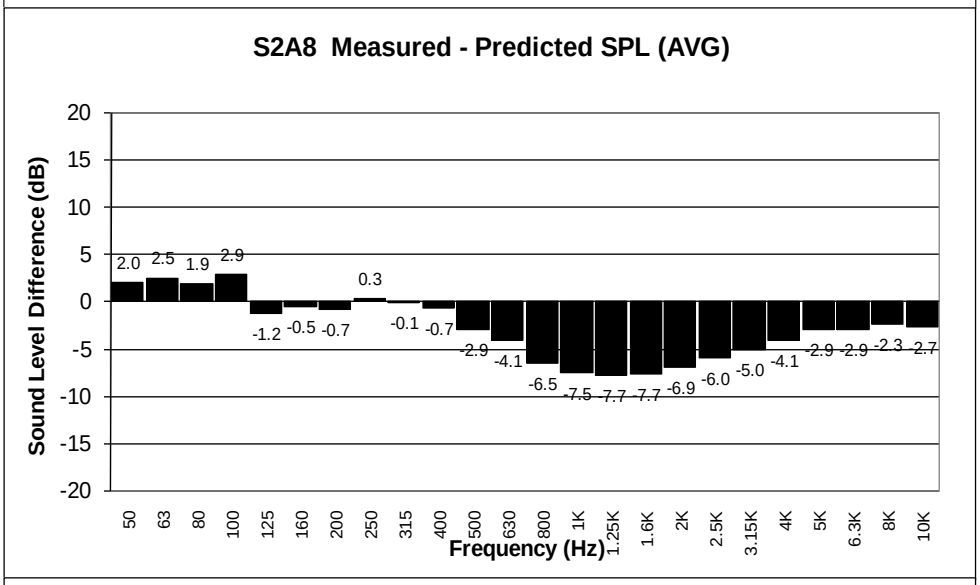


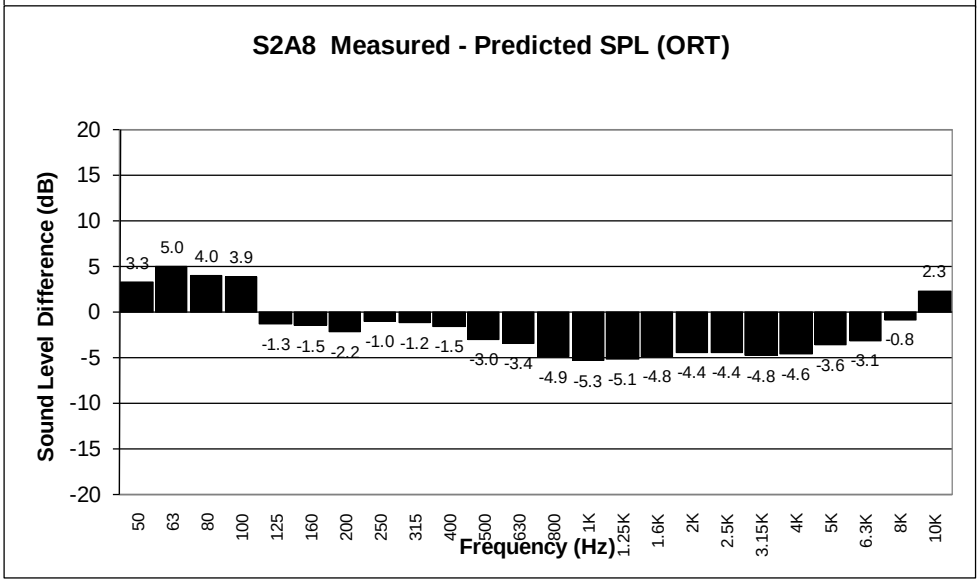




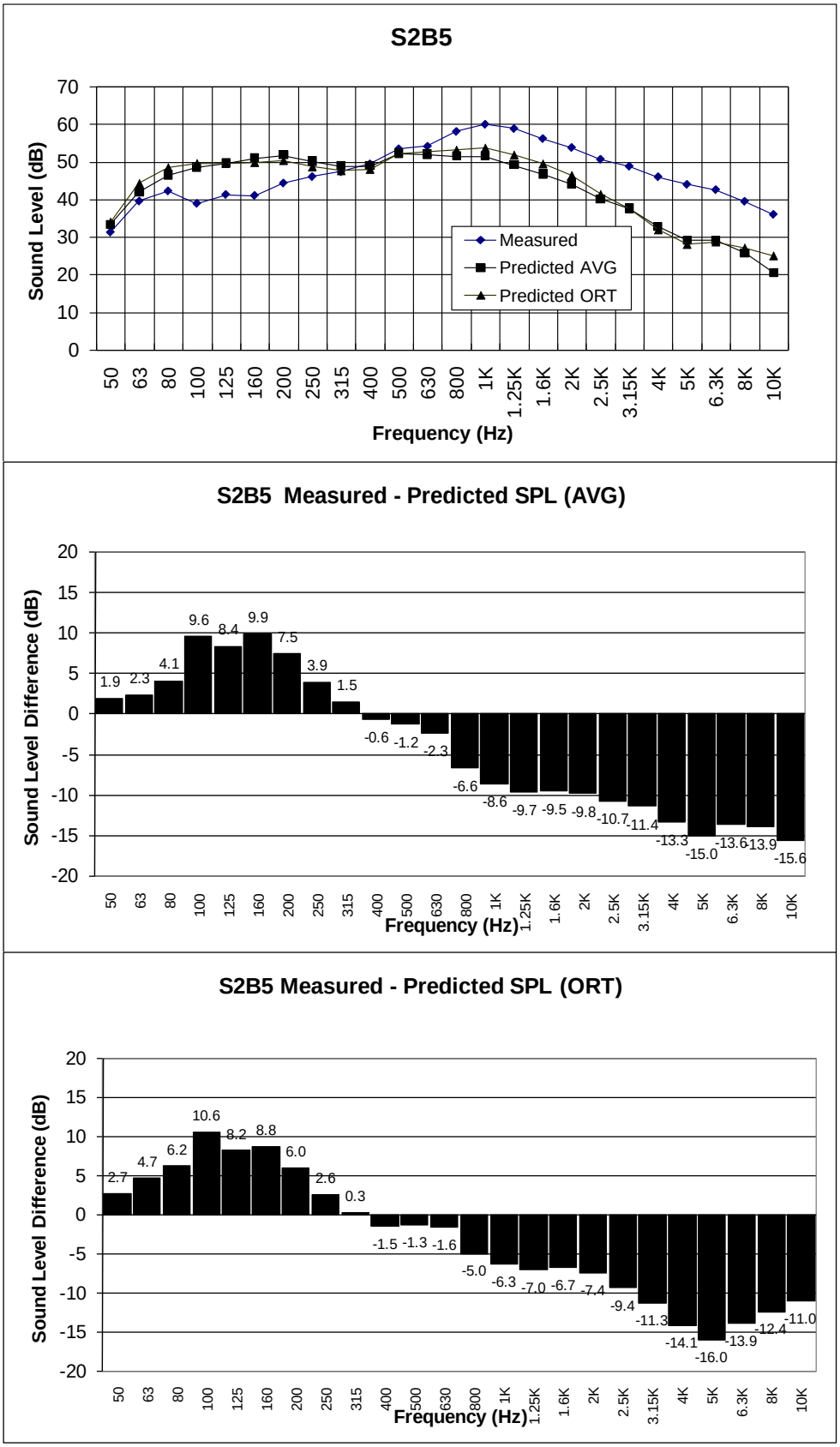
Site 2, Area A, Microphone 8



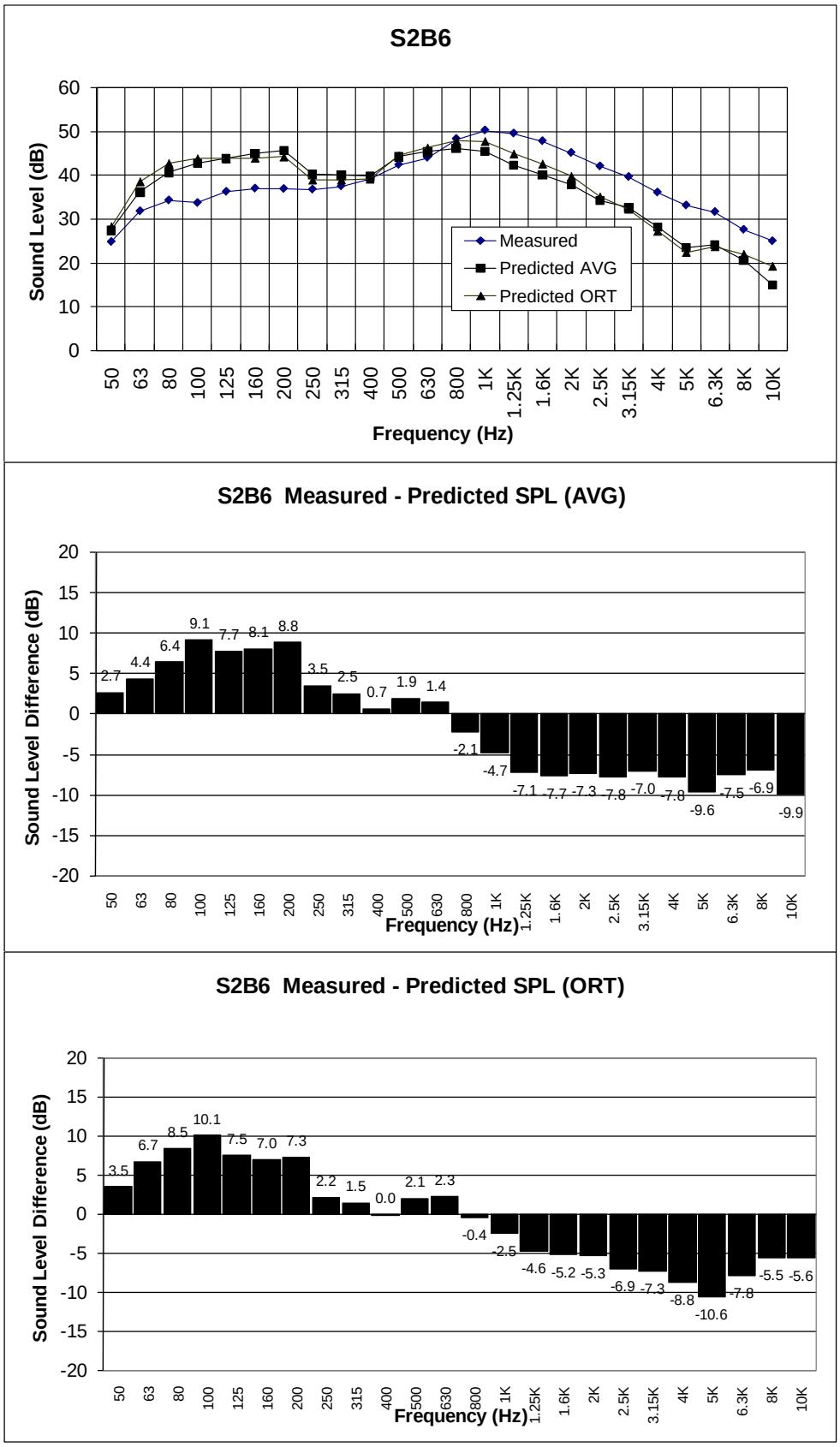




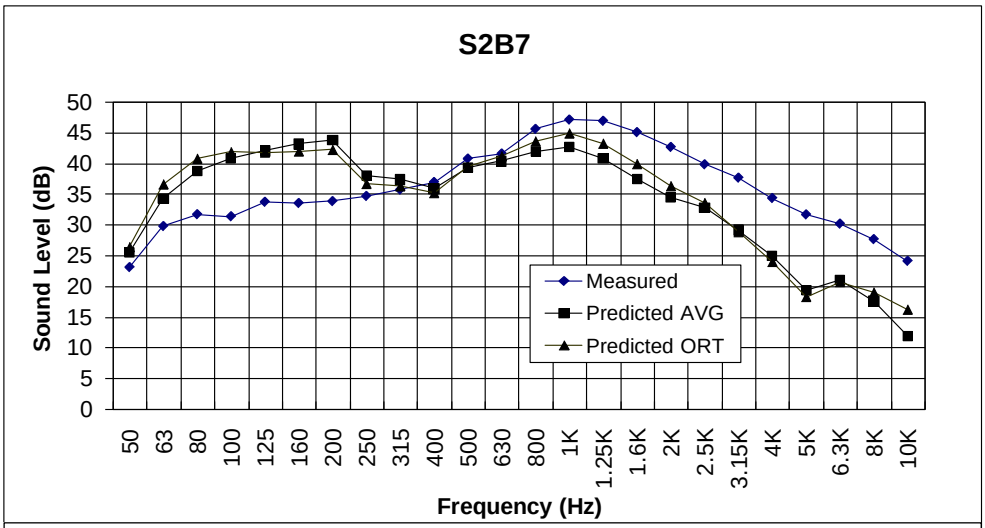
Site 2, Area B, Microphone 5

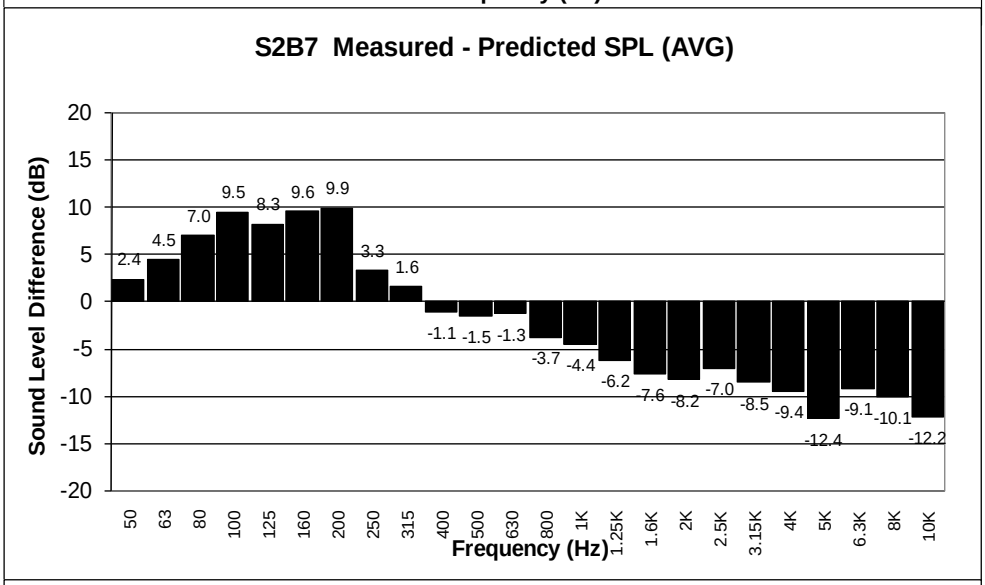


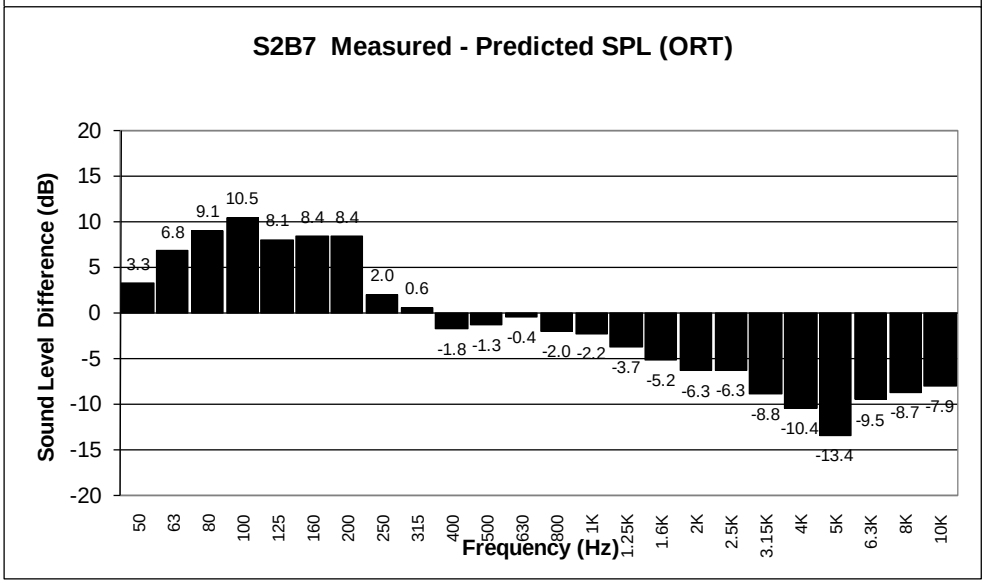
Site 2, Area B, Microphone 6



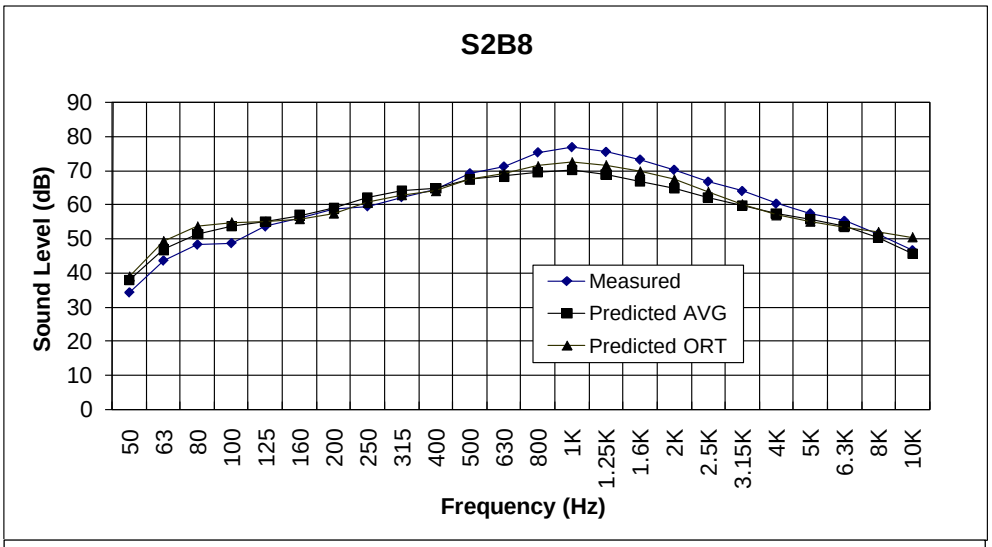
Site 2, Area B, Microphone 7

