Comparison and Testing of Various Noise Wall Materials

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16. Abstract

Noise barriers are a necessary structure along the highway to protect the local residents from excessive road noise. There are many different materials from which noise barriers can be constructed. As of 2004, the most widely used noise barrier material was concrete which accounts for approximately 80 percent of all the noise barriers in the United States. Other noise barrier materials include metal, plastic, wood or soil. Each of the materials used to construct noise barrier has advantages and disadvantages both acoustically and aesthetically.

This study was done to determine which of the currently used noise barrier materials in Ohio produced the largest noise reduction. There were seven different materials field tested across the State of Ohio; absorptive concrete walls, reflective concrete walls, hollow fiberglass walls, rubber-filled fiberglass walls, steel walls, clear walls and earthen berms). The noise barriers were tested by measuring noise levels in front of the barrier, above the barrier and behind the barrier, while recording traffic data (volume, class, and lane position) and atmospheric conditions. The noise reduction results across the various barrier materials were then compared to determine which material yielded the greatest noise reduction. The TNM parameters were set to replicate each site that was tested and the noise reduction results from the model were recorded. The results from the model and the field were then compared to determine if the model is an accurate representation of the field.

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Comparison and Testing of Various Noise Wall Materials

Draft 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

As a consequence of the National Environmental Policy Act (NEPA) of 1969, federal regulations were promulgated (23 CFR Part 772, rev. 2010) to ensure that the NEPA requirements would be met for major federally funded projects in the environmental area of traffic noise. These regulations provide the basis for Federal Highway Administration (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].

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.

The TNM model provides a method for predicting highway noise levels for various noise barrier alignments and heights as well as allowing various components that are customizable to many situations [FHWA, 2011]. The major customizable components consist of vehicle volume and class, site layout and topography, and various metrological conditions. These parameters provide the user with the ability to change and adapt the model to certain situations requiring analysis. If the model can provide accurate representations of the field situation, it could save a considerable amount of time and money required for field testing.

A traffic noise simulation model is an indispensable tool used in the process of mitigating traffic noise impacts. The FHWA 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).

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.

Noise analyses are typically conducted for noise sensitive land uses that are within 600 feet 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.

The ODOT procedures [ODOT, 2008] specify the steps to be taken for a noise analysis, beginning with a noise screening stage, which occurs 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 with an analysis of the reasonability and feasibility of the abatement alternatives.

For state DOTs to use federal funds for their interstates, they are required to provide noise abatement if the existing or projected equivalent noise levels reach 67 dB or greater [FHWA, 2006]. These maximum thresholds set by the FHWA can be seen in Table 1.1. In most cases, abatement is needed for a violation of Activity B (Residential) in a new highway or highway expansion projects. Prior to any construction, the governing agencies in charge of the project must comply with section 4(f) of the National Environmental Policy Act (NEPA). These noise impacts fall under section 4(f) and must have a plan to mitigate any noise level increase past the set threshold. To comply with these requirements, DOTs conduct various noise testing prior to any changes to examine existing condition of a highway and compare that with TNM predicted noise levels with noise abatement.

In order to remain current with advancements in technology, the ODOT noise mitigation policy and procedures require a periodic review of abatement alternatives, noise abatement performance, durability issues, and environmental impacts. As a result of this periodic review, ODOT has identified the need to research the applicability and performance of currently available noise wall materials, durability and performance.

Table 1.1. Noise Abatement Criteria Set By FHWA-Part 772 [FHWA, 2006]

Activity category	Activity Leq(h)	Criteria[2] L10(h)	Evaluation location	Activity description
A	57	60	Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B[3]	67	70	Exterior	Residential.
C[3]	67	70	Exterior	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings.
D	52	55	Interior	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios.
E[3]	72	75	Exterior	Hotels, motels, offices, restaurants/bars, and other developed lands, properties or activities not included in A-D or F.
F				Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing.
G				Undeveloped lands that are not permitted.

1.1. Problem

Noise barriers are a necessary structure along the highway to protect the local residents from excessive road noise. There are many different materials from which noise barriers can be constructed. As of 2004, the most widely used noise barrier material was concrete which accounts for approximately 80 percent of all the noise barriers in the United States [FHWA, 2006]. Other noise barrier materials include metal, plastic, wood or soil. Each of the materials used to construct noise barrier has advantages and disadvantages both acoustically and aesthetically.

This study was done to determine which of the currently used noise barrier materials in Ohio produced the largest noise reduction. There were seven different materials field tested across the State of Ohio; absorptive concrete walls, reflective concrete walls, hollow fiberglass walls, rubber-filled fiberglass walls, steel walls, clear walls and earthen berms). The noise barriers were tested by measuring noise levels in front of the barrier, above the barrier and behind the barrier, while recording traffic data (volume, class, and lane position) and atmospheric conditions. The noise reduction results across the various barrier materials were then compared to determine which material yielded the greatest noise reduction. The TNM parameters were set to replicate each site that was tested and the noise reduction results from the model were recorded. The results from the model and the field were then compared to determine if the model is an accurate representation of the field.

This research project evaluated various noise wall types (absorptive and reflective), materials (hollow fiberglass walls, rubber-filled fiberglass walls, concrete walls, steel walls, clear walls and earthen walls), performance and durability. Though this analysis, the research team determined the most effective noise wall material for the reduction of traffic generated noise associated with freeways for a location and situation. This research will improve ODOT's policy and procedures related to the selection and specification of noise abatement walls throughout the state for new construction projects.

1.2. Literature Review

A literature review was conducted on noise abatement wall materials (including absorptive and reflective materials) to obtain information on the advantages and disadvantages of each material, the noise reduction potential including the Sound Transmission Class (STC) rating, the costs of the material, transportation, erection and maintenance, durability, and service life estimates. Extensive literature searches were conducted through web-based queries, as well as queries through specific agency search engines (such as the Transportation Research Board). Literature searches were also conducted for all relevant transportation journals and other published reports and documents. Each of the papers and reports was critically reviewed for the following: objectives, concerns, data and analysis tools, performance measures, evaluation methodology, impacts, innovative technology used, and results. A comprehensive state-of-the-art literature review was prepared herein containing the summaries and critiques organized by groups of similar topics.

Traffic noise analyses typically involve a consideration of the noise source, the noise propagation path, and the receiver of the noise as well as the relationship between the source, path, and receiver to determine whether noise impacts will occur. Further, strategies to mitigate vehicular noise impacts are typically targeted at one or more of these elements. Noise abatement walls, the focus of this research, can be categorized as a part of the noise propagation path and are frequently utilize to mitigate vehicular noise.

As a sound wave is propagated along a path from its source to the receiver, its level is diminished by a number of attenuation mechanisms. The attenuation mechanisms associated with sound propagation are commonly referred to as geometric spreading, barrier attenuation, ground attenuation, air attenuation, and other miscellaneous attenuations, such as reflections from walls of buildings or other vertical surfaces, foliage, houses located in the propagation path, and the effects of atmospheric weather conditions.

In general, noise barriers are objects that break the line-of-sight between the noise source and the receiver (i.e. a house) of the noise. Barriers can be natural landforms, constructed earthen berms, walls, or combination of walls and berms, etc. If the materials that form the barrier have adequate density, a negligible amount of noise will be transmitted through the barrier. The only way that noise from the source can be propagated to the receiver is over the top of the barrier. As the sound wave reaches the top edge of the barrier, it will be diffracted and a proportion of this diffracted energy will reach the receiver.

The amount of diffraction, and thus noise reduction for a given frequency band, produced by a barrier depends upon the geometry of the site, including the relative distances between the source, the barrier, and the receiver as well as the differences in elevation of the source, receiver, and the top edge of the barrier. In all cases for the same relative difference in elevations, a receiver that is farther from the barrier will experience less reduction of noise than receivers close to the barrier. For this reason, traffic noise barriers are not effective at reducing noise levels for receivers located at large distances from the noise source. To summarize, the noise reduction produced by a barrier of adequate density for a given frequency, depends only upon the geometric relationships between the source, barrier, and receiver; it is not dependent upon the source itself. For example, if a noise barrier produces an 8 decibel (dB) reduction in a given frequency band for a given source with a reference level of 70 dB, the barrier will still produce an 8 dB reduction if the source level is increased to 80 dB. Therefore, if a low-noise pavement type is replaced by a high-noise pavement type, the reduction in noise level (i.e. insertion loss) will still be the same in each frequency band.

The insertion loss is defined as the difference in noise levels before and after noise barrier installation and is commonly used as the basis for determining effectiveness of a barrier or noise abatement wall. The determination of insertion loss provided by outdoor noise barriers is, in most cases, difficult due to the lack of measured noise levels at the study sites prior to barrier installation and the inability to estimate accurately these before levels [Acoustical Society, 1998].

There are three commonly accepted methods for the determination of insertion loss; the direct measured method, the indirect measure method and the indirect predicted method. The direct measured method, which is preferred, is used in situations where the source is present before the barrier is built. After accounting for differences in traffic volumes before and after the installation of the barrier, the insertion loss is essentially the difference in the noise measurements. The indirect measured method is used where the noise barrier is already in place and no measurements of the source were made prior to barrier construction. In this method, the levels of the source without a barrier are collected along a roadway section in close proximity to the barrier section being studied. To use this method, equivalence, in terms of the terrain for both the no-barrier and the barrier sections must be established. The indirect predicted method is used in situations where neither of the other methods can be applied by using a prediction model, such as the TNM, to determine the before noise levels.

Sound waves can take three paths as they approach a noise barrier [FHWA, 2000]. The waves can pass above the wall, they can travel through the wall (transmission), or they can bend over the top edge of the wall (diffraction). These paths can be seen in Figure 1.1.

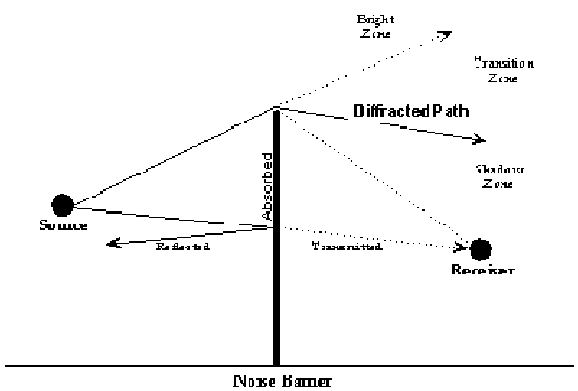

Figure 1.1. Three paths of sound waves [FHWA,2000]

The reflections from parallel barriers can cause increased noise levels at the receivers behind the noise barrier [Anderson et. al, 2003]. This phenomenon is known as performance degradation and is shown in Figure 1.2.

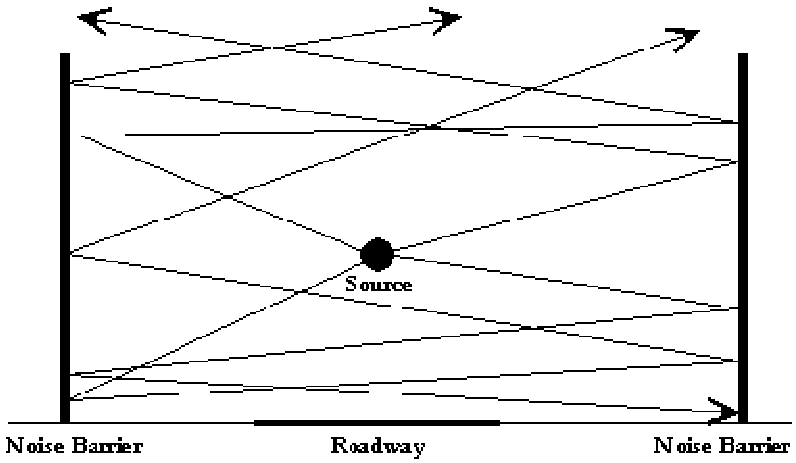

Figure 1.2. Reflection of noise in parallel barrier situation [FHWA, 2000]

Herman proved this phenomenon by testing a pair of reflective parallel barriers and a pair of absorptive parallel barriers [Herman, 1991]. These tests showed that the degradation difference between the pairs of reflective versus absorptive barriers was around 5dB at a high frequency (3150-5000 Hz). The barriers had similar degradation, around 0.5 dB, at a low frequency (160-315Hz). Fleming and Rickley also found that that the addition of an opposing reflective barrier to an existing reflective barrier had a degradation that varied from 0.6-2.8dB [Fleming and Rickley, 1992].

There are two different types of microphones needed for analysis, a reference microphone and multiple receiver microphones [FHWA, 2000]. The reference microphone is used to measure the sound source unaffected by any attenuation and can either be placed approximately five feet above the barrier or away from the barrier at a control site. Receiver microphone positions are dependent on the purpose of the study and can be set-up in many different configurations. Harris conducted an experiment to evaluate the effectiveness of a noise barrier. In this study, he placed a reference microphone away from any obstructions and placed receivers behind the wall in residents' backyards [Harris, 1982]. The levels recorded by the reference microphone were compared to levels recorded by the microphones placed behind the wall. Watts and Godfrey used a similar microphone set-up when testing sound absorptive materials [Watts and Godfrey, 1999]. In this study, the reference microphones were placed 230 meters down the highway from the barrier. In order to measure reflections caused by the barrier, the receiver microphones were placed at the same horizontal distance from the barrier but were placed at different heights (2 meters, 5.5 meters, and 9 meters). Fleming and Rickley used a different approach with the reference microphone location but had a similar receiver microphone placement as the previously mentioned studies [Fleming and Rickley, 1992]. In this study, the reference microphone was placed on a pole five feet above the barrier. The receiver microphones were placed on the same plane but at three different heights measured from the bottom of the barrier (-8 feet, 2.5 feet, and 13 feet).

1.2.1. 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]. Therefore, noise production along interstates or freeways is due to tire/road noise based upon traditional speeds occurring above the cross-over speed.

1.2.2. Road Surface Influence on Tire/Road Noise

There are many sources of noise when a vehicle travels down a roadway, the most prominent of which is the tire/road interaction [FHWEA, 2004-2]. This is especially evident when a vehicle is traveling at highway speeds as shown in Figure 1.3.

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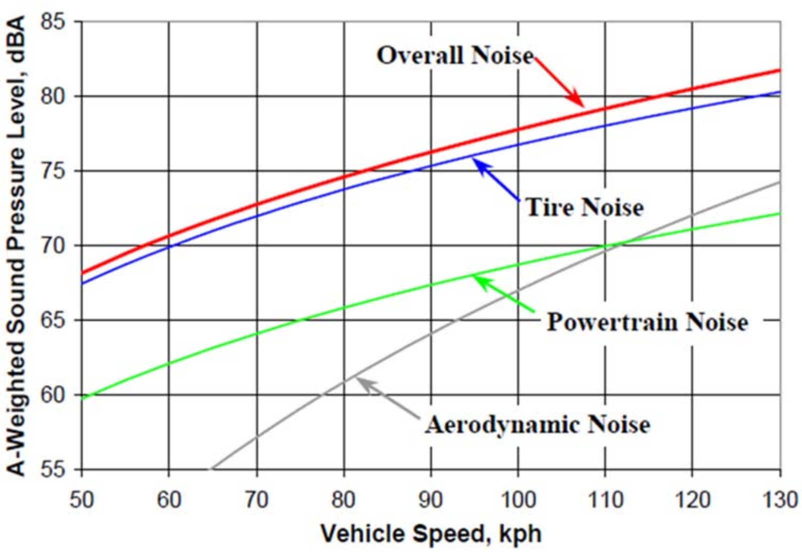

Figure 1.3. Comparison of noise levels separated by component [Donovan, 2007]

There are several pavement parameters that also 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 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 indicated that noise levels from Portland cement concrete pavement decrease with age for approximately the first eight years of service; however, unexpected vehicular volume increases decrease this period. After eight years, the noise levels generated by Portland cement concrete pavement increases due to irregularities in surface treatment (grooving or tining) becoming work exposing aggregate in the pavement which increases the surface texture and thereby the noise levels. Herman et al. investigated two different pavement materials with multiple surface treatments to determine the difference in noise levels [Herman, 2000]. Of the pavements tested, the portland cement concrete was 2.5-6.7 dB louder than the asphalt concrete. In addition to pavement types, ageing affects the noise from the tire/road interaction. Multiple studies have shown that as pavement ages, the traffic noise increases at an average rate of 0.1dB per year[Herman, 2000; Donavan and Rymer, 2011].

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.

1.2.3. Absorptive verses Reflective Noise Abatement Walls

Numerous studies have been conducted to compare the sound level impact from using either reflective noise barriers or absorptive barriers. Barriers are typically made absorptive by applying treatments to either the top edge of a barrier, in order to reduce the energy of sound waves which diffract over the top of the barrier, or to the face of a barrier, in order to prevent multiple reflections of the sound waves. Watts compared the noise level effects of single barriers, reflective parallel barriers, and absorptive parallel barriers [Watts, 1996]. The sound level was found to increase by 3.1 dB when a reflective parallel barrier was utilized as opposed to a decrease of 2.7 dB with an absorptive treatment. However in a later study, Watts and Godfrey performed field measurements comparing the use of panels which were reflective on one side and absorptive on the other [Watts and Godfrey, 1999]. Measurements were taken for the absorptive barriers and the panels were then reversed to repeat the measurements for the reflective barriers. The differences in the equivalent sound level between barrier treatments was not found to be statistically significant at a 95 percent level of confidence, as the differences were almost all less than 1 dB.

Mongeau, Bolton, and Suh conducted field measurements at a location where two noise barriers overlapped and an absorptive treatment was installed on the vertical edge of the barrier located closest to the roadway [Mongeau et al., 2003]. The measurements showed that the sound level behind the barriers decreased between 2 dB and 5 dB when the absorptive treatment was installed.

Anderson et al. used the FHWA TNM to examine increases in noise levels which would result from using a more reflective barrier surface, a 6-inch reflective cap on the top of the barrier, a 2-foot reflective base on the barrier, and from the combination of all three treatments [Anderson et al., 2003]. The results of this study indicate that even small changes to the reflectivity of the noise barrier can result in increased sound levels.

Menge and Barrett reviewed the history of the California Department of Transportation's experiences with the issue of noise barriers and reflections [Menge and Barrett, 2011]. Through multiple studies, the use of absorptive materials on barriers was found to range from no significant change in sound level to noise reductions of 5 dB. Additionally, Menge and Barrett conclude that reflections from noise barriers may result in a decrease of one to two dB of insertion loss, which may result in a barrier violating the 5 dB minimum that is required by both Federal and state policies.

In the State of Ohio, Herman tested reflective and absorptive barriers in single and parallel configurations using a constant noise source [Herman, 1992]. It was found that the degradation of single reflective barrier performance due to the addition of a reflective parallel barrier increased for lower source heights, higher barriers, greater receiver distances, and higher frequencies. A follow-up study was conducted in 1997 when 1200 residents living in the vicinity of I-71 in Cincinnati were surveyed to determine their perceived effectiveness of single and parallel noise walls [Herman et al. 1997]. It was found that residents protected by a single barrier were more likely to hold favorable opinions about the effectiveness of the noise barriers than either those residents protected by parallel barriers or those located in areas with the highway located between them and a single barrier.

Several types of noise barriers and configurations can be used to reduce the excessive noise caused by vehicles on a roadway. Anderson, Ross, Menge, and Arnold evaluated the current Virginia Department of Transportation (VDOT) methods used when dealing with noise abatement issues [Anderson et. al, 2003]. VDOT normally uses an absorptive barrier panel with a noise reduction coefficient (NRC) of 0.8, but it was found that this value could not be reliably replicated and that the material was not as durable as expected. To better attain a stable NRC and meet VDOT's durability standards, three different modifications were made to their absorptive barrier design. The three modifications were: more reflective surface (NRC 0.7 instead of 0.8), addition of a 6 in. reflective cap along the top of the wall, or addition of a 2ft reflective base along the bottom of the wall. Three different barrier configurations were used to test these modifications: barrier and receivers on the same side of the roadway, barrier and receivers on the opposite side of the roadway, and, barrier and receivers on the both sides (parallel) of the roadway

The highest recorded noise levels occurred when the receivers were located opposite the barrier and the wall had all three modifications. This resulted in a 2.7 dB increase compared to no modifications. When the receivers are on the same side of the barrier, the worst case was an increase of 0.8 dB when all three modifications where used. Lastly, the worst case for the parallel barriers was an increase of 1.5 dB and also had all three modifications. Using these results, they determined that the addition of these modifications increased the noise levels.

1.2.4. Characteristics of Various Noise Barrier Materials

In 2008, Guidelines for Selection and Approval of Noise Barrier Products was released as part of the National Cooperative Highway Research Program (NCHRP) Project 25-25, Task 40 [Ernst et al., 2008]. In this report, the results of a survey of state departments of transportation (DOTs) showed that the four most important criteria for evaluating barriers and materials are durability, acoustical properties, material and installation cost, and maintenance issues. The responses for these four issues were given the two highest ratings of “essential” and “very important” by 77 percent of the DOTs surveyed.

The issues of durability and maintenance of noise barriers are interrelated. Barriers which are considered durable will likely require less maintenance than barriers which are not durable. Generally, barriers which have significant mass and density are considered to be durable and also provide more resistance to sound transmission through the barrier. The results of the DOT survey showed that wooden noise barriers had the most durability problems due to the warping and cracking that naturally occurs over time (8). Accordingly, timber barriers were reported to have the most maintenance issues, but precast concrete and proprietary materials were also identified as barriers with known maintenance issues [Ernst et al., 2008].

According to the FHWA Noise Barrier Design Handbook, the Sound Transmission Class (STC) rating is the transmission loss value for the reference contour at 500 Hz [Fleming et al., 2000]. As a result, the STC rating is not designed for lower frequencies of traffic noise, so the STC rating is typically 5 to 10 dB greater than the transmission loss provided. The FHWA Noise Barrier Design Handbook provides approximate transmission loss values for common noise barrier materials. Concrete barriers, metal barriers, and transparent barriers provide 34 to 40 dB, 18 to 27 dB, and 22 dB of transmission loss, respectively [Fleming et al., 2000].

While it is not a preferred acoustical property for the FHWA, STC ratings for various barrier types were found from product literature provided by the manufacturers. For the hollow and rubber-filled fiberglass walls, Carsonite was found to manufacture both barrier types in their AcoustaShield product [Carsonite Composites, 2011]. No particular noise barrier manufacturer could be found to provide STC ratings for concrete walls. However, the Portland Cement Association did provide information for several types of concrete and masonry walls and a 6-inch thick cast concrete wall was selected as the closest example of a noise barrier [PCA, 2012]. For steel walls, the Industrial Acoustics Company manufactures the Noishield FS and SFS Barriers which are each free-standing sound absorptive steel barriers [Industrial Acoustics, 1993]. Current information could not be found on the STC rating for reflective steel barriers to contrast the absorptive barriers. CYRO Industries manufactures the Paraglas Soundstop transparent noise barriers in 15-mm, 20-mm, and 25-mm thicknesses [CYRO, 2007]. Emerald City Products was provided as a retailer of the Acoustifence fabric system that is manufactured by Acoustiblok Corporation [Emerald City Products, 2012]. The STC ratings found for each of the barrier types described above are summarized in Table 1.2 below.

Table 1.2. STC Ratings for Various Noise Barrier Types

Barrier Type (Product)	STC Rating
Hollow Fiberglass Walls (AcoustaShield)	28
Rubber-filled Fiberglass Walls (AcoustaShield)	37
Concrete Walls (Portland Cement Association)	53
Steel Walls (Noishield FS and SFS Barriers)	30 to 33
Clear Walls (Paraglas Soundstop)	34 to 37
Acoustifence Fabric System	28
Earthen Berm	23
Wood Wall	26

1.2.4.1. Clear

The clear or transparent noise barrier helps DOTs meet two objectives because they have adequate acoustic properties for sound abatement and are aesthetically pleasing to residents and motorists [Humphries, 2008]. One example of use of clear barriers is the Marquette Interchange in Milwaukee, Wisconsin. This particular noise barrier gave drivers a view of the city skyline while also keeping the road noise from reaching the residents. The clear barriers also provide a free source of advertising for businesses located next to the highway [Rocchi and Pederson, 1990]. In Baltimore, Maryland, the transparent barriers met both of the objectives [Douglass and Drinkwater, 1982]. The barriers had an insertion loss of 10dB and did not block the view of a school from I-95.Transparent barriers are usually made of plastic or acrylic panels [FHWA, 2000]. The main reason DOTs use this type of barrier instead of traditional barriers is to preserve scenic views for motorist and residents. Transparent panels cost approximately 20 times more than standard concrete panels so there must be significant justification for use. According to FHWA, the Sound Transmission Class (STC) of the transparent panels is 22 dB [FHWA, 2000]. In addition to the acoustics of the transparent panels, they are considered to be a reflective material [Rocchi and Pederson, 1990].

1.2.4.2. Concrete

Concrete barriers can have either reflective or absorptive properties [Menge and Barrett, 2011]. May and Osman performed sound testing for both reflective and absorptive concrete barriers . An insertion loss of 7.50 dB was found for the absorptive face, while an insertion loss of 8.19 dB was found for the reflective face. Herman examined both reflective and absorptive faces for a single concrete barrier and saw no statistical difference between the two [Herman, 1991]. Approximately 50 percent of all noise barriers in the North America (United States, Canada and Mexico) are made from concrete [FHWA, 2000]. Of the materials used to make noise barriers, concrete has the highest STC value ranging from 34-40 dB. Along with the transmission qualities of concrete, the face can be altered to make the wall more absorptive [May and Osman, 1980].

1.2.4.3. Metal

Metal barriers, are similar to concrete barriers, in that they can either be reflective or absorptive. Metals barriers can be made out of steel, stainless steel or aluminum [FHWA, 2000]. The FHWA noted that the steel can either be galvanized or weathering steel (allows for rusting). Depending on the gauge of the metal, the STC value ranges from 18-27 dB. Watts and Godfrey examined the noise transmission of an aluminum barrier with either a reflective or an absorptive face [Watts and Godfrey, 1999]. Microphones were placed at various heights behind the barrier and only one height (1.7 m) was found to have a significant difference at 95 percent level of confidence. At this height the absorptive face had a 13.43 dB loss and the reflective face had a 12.99 dB loss.

1.2.4.4. Plastic

Plastic noise barriers can be used in most circumstances and can be produced to have a similar appearance and acoustic properties as any other barrier material [FHWA, 2000]. Roschke and Esche examined the insertion loss of a recycled plastic barrier [Roschke and Esche, 1999]. The indirect before method was utilized to find a 17.1 dB insertion loss. Plastic barriers can be made of polyethylene, PVC, or fiberglass and have a typical STC value of 22 dB [FHWA, 2000]. Carsonite Composites, a manufacturer of fiberglass barriers, sells both filled and unfilled fiberglass barriers [Carsonite, 2013]. The first barrier is filled with recycled-rubber and has a STC and NRC values of 37 and 0.15, respectively. The unfilled barrier has STC and NRC values of 28 and 0.20, respectively. Saadeghvaziri and MacBain tested the properties of their prototype of a recycled plastic barrier design [Saadeghvaziri and MacBain, 1998]. This prototype had a STC and NRC of 37 and 0.10, respectively. Other recycled plastic barriers in the study had STCs and NRCs of 25 and 0.15.