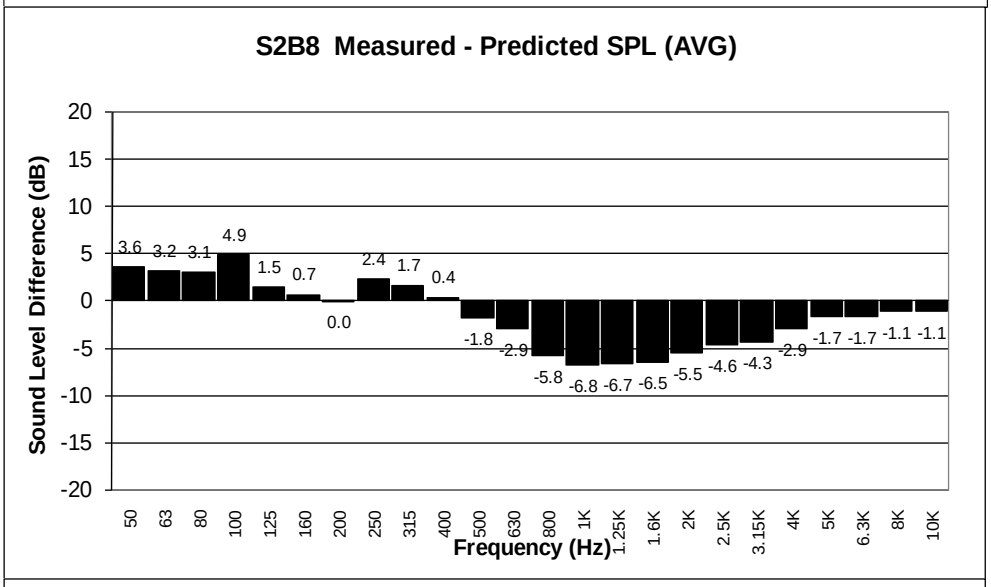


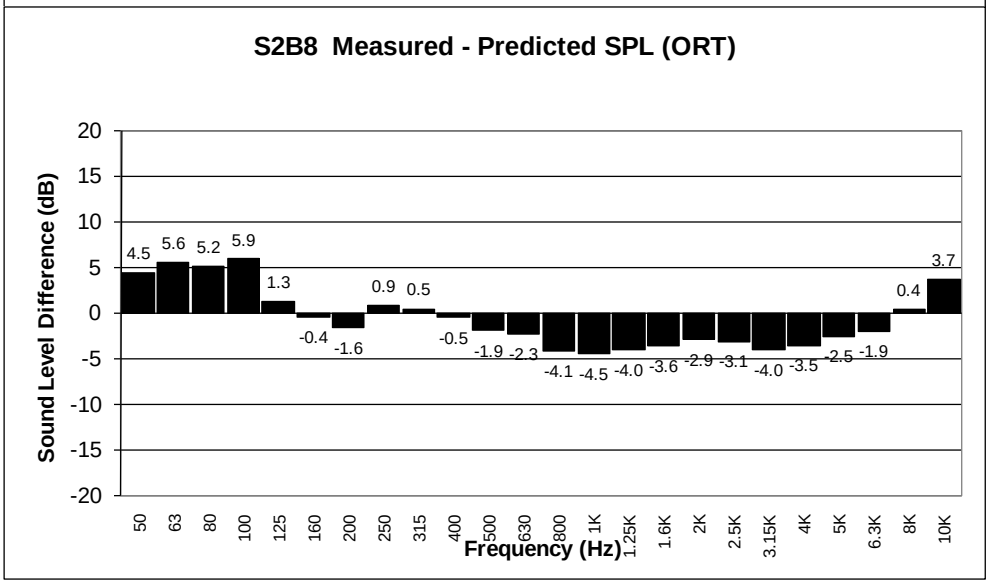




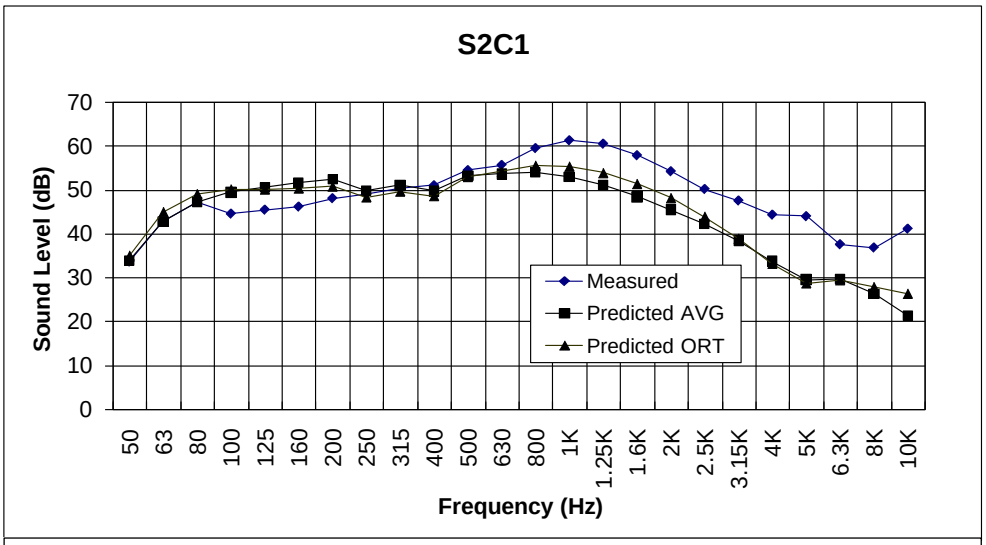
Site 2, Area B, Microphone 8

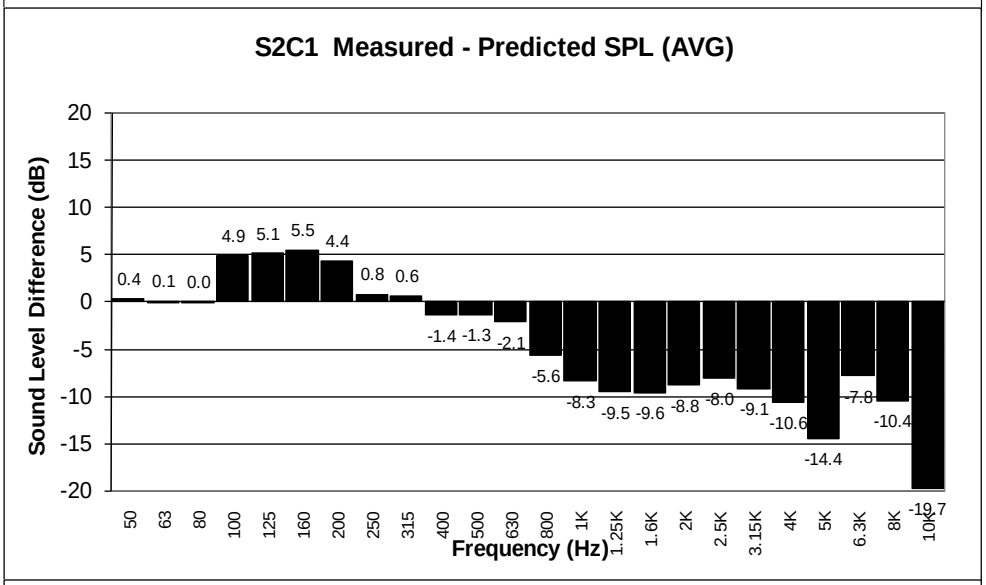


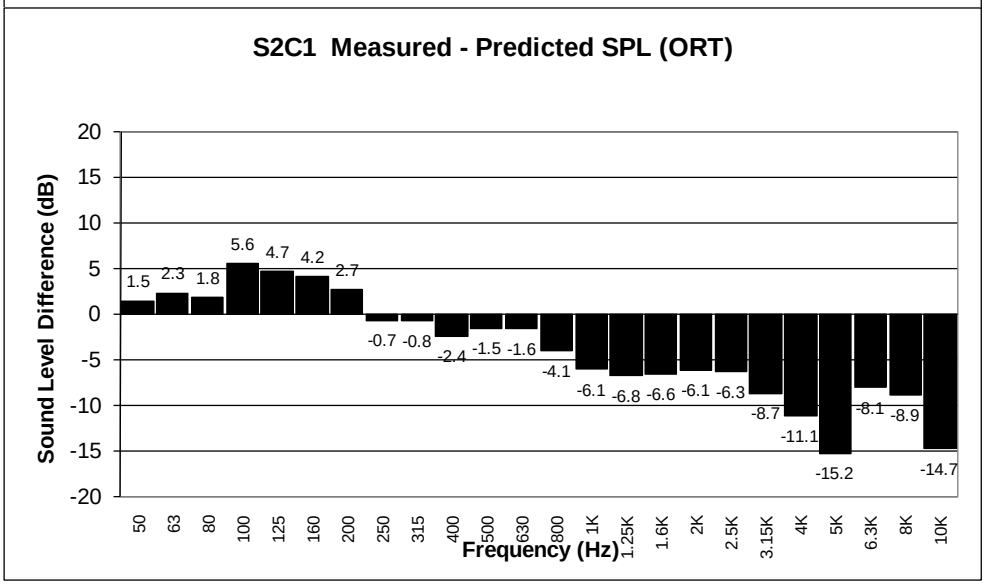




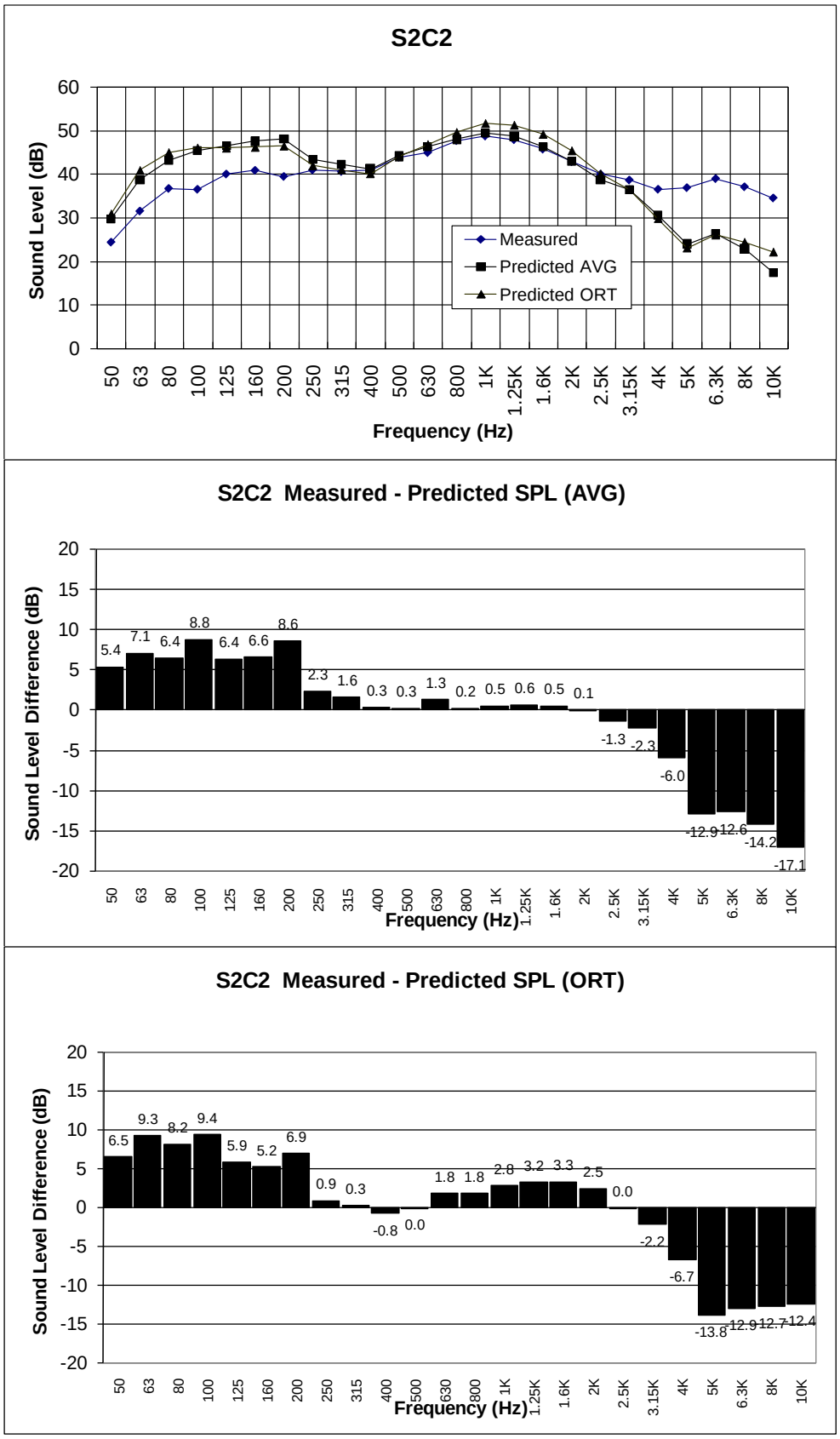
Site 2, Area C, Microphone 1



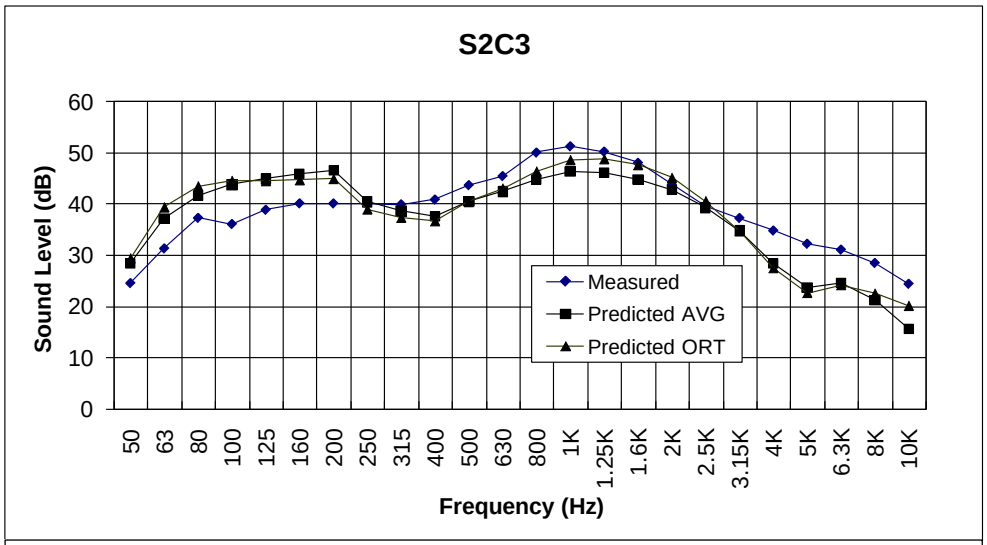


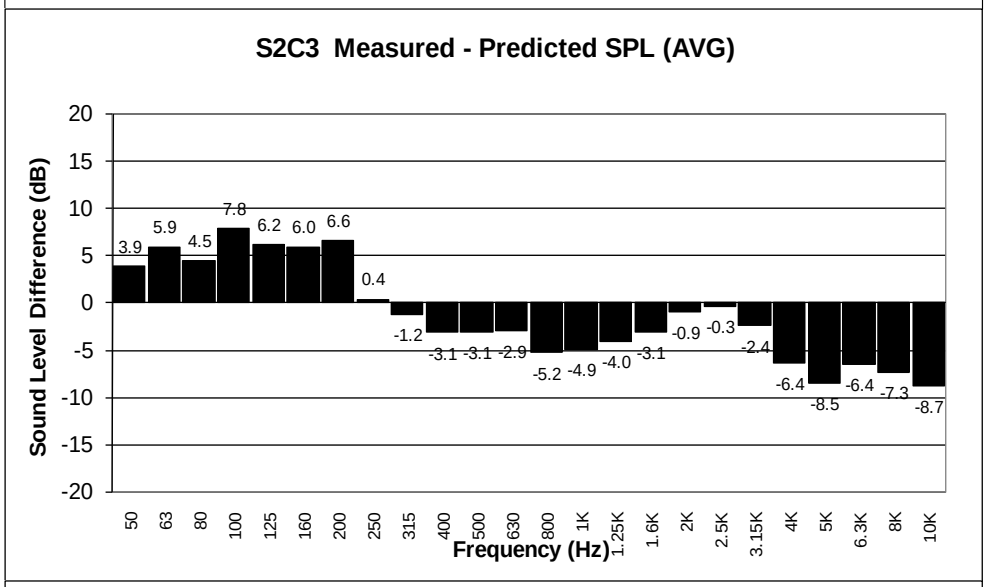


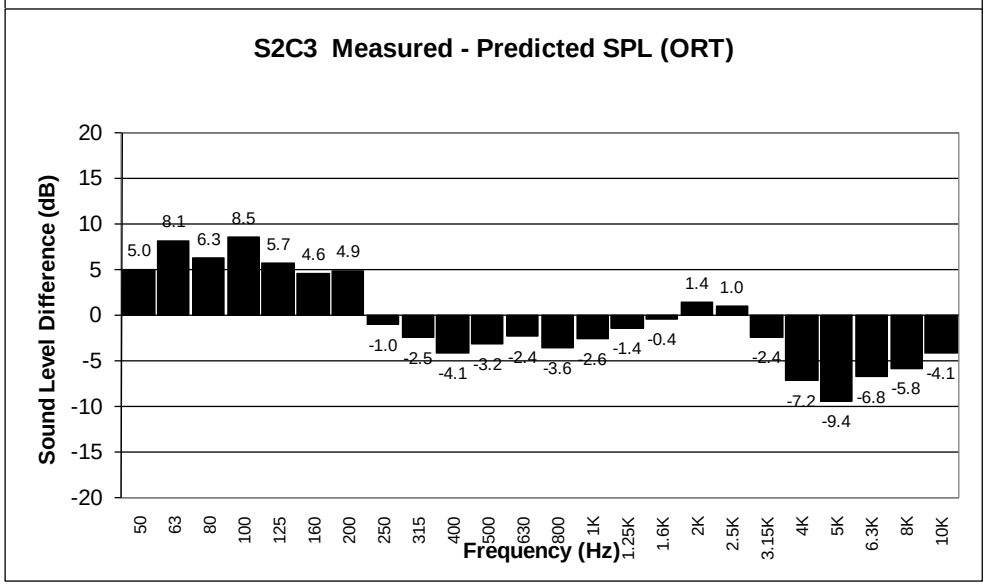
Site 2, Area C, Microphone 2