1.2.4.5. Wood

In 1987, 17 percent of constructed noise walls were wooden; however, the usage declined with only 13 percent of constructed barriers in 2004 [FHWA, 2000]. Boothby et al. compared concrete barriers to wooden barriers (plywood, wood post and panel, and glue-laminated wood) and found in most cases the concrete barriers performed better than the wooden barriers [Boothby et. al, 1996]. The average insertion losses for the plywood, post and panel, and glue laminated wood are 14.5 dB, 20.5 dB, and 15 dB, respectively. The glue laminated barrier had a similar insertion loss to the concrete barrier, which has an insertion loss of 20 dB. Wooden barriers can either be treated wood or plywood and can be made from many different species of trees [FHWA, 2000]. Depending on the thickness, the STC value can range from 18-24dB. A problem with wooden barriers is that they may warp which creates voids in the panels thereby reducing the wall's effectiveness [Sterling, 1984]. To prevent warping, higher grade and pressure treated lumber, although more costly, must be utilized.

1.2.4.6. Earthen Berms

Earthen berms are considered highly absorptive because of the soil and grass covering [Morgan and Peeling, 2012]. An earthen berm can provide a 1-3 dB increase in insertion loss when compared to a wall with a similar height and length [FHWA, 2000]. Menge stated that earthen berms perform well in parallel barrier situations due to their ability to act as a single barrier without the drawbacks of parallel barriers [Menge, 1980]. Earthen berms can also be used to increase the height of a normal wall barrier by building the wall on top of the berm. The New Brunswick Department of Transportation used the FHWA's TNM to compare a traditional wall to a berm and wall combination [NBDOT, 2012]. When the models were compared they found that, on average, the wall berm combination had a reduction of 6.4 dB while the traditional wall only reduced sound levels by 5.8 dB. The berm and wall combination was also field tested and had a 6.6 dB reduction on average. Morgan and Peeling noted that there are multiple benefits to using an earthen berm instead of a traditional wall [Morgan and Peeling, 2012]. The earthen berm requires little to no maintenance and residents consider it to be more aesthetically appealing than a wall. Unfortunately, the drawback to earthen berms is the amount of land required for construction, which is generally not available in noise sensitive areas such as urban or suburban areas.

1.2.4.7. Acoustic Fabric Fence

Very little research has been conducted on the Acoustifence material; however, early public opinion has been positive [Acoustiblock, 2010 and 2012]. In Seattle, Washington the Acoustifence was used as a short-term solution to mitigate excessive rail noise [Acoustiblock, 2010]. It was found that with the Acoustifence material, all FHWA noise abatement standards were meet. The city then decided that the Acoustifence would be the permanent solution to mitigate excessive rail noise. Bay City, Michigan encountered a similar situation where residents were complaining about the idling trucks noise at the local Coca-Cola plant [Acoustiblock, 2012]. After the installation of the Acoustifence, the local Bay City residents were pleased with the aesthetics and the effectiveness of the Acoustifence. According to Acoustiblok, the manufacture of Acoustifence, the Acoustifence provides a STC of 28 at 1000 Hz and a STC of 40 at 6300 Hz. The Acoustifence is also highly reflective with an NRC of 0.05 [Acoustiblock, 2013].

1.2.5. Noise Barrier Life Cycle Cost

Recently, FHWA conducted an inventory of the noise barriers constructed nationwide prior to 2008 and found that concrete and block were the most widely used materials for the construction of noise barriers (54 percent and 19 percent, respectively) while absorptive materials have been used considerably less (2 percent) [FHWA, 2007]. However, from 2003-2007, the price per square foot for concrete, block, and absorptive barriers was found to be $29, $25, and $23, respectively. For the same time period, the cost for metal barriers was found to be $15 per square foot; however, this cost data is largely based upon barriers constructed only in Georgia. The Acoustifence system, which consists of rolls that are 30-feet in length and 6-feet in height, can be purchased for $759 per roll, equating to a price per square foot of approximately $4 [Emerald City Products]. However, the Acoustifence fabric requires a fence for installation which would increase the price per square foot. Cost information for the transparent and fiberglass noise barriers was not readily available.

Morgan, Kay, and Bodapati conducted a life-cycle cost analysis (LCCA) for different types of noise barriers to determine which type of barrier material is most cost-effective [Morgan et al., 2001]. The types of noise barriers used in the LCCA included earth berms, precast concrete, timber, Durisol, steel, and aluminum. The LCCA indicated that earth berms have the lowest life-cycle cost (LCC) whereas metal barriers with absorptive panels have the highest LCC. The sensitivity analysis indicated that the LCC of a barrier was most affected by the initial construction cost and the service life of the barrier. Morgan, Kay, and Bodapati indicated that a lack of available historical cost data could impact the usefulness of the LCCA.

In addition to the material chosen, economic value is an important characteristic of noise barriers. In 2001, Morgan et al. investigated the life cycle cost of different noise barrier materials while considering the service life and construction cost [Morgan et. al, 2001]. Along with noise abatement requirements, DOTs have structural and aesthetic requirements for noise walls [Kay et. al, 2001]. The combination of these three parameters used to estimate the noise barrier service life is shown in Table 1.3. Along with the service life, the overall cost of the noise barrier must be considered. The construction cost is broken down into two components: primary construction cost and future maintenance cost. Both of these costs are based on the type of noise barrier material and design [Morgan et. al, 2001]. Table 1.4 shows a breakdown of the primary and future cost of multiple noise barrier materials. Tables 1.3 and 1.4 can be used to make economical decision about noise barrier material selection and design. The cost of a noise barrier is not the only factor to consider when deciding on what type of barrier should be chosen. DOTs must also consider the workable area for the noise barrier and the public attitude towards the noise barrier [ICF, 2008].

Table 1.3. Estimated noise barrier service life [Morgan et. al, 2001]

Material	Service life (years)
Earth berm	50+
Precast concrete, full-height panels with monolithic posts	50
Precast/prestressed concrete cantilever	50
Precast/prestressed concrete stacked panels[a]	50
Fanwall	50
Carsonite	50
Durisol	25
Noishield steel[b]	25
Noishield aluminum	25
Glue-laminated wood	25
Tropical hardwood and softwood post-and-panel	25

[a]Stacked panels (similar to the Soundcore barrier) have not been built in Illinois to date.
[b]Estimated service life for Noishield steel is based on redesigned panels used successfully on projects outside Illinois.

Table 1.4. Estimated noise barrier life cycle cost [Morgan et. al, 2001]

Barrier	Estimated ICC [dollars/m² (dollars/ft²)]	Discounted future costs [dollars/m² (dollars/ft²)]	Estimated LCC [dollars/m² (dollars/ft²)]
Earth berm	111 (10.33)	39 (3.60)	150 (13.93)
Precast/prestressed concrete stacked panels, steel posts	212 (19.67)	43 (4.03)	255 (23.70)
Precast/prestressed concrete stacked panels, concrete posts	262 (24.33)	28 (2.62)	290 (26.95)
Timber post-and-panel (hardwood or softwood)	180 (16.70)	122 (11.35)	302 (28.05)
Precast/restressed cantilever	291 (27.00)	30 (2.80)	321 (29.80)
Carsonite	273 (25.33)	50 (4.65)	323 (29.98)
Precast concrete, full-height panels, monolithic posts	305 (28.33)	28 (2.62)	333 (30.95)
Glue-laminated wood	197 (18.33)	145 (13.48)	342 (31.81)
Durisol	212 (19.67)	152 (14.14)	364 (33.81)
Noishield steel	298 (27.67)	131 (12.19)	429 (39.86)
Noishield aluminum	377 (35.00)	163 (15.15)	540 (50.15)

2. RESEARCH OBJECTIVES

The main objective of this research was to provide recommendations to ODOT on the effectiveness of various noise wall materials in order to update ODOT's noise abatement policies and procedures.

In order to fulfill the objectives of this research proposal, three experimental plans were required. The experimental plans (1) Quantified the noise reduction potential (performance) and durability of various noise abatement wall designs including hollow fiberglass walls, rubber-filled fiberglass walls, concrete walls, steel walls, clear walls, and earthen berms; (2) Quantified the noise reduction potential (performance) and durability of absorptive concrete walls verses reflective concrete walls specifically for receptor and noise sensitive locations; and (3) Quantified the noise reduction potential (performance) of the Acoustic Fence Fabric System (AFF). Other research objectives included an examination of the durability of the various noise abatement walls and an evaluation of the life-cycle cost for noise abatement walls.

There are three questions that the research was aimed at answering:

- Does the TNM accurately represent field data for various noise barrier materials (including the AFF)?
- Do absorptive or reflective noise barrier materials or additional supplemental materials on a noise wall impact noise levels at the receptor?
- Does the type of noise wall materials impact the noise levels at receptor locations (including the AFF)?

2.1. Experimental Plan for Various Noise Abatement Wall Designs (including the AFF)

In order to quantify the noise reduction potential of various noise abatement wall designs, the proposed experimental plan compared three data sets.

The first paired data set evaluated the differences, if any, between the collected noise data and the noise predictions as modeled in the Traffic Noise Model (TNM). The existing field conditions (including traffic volumes, heavy vehicle distributions and geometric information) were modeled in the TNM to determine the predicted noise levels with the noise abatement wall installed. The comparison examined the differences, if any, between the model and the actual noise data collected in the field.

The second paired data set evaluated the differences, if any, between the collected noise data and the general STC rating for similar materials.

The third paired data set evaluated the differences, if any, between the various noise wall materials using the collected noise data. A comparison of the field determined insertion losses were utilized to assess the noise reduction potential by material type. .

In order to evaluate the fabric system, an existing chain link fence located along an ODOT freeway or highway was utilized for the installation of at least 250 feet of fabric, in order to limit the costs for construction of a new chain link fence system. It was desired that the existing chain link fence be at least six feet in height or a maximum of ten feet in height.

2.2. Experimental Plan for Absorptive verses Reflective Walls

The noise reduction differences of sound absorptive concrete wall designs verses reflective concrete wall designs were quantified using the following experimental plan. The data sets were evaluated using a comparative parallel evaluation plan which assumes that the noise data collected for the sound absorptive wall sites in comparable receptor locations were similar to the noise data collected for the reflective wall sites. Any difference in the comparison of the noise data would indicate that the walls do not provide the same level of noise reduction at the receptor locations. The walls producing the greatest level of noise reduction were then considered to perform at a higher level.

3. GENERAL DESCRIPTION OF THE RESEARCH

3.1. Site Selection

Through coordination with ODOT, several potential sites were identified and 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 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. Due to the presence of vegetation, it was assumed that previous standards indicating thick vegetation (of approximately 100 feet in depth) can absorb and scatter up to 5 dB of noise.

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.

3.2. Study Locations

There were 17 noise barrier sites that were chosen for analysis. Of these 17 sites, only 14 of the noise barriers were permanent structures. The 14 barriers were comprised of two clear barriers, four concrete barriers, two earthen berms, two hollow fiberglass barriers, one rubber filled fiberglass, two steel barriers, and one wooden barrier. The other three locations were test sites for the acoustic fabric fence. These sites were chosen to evaluate the different materials that can be used to construct noise barriers. Microphone locations at each site varied depending on site restrictions and geometry. A brief description of each site is provided in the following sections with a summary provided in Table 3.1.

Table 3.1. Study Location Details

Site No.	County	Route	Material	Wall Height	Distance from Pavement	STC	Temp. (F)	% Rel. Humidity
1	Franklin	I-71	Clear	12’	40’	37	76	32
2	Franklin	I-71	Clear	16’	35’	37	85	51
3	Greene	I-675	Refl.Concrete	13’	35’	53	70	40
4	Montgomery	I-75	Abs. Concrete	15’	40’	53	95	32
5	Stark	I-77	Abs. Concrete	17’	60’	53	75	70
6	Warren	I-75	Abs. Concrete	15’	80’	53	84	74
7	Cuyahoga	I-480	Earthen Berm	8’	60’	23	75	45
8	Miami	I-75	Earthen Berm	8’	80’	23	68	50
9	Cuyahoga	I-71	Hol. Fiberglass	18’	50’	28	78	45
10	Cuyahoga	I-90	Hol. Fiberglass	13’	65’	28	70	45
11	Greene	I-675	RF Fiberglass	13’	35’	37	80	65
12	Franklin	I-71	Steel	17’	60’	33	76	35
13	Franklin	I-670	Steel	12’	35’	33	74	40
14	Franklin	I-70	Wood	18’	30’	26	68	35
15	Franklin	SR-161	AFF	13’	25’	28	78	64
16	Hamilton	I-75	AFF	6’	40’	28	80	87
17	Hamilton	SR-126	AFF	4’	45’	28	70	100

3.2.1. Franklin County I-71 Clear Barrier (Site 1)

Site 1 was a part clear and part absorptive concrete single noise barrier located in a residential area along I-71 North near the Lighthouse Church. The portion of the barrier that was chosen for analysis was the clear section. Figure 3.1 shows the point where the noise barrier changes from a complete concrete barrier to a clear and concrete barrier. Approximately four feet from the ground up is concrete while the other eight feet is made of clear panels, as seen in Figure 3.2. As stated in the Field Recording section, there were five microphones placed behind the wall and two placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.3.

Figure 3.1. Site 1 highway view of part concrete wall and part clear wall

.Figure 3.2. Site 1 highway view of clear wall testing location

Figure 3.3. Site 1 microphone locations

3.2.2. Franklin County I-71 Clear Barrier (Site 2)

Site 2 was a part clear and part absorptive concrete single noise barrier located in a residential area along I-71 North near Moon Road. The portion of the barrier that was chosen for analysis was the clear section. Approximately six feet from the ground up was concrete while the other ten feet was the clear panels as seen in Figure 3.4. The microphone locations at Site 2 varied from the other sites. Due to the spatial restrictions caused by the garage behind Microphone 4, Microphones 5 and 6 were place 25 feet to the south of Microphones 2 and 3, respectively. Microphone 1 was located five feet above the wall. The configurations of the five microphones placed behind the wall, two placed in front of the wall and one above the wall can be seen in Figure 3.5.

Figure 3.4. Site 2 highway view of clear wall testing location

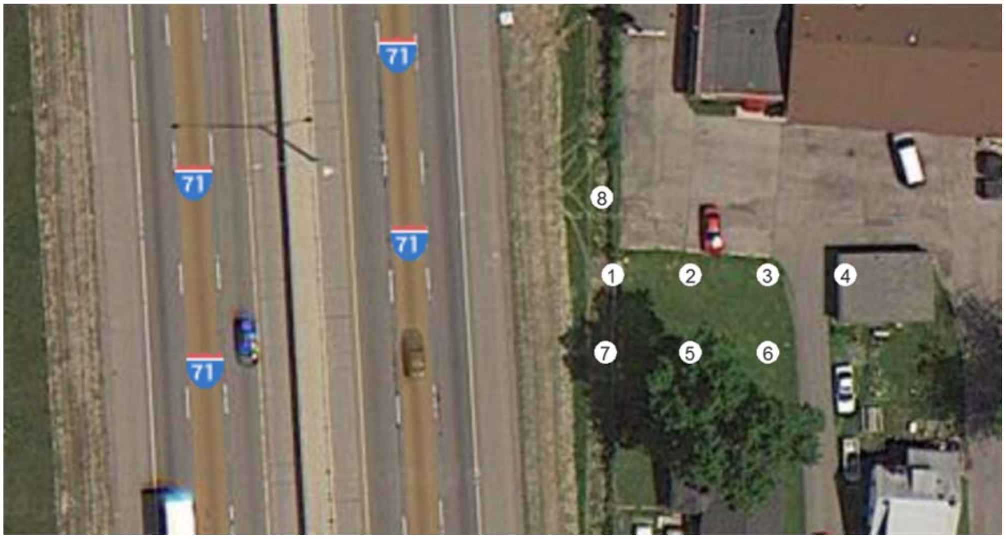

Figure 3.5. Site 2 microphone locations

3.2.3. Greene County I-675 Reflective Concrete Barrier (Site 3)

Site 3 was a reflective concrete parallel noise barrier located in a residential area along I-675 near McEwen Road. The northbound wall was chosen for analysis. The wall was approximately 13 feet tall and is shown in Figure 3.6. The microphone locations at Site 3 followed the array distance from the wall of 25 feet with the exception of Microphone 6. Due to a large tree located in the desired position, Microphone 6 was placed 25 feet to the east of Microphone 5. Microphone 1 was located five feet above the wall. The configurations of the five microphones placed behind the wall, two placed in front of the wall and the one above the wall can be seen in Figure 3.7.

Figure 3.6. Site 3 highway view of reflective concrete wall testing location

Figure 3.7. Site 3 microphone locations

3.2.4. Montgomery County I-75 Absorptive Concrete Barrier (Site 4)

Site 4 was an absorptive concrete single noise barrier located in a residential area along I-75 South near Stop 8 Road. The wall was approximately 15 feet tall with a 2 ½ feet tall Jersey barrier located 1 ½ feet to the east of the wall. This configuration can be viewed in Figure 3.8. The microphone locations at Site 4 were all set back 15 feet from the wall because the wall located directly on the I-75 South shoulder. From the point where the reference microphone was placed, the array distance of 25 feet behind Microphone 1 was followed with the exception of Microphone 6. Since the desired location for Microphone 6 was in the middle of Arthur Avenue, Microphone 6 was placed 25 feet to the east of Microphone 1. Microphone 1 was located five feet above the wall. The configurations of the five microphones placed behind the wall, two placed in front of the wall, and one above the wall can be seen in Figure 3.9.

Figure 3.8. Site 4 highway view of absorptive concrete wall testing location

Figure 3.9. Site 4 microphone locations

3.2.5. Stark County I-77 Absorptive Concrete Barrier (Site 5)

Site 5 was an absorptive concrete single noise barrier located in a residential area along I-77 South near Belden Village Street. The wall was approximately 17 feet tall and can be viewed in Figure 3.10. The locations at Site 5 for Microphones 2 through 6 were placed at the array distance of 25 feet behind the noise barrier while Microphones 7 and 8 were placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.11.

Figure 3.10. Site 5 highway view of absorptive concrete wall testing location

Figure 3.11. Site 5 microphone locations

3.2.6. Warren County I-75 Absorptive Concrete Barrier (Site 6)

Site 6 was an absorptive concrete single noise barrier located in a residential area along I-75 South near Shaker Road. The wall was approximately 15 feet tall and can be viewed in Figure 3.12. The locations at Site 6 for Microphones 2 through 6 were placed at the array distance of 25 feet behind the noise barrier while Microphones 7 and 8 were placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.13.

Figure 3.12. Site 6 highway view of absorptive concrete wall testing location

Figure 3.13. Site 6 microphone locations

3.2.7. Cuyahoga County I-480 Earthen Berm (Site 7)

Site 7 was an earthen berm noise barrier located in a residential area along I-480 east near Pearl Road. The berm height from the ditch line to the top was approximately 15 feet, but the top of the berm was only around 8 feet above the roadway. This topography can be viewed in Figure 3.14 and Figure 3.15. The microphone locations at Site 7 were placed at the array distance of 25 feet. Microphone 1 was placed on the top of the berm, while Microphones 2 and 3 were placed on the back side of the mound and microphones 4, 5, and 6 were placed on flat ground behind the berm. Microphones 7 and 8 were placed in the ditch line in front of the berm. This configuration can be seen in Figure 3.16.

Figure 3.14. Site 7 highway view of earthen berm testing location

Figure 3.15. Site 7 highway view along the ditch line of the earthen berm

Figure 3.16. Site 7 microphone locations

3.2.8. Miami County I-75 Earthen Berm (Site 8)

Site 8 was an earthen berm noise barrier located in a residential area along I-75 north near East Evanston Road. The berm height from the ditch line to the top was approximately 10 feet, but the top of the berm was only around 8 feet above the roadway. This topography can be viewed in Figure 3.17 and 3.18. The microphones at Site 8 were placed at the array distance of 25 feet. Microphone 1 was placed on the top of the berm, while Microphones 2 and 3 were placed on the back side of the mound and Microphones 4, 5, and 6 were placed on flat ground behind the berm. Microphones 7 and 8 were placed in the ditch line in front of the berm and fence. This configuration can be seen in Figure 3.19.

Figure 3.17. Site 8 highway view of earthen berm testing location

Figure 3.18. Site 8 highway view along the ditch line of the earthen berm

Figure 3.19. Site 8 Microphone locations

3.2.9. Cuyahoga County I-71 Hollow Fiberglass Barrier (Site 9)

Site 9 was a hollow fiberglass parallel noise barrier located in a residential area along I-71 near Sheldon Road. The southbound wall was chosen for analysis. The wall was approximately 18 feet tall and can be viewed in Figure 3.20. The locations at Site 9 for Microphones 2 through 6 were placed at the array distance of 25 feet behind the noise barrier while Microphones 7 and 8 were placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.21.

Figure 3.20. Site 9 highway view of hollow fiberglass wall testing location

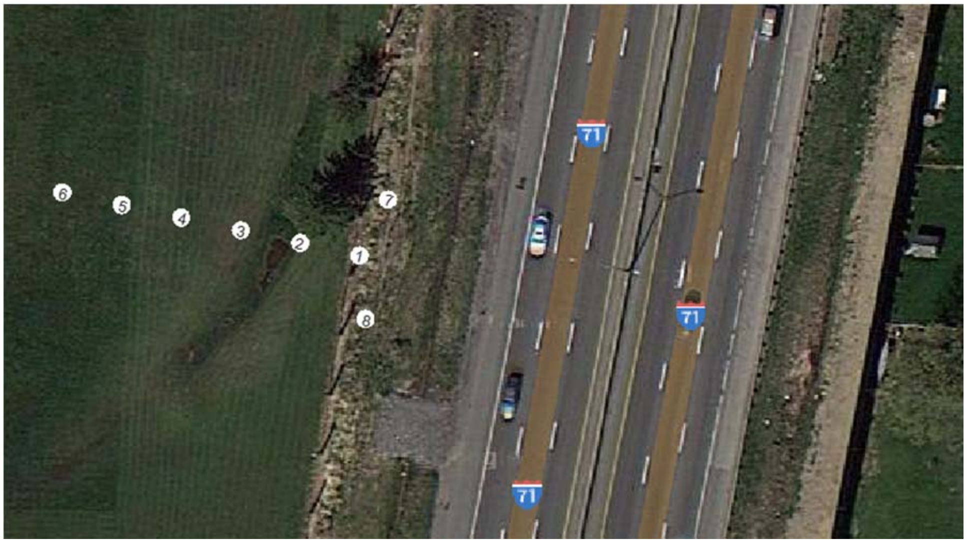

Figure 3.21. Site 9 microphone locations

3.2.10. Cuyahoga County I-90 Hollow Fiberglass Barrier (Site 10)

Site 10 was a hollow fiberglass parallel noise barrier located in a residential area along I-90 near Wooster Road. The north bound wall was chosen for analysis. The wall was approximately 13 feet tall and can be viewed in Figure 3.22. Microphones 2 through 6 at Site 10 were placed at the array distance of 25 feet behind the noise barrier while Microphones 7 and 8 were placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.23.

Figure 3.22. Site 10 highway view of hollow fiberglass wall testing location

Figure 3.23. Site 10 microphone locations

3.2.11. Greene County I-675 Rubber Filled Fiberglass Barrier (Site 11)

Site 11 was a rubber filled fiberglass parallel noise barrier located in a residential area along I-675 near Indian Ripple Road. The northbound wall was chosen for analysis. The wall was approximately 13 feet tall and can be viewed in Figure 3.24. Microphones 2 through 6 at Site 11 were placed at the array distance of 25 feet behind the noise barrier while Microphones 7 and 8 were placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.25.

Figure 3.24. Site 11 highway view of rubber filled fiberglass wall testing location

Figure 3.25. Site 11 microphone locations

3.2.12. Franklin County I-71 Steel Barrier (Site 12)

Site 12 was a steel parallel noise barrier and was located in a residential area along I-71 near Park Road. The south bound wall was chosen for analysis. Figure 29 shows the location chosen for analysis as viewed from the highway. Since the wall is not visible from the highway in Figure 3.26, Figure 3.27 was provided to show the north bound wall at the testing locations. Both of these walls are approximately 17 feet tall. Microphones 2 through 4 at Site 12 were placed at the array distance of 25 feet behind the noise barrier while microphones 5 and 6 were placed 25 feet north and south, respectively. Microphones 7 and 8 were placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.28.

Figure 3.26. Site 12 highway view of steel wall testing location

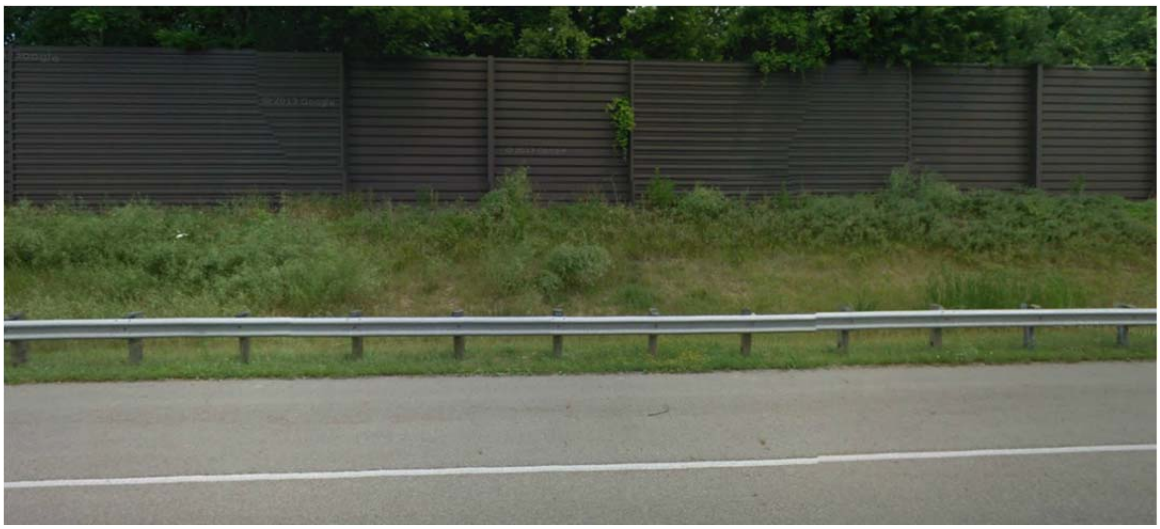

Figure 3.27. Site 12 highway view of steel wall opposite of testing location

Figure 3.28. Site 12 microphone locations

3.2.13. Franklin County I-670 Steel Barrier (Site 13)

Site 13 was a steel single noise barrier located in a residential area along I-670 West near North Nelson Road. The wall was approximately 12 feet tall and can be viewed in Figure 3.29. Directly behind the barrier there was a steep decline in elevation into a flat open field this can be seen in Figure 3.30. Microphone 1 was placed on the top of the hill, while microphones 2 and 3 placed on the back side of the mound and Microphones 4, 5, and 6 were placed on flat ground behind the berm. Microphones 7 and 8 were placed in the ditch line in front of the wall along the walkway. This configuration can be seen in Figure 3.31.

Figure 3.29. Site 13 highway view of steel wall testing location

Figure 3.30. Site 13 behind steel wall

Figure 3.31. Site 13 microphone locations

3.2.14. Franklin County I-70 Wooden Barrier (Site 14)

Site 14 was a wooden single noise barrier located in a residential area along I-70 West near Hilliard Rome Road. The wall was approximately 18 feet tall and can be viewed in Figure 3.32. Microphones 2 through 6 at Site 14 were placed at the array distance of 25 feet behind the noise barrier while Microphones 7 and 8 were placed in front of the wall. Microphone 1 was located five feet above the wall. This configuration can be seen in Figure 3.33.