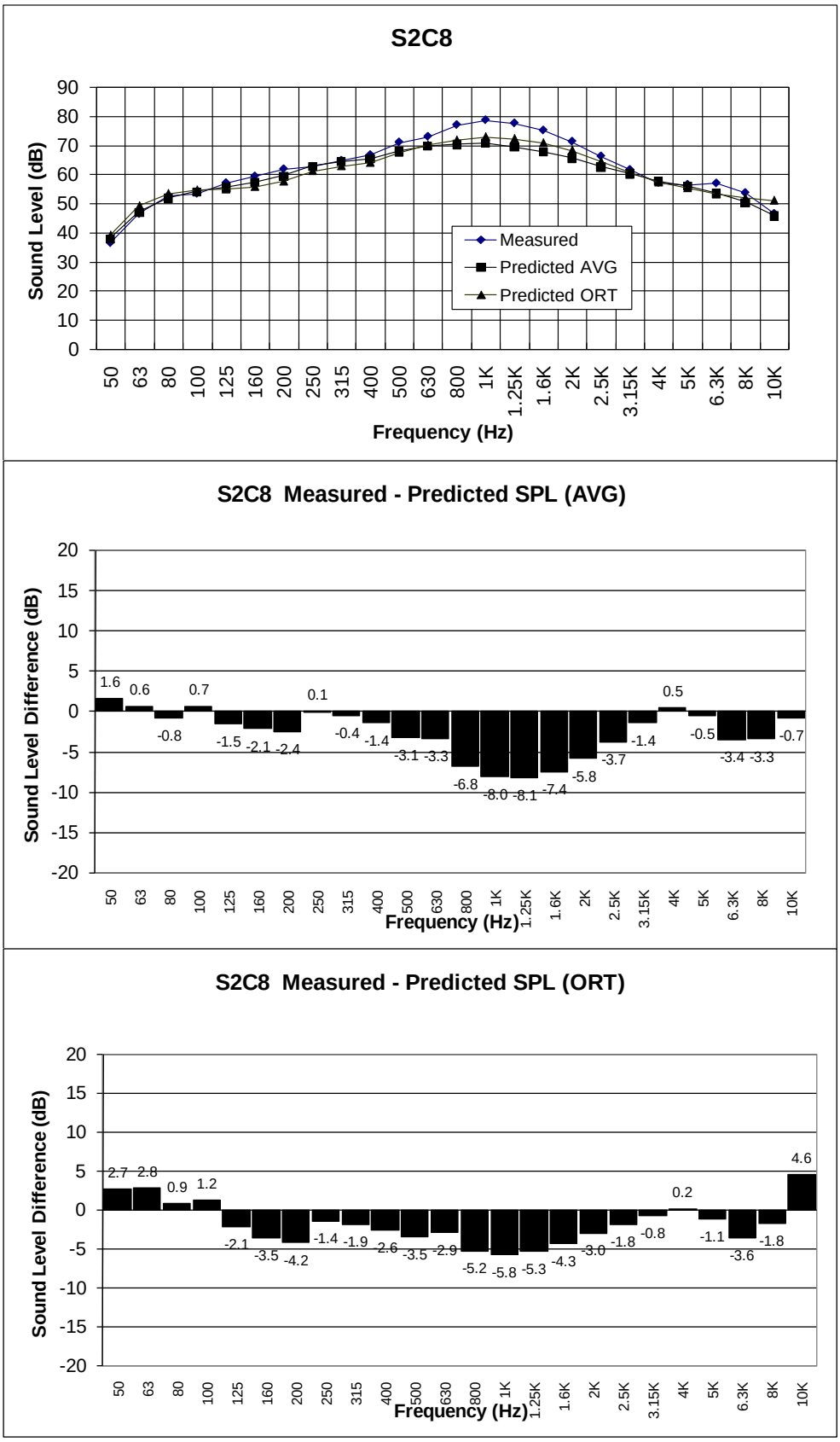
Site 2, Area C, Microphone 3



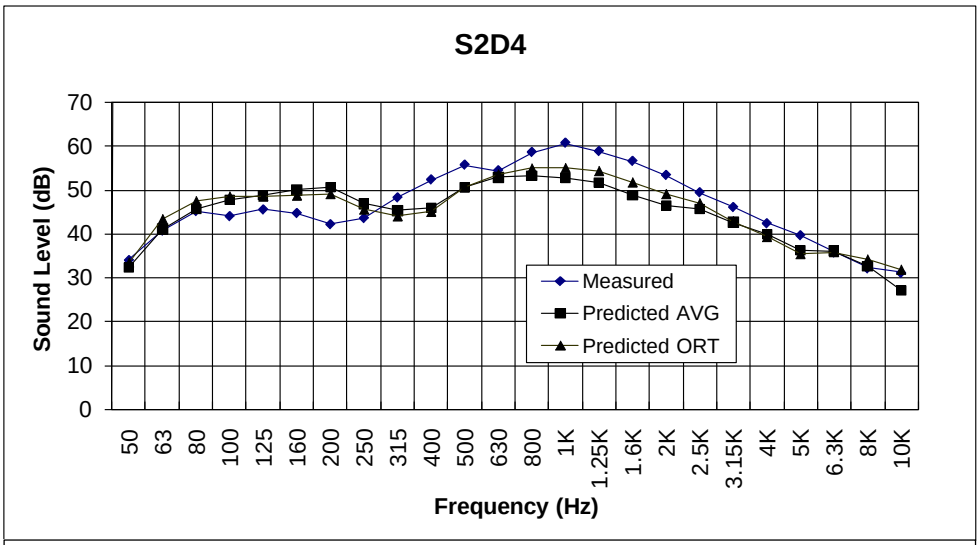


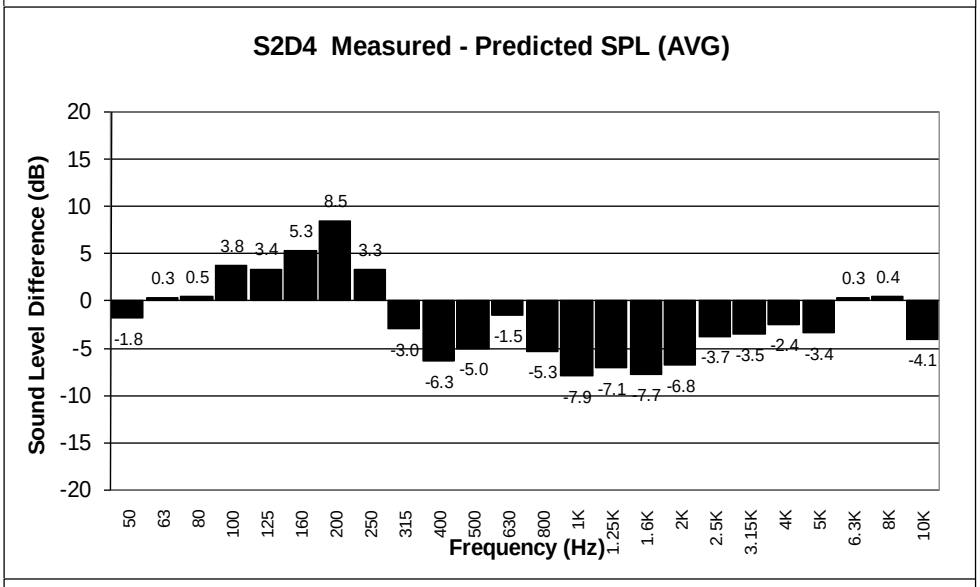


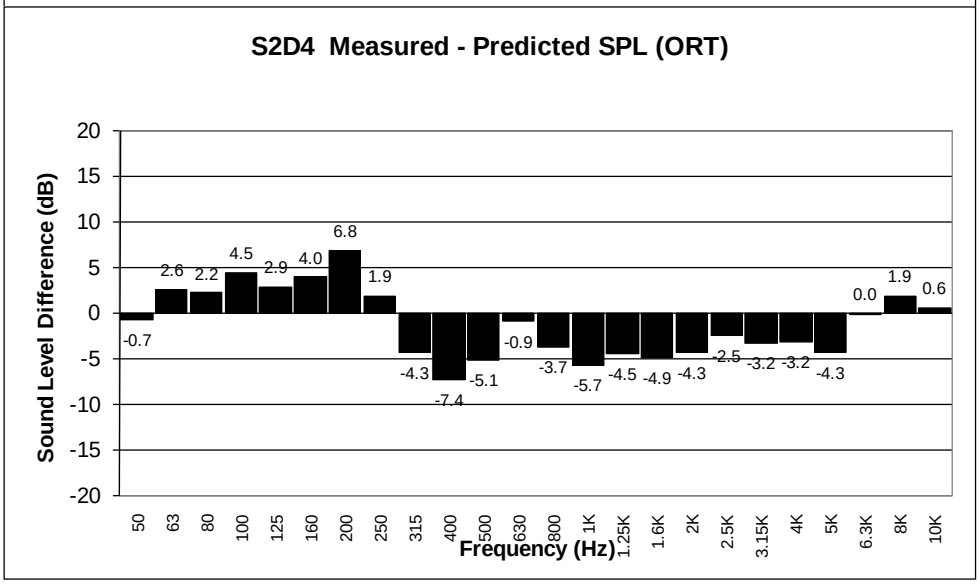
Site 2, Area C, Microphone 8



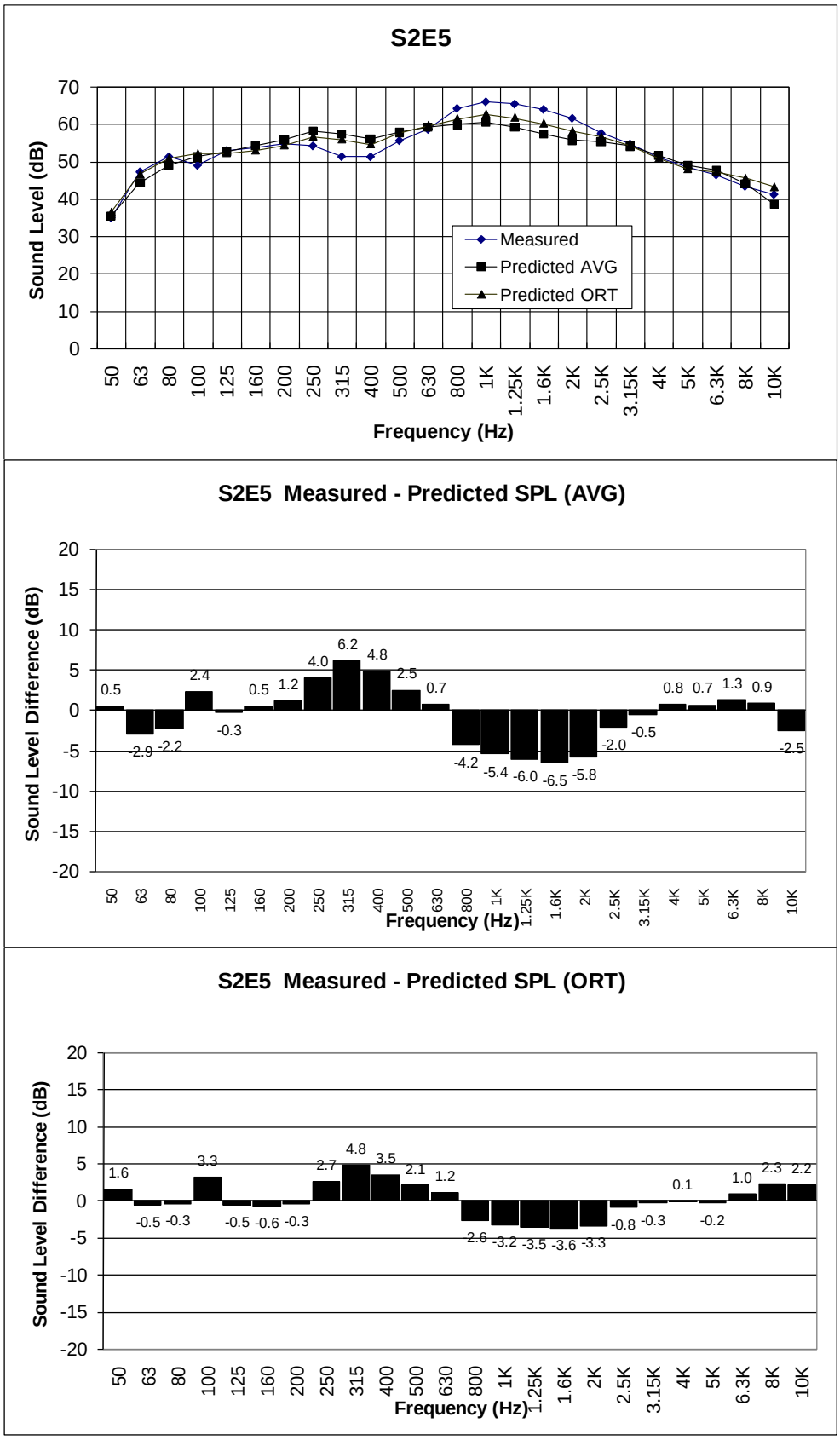
Site 2, Area D, Microphone 4



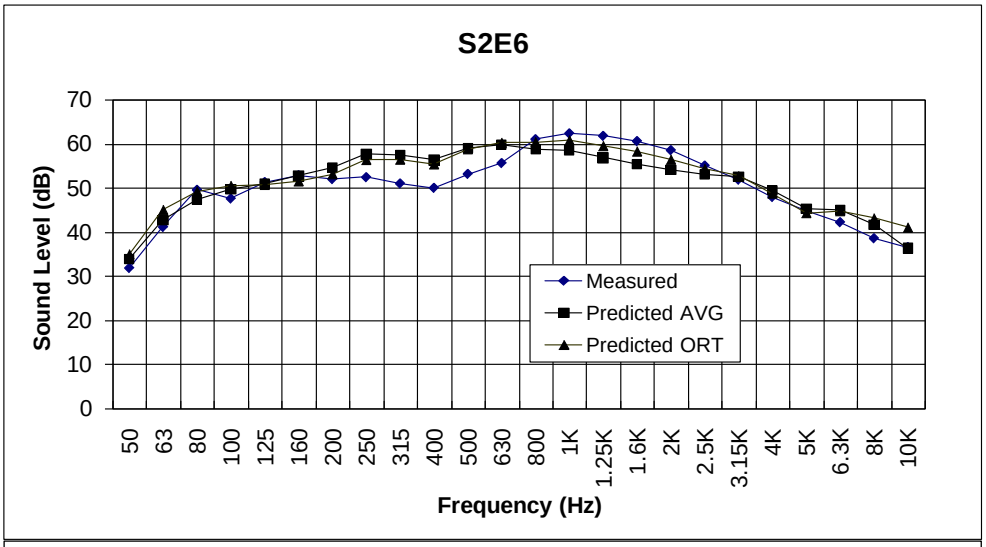


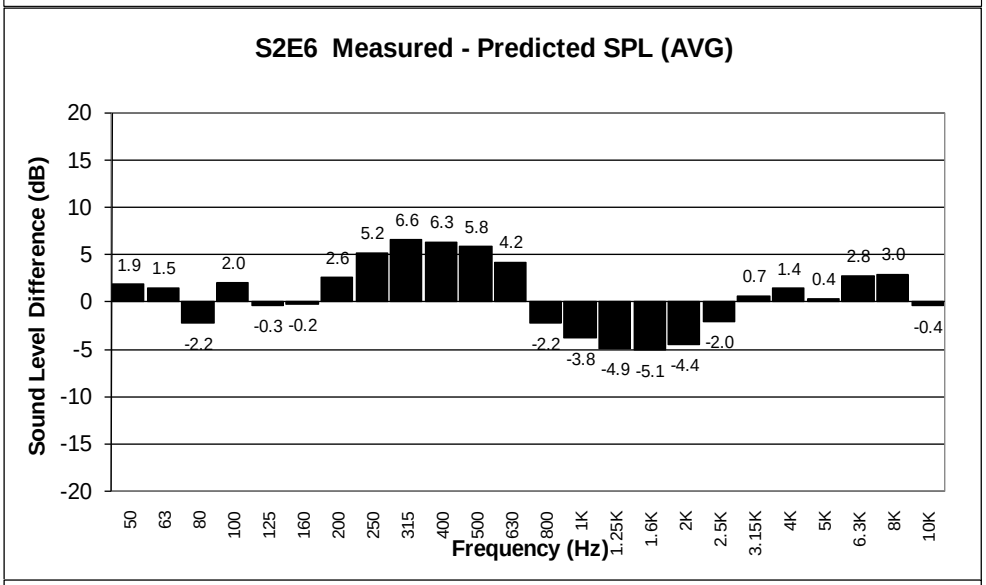


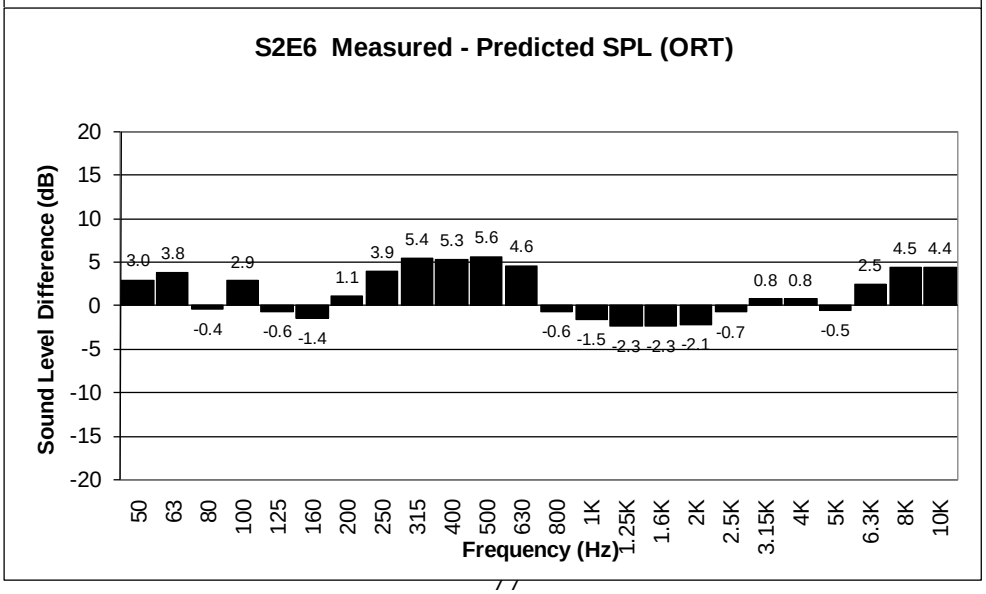
Site 2, Area E, Microphone 5



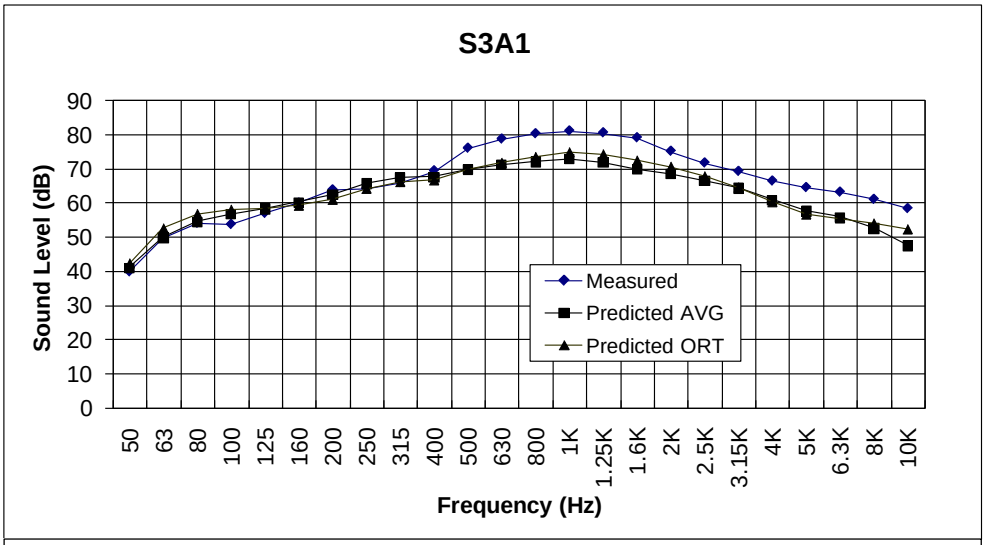
Site 2, Area E, Microphone 6

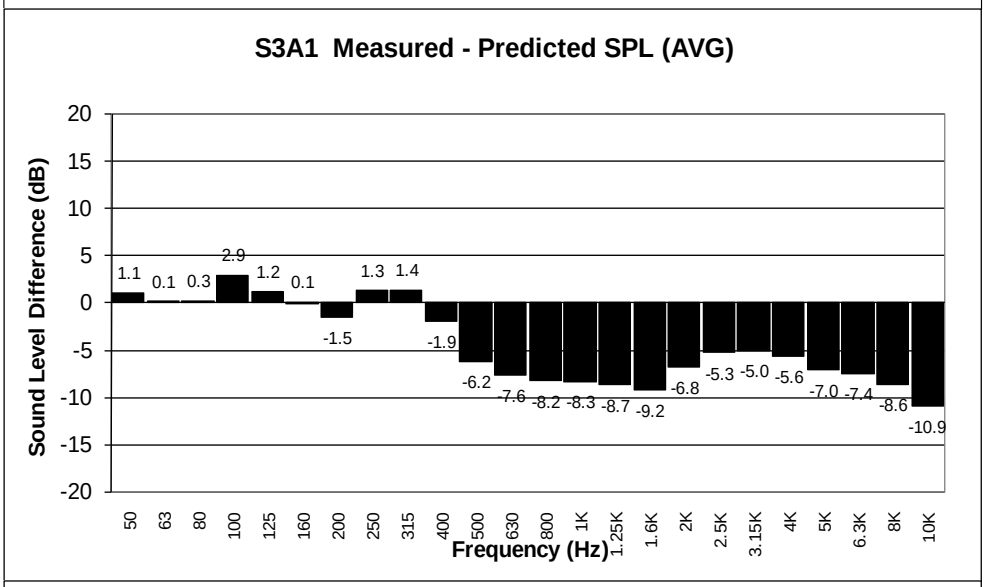


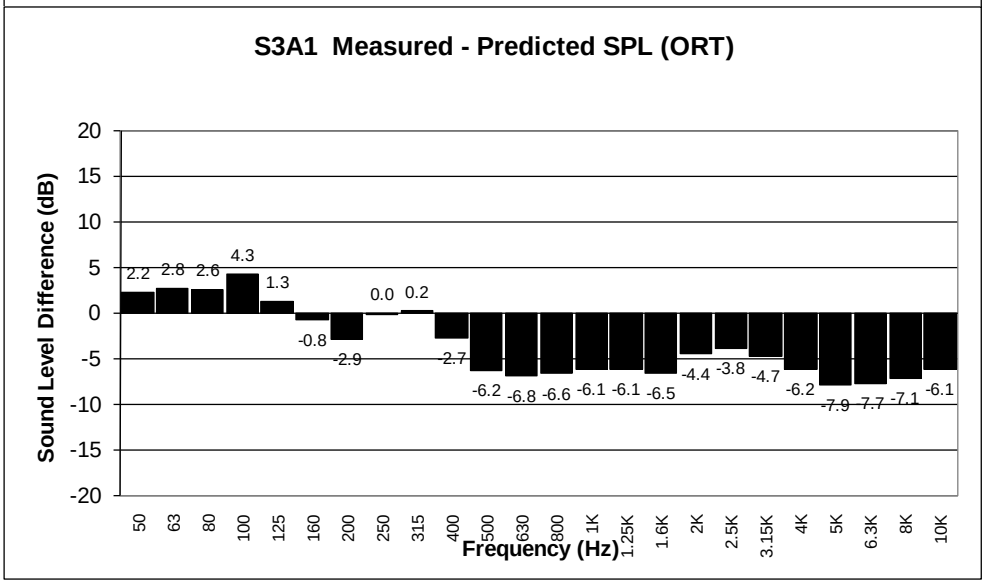




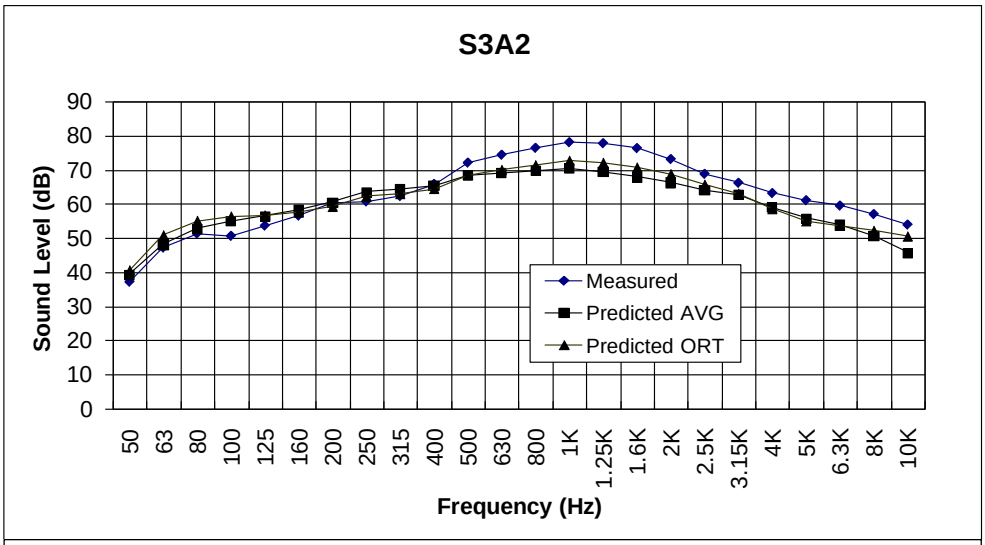
Site 3, Area A, Microphone 1

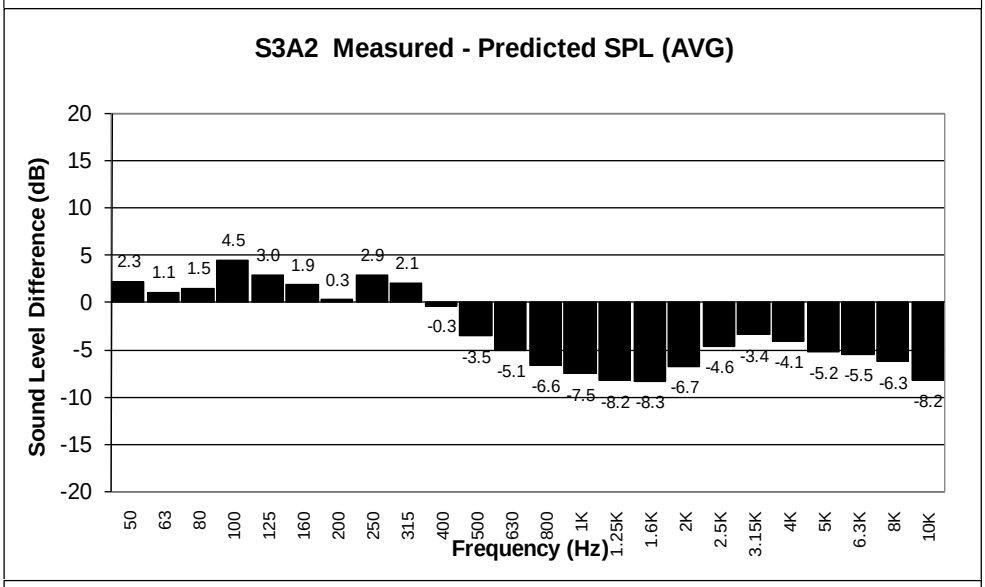


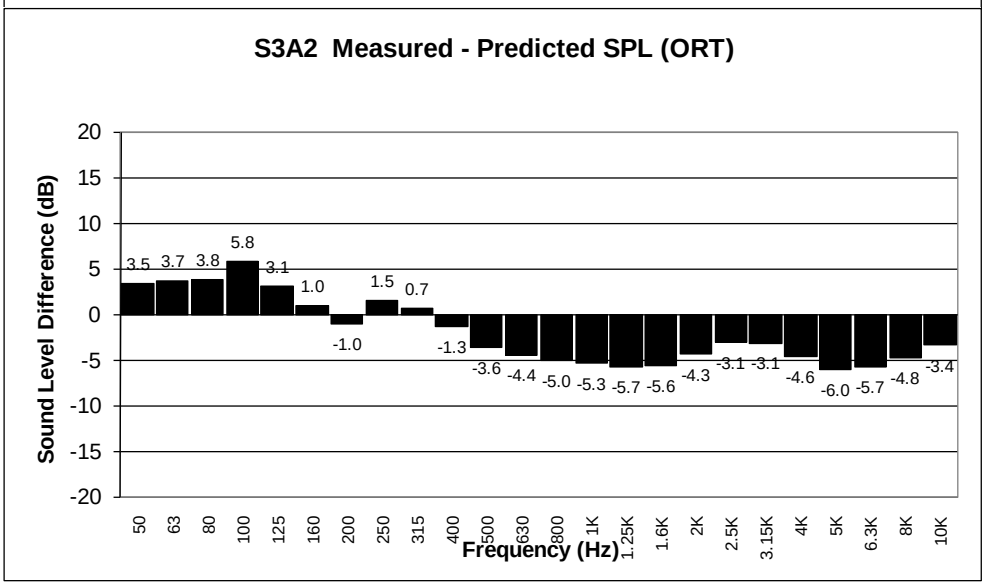




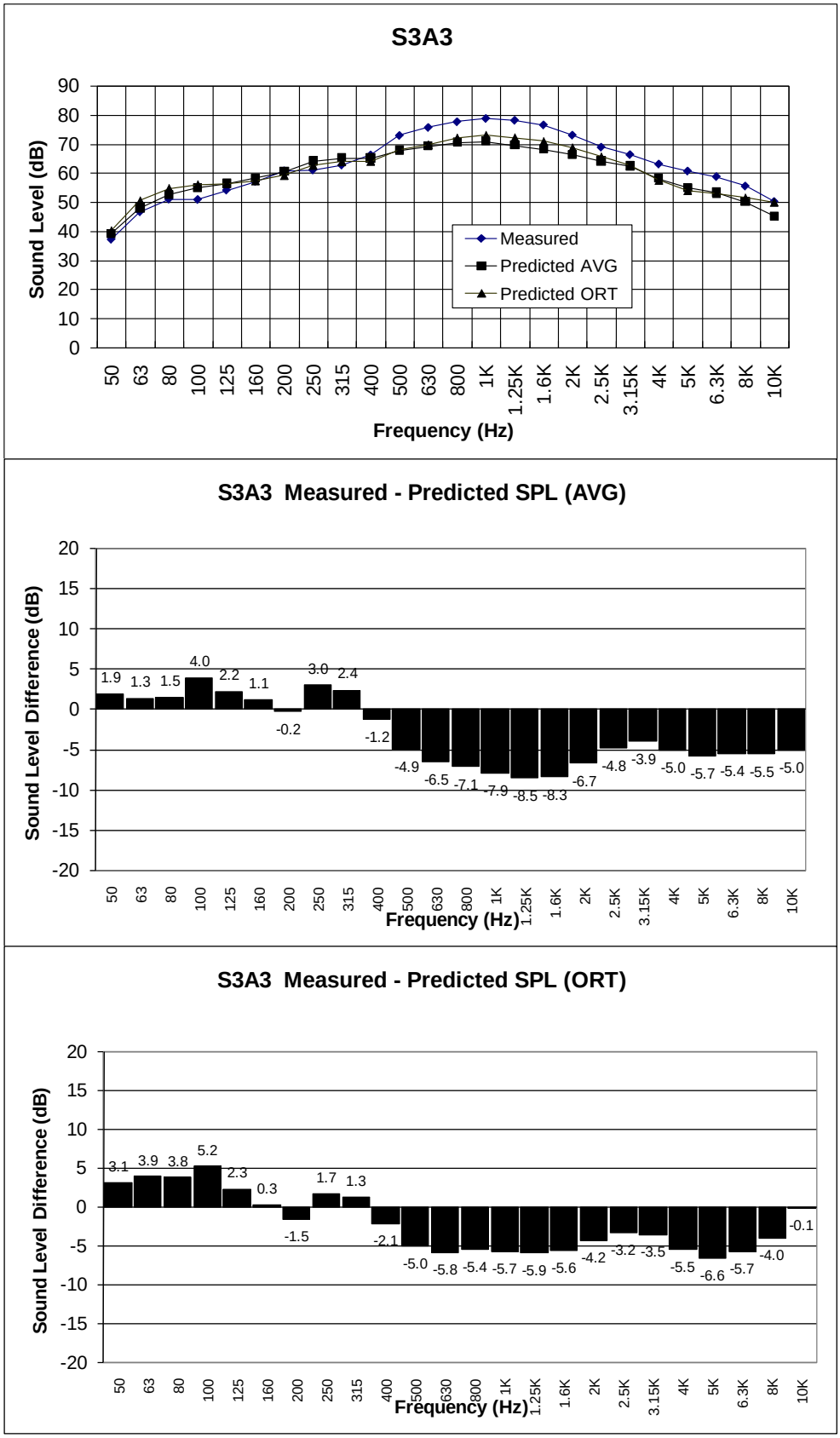
Site 3, Area A, Microphone 2



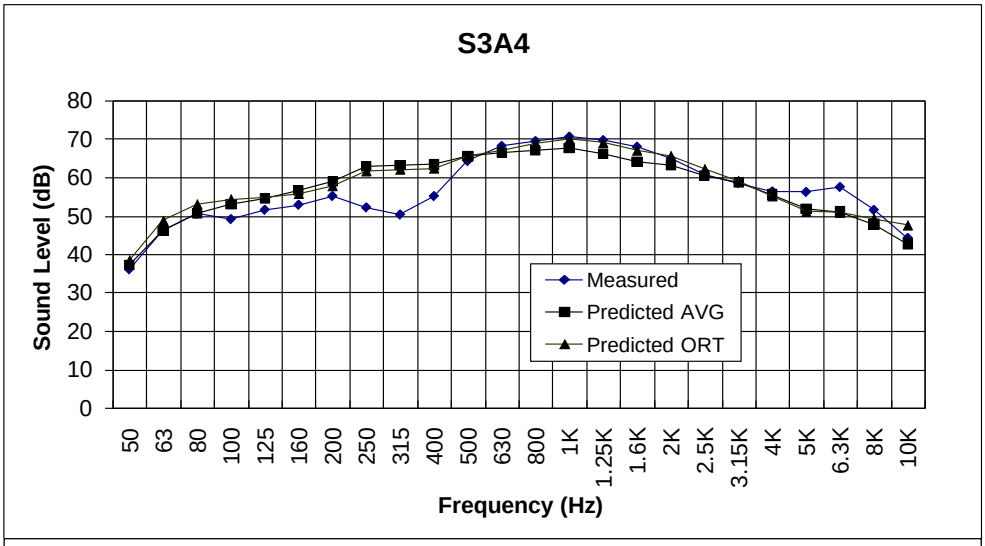


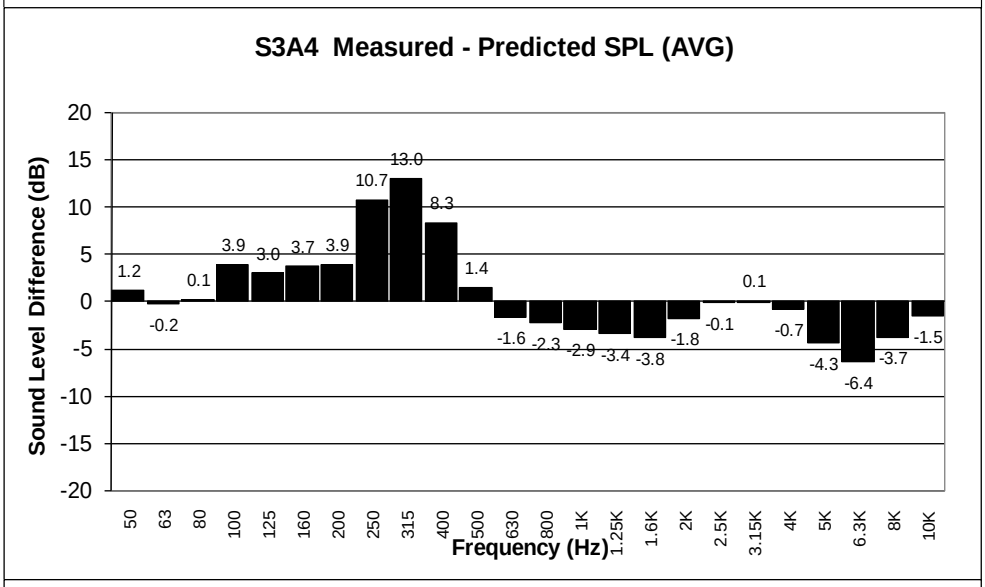


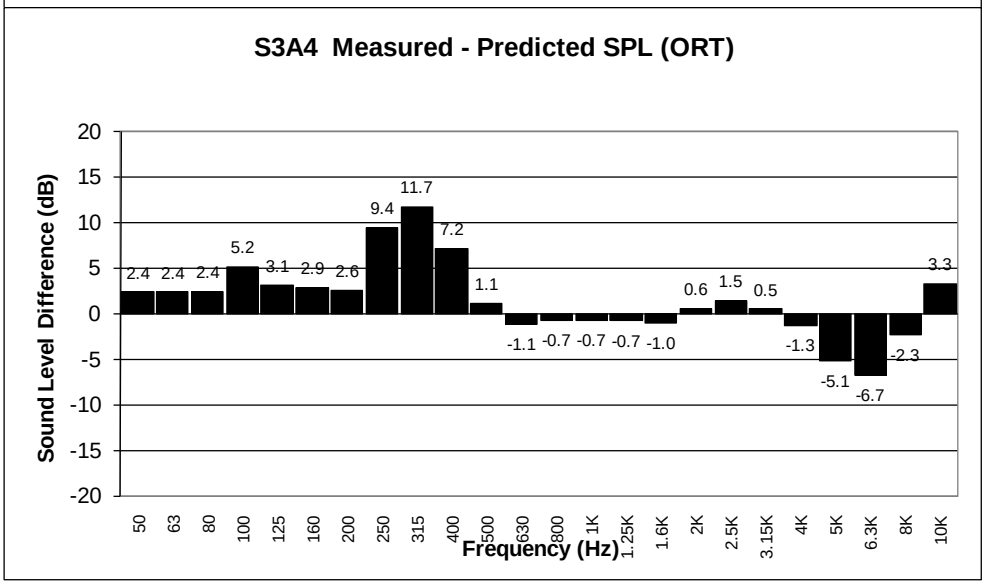