Figure 3.32. Site 14 highway view of wooden wall testing location

Figure 3.33. Site 14 microphone locations

3.2.15. Franklin County SR-161 Acoustic Fabric Fence (Site 15)

Site 15 was an acoustic fabric fence barrier and located in a commercial area along SR-161 Sunbury Road. The fence was a combination of a 7 foot permanent concrete wall and 10 foot tall chain-link fence. The roadside view of this structure can be viewed in Figure 3.34. Microphone 1 was located five feet above the wall, at approximately 13 feet. Microphone 2 was placed directly behind the fence at a height 3 feet. The setup for Microphones 1 and 2 was selected to measure the immediate insertion loss provided by the acoustic fabric. Microphone 3 was placed at 25 feet behind Microphones 1 and 2, while Microphone 4 was placed at 75 feet behind Microphone 1 due to the parking lot. Microphones 5 and 6 were placed at 25 feet east and west of the formation, respectively. Due to the proximity of the shoulder and traffic to the barrier wall, a microphone was not placed in front of the wall. Prior to proceeding with the placement of the acoustic fabric fence, it was determined there was no statistical difference between the noise level readings at the microphones in front of the walls (Microphones 7 and 8) and Microphone 1. Therefore, it was determined that only Microphone 1 was necessary for analysis. This configuration can be seen in Figure 3.35.

Figure 3.34. Site 15 highway view of acoustic fabric fence testing location

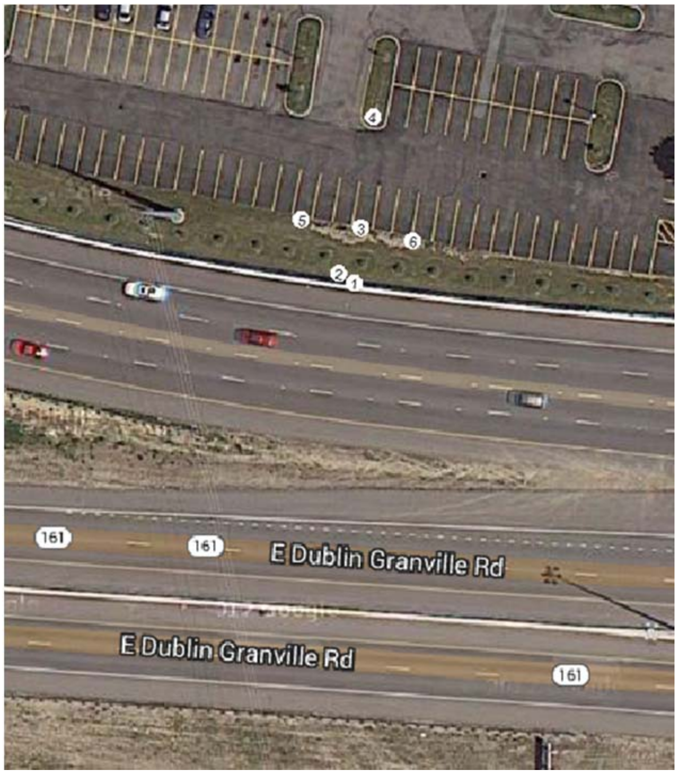

Figure 3.35. Site 15 microphone locations

3.2.16. Hamilton County I-75 Acoustic Fabric Fence (Site 16)

Site 16 was an acoustic fabric fence barrier located in an industrial area along I-75 South near Paddock Road. The fence was a 6 foot tall chain-link fence and can be viewed in Figure 3.36. Microphone 1 was mounted at a height of 11 feet directly above the fence. Microphone 2 was placed directly behind the fence at a height of 3 feet. The setup for Microphones 1 and 2 was selected in order to measure the immediate insertion loss provided by the acoustic fabric. Microphone 3 through 6 were placed at the array distance of 25 feet behind microphones 1 and 2. Prior to proceeding with the placement of the acoustic fabric fence, it was determined there was no statistical difference between the noise level readings at the microphones in front of the walls (Microphones 7 and 8) and Microphone 1. Therefore, it was determined that only Microphone 1 was necessary for analysis. This configuration can be seen in Figure 3.37.

Figure 3.36. Site 16 highway view of acoustic fabric fence testing location

Figure 3.37. Site 16 microphone locations

3.2.17. Hamilton County SR-126 Acoustic Fabric Fence (Site 17)

Site 17 was an acoustic fabric fence barrier located in a residential area along SR-126 near Kenwood Road. The fence was a 4 foot tall chain-link fence and can be viewed in Figure 3.38. Microphone 1 was located directly above the wall at a height of 9 feet. Microphone 2 was placed directly behind the fence at a height of 3 feet. The setup for Microphones 1 and 2 was selected in order to measure the immediate insertion loss provided by the acoustic fabric. Microphones 3 through 6 were placed at the array distance of 25 feet behind Microphones 1 and 2. Prior to proceeding with the placement of the acoustic fabric fence, it was determined there was no statistical difference between the noise level readings at the microphones in front of the walls (Microphones 7 and 8) and Microphone 1. Therefore, it was determined that only Microphone 1 was necessary for analysis. This configuration can be seen in Figure 3.39.

Figure 3.38. Site 17 highway view of acoustic fabric fence testing location

Figure 3.39. Site 17 microphone locations

4. INSTRUMENTATION AND SETUP

4.1. Instrumentation

In this study there were eight sets of recording devices used, each set consisting of a Larson Davis sound level meter (SLM) (model 812) with a ½-inch diameter random incidence condenser microphone (Model 2559), a Larson Davis preamplifier (model PRM900B), and a Sony Digital Audio Tape (DAT) recorder (Model TCD-D8) mounted together on an aluminum plate attached to a sturdy tripod. Each SLM was connected to the DAT using a 1/8-inch cable. Each SLM and DAT was numbered from 1 through 8 and paired with their corresponding number (i.e. SLM 1 paired with DAT 1). This set-up can be seen in Figure 4.1. Once the aluminum plate was placed on the tripod, the microphone head was placed at a height of five feet above the ground and at an angle of 70 degrees above horizontal [5]. The microphone was equipped with a foam wind noise reducing filter. From henceforth, the sets of SLMs and DATs will be referenced as microphones.

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.

1. SLM
2. Preamplifier
3. Microphone
4. DAT
5. 1/8-in Cable
6. Aluminum Plate

Figure 4.1. SLM and DAT setup

The traffic noise recordings were analyzed using a Larson Davis 2900B Real Time Analyzer (RTA) (model 3200) seen in Figure 4.2. During System Normalization (see below) the RTA was used with its microphones and microphone preamplifiers 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.

Figure 4.2. RTA

The site characteristics can be grouped into three categories: traffic, weather, site topography. Traffic data that was collected consisted of volume, lane position, and speed. The volume and lane position was collected using a Sony HD video camera (model HDR-FX1), while the speed was collected using an UltraLyte laser speed gun (model LR B). Weather data consisted up of wind speed, air temperature, pavement temperature, and humidity. Wind speed and air temperature were collected using a Davis Instruments Weather Wizard (model III). Pavement temperature was collected using an Omegasocpe Hand Held Infrared Thermometer (model OS 520), while the humidity was determined using the National Oceanic and Atmospheric Administration (NOAA) website, noaa.gov. Site topography and microphone locations were collected using a Leica Total Station (model TCR 705) with multiple Leica Prisms (model GPR1). Once all necessary elevations were obtained, the data was imported into AutoCAD Civil 3D to produce a topographic map.

4.2. 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.

4.3. 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. 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.

4.4. Normalization

When using eight different microphones, small variations in measured sound levels between the devices were anticipated when recording the same noise source. The process of system normalization was done to negate this difference and is described herein. All eight microphones were positioned next to each other at a close distance (<1ft) and at a height of five feet above the ground parallel to the roadway. They were positioned like this so that each set was exposed to the same traffic noise at the same time. This set-up can be seen in Figure 4.3 and Figure 4.4. A fifteen minute recording session was completed and then was analyzed using the RTA to find the microphones 1/3-octave frequency bands. Microphone 1 was selected to be the master and was compared to Microphone 2 through Microphone 8. Each of the seven comparisons equated to a correction factor for the remaining sets. These correction factors are used to calculate levels recorded by Microphone 2 through Microphone 8 corresponding to the same values recorded by Microphone 1. Normalization factors for each of the eight recording sets were embedded in the analysis spreadsheet used to finalize the acoustic data.

Figure 4.3. Front view of system normalization

Figure 4.4. Side view of system normalization

4.5. Field Recording

Before traveling to any recording site, the weather forecast was examined using the NOAA website to check for acceptable weather conditions (i.e. wind speed, precipitation, and humidity). Once weather conditions were deemed acceptable, the recording preparation process was performed. All eight clocks on the DATs were synchronized within one second of each other with a cell phone clock reading hours, minutes, and seconds. All eight SLMs went through an extensive calibration process to ensure that all of the settings required for the recording session were correct. This SLM calibration process only needed to be performed once at the beginning of the project and can be seen in Appendix B. All eight DATs also went through a setting check before each recording, and the process can be seen in Appendix B.

After all devices were appropriately configured, a calibration tone was recorded on each tape. The calibrator used for this tone was a Bruel and Kajaer (B & K) Acoustic Calibrator (model 4231) and is molded to fit and seal around the top of the Larson Davis microphone heads. The B & K calibrator emitted a constant 1000 Hz tone at 94 dB that was recorded for 30 seconds on each tape prior to each recording session. The tones are used to calibrate the RTA to each specific DAT before analyzing each recording.

After the calibration tones were recorded each microphone was placed in its desired location and was similar at each site. Microphone 1 was used as the reference microphone and was placed behind the noise wall at a height of five feet above the wall. Microphones 2 through Microphone 6 were located at an array distance of 25 feet perpendicular to the wall while Microphone 7 and Microphone 8 were placed directly in front of the barrier at a distance of 25 feet left and right of the reference microphone, respectively.

Once the microphones were in place and ready to start recording, three researchers went to the nearest overpass to record both vehicular speed and volume by vehicle class and lane. Two researchers were placed behind the wall to monitor Microphones 1 through Microphone 6, wind speed, air temperature, and humidity. These two researchers also recorded the start and end times of each recording session and noted any times of extraneous or unrelated noise that occurred during the recording session (i.e. airplane, dog barking…etc.). One researcher was placed in front of the wall and was responsible for monitoring Microphones 7 and Microphone 8 and noting the pavement temperature. Any minutes deemed unusable were then expunged from the data set during the data reduction process. Once all researchers were in place, a start and finish time was determined. Each recording session was 30 minutes in length unless more than five minutes had to be eliminated. If this occurred, the recording session was increased by 15 minutes to a total of 45 minutes. After the recording session was finished, the tapes were taken out of the DATs and labeled with the corresponding DAT number by date and location.

4.6. Data Reduction

Once the field recording sessions were completed, the DATs were then played back through the RTA for analysis. The field recordings were analyzed one site at a time. The RTA has two channels so that two DATs can be analyzed at the same time. Figure 4.5 shows the RTA and DAT configuration. Two functions are used to analyze the recordings, calibration function and read function. The calibration function was used to calibrate the RTA to the DAT before each recording. The 94 dB tone, recorded before each session, was played through the RTA as the calibration tone. After each channel was calibrated, the field recordings were played through the RTA and saved on the RTA memory. The RTA saved the field recordings in un-weighted 1/3 octave bands in minute-by-minute grouping as a binary file. The files for each site were then transferred through the RTA's serial port and ultimately onto a computer. Larson Davis provided a program called "RTAUtil32" to translate the binary file output from the RTA into a CSV quasi-spreadsheet file containing all of the data provided by the RTA. The un-weighted 1/3 octave band results were then utilized in a spreadsheet which applied the correction factors from the system normalization. Results were then A-weighted and organized by site and microphone location.

1. RTA 2. Floppy Disk Input 3. DAT Recordings

4. DAT Output Cable

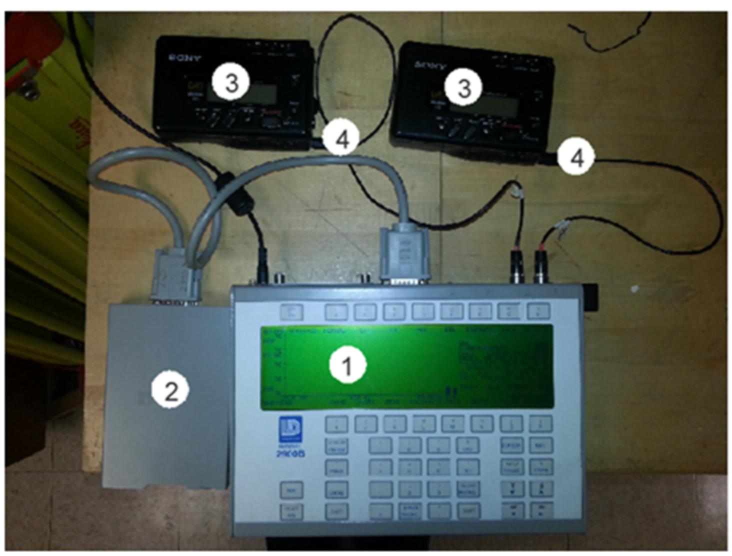

Figure 4.5. Data Reduction Setup

4.7. Field Procedures for the Absorptive and Reflective Material Comparison

The traditional approach to quantifying the benefit of absorptive noise walls utilizes sound level measurements of traffic noise made at locations on the receiver side of the noise walls for both reflective sites and absorptive sites for comparison. Any reduction in the measured levels for absorptive noise walls compared to reflective noise walls is then attributed to the absorptive material. Conceptually, this approach is straight forward, and the results directly relate to the experience of residents who are exposed to the noise. However, for this simple comparison of measured sound levels to be valid, all geometric, traffic, and atmospheric conditions must be equivalent for the reflective and absorptive noise walls.