Site 3, Area A, Microphone 3



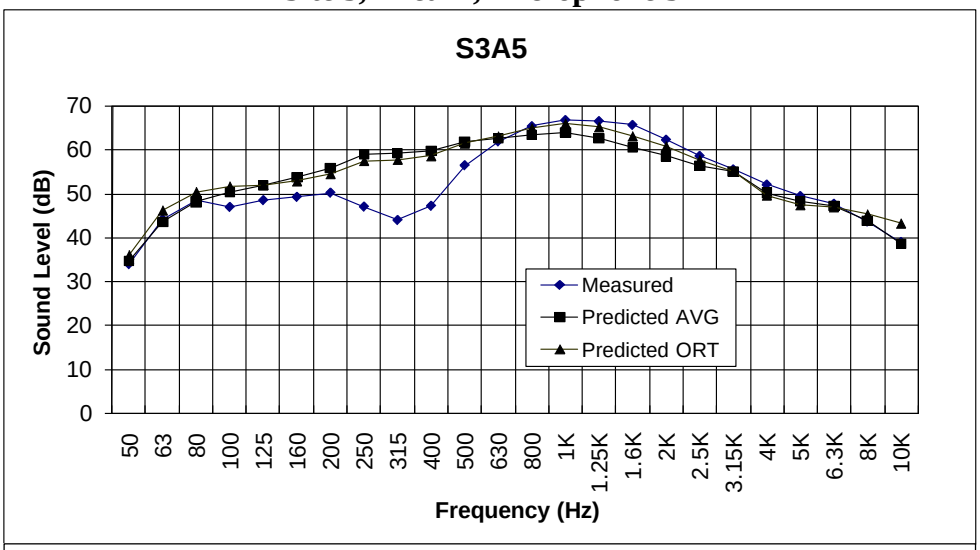
Site 3, Area A, Microphone 4

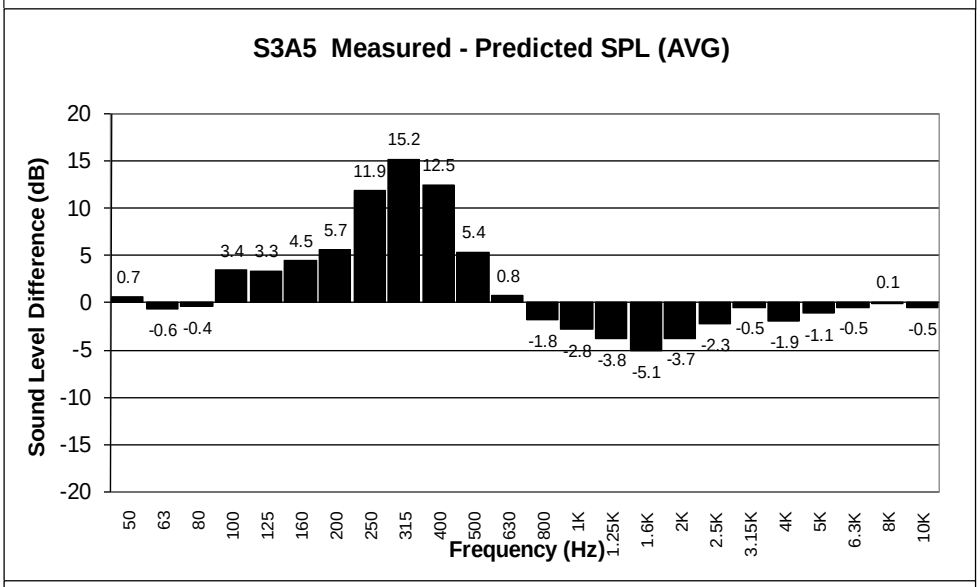


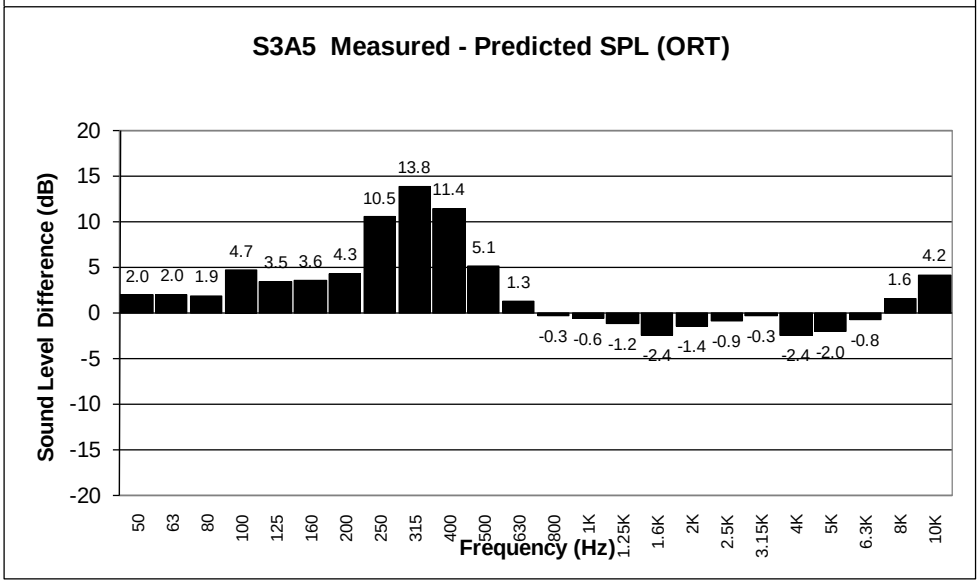




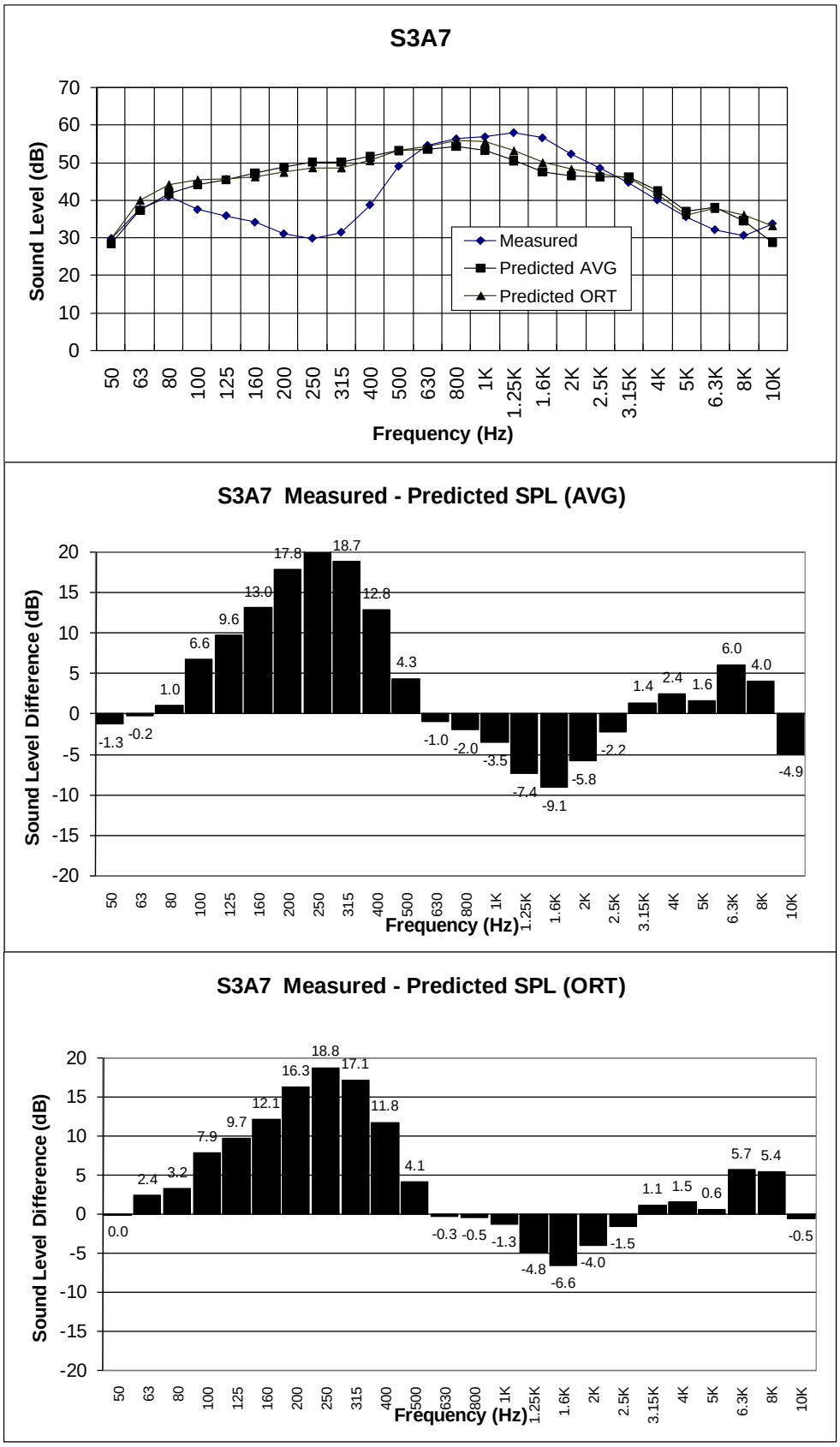
Site 3, Area A, Microphone 5



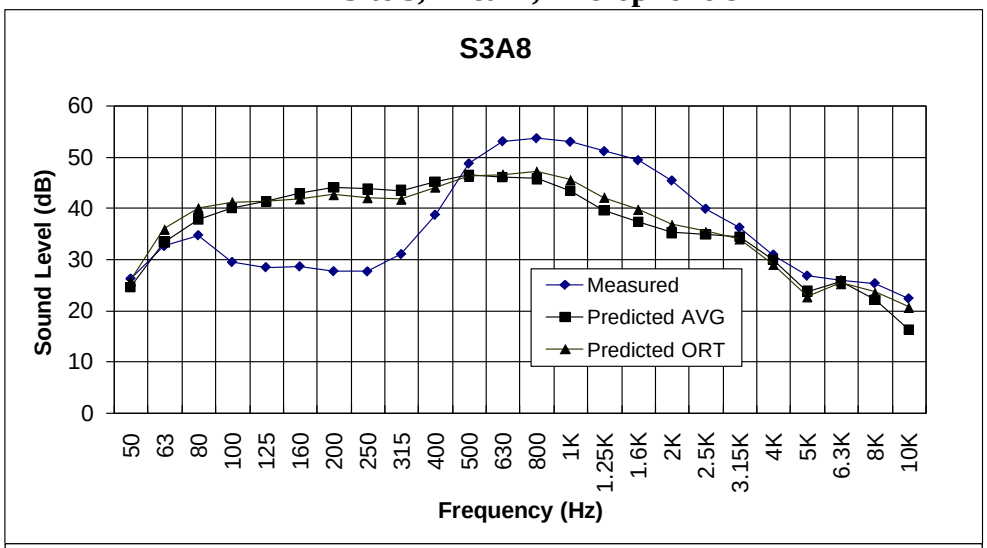


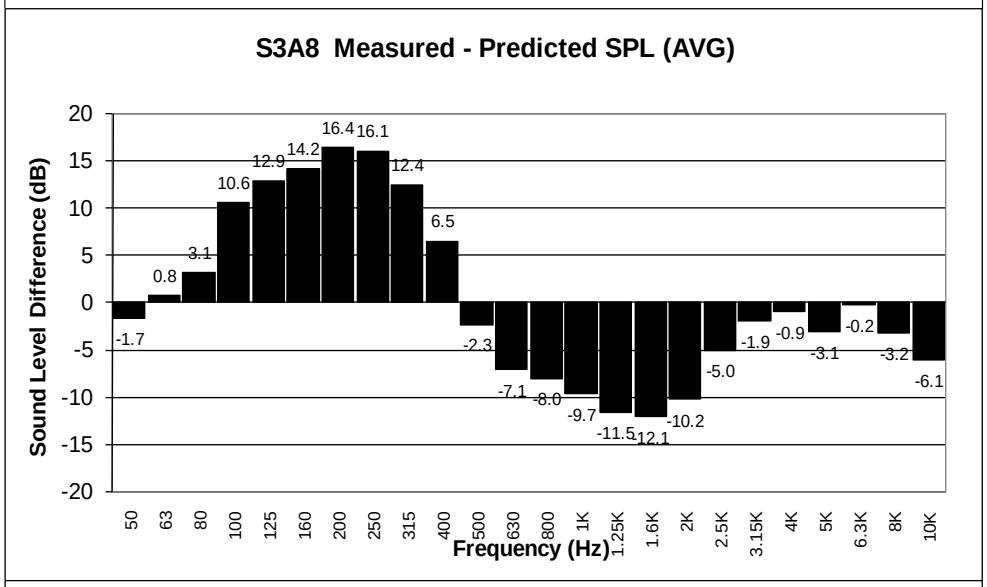


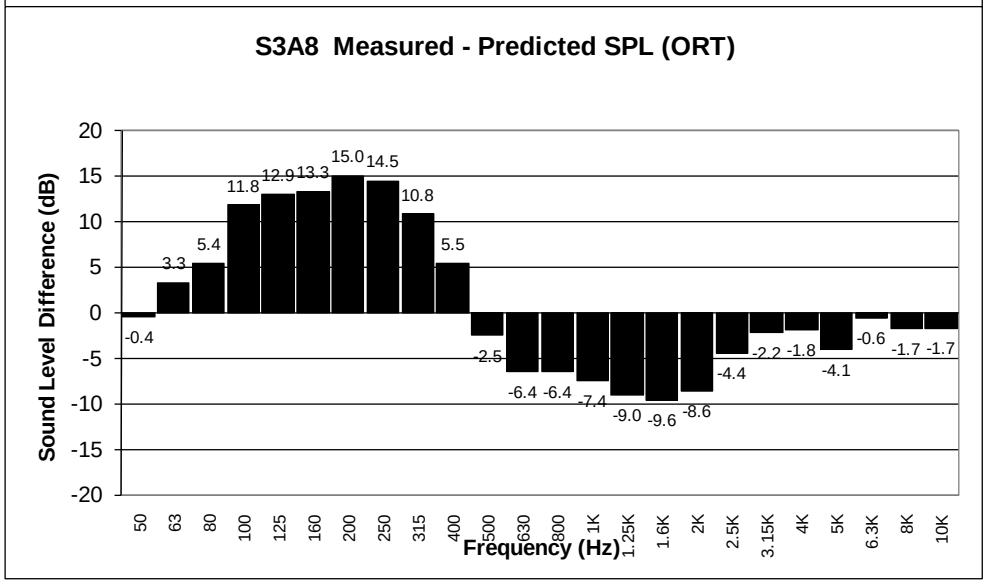
Site 3, Area A, Microphone 7



Site 3, Area A, Microphone 8

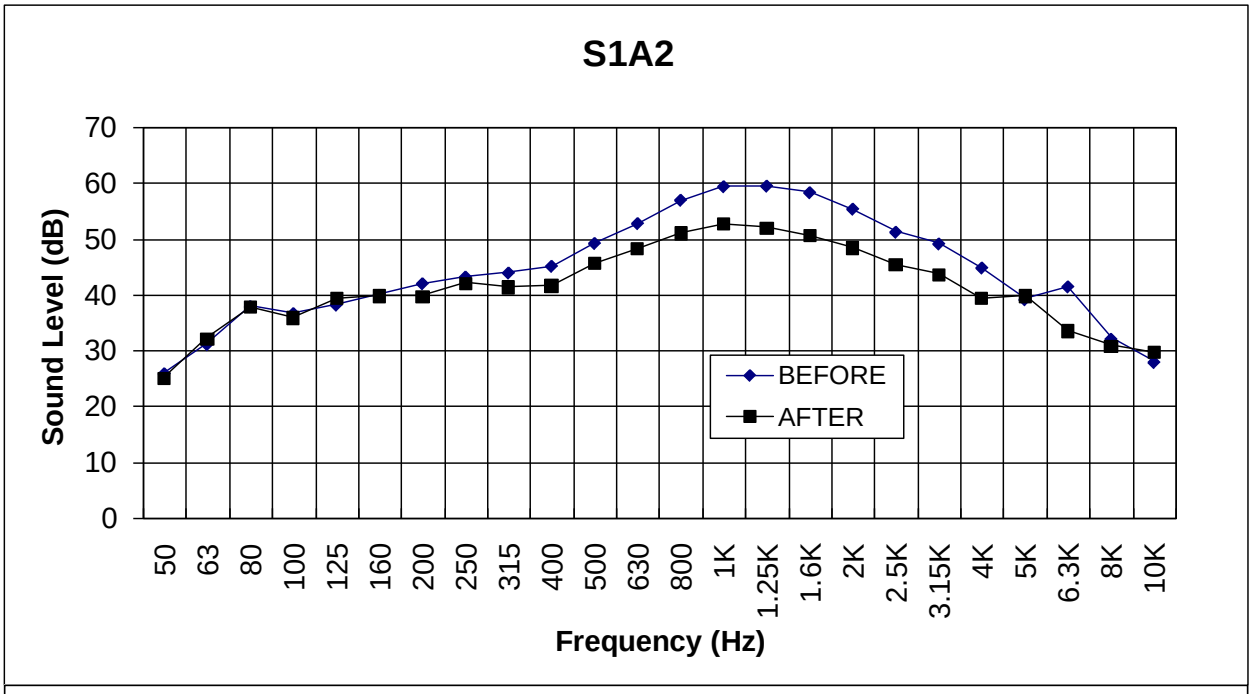


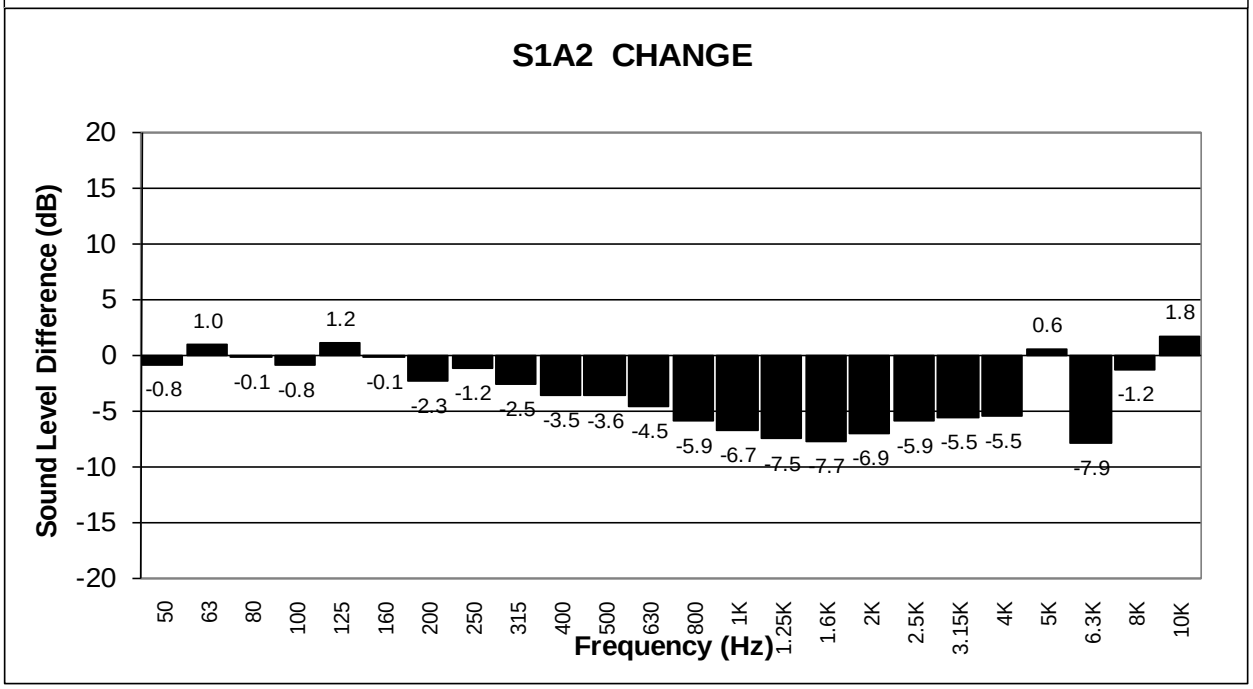




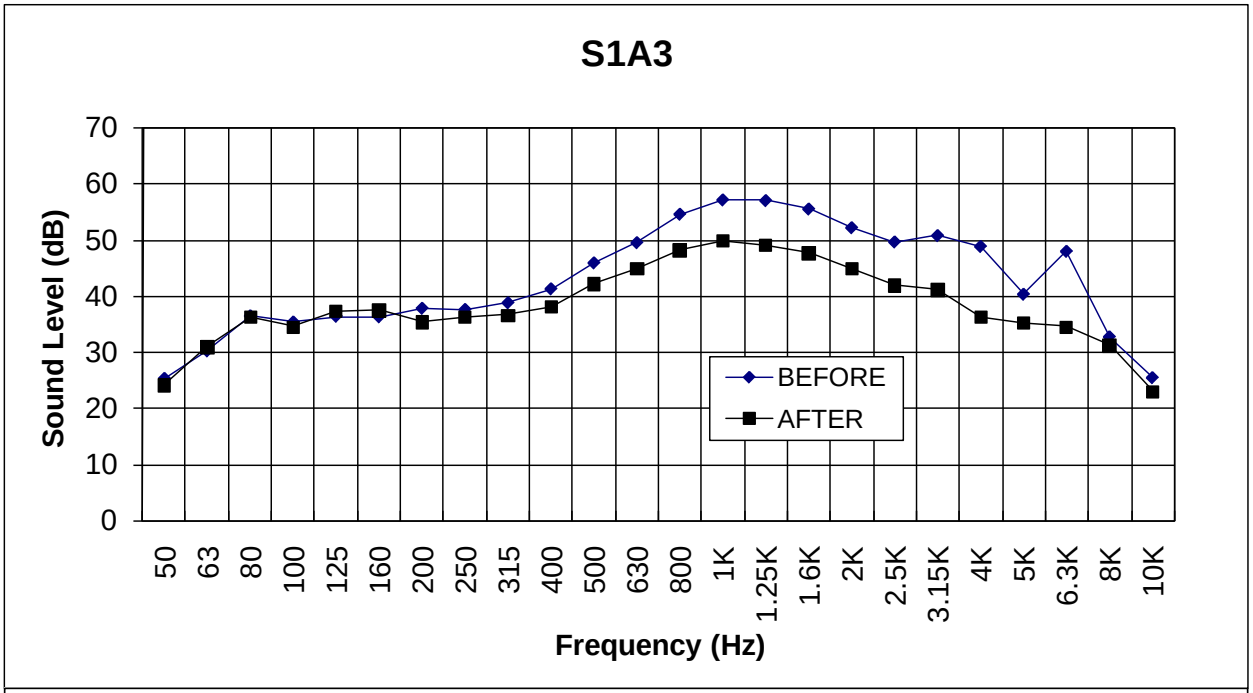
APPENDIX D

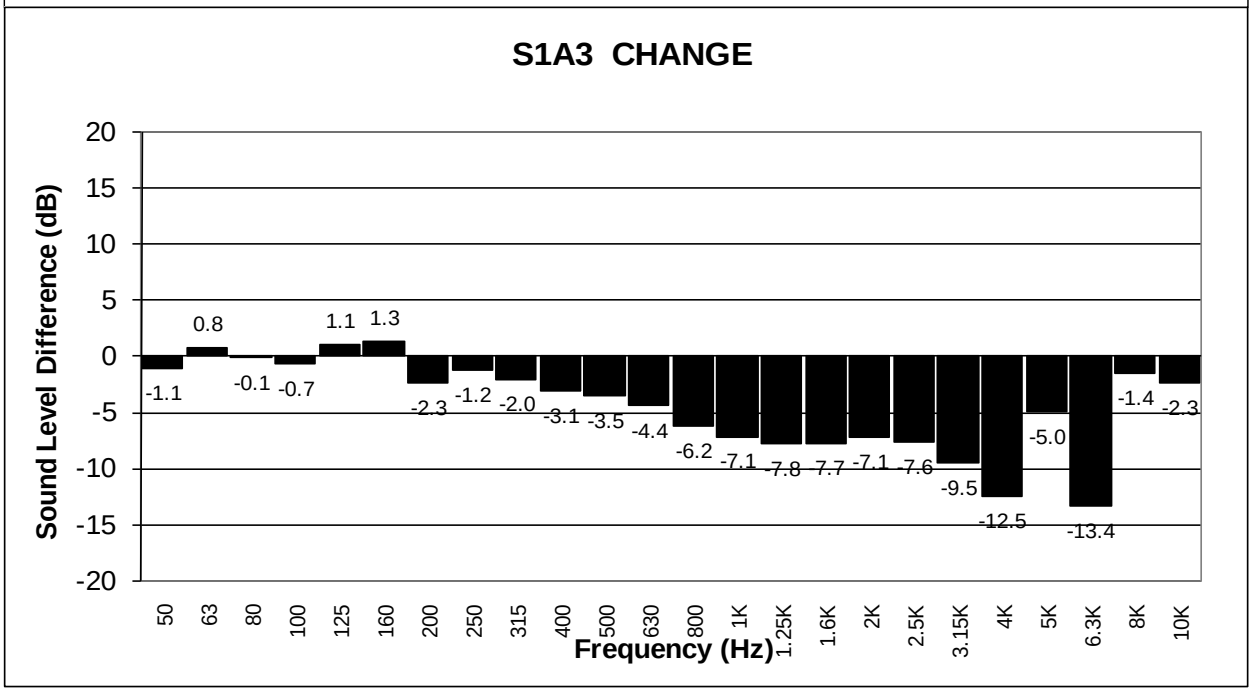
Site 1, Area A, Microphone 2



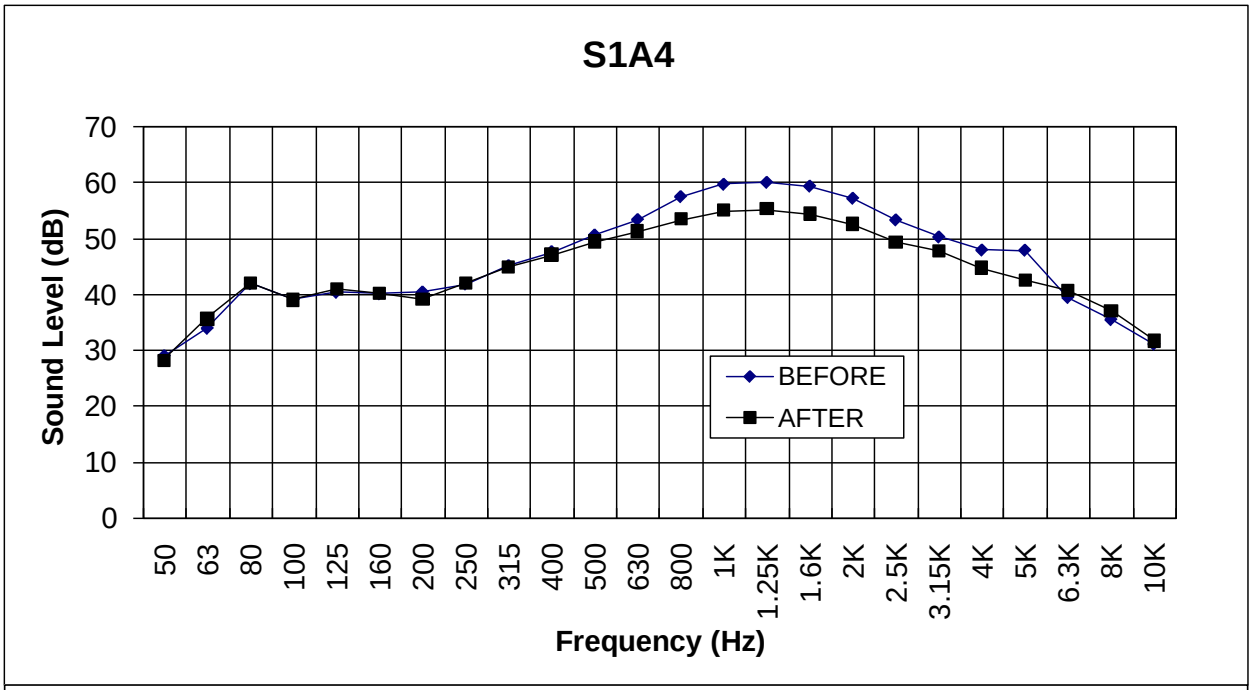


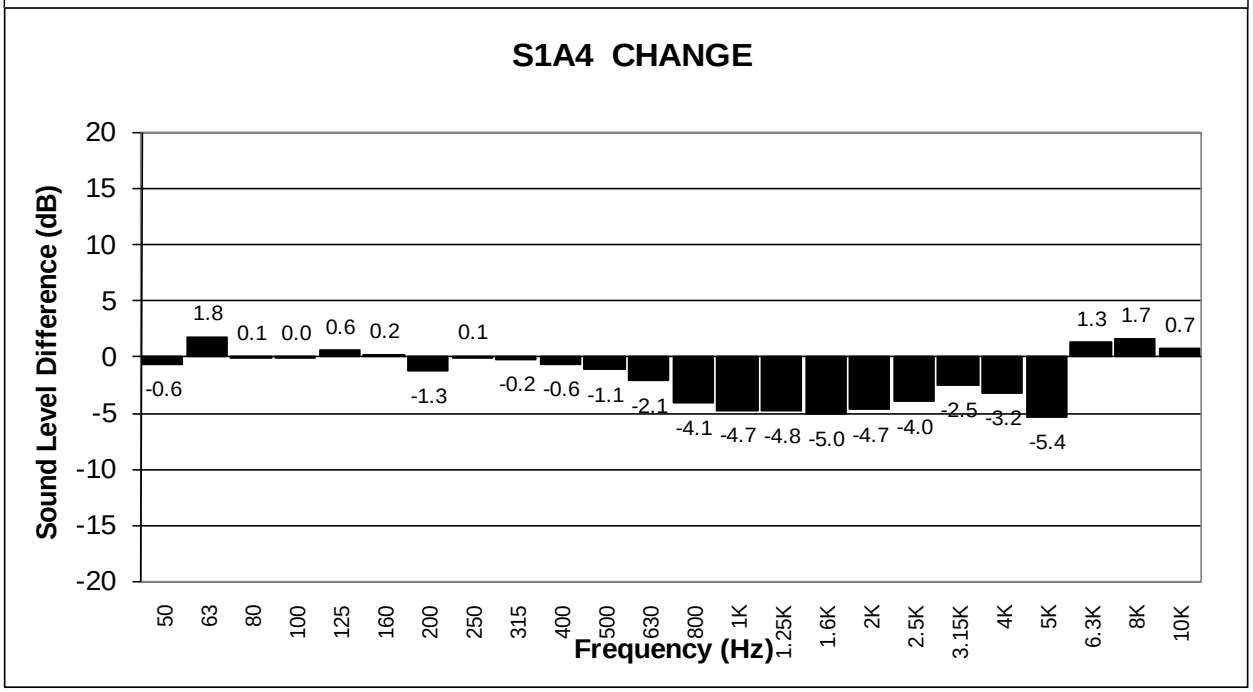
Site 1, Area A, Microphone 3



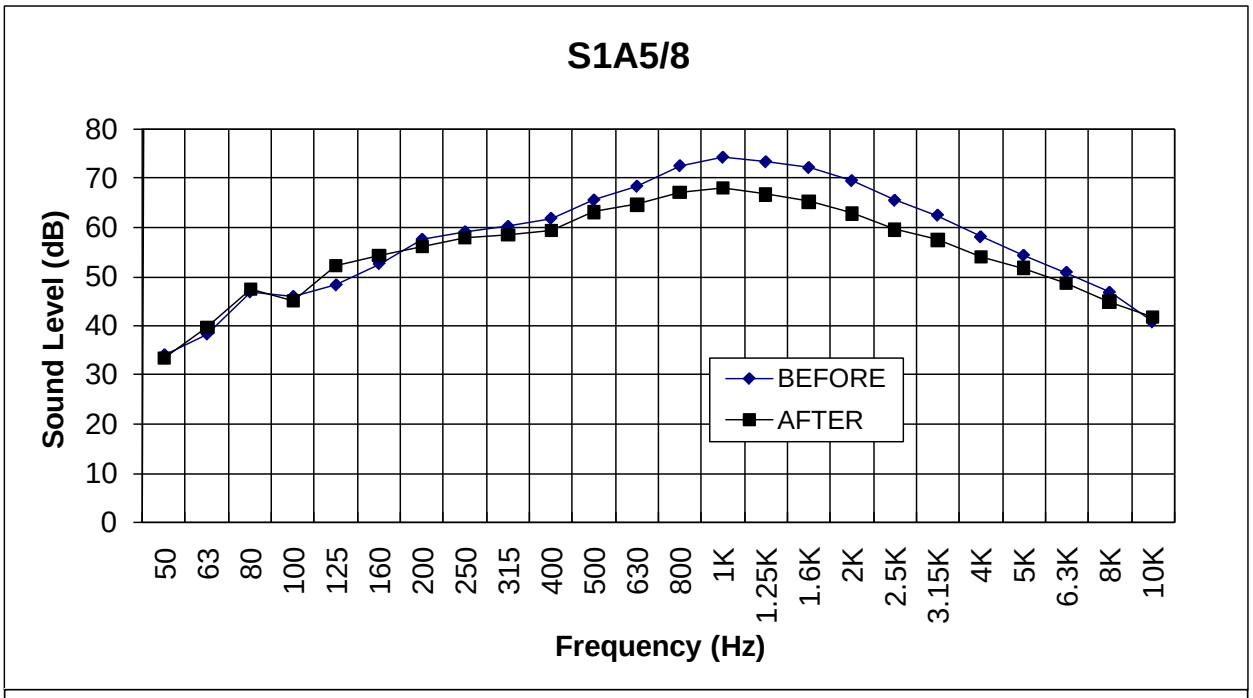


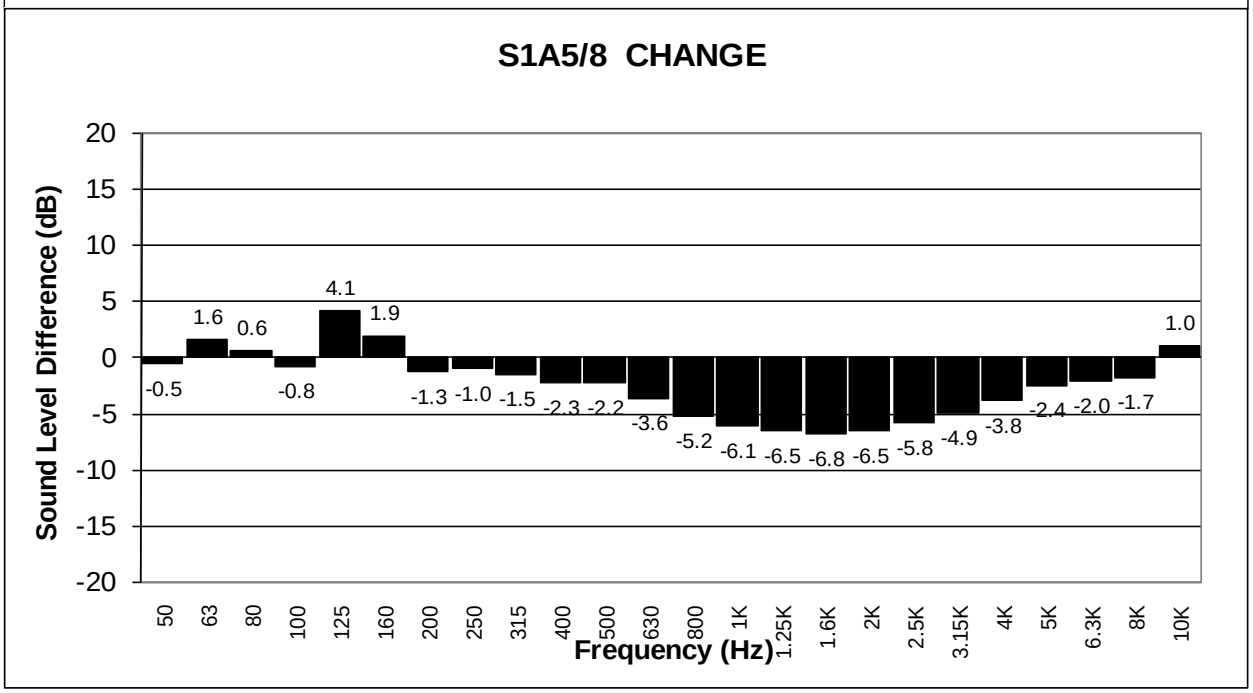
Site 1, Area A, Microphone 4



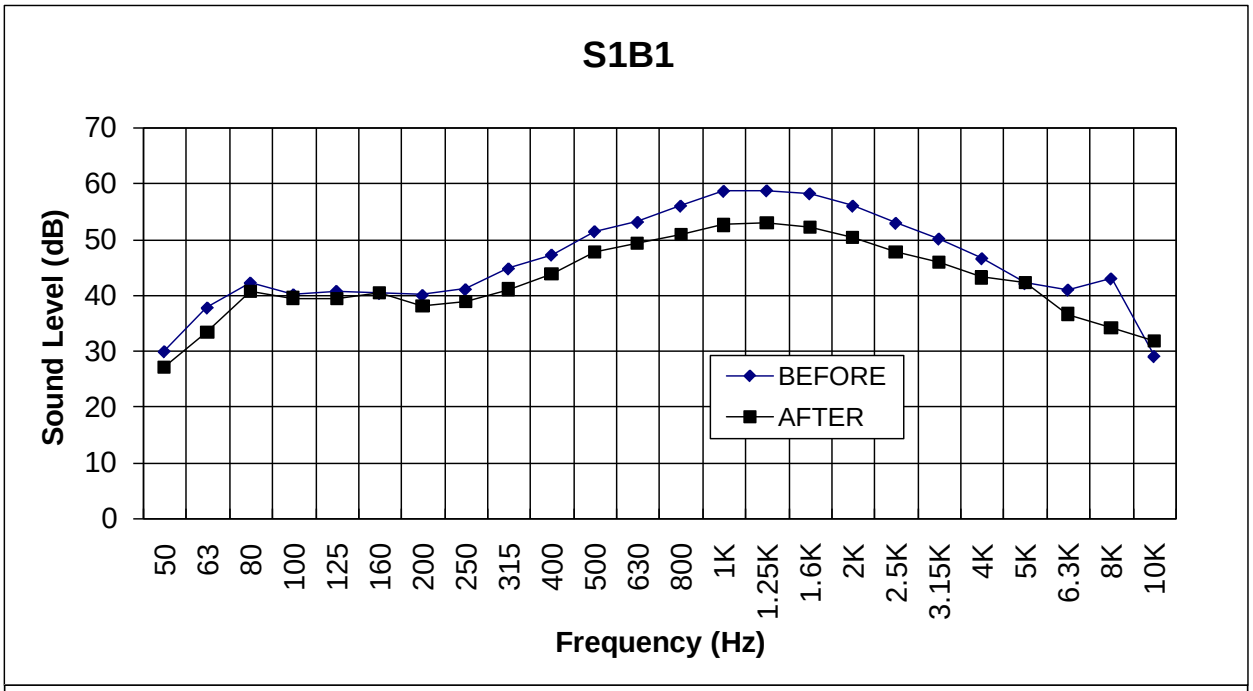


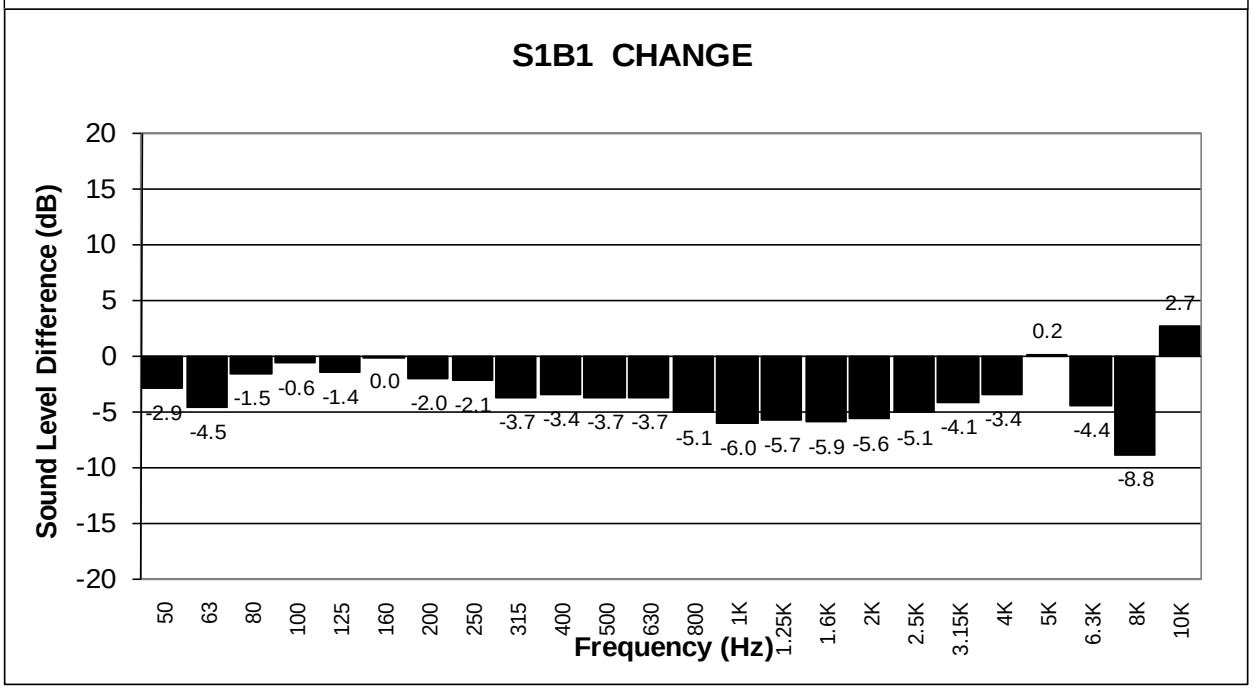