The traditional approach was planned as the primary basis for the evaluation of absorptive noise walls for this project. However, an experimental method was also planned as a secondary approach to augment the traditional approach. For a number of years L. Herman has been leading the development of a system at Ohio University that uses a specific, repeatable computer generated noise that can be propagated from a loudspeaker in the presence of other noise sources, and recorded at a point of interest. The specific noise (test signal) can subsequently be identified and isolated by using signal processing techniques. Prior to this project the experimental system, in its current configuration, had been tested at several outdoor sites with promising results. However, in this project the experimental system, was used for the first time to directly evaluate absorptive qualities at close proximity to barrier surfaces in the presence of traffic operations.
Typically, absorptive noise walls are designed as a composite with the sound absorbing materials exposed to the highway side of the noise walls. Therefore, the experimental system for the evaluation of absorptive noise walls compared to reflective barrier was located on the highway side of the noise walls. In addition to providing a secondary approach to the traditional method of absorptive barrier evaluation, the use of the system for this project was viewed as an opportunity to test the system in a different environment to better understand its capabilities and limitations, as well as to establish direction for further development.

All noise barrier surfaces absorb some noise and reflect the remainder of the noise. The distinction between reflective and absorptive noise walls lies in the proportion of absorption. Reflective noise walls absorb very little of the incident sound energy. Absorptive noise walls, on the other hand, are designed to absorb significantly more noise and reflect less noise. The amount of absorption will vary for different sound frequencies, depending on the physical properties of the sound absorbing materials. The objective of the tests described below was to quantify any difference in level (dB) for a sound wave reflected from an absorptive barrier surface compared to a sound wave reflected from a reflective barrier surface for the frequency range of 200 Hz to 2 KHz. It follows that the noise levels measured are not noise levels experienced by receivers on the residential side of noise walls, as would be the case with the traditional approach to a comparison of absorptive and reflective noise walls. Rather, the focus of this approach is on the sound absorbing effectiveness of the noise wall materials themselves.

The selection of test sites began with a review of the ODOT noise barrier inventory to identify the locations of concrete absorptive noise walls. The manufacturers of the sound absorbing noise walls were identified to ensure that they would be represented in the samples measured. As a result, four manufacturers of sound absorbing noise walls were found to dominate the installations in Ohio: Durisol, Faddis, Mack, and Soundcore, with Durisol being the most common. Candidate locations were then viewed online to observe their lengths, proximity to interchanges or intersections, general terrain features (including cut or fill), accessibility, and distances from noise walls to edge of pavement, etc. Finally, a field review was conducted by visiting the more promising locations to determine the ones that offered excellent test conditions. As a result of this process, six barrier locations were selected (four in Franklin Co. and two in Hamilton Co.), five of which were absorptive (one for each manufacturer, except two for Durisol) and one reflective barrier location.

All test equipment was located in the roadside areas between the edge of pavement and the noise barrier. Two categories of test equipment were utilized: noise sending and noise receiving. The noise sending equipment consisted of a power supply, a digital audio tape (DAT) and player containing the test signals, an amplifier, and a loudspeaker to broadcast the test signals. The receiving equipment consisted of sound level meters, complete with microphones and preamplifiers, DAT recorders to store the received noise. The received noise (a mix of traffic noise and test signals) was obtained from the preamplifier for direct transfer to the DAT. The sound level meters were only used for monitoring and reference during the measurements.
The microphones, for all tests, were located between the loudspeaker and the noise wall as shown in the photo, Figure 4.6. Two separate sections of the noise barrier were selected at each location to better sample barrier performance. Each test consisted of a calibration tone followed by 20 repetitions of the test signals. From the six barrier sites distributed in Franklin and Hamilton Counties, a total of 34 separate data sets were obtained after disqualified tests had been eliminated. Each data set involved 20 test signal measurement samples.

Figure 4.6. Absorptive and Reflective Material Testing

The stored digital data, which consisted of the recorded ambient traffic noise and the embedded test signal noise, was subsequently transferred from the DAT to a computer file. The computer file was then converted to the appropriate format for the analysis program, which was developed specifically to identify and extract the test signal noise from the ambient traffic noise. The signal analysis program reported both the levels of the direct test signal (the signal that reached the microphone directly from the loudspeaker) and the reflected test signal (the signal that reached the microphone after being reflected from the noise wall). For a given setup (same loudspeaker, microphone, and noise wall positions) the difference in the direct and reflected levels (DL-RL) would be expected to be the same for noise walls constructed of the same material. However, the difference in levels would not be expected to be the same for a reflective and an absorptive noise wall. The additional sound energy absorbed by the absorptive noise wall would be expected to reduce the level of the reflected test signal, thus increasing the difference between the direct and reflected test signal levels. This difference in test signal levels, (Absorptive DL-RL) minus (Reflective DL-RL), referred to in this report as the Relative Average Level (RAL), provided the basis for evaluating the performance of absorptive noise walls, relative to reflective noise walls.

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 collected. Speed data 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 5.1 with the inside lanes corresponding to the faster lane of traffic and the outside lane being the slower lane of traffic.

Table 5.1. Traffic count and speed data collected

	Light Vehicles		Medium Vehicles		Heavy Trucks	
Data Description	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)
Site 1						
Northbound Inside Lane……..	1128.0	67.8	14.0	60.7	18.0	65.4
Northbound Middle-In Lane……	1176.0	65.8	52.0	62.8	128.0	60.0
Northbound Middle-Out Lane…	616.0	60.4	54.0	58.1	48.0	57.7
Northbound Outside Lane…….	710.0	51.0	18.0	48.2	16.0	58.6
Southbound Outside Lane……..	1148.0	69.9	42.0	0	78.0	66.0
Southbound Middle-Out Lane…	1326.0	65.9	40.0	64.5	136.0	62.3
Southbound Inside Lane…….	1004.0	62.1	2.0	58.0	20.0	61.1
Site 2						
Northbound Inside Lane……..	882.0	69.2	10.0	57.0	10.0	65.0
Northbound Middle-Out Lane…	1478.0	65.7	6.0	64.5	112.0	62.6
Northbound Outside Lane…….	1026.0	61.2	12.0	55.0	40.0	57.3
Southbound Outside Lane……..	938.0	62.3	12.0	60.2	74.0	59.7
Southbound Middle-Out Lane…	1170.0	67.2	18.0	63.9	130.0	62.6
Southbound Inside Lane…….	830.0	70.8	2.0	0	12.0	62.8
Site 3						
Northbound Inside Lane……..	112.0	69.2	0.0	0.0	2.0	70.5
Northbound Middle-Out Lane…	542.0	67.2	16.0	66.0	24.0	64.6
Northbound Outside Lane…….	630.0	62.4	4.0	0.0	24.0	59.5
Southbound Outside Lane……..	666.0	64.1	6.0	60.0	12.0	61.0
Southbound Middle-Out Lane…	454.0	66.0	2.0	60.5	38.0	63.9
Southbound Inside Lane…….	96.0	70.3	2.0	67.0	0.0	0.0

Table 5.1. Traffic count and speed data collected (Cont'd)

Data Description	Light Vehicles Volume (vph)	Light Vehicles Speed (mph)	Medium Vehicles Volume (vph)	Medium Vehicles Speed (mph)	Heavy Trucks Volume (vph)	Heavy Trucks Speed (mph)
Site 4						
Northbound Inside Lane……..	1018.0	70.4	14.0	68.0	36.0	67.0
Northbound Middle-Out Lane…	1020.0	64.8	44.0	63.6	208.0	63.3
Northbound Outside Lane…….	1124.0	64.1	60.0	61.6	144.0	59.5
Southbound Outside Lane……..	1010.0	61.6	58.0	59.5	192.0	61.2
Southbound Middle-Out Lane…	884.00	67.3	46.0	66.4	242.0	63.9
Southbound Inside Lane…….	744.0	72.9	10.0	66.0	18.0	67.8
Site 5						
Northbound Inside Lane……..	724.0	69.4	10.0	0.0	22.0	63.0
Northbound Middle-In Lane……	804.0	64.5	80.0	62.7	138.0	62.9
Northbound Outside Lane…….	1240.0	58.6	44.0	60.3	42.0	59.0
Southbound Outside Lane……..	1052.0	60.9	58.0	59.3	110.0	58.1
Southbound Middle-In Lane…	958.0	65.6	48.0	62.9	172.0	62.4
Southbound Inside Lane…….	680.0	69.3	10.0	68.0	18.0	65.3
Site 6						
Northbound Inside Lane……..	732.0	78.1	4.0	0.0	12.0	71.0
Northbound Middle-In Lane……	944.0	72.8	12.0	68.4	80.0	64.3
Northbound Middle-Out Lane…	596.0	69.8	36.0	64.4	124.0	63.8
Northbound Outside Lane…….	612.0	65.6	20.0	62.5	120.0	64.8
Southbound Outside Lane……..	388.0	64.3	8.0	58.0	132.0	60.1
Southbound Middle-Out Lane…	572.0	67.3	12.0	64.7	212.0	64.5
Southbound Middle-In Lane…	1008.0	71.3	44.0	67.3	72.0	64.5
Southbound Inside Lane…….	860.0	74.1	4.0	70.0	0.0	0.0
Site 7						
Eastbound Inside Lane……..	744.0	70.5	4.0	0.0	4.0	65.0
Eastbound Middle-In Lane……	970.0	66.2	20.0	64.7	38.0	57.4
Eastbound Middle-Mid Lane…	934.0	62.5	32.0	61.3	34.0	59.2
Eastbound Middle-Out Lane…	944.0	59.3	36.0	59.0	32.0	58.1
Eastbound Outside Lane…….	886.0	63.1	16.0	57.8	6.0	50.0
Westbound Outside Lane……..	1292.0	58.0	10.0	56.7	14.0	54.6
Westbound Middle-Out Lane….	918.0	61.7	30.0	60.4	66.0	54.0
Westbound Middle-Mid Lane….	1282.0	62.6	30.0	58.6	66.0	57.9
Westbound Middle-In Lane…	1414.0	63.7	26.0	59.0	80.0	59.9
Westbound Inside Lane…….	1724.0	67.1	16.0	67.5	6.0	69.0
Site 8						
Northbound Inside Lane……..	454.0	74.7	0.0	0.0	4.0	70.0
Northbound Middle-Out Lane…	668.0	70.8	18.0	67.8	172.0	65.7
Northbound Outside Lane…….	424.0	67.5	44.0	62.9	244.0	62.8
Southbound Outside Lane……..	350.0	66.8	58.0	63.5	194.0	62.7
Southbound Middle-Out Lane…	774.0	69.8	46.0	64.7	146.0	64.8
Southbound Inside Lane…….	552.0	72.6	2.0	69.0	16.0	68.0

Table 5.1. Traffic count and speed data collected (Cont'd)

Data Description	Light Vehicles		Medium Vehicles		Heavy Trucks	
	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)
Site 9						
Northbound Inside Lane……..	546.0	70.3	4.0	64.7	0.0	0.0
Northbound Middle-In Lane……	1034.0	66.8	30.0	62.3	26.0	61.7
Northbound Outside Lane…….	972.0	64.6	38.0	60.6	36.0	59.5
Southbound Outside Lane……..	1100.0	62.2	64.0	58.2	56.0	56.4
Southbound Middle-In Lane….	1060.0	66.3	46.0	62.4	56.0	59.4
Southbound Inside Lane…….	610.0	69.3	6.0	69.0	4.0	65.0
Site 10						
Eastbound Inside Lane……..	638.0	64.5	4.0	0.0	4.0	69.0
Eastbound Middle-In Lane……	1022.0	62.3	10.0	57.2	110.0	59.3
Eastbound Middle-Out Lane…	594.0	61.4	42.0	58.3	86.0	56.5
Eastbound Outside Lane…….	660.0	59.8	18.0	56.3	10.0	58.5
Westbound Outside Lane……..	556.0	59.2	26.0	56.5	10.0	54.3
Westbound Middle-Out Lane….	718.0	60.6	66.0	57.4	142.0	57.0
Westbound Middle-In Lane….	826.0	64.3	28.0	60.9	56.0	0.0
Westbound Inside Lane…….	204.0	67.9	0.0	0.0	0.0	0.0
Site 11						
Northbound Inside Lane……..	352.0	71.8	2.0	71.0	10.0	67.5
Northbound Middle-Out Lane…	712.0	69.2	34.0	66.8	62.0	67.2
Northbound Outside Lane…….	592.0	67.7	38.0	63.5	58.0	63.4
Southbound Outside Lane……..	718.0	65.1	46.0	60.1	31.0	61.0
Southbound Middle-Out Lane…	722.0	68.1	29.0	64.7	57.0	63.5
Southbound Inside Lane…….	283.0	70.7	2.0	0.0	3.0	70.0
Site 12						
Northbound Inside Lane……..	318.0	71.3	4.0	0.0	26.0	67.5
Northbound Middle-In Lane……	522.0	69.6	12.0	0.0	144.0	66.0
Northbound Middle-Out Lane…	364.0	69.8	40.0	66.8	126.0	63.6
Northbound Outside Lane…….	760.0	69.5	12.0	63.0	20.0	65.0
Ramp-In	872.0	67.5	14.0	62.0	0.0	0.0
Ramp-Out	478.0	65.7	4.0	61.5	6.0	63.5
Southbound Outside Lane……..	1032.0	65.2	30.0	114.0	60.6	0
Southbound Middle-Out Lane…	954.0	66.9	26.0	63.5	130.0	63.1
Southbound Middle-In Lane….	676.0	66.9	24.0	65.0	98.0	64.6
Southbound Inside Lane…….	370.0	70.8	0.0	0.0	6.0	67.3
Site 13						
Eastbound Inside Lane……..	810.7	70.0	5.1	64.0	5.1	66.8
Eastbound Middle-Out Lane…	1043.8	68.1	25.7	63.1	36.0	64.1
Eastbound Outside Lane…….	1150.1	63.4	54.8	61.0	73.7	62.3
Westbound Outside Lane……..	967.0	62.7	43.0	59.5	45.0	57.5
Westbound Middle-Out Lane….	1333.0	65.1	33.0	62.3	48.0	62.2
Westbound Inside Lane…….	742.0	68.9	3.0	0.0	0.0	0.0

Table 5.1. Traffic count and speed data collected (Cont'd)