Site 1, Area A, Microphone 5



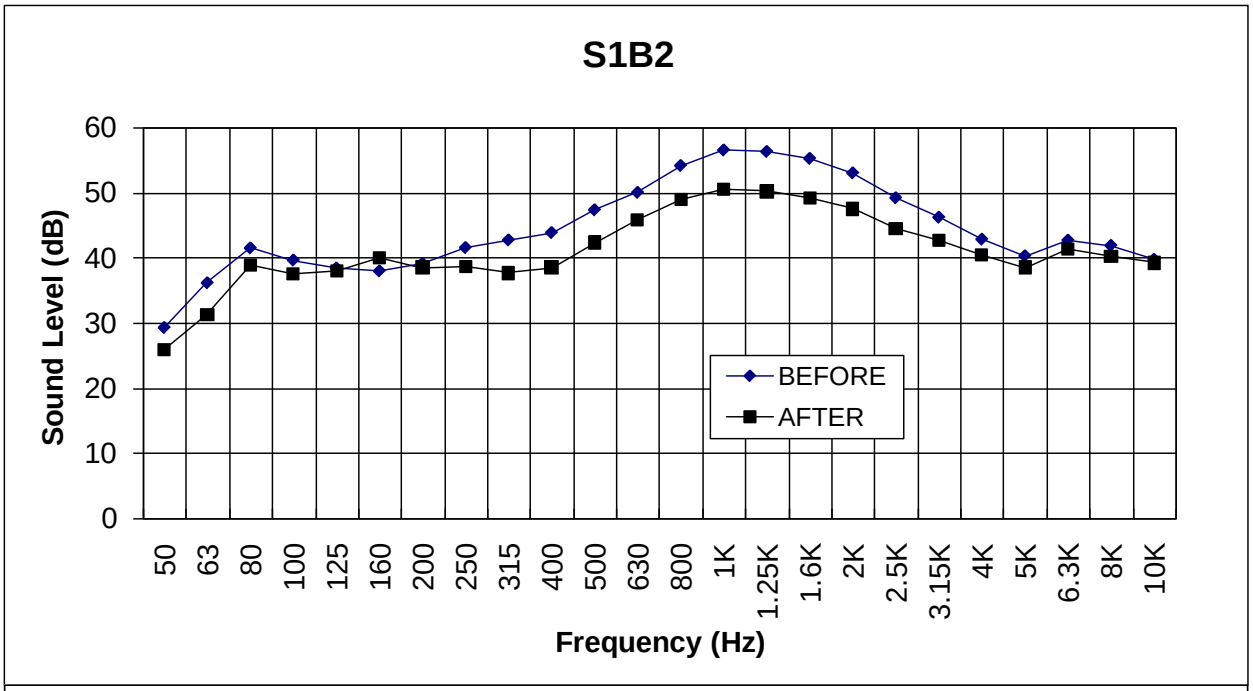


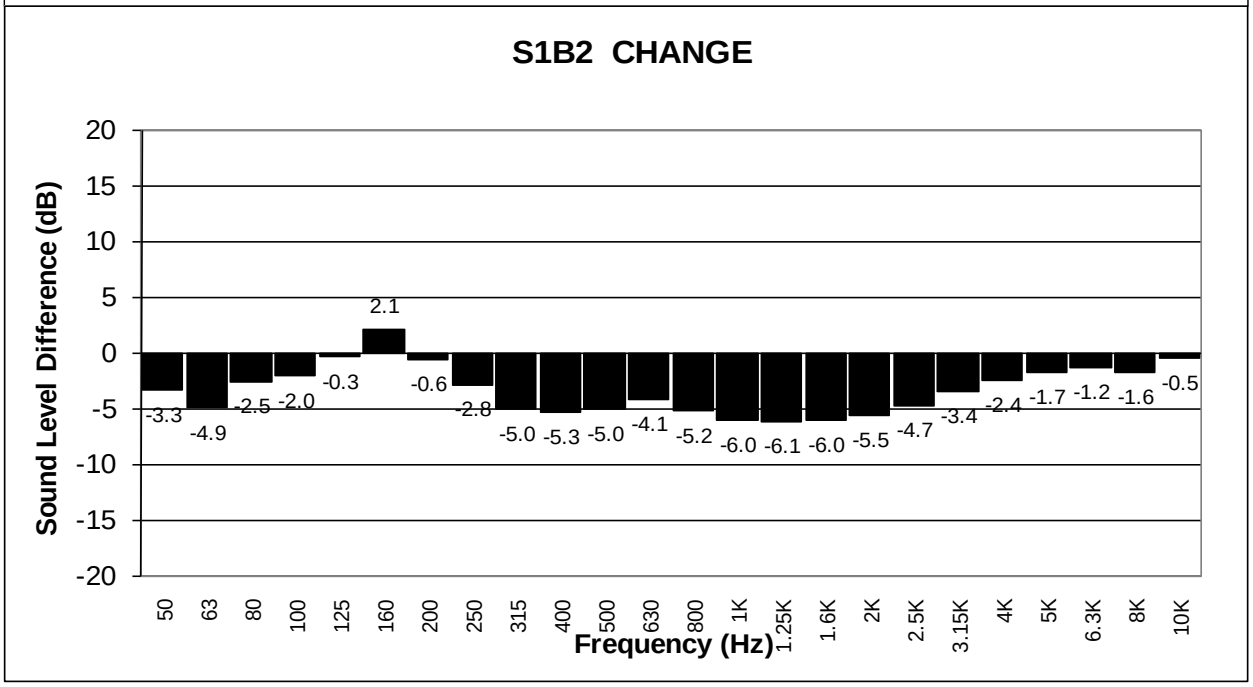
Site 1, Area B, Microphone 1



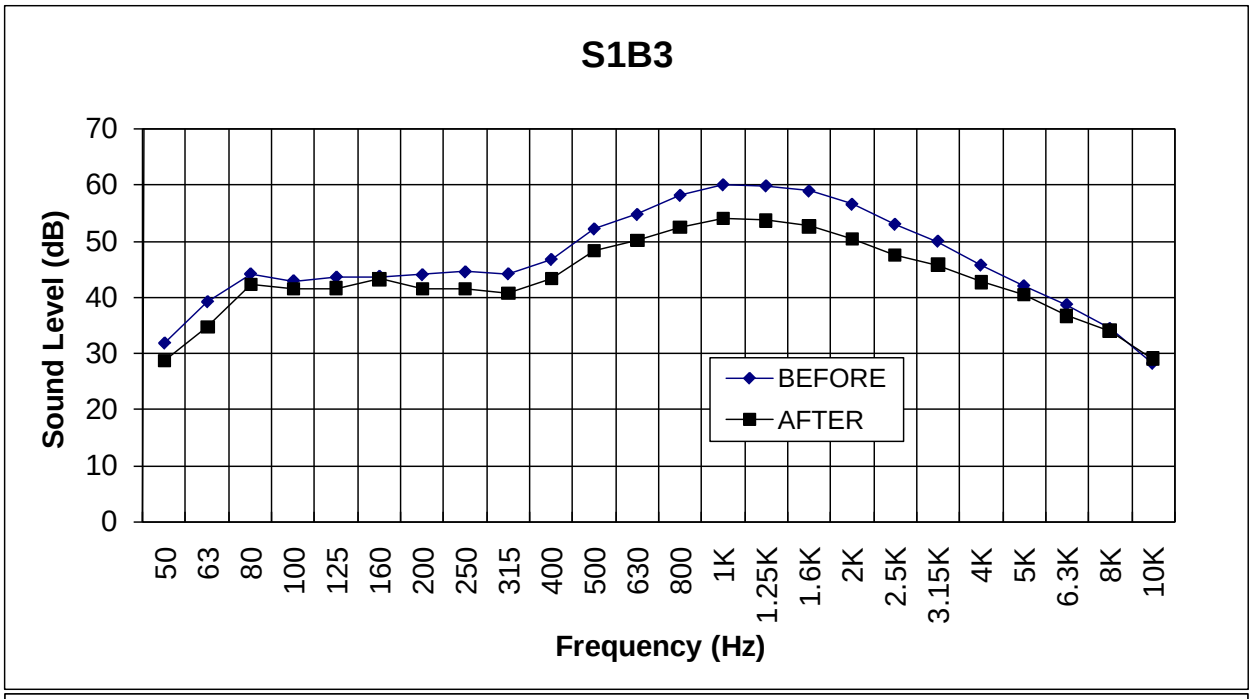


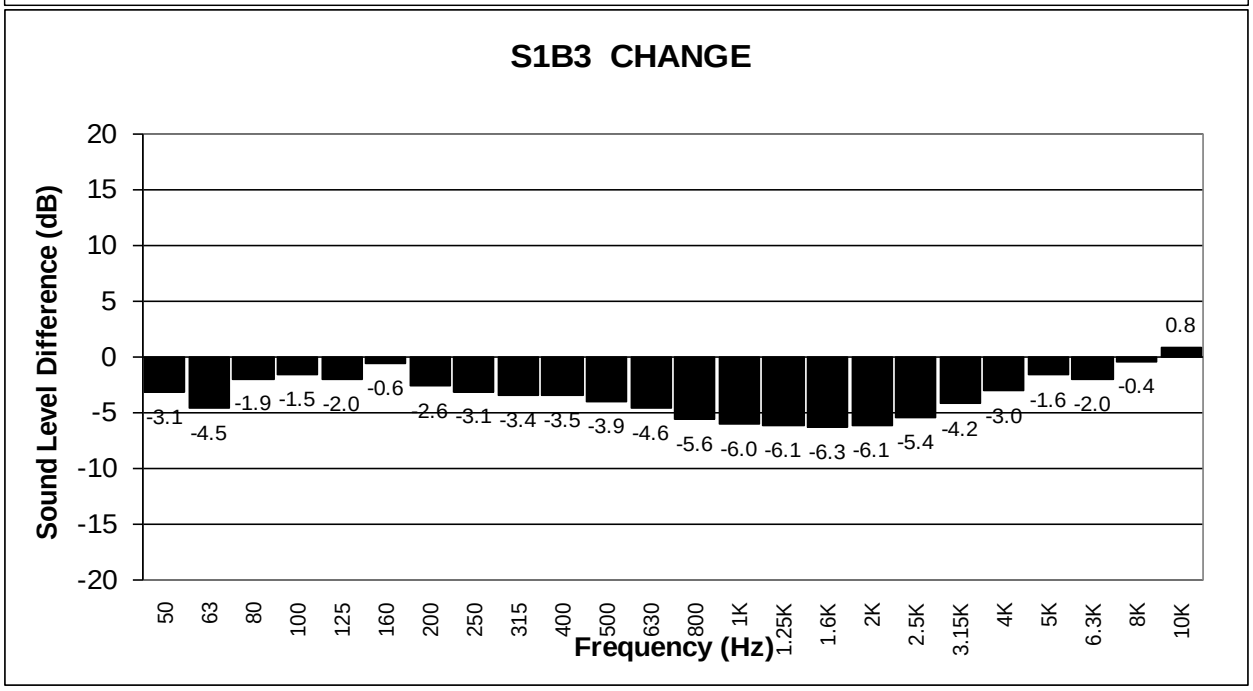
Site 1, Area B, Microphone 2



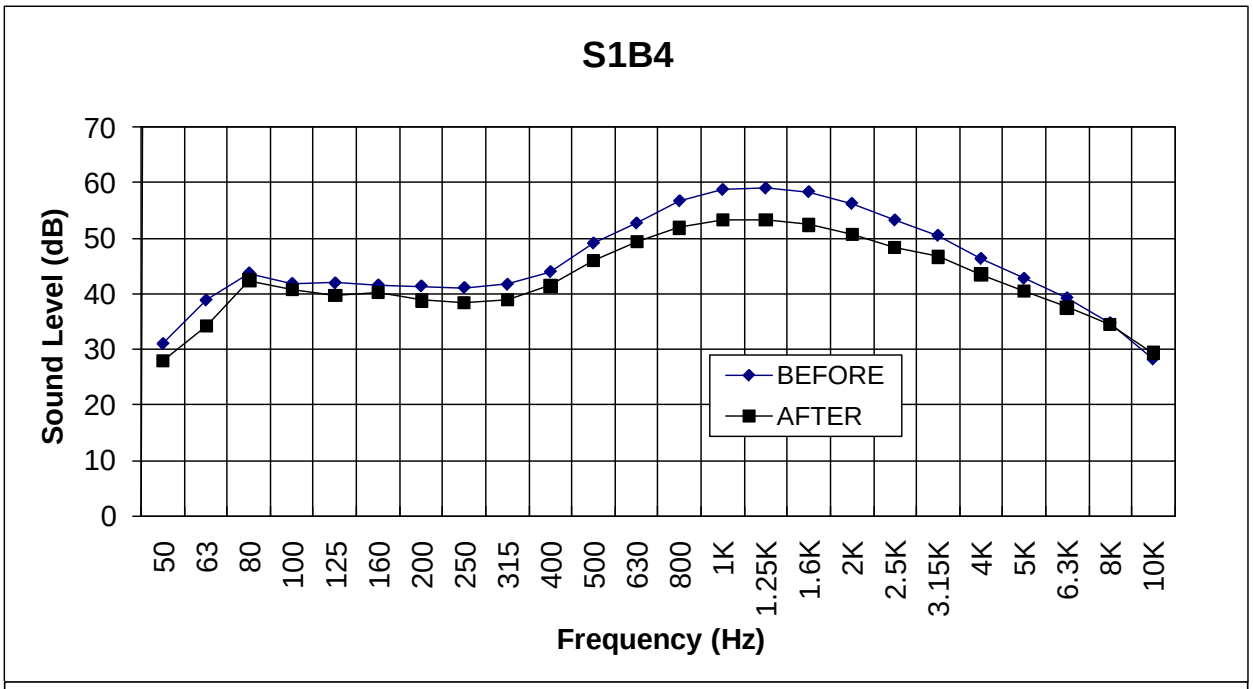


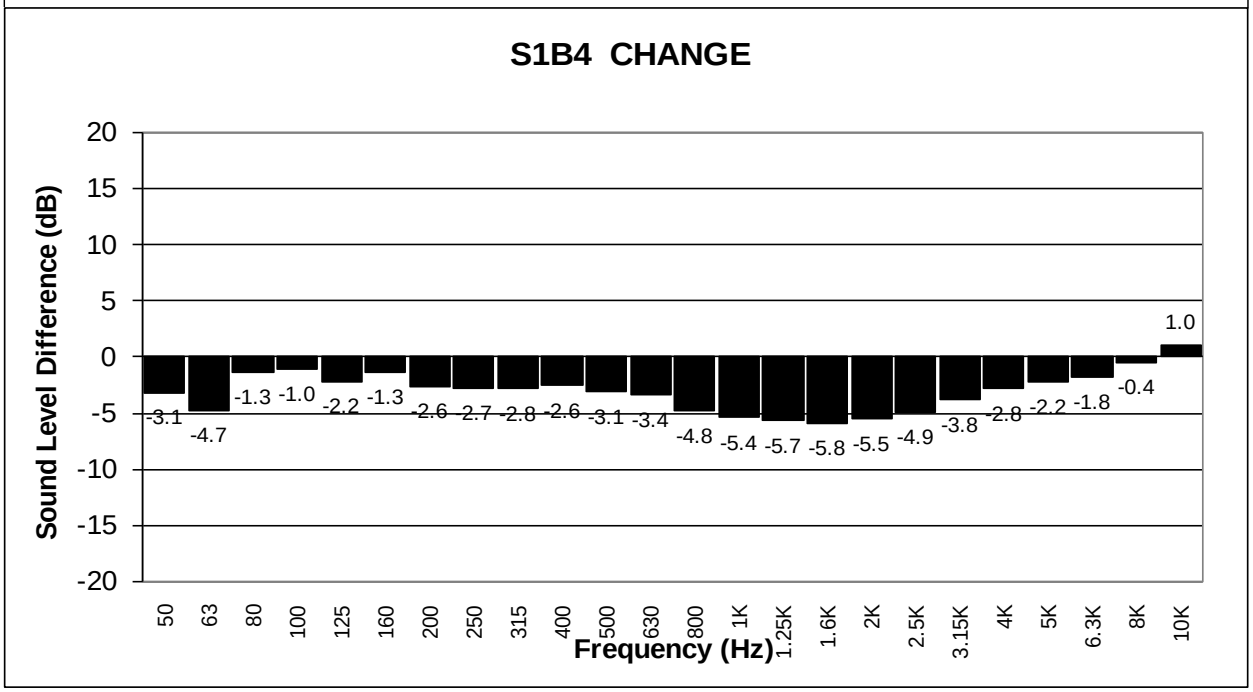
Site 1, Area B, Microphone 3



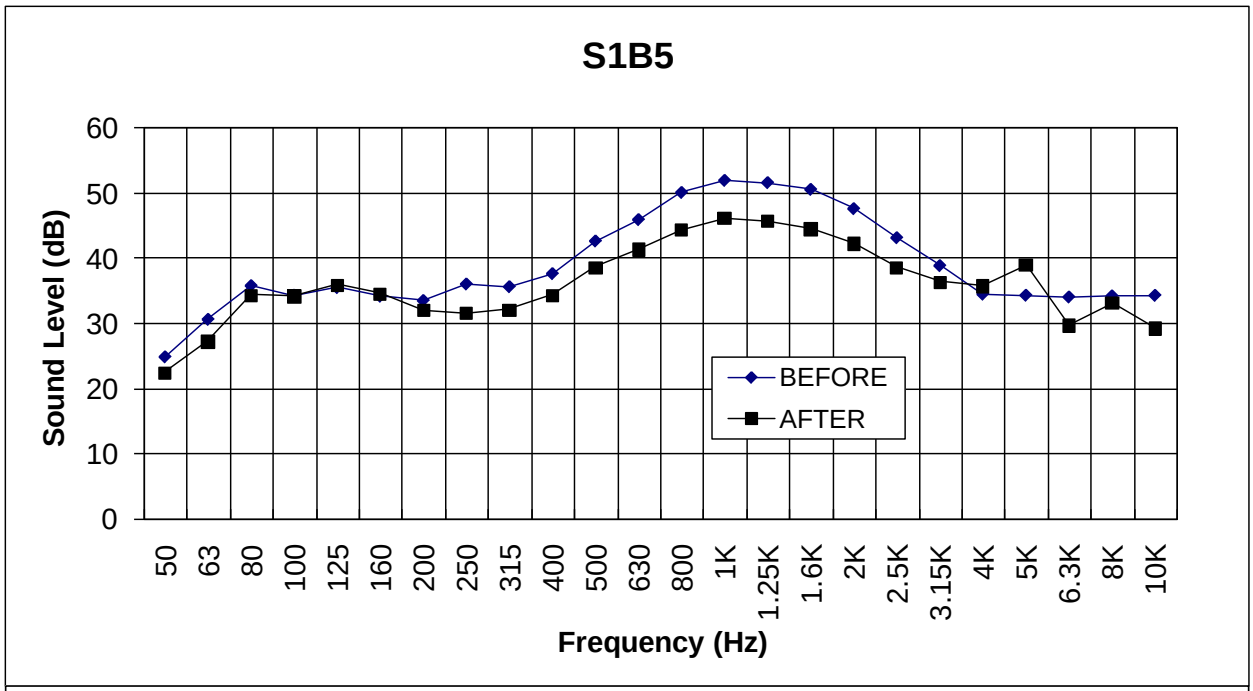


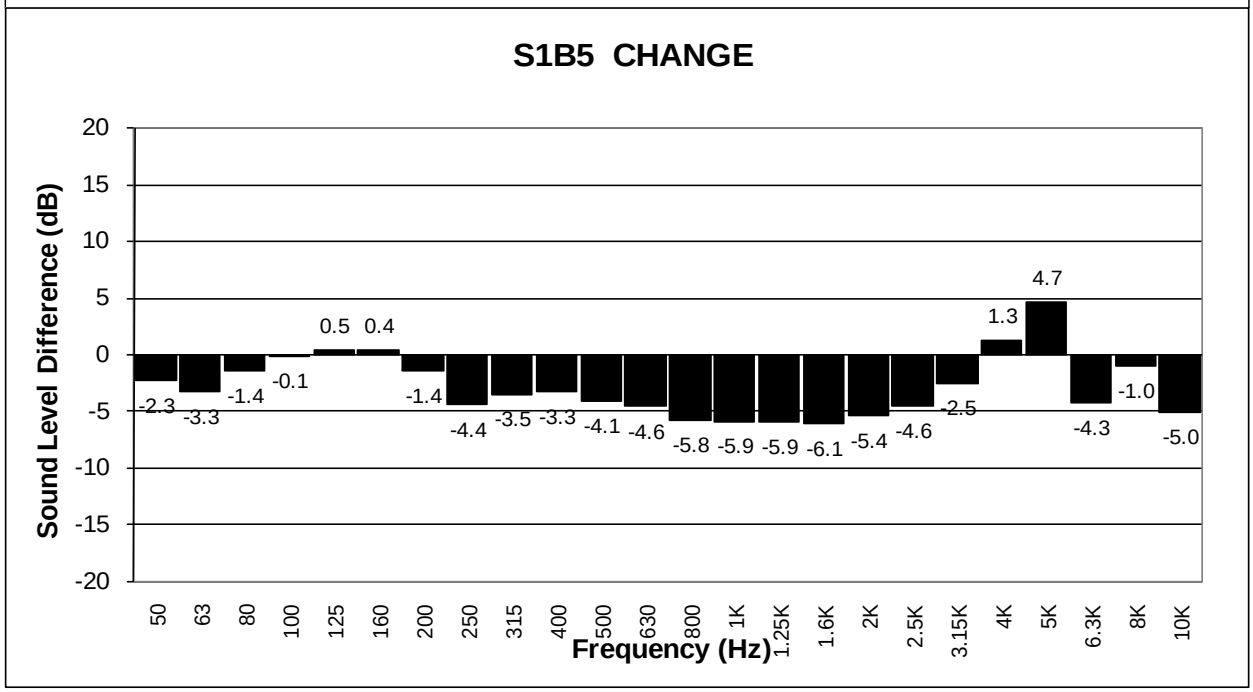