Data Description	Light Vehicles		Medium Vehicles		Heavy Trucks	
	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)	Volume (vph)	Speed (mph)
Site 14						
Eastbound Inside Lane……..	308.0	72.1	6.0	67.0	0.0	0.0
Eastbound Middle-Out Lane…	598.0	70.3	30.0	67.6	234.0	65.3
Eastbound Outside Lane…….	260.0	67.7	24.0	63.3	300.0	62.1
Westbound Outside Lane……..	218.0	65.9	38.0	60.3	212.0	63.6
Westbound Middle-Out Lane….	540.0	67.8	42.0	65.9	152.0	65.8
Westbound Inside Lane…….	414.0	71.9	8.0	73.0	8.0	66.0
Site 15						
Eastbound 161 Inside Lane...	130.0	61.0	0.0	0.0	2.0	54.0
Eastbound 161 Outside Lane	274.0	57.6	20.0	0.0	4.0	43.0
Eastbound 161 In-Inside Lane	508.0	61.5	12.0	63.0	14.0	56.0
Eastbound 161 In-Out Lane…	442.0	61.6	14.0	55.0	16.0	57.6
Eastbound 161 Out-In Lane…	508.0	62.0	42.0	57.0	30.0	56.5
Eastbound 161 Out-Out Lane…	342.0	61.2	8.0	0.0	2.0	59.0
Westbound 161 Inside Lane…..	502.0	63.5	12.0	56.0	8.0	69.0
Westbound 161 Outside Lane..	594.0	62.8	22.0	54.3	20.0	58.8
Westbound 161 In-Inside Lane..	612.0	62.1	30.0	53.0	24.0	56.7
Westbound 161 Mid-In Lane…..	316.0	55.8	28.0	49.6	6.0	44.0
Westbound 161 Mid-Out Lane.	302.0	60.3	18.0	57.0	0.0	0.0
Westbound 161 Outside Lane	122.0	59.7	2.0	59.0	0.0	0.0
Site 16						
Northbound Inside Lane……..	1102.0	62.0	26.0	62.2	82.0	59.1
Northbound Middle-In Lane……	920.0	58.4	102.0	55.2	344.0	56.5
Northbound Outside Lane…….	1590.0	57.3	126.0	54.0	100.0	54.5
Southbound Outside Lane……..	1408.0	52.7	136.0	50.4	140.0	49.3
Southbound Middle-Out Lane…	1096.0	58.6	58.0	51.3	308.0	54.8
Southbound Inside Lane…….	1092.0	62.8	18.0	61.5	32.0	61.4
Site 17						
Eastbound Inside Lane……..	276.0	61.2	16.0	53.5	0.0	0.0
Eastbound Outside Lane…….	1220.0	56.7	32.0	51.0	14.0	54.3
Westbound Outside Lane……..	1078.0	55.4	36.0	48.9	40.0	48.8
Westbound Inside Lane…….	392.0	58.1	10.0	51.5	6.0	55.0

6. TNM MODELING METHODOLOGY

Noise models for this project were prepared using the FHWA Traffic Noise Model (TNM) version 2.5. Models were developed in accordance with the FHWA TNM 2.5 User's Guide and the TNM 2.5 FAQ. When a direct before and after analysis is not possible, the FHWA Traffic Noise Model is used to predicted the noise levels. The TNM allows for the user to manipulate the model to closely resemble field conditions. The model has many different inputs such as the traffic volume and type of vehicles, site geometry (position of the wall or the road), and meteorological data (humidity or temperature). With these parameters and the topographical information (road and wall elevations), the model should be able to accurately predict the decibel levels that will be observed and the amount of insertion loss the wall will provide. Figure 6.1 and Figure 6.2 show the plan and profile view of a site in TNM 2.5. In the plan and profile views the green lines represent topographic lines, the red lines represent the barriers (i.e. noise barriers or Jersey barriers), the black lines represent the roadway, and the black squares represent the microphone location. Once the different parameters are in place, receiver locations are marked in the model. In this study, the receiver locations in TNM were where the microphones were placed in the field. After the receiver locations were marked, the program was run. The model output can be seen in Figure 6.3. This output compiles the noise level at the receivers with and without the wall as well as reduction due to the wall. This output was compared to the field data to examine how closely the model resembled the field.

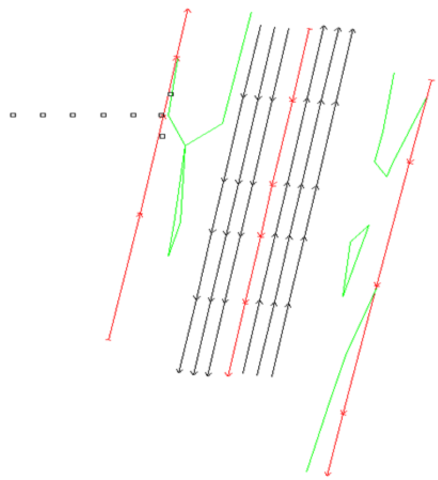

Figure 6.1. Site 9 TNM plan view

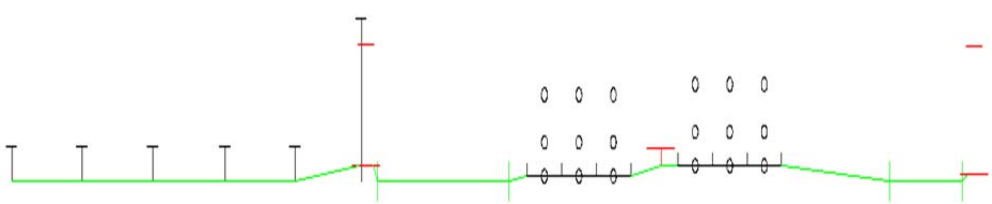

Figure 6.2.Site 9 TNM profile view

BARRIER DESIGN: BARUP

ATMOSPHERICS: 78 deg F, 45% RH

Average pavement type shall be used unless a State highway agency substantiates the use of a different type with approval of FHWA.

Receiver Name	No.	#DUs	Existing LAeq1h	No Barrier LAeq1h Calculated	No Barrier LAeq1h Crit'n	Increase over existing Calculated	Increase over existing Crit'n Sub'l Inc	Type Impact	With Barrier Calculated LAeq1h	Noise Reduction Calculated	Noise Reduction Goal	Calculated minus Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB	dB
1	1	1	0.0	75.8	66	75.8	10	Snd Lvl	75.8	0.0	8	-8.0
2	2	1	0.0	71.9	66	71.9	10	Snd Lvl	56.5	15.4	8	7.4
3	3	1	0.0	70.0	66	70.0	10	Snd Lvl	56.2	13.8	8	5.8
4	4	1	0.0	68.3	66	68.3	10	Snd Lvl	55.6	12.7	8	4.7
5	5	1	0.0	66.3	66	66.3	10	Snd Lvl	54.8	11.5	8	3.5
6	6	1	0.0	65.3	66	65.3	10	—	54.1	11.2	8	3.2
7	7	1	0.0	74.6	66	74.6	10	Snd Lvl	74.6	0.0	8	-8.0
8	8	1	0.0	75.1	66	75.1	10	Snd Lvl	75.1	0.0	8	-8.0

Figure 6.3. Site 9 TNM Results

7. STATISTICAL ANALYSIS METHODOLOGY

A statistical analysis was done to determine which noise barrier material provided a significantly higher noise reduction compared to other materials. Also the TNM data was compared to the field data to determine if any significant difference existed between the two. The program SPSS was used for all statistical analysis. For this analysis, the difference between the reference microphone (MIC 1) and the microphones behind the wall (MIC 2 through 6) was taken and averaged for every site. The same steps were taken to obtain the average noise differential for the TNM data sets. An independent t-test was conducted to analyze the data between materials and a paired t-test was run on the TNM and field data together. These tests helped determine whether there was a significant difference between the different noise barrier materials and whether there was a significant difference between the model and their corresponding field site.

7.1. Paired T-Test

The paired t-test is used compare two means when the participants are each exposed to two or more scenarios. For this analysis the noise barrier site would be considered the participant, while the model and field observations would act as the scenarios. The results from this analysis will report any significant differences between the sites field and model data.

To run a paired t-test, the data must be normal. To check if a data set is normal, either a visual assessment of the bell curve on the histogram can be done or use Equation 7.1 to calculate a Z-score for the data set. If this Z_{skew} is less than 1.96 then the data is not significantly skewed and is therefore normal.

Equation 7.1. Z-Score for Skewness

$$Z_{skew} = \frac{skewness}{standard\ error\ of\ skewness}$$

If the assumption of normality is violated two options exist: 1. Transform the existing data set to become normal or 2. Run the non-parametric t-test (Wilcoxon Signed Rank Test)[Field, 2005]. In the case of this study, the data sets were normal and the analysis could proceed. The following equation is needed to run this analysis:

Equation 7.2. Paired T-Test[Field, 2005]

$$t = \frac{\overline{D} - \mu_d}{s_D / \sqrt{N}}$$

$\overline{D}$ - Mean difference between samples

μ_d - Difference between population means~ $\mu_d=0$ due to no difference in population

$s_D / \sqrt{N}$ – Standard error of the differences

After Equation 7.2 is run, the results are checked to if any test was significant. For this analysis, at 95% confidence and 4 degrees of freedom, the significant value is 2.776 (from the t-distribution table)[Field, 2005]. A significant result occurs when the calculated t value is greater than this number, meaning that the results from the model are significantly different than the field results.

7.2. One-Way Analysis of Variance

The statistical analysis was conducted to determine if the differences between the various materials were attributable to the material or chance. In order to compare several means simultaneously in the simulator experiment, a one-way analysis of variance (ANOVA) was utilized to determine if the means were similar. Although a Student's t-test could have been conducted on the same data, several iterations of the t-test would have been required to compare all possible scenarios. However, the Type 1 error rate is greater when multiple t-tests are conducted. On the other hand, the ANOVA determines the level of confidence based upon the number of variable categories that are being compared.

To perform the ANOVA, an F-statistic is calculated which is equal to the mean squares between the groups divided by the mean squares within the groups. If F- calculated was greater than the F-critical obtained in available statistical tables, the difference in the means was statistically significant. When conducting the ANOVA test, the Levene's test for equal variances was performed simultaneously. When the Levene's test indicated that the variances were equal, the ANOVA calculated F-statistic was reported. The equations used to perform this test are as follows [Field, 2005]:

$$SS_T = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \frac{T^2}{N}$$

Where:

SS_T = Total sum of squares

$\sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2$ = squared scores summed across all individuals and groups

K = Number of groups

n = Number of observations

T = sum of scores summed across all observations and groups

N = total number of scores

$$SS_B = \sum_{k=1}^{K} \frac{T_k^2}{n_k} - \frac{T^2}{N}$$

Where:

SS_B = Sum of squares between-groups

T_k= sum of observations for k^{th} group

$$SS_W = \sum_{k=1}^{K}\sum_{i=1}^{n_k} X_{ik}^2 - \sum_{k=1}^{k} \frac{T_k^2}{n_k}$$

Where:

SS_W = Sum of squares within-groups

$$MS_B = \frac{SS_B}{K - 1}$$

$$MS_W = \frac{SS_W}{N - K}$$

$$F_{calc} = \frac{MS_B}{MS_W}$$

Where:

MS_B = Mean sum of squares between-groups

MS_W = Mean sum of squares within-groups

When statistically significant results are obtained in the ANOVA, the only conclusion that can be drawn from the test is that differences exist between the means. However, the determination of which two means are in fact not equal cannot be concluded. Therefore, in order to solve this issue, post-hoc tests can be utilized to assist in specific comparisons among groups. There are numerous post-hoc tests that have been established for various assumptions or violation of assumptions. Most of the post-hoc tests have been shown in past statistical research to withstand small deviations from normality. The Gabriel post hoc test was utilized due to the heterogeneous variances, small sample sizes and unequal sample sizes of the data set.

The statistical tests performed in this research indicated whether the differences in comparisons made were statistically significant. However, a comparison being significantly statistically different indicates only that the probability of the difference between the experimental data and the expected values computed from a given statistical distribution occurring due to chance is less than the significance level, in this research alpha equaled 0.05.

Statistical significance is based on the standard error of the sample which can be controlled by sample sized. Large sample sizes lower the standard error and will correspondingly lower the threshold for considering differences to be significant. Conversely, a small sample size can cause a large difference between groups to be statistically insignificant when, in reality, the difference may be practically significant.

One method provided to consider the practical significance of a result is through the calculation of the effect size. The effect size calculated is a measure of the number of standard deviations the difference between the groups is from the null hypothesis. The effect size was calculated by dividing the mean difference of the two groups by the pooled variance.

8. RESULTS

8.1. Comparison of Measured (Field) and Predicted (TNM) Noise Levels

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 also yielded similar data sets for predicted noise levels for each microphone location.

The following sections describe the analysis and display the results for the comparison of predicted levels with measured levels. The analysis of the broadband noise levels is given first, followed by the comparison of predicted levels in 1/3 octave frequency bands.

8.1.1. Broadband Noise Levels

The measured and predicted noise levels for each study location are shown by microphone in Table 8.1. 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. 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.