Site 1, Area B, Microphone 4



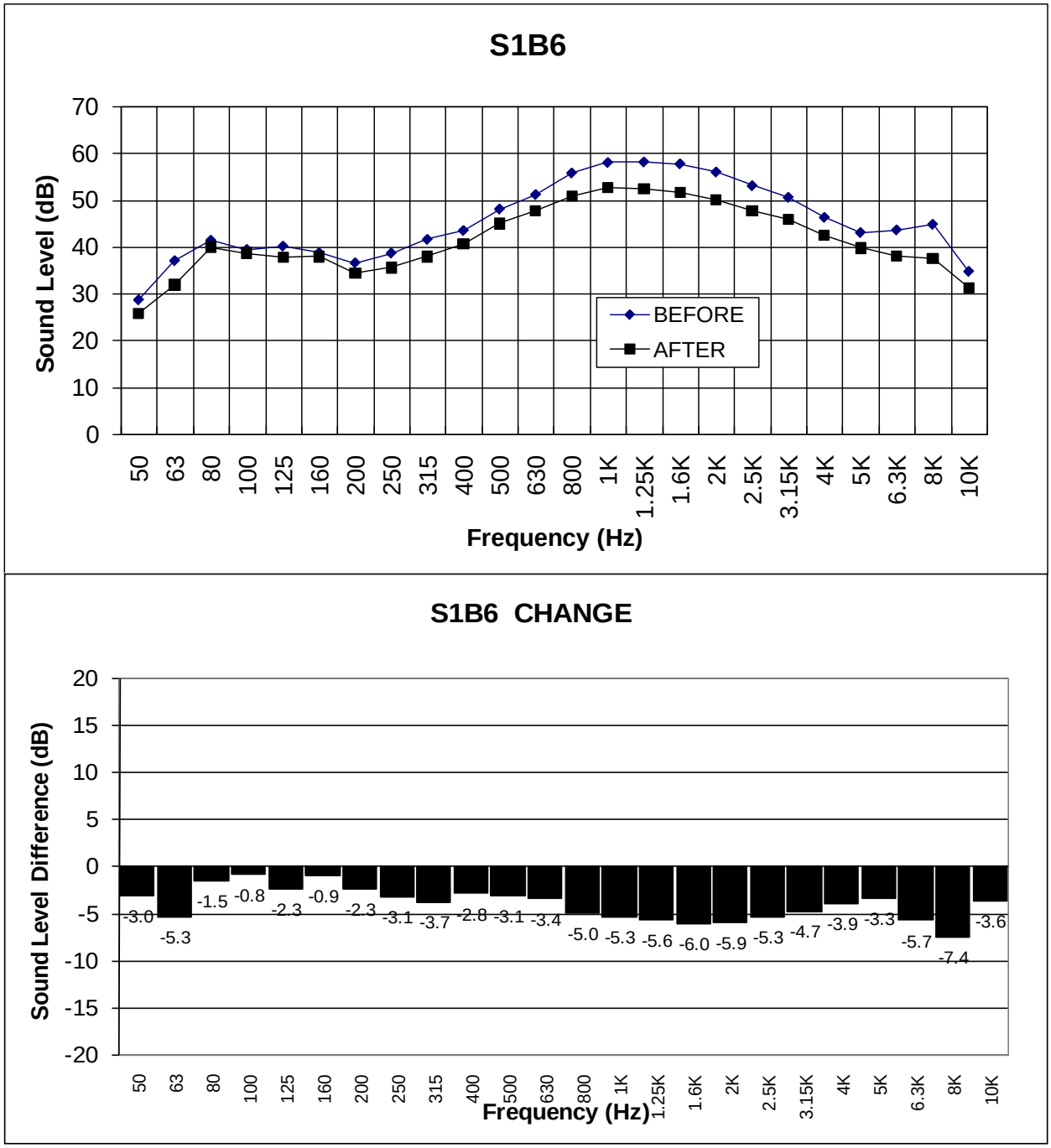


Site 1, Area B, Microphone 5

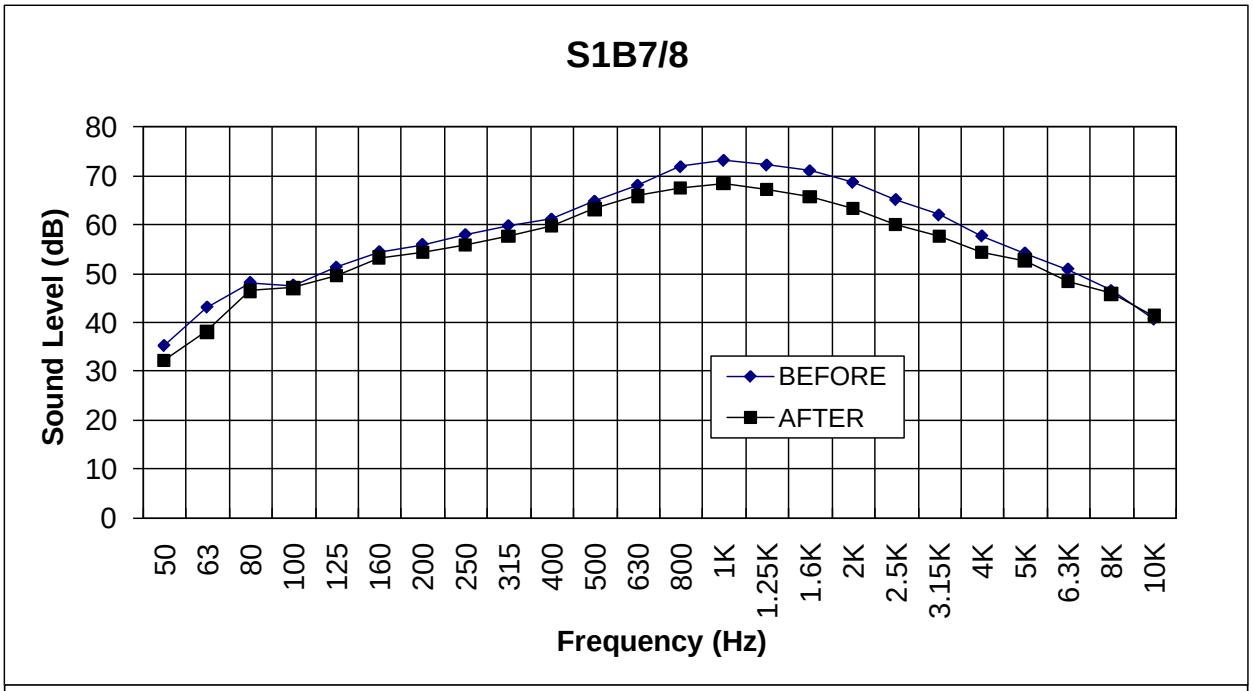


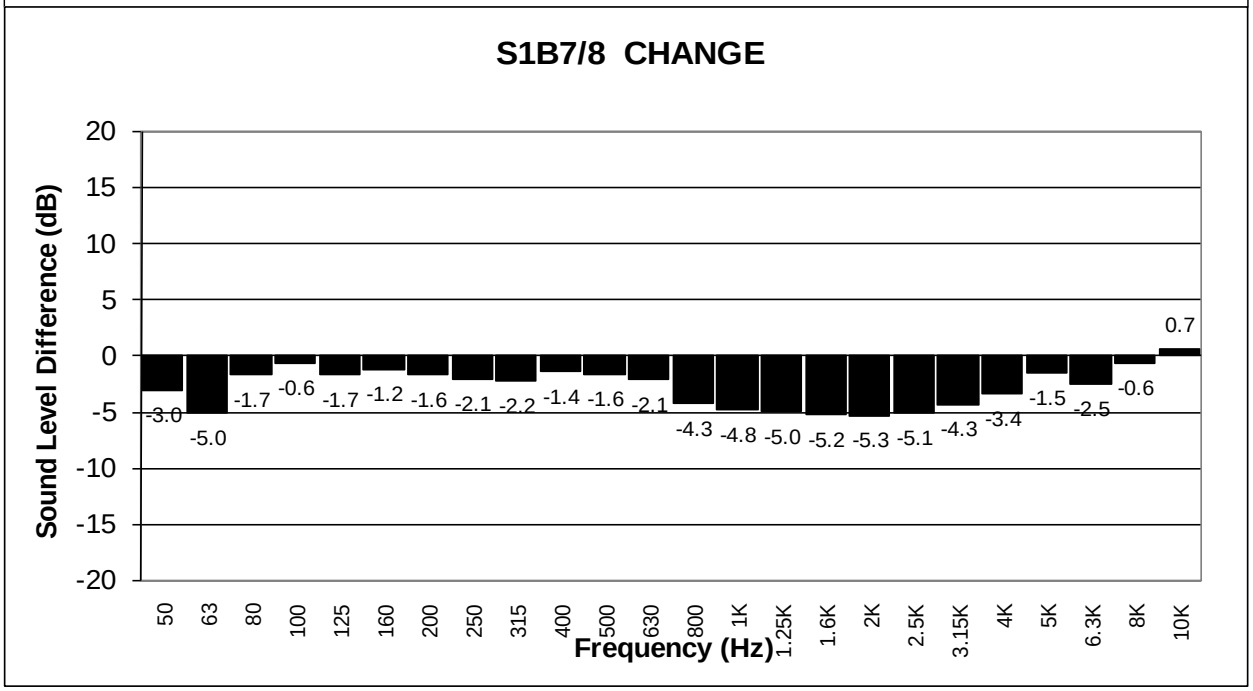


Site 1, Area B, Microphone 6

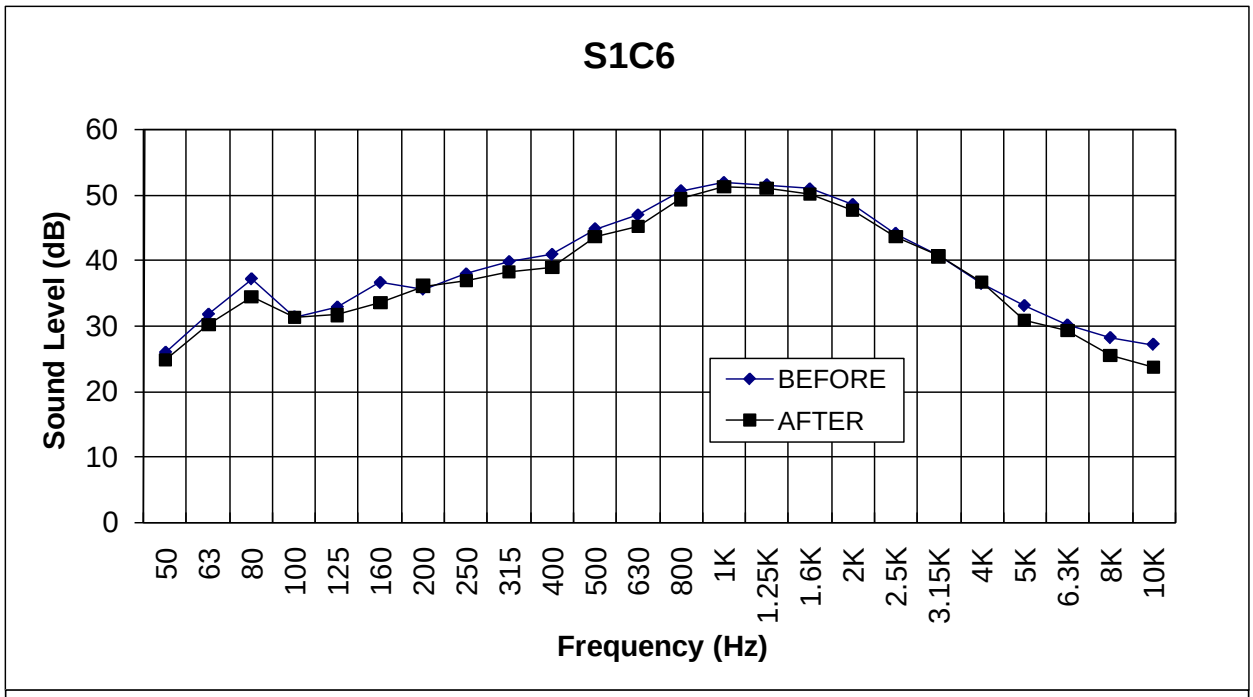


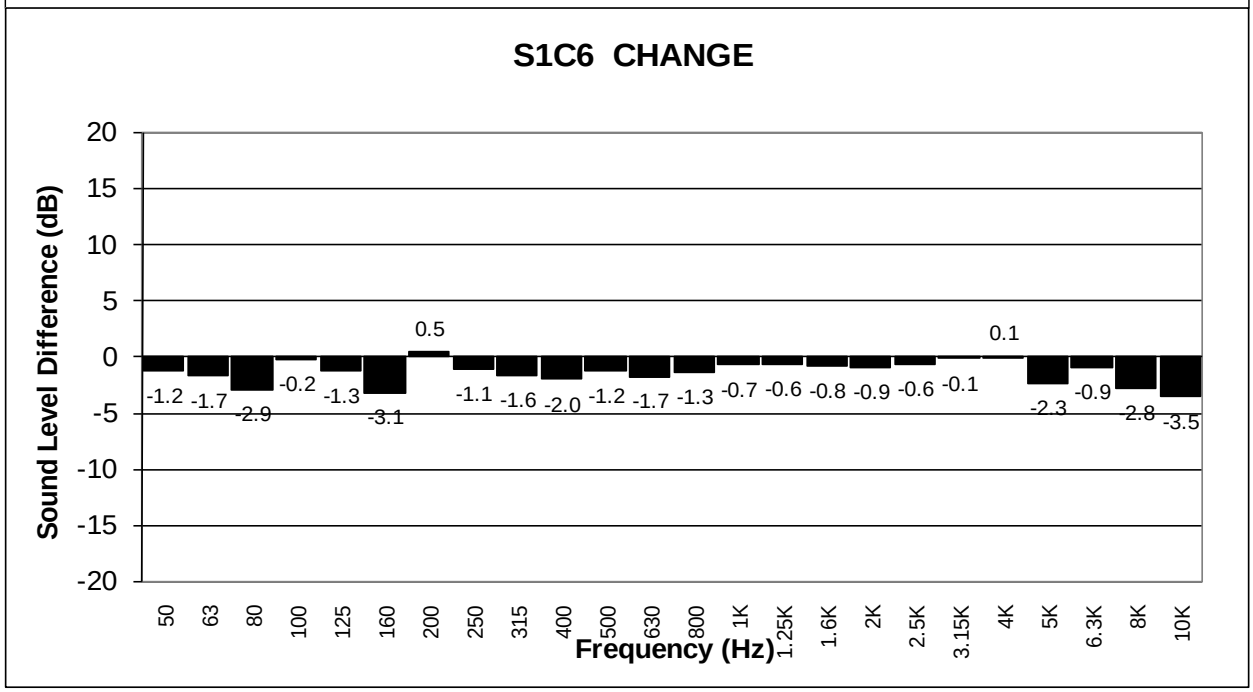
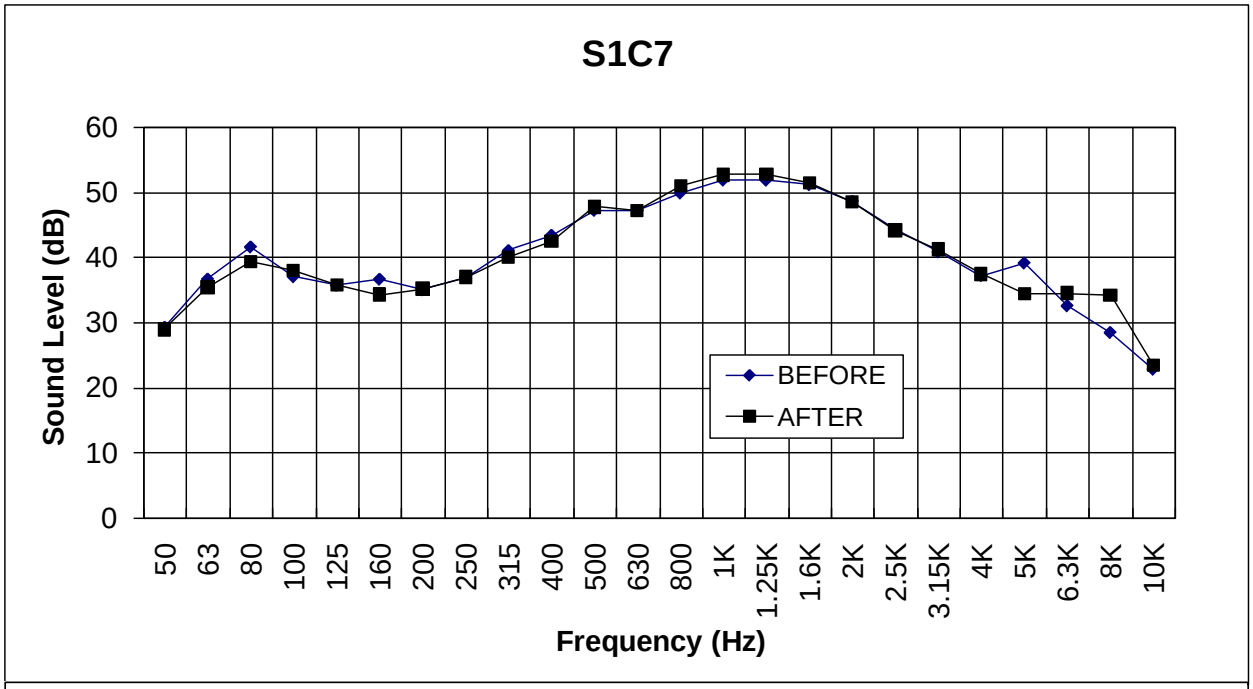
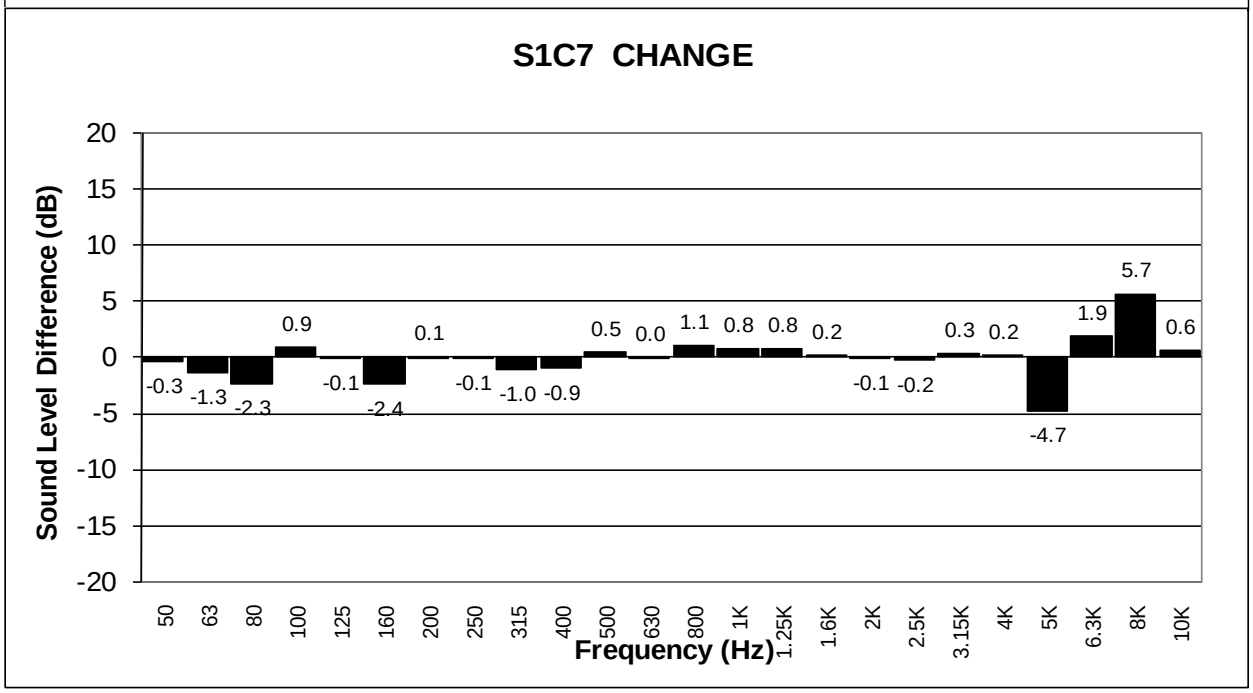
Site 1, Area B Microphone 7





Site 1, Area C, Microphone 6





Site 1, Area C, Microphone 7