Table 8.1. Measured (Field) and Predicted (TNM) Broadband Levels

Description	Measured (Field) Level (dB)	Predicted (TNM) Level (dB)	TNM Error (dB)
Site 1			
Microphone 1	77.6649	75.9214	1.7435
Microphone 2	62.35685	74.1996	-11.84275
Microphone 3	62.50079	73.2517	-10.75091
Microphone 4	61.51526	72.4882	-10.97294
Microphone 5	59.7337	71.5942	-11.8605
Microphone 6	59.04357	70.9135	-11.86993
Microphone 7	78.37225	75.1162	3.25605
Microphone 8	77.29234	74.9128	2.37954

Table 8.1. Measured (Field) and Predicted (TNM) Broadband Levels (Cont'd)

Description	Measured (Field) Level (dB)	Predicted (TNM) Level (dB)	TNM Error (dB)
Site 2			
Microphone 1	78.81912	77.3424	1.47672
Microphone 2	61.75268	74.0851	-12.33242
Microphone 3	60.94008	72.1556	-11.21552
Microphone 4	61.94361	70.6305	-8.68689
Microphone 5	61.44883	74.3398	-12.89097
Microphone 6	61.16802	72.4921	-11.32408
Microphone 7	78.11937	76.9221	1.19727
Microphone 8	76.95121	76.4791	0.47211
Site 3			
Microphone 1	79.43767	72.7051	6.73257
Microphone 2	60.89651	70.2325	-9.33599
Microphone 3	59.07666	68.7652	-9.68854
Microphone 4	58.07004	67.7026	-9.63256
Microphone 5	57.54067	66.5744	-9.03373
Microphone 6	57.6862	66.1535	-8.4673
Microphone 7	77.16695	73.1971	3.96985
Microphone 8	78.11663	73.0832	5.03343
Site 4			
Microphone 1	76.47796	79.9586	-3.48064
Microphone 2	65.48726	72.84	-7.35274
Microphone 3	N/A	71.3189	-71.3189
Microphone 4	62.99619	70.1182	-7.12201
Microphone 5	65.11324	78.2604	-13.14716
Microphone 6	65.80741	78.2727	-12.46529
Microphone 7	85.42135	82.5504	2.87095
Microphone 8	85.28895	82.2166	3.07235
Site 5			
Microphone 1	77.96831	74.0572	3.9111
Microphone 2	60.11528	71.0601	-10.94482
Microphone 3	60.20395	69.4657	-9.26175
Microphone 4	60.33505	67.0847	-6.74965
Microphone 5	60.46898	65.1072	-4.63822
Microphone 6	59.90644	63.2166	-3.31016
Microphone 7	79.3175	73.6058	5.7117
Microphone 8	78.881	73.245	5.636

Table 8.1. Measured (Field) and Predicted (TNM) Broadband Levels (Cont'd)

Description	Measured (Field) Level (dB)	Predicted (TNM) Level (dB)	TNM Error (dB)
Site 6			
Microphone 1	78.82026	76.0412	2.77906
Microphone 2	62.18639	73.2113	-11.02491
Microphone 3	62.35414	71.713	-9.35886
Microphone 4	62.2104	70.1377	-7.9273
Microphone 5	56.34325	68.5984	-12.25515
Microphone 6	57.90681	67.1535	-9.24669
Microphone 7	78.99123	75.4293	3.56193
Microphone 8	78.38149	75.0417	3.33979
Site 7			
Microphone 1	75.40163	74.9711	.43053
Microphone 2	64.00996	73.6174	-9.60744
Microphone 3	70.0287	72.308	-2.2793
Microphone 4	62.101	70.5198	-8.4188
Microphone 5	61.90228	68.434	-6.53172
Microphone 6	61.35039	65.8615	-4.51111
Microphone 7	69.80784	73.0523	-3.24446
Microphone 8	70.14535	73.3313	-3.18595
Site 8			
Microphone 1	76.73748	74.301	2.43648
Microphone 2	61.56562	71.2564	-9.69078
Microphone 3	58.02592	69.1225	-11.09658
Microphone 4	59.27255	67.4666	-8.19405
Microphone 5	59.99434	66.0664	-6.07206
Microphone 6	59.66102	65.0436	-5.38258
Microphone 7	77.74319	75.7427	2.00049
Microphone 8	78.49119	76.1178	2.37339
Site 9			
Microphone 1	76.68142	75.8011	0.88032
Microphone 2	57.5216	71.9043	-14.3827
Microphone 3	57.51478	70.0058	-12.49102
Microphone 4	57.2849	68.3376	-11.0527
Microphone 5	57.7834	66.3143	-8.5309
Microphone 6	57.49848	65.3178	-7.81932
Microphone 7	76.15441	74.6438	1.51061
Microphone 8	74.88187	75.0933	-0.21143
Site 10			
Microphone 1	78.17419	74.1805	3.99369
Microphone 2	62.41904	71.1469	-8.72786
Microphone 3	62.63844	67.8897	-5.25126
Microphone 4	61.60854	65.9041	-4.29556
Microphone 5	59.93086	63.4676	-3.53674
Microphone 6	59.42985	61.9658	-2.53595
Microphone 7	79.05309	72.9383	6.11479
Microphone 8	77.40777	73.2457	4.16207

Table 8.1. Measured (Field) and Predicted (TNM) Broadband Levels (Cont'd)

Description	Measured (Field) Level (dB)	Predicted (TNM) Level (dB)	TNM Error (dB)
Site 11			
Microphone 1	79.43767	76.5442	2.89347
Microphone 2	64.16298	71.7001	-7.53712
Microphone 3	63.93251	69.6998	-5.76729
Microphone 4	63.59887	68.0219	-4.42303
Microphone 5	61.98462	66.4379	-4.45328
Microphone 6	61.22255	64.699	-3.47645
Microphone 7	80.54127	77.2506	3.29067
Microphone 8	78.90107	77.0794	1.82167
Site 12			
Microphone 1	80.24264	75.1523	5.09034
Microphone 2	36.0266	71.8603	-35.8337
Microphone 3	62.41872	69.4423	-7.02358
Microphone 4	60.58395	67.2226	-6.63865
Microphone 5	65.82934	72.0852	-6.25586
Microphone 6	66.38221	72.1215	-5.73929
Microphone 7	81.33541	78.4427	2.89271
Microphone 8	82.03203	78.334	3.69803
Site 13			
Microphone 1	79.56579	77.5478	2.01799
Microphone 2	58.85324	68.5426	-9.68936
Microphone 3	58.65019	61.7539	-3.10371
Microphone 4	56.89495	61.4321	-4.53715
Microphone 5	57.25285	61.7383	-4.485.45
Microphone 6	57.0334	61.1026	-4.0692
Microphone 7	79.04319	77.0216	2.02159
Microphone 8	79.75855	76.9243	2.83425
Site 14			
Microphone 1	80.65668	76.7387	3.91798
Microphone 2	23.65345	74.1286	-50.47515
Microphone 3	65.69627	72.4243	-6.72803
Microphone 4	66.07722	71.0945	-5.01728
Microphone 5	66.50625	69.8411	-3.33485
Microphone 6	17.0602	68.5165	-51.4563
Microphone 7	79.81828	76.4079	3.41038
Microphone 8	78.61723	76.3719	2.24533
Site 15			
Microphone 1	77.98873	76.5152	1.47353
Microphone 2	68.10419	77.4194	-9.31521
Microphone 3	63.48717	70.1013	-6.61413
Microphone 4	63.36739	69.6072	-6.23981
Microphone 5	64.13452	64.91385	-6.48548
Microphone 6	6491385	63.8506	1.06325

Table 8.1. Measured (Field) and Predicted (TNM) Broadband Levels (Cont'd)

Description	Measured (Field) Level (dB)	Predicted (TNM) Level (dB)	TNM Error (dB)
Site 16			
Microphone 1	83.12888	78.4682	4.66068
Microphone 2	73.86054	77.049	-3.18846
Microphone 3	75.38142	74.2283	1.153.12
Microphone 4	72.45776	72.6885	-0.23074
Microphone 5	69.46295	71.6267	-2.16375
Microphone 6	69.39211	70.1103	-0.71819
Site 17			
Microphone 1	72.70397	71.8568	0.84717
Microphone 2	65.17719	69.3351	-4.15791
Microphone 3	62.41249	67.8979	-5.48541
Microphone 4	61.59751	65.9365	-4.33899
Microphone 5	60.83479	63.9569	-3.12211
Microphone 6	60.20814	62.3724	-2.16426

8.1.2. 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 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, FRA-71 by Lighthouse Church (Clear Wall) are given in Figures 8.1 and 8.2, as an example. While the broadband results shown in Table 8.1 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. In general for the reference microphone, Microphone 1, and the two microphones in front of the wall, the TNM, model produced a fairly similar prediction to the measured levels. However, for the receptor microphones, Microphones 2 through 6, the TNM model over-predicted the noise levels or in other words, under-predicted the noise reduction levels. It should be noted that the prediction levels varied by wall type.

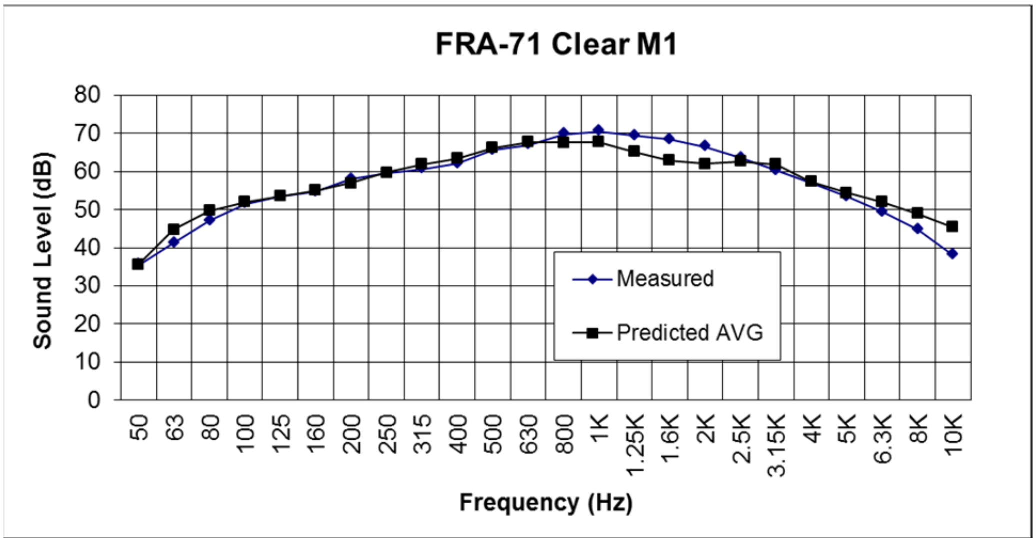

Figure 8.1. Measured and predicted one-third octave sound levels for FRA-71 by Lighthouse Church

The specific differences between predicted and measured noise levels in one-third octave frequency bands are shown in Figure 8.2. As an example, it can be seen that the maximum difference between predicted and measured levels is an over-prediction of 7.4 dB which occurred in the 10,000 Hz frequency band. While this figure is 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 8.1 and 8.2, are provided in Appendix C.

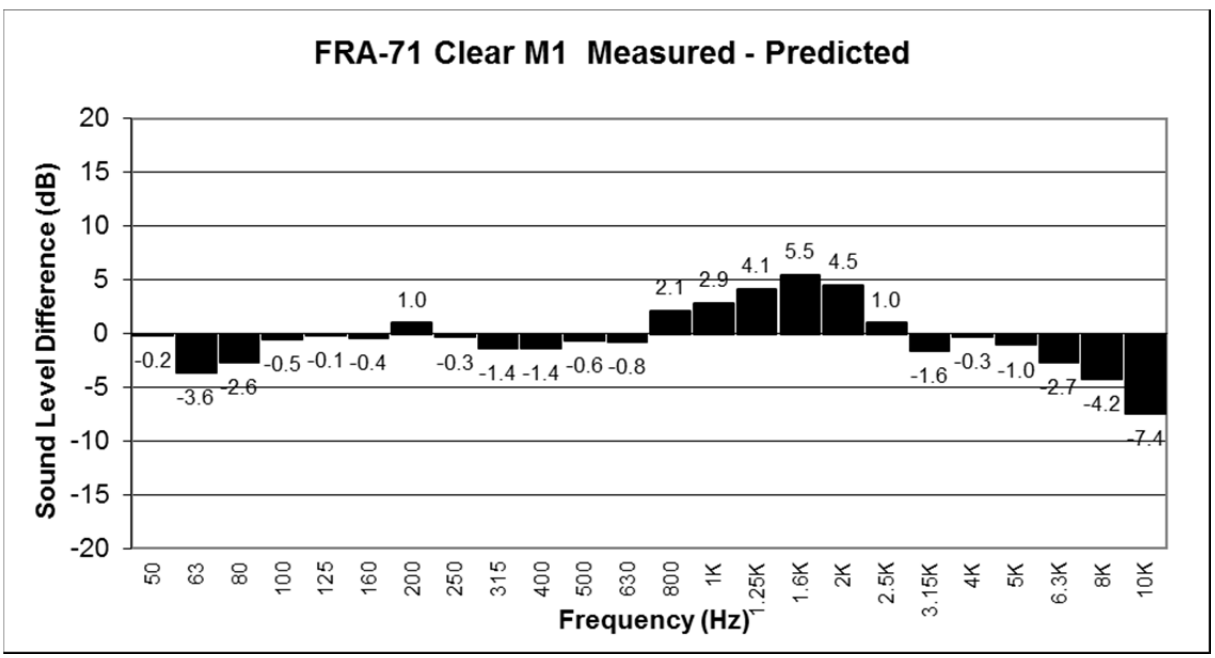

Figure 8.2. The differences between noise levels predicted and measured levels

8.1.3. Statistical Analysis

The FHWA's TNM 2.5 can be a useful tool when predicting highway noise levels. To verify that the TNM 2.5 model correctly predicted noise levels, the results from TNM 2.5 Model were compared to the results from the field measurements. The paired t-test was used to compare each site to its corresponding model. The paired t-test matched each microphone in the field to the microphone in the model. The results can be found in Table 8.2.

Table 8.2. Comparison of Measured and Predicted Noise Levels

Site No.	Material	Paired Comparison	Paired Difference			Degrees of Freedom	2-Tailed Significance
			Mean	Standard Deviation	Standard Mean Error		
1	Clear	FRA-71 (Church)	-6.24	7.23	2.56	7	0.045*
2	Clear	FRA-71	-6.66	6.51	2.30	7	0.023*
3	Refl. Concrete	GRE-675	-3.80	7.54	2.67	7	0.197
4	Abs. Concrete	MOT-75	-5.37	6.59	2.49	6	0.074
5	Abs. Concrete	STA-77	-2.46	6.71	2.37	7	0.335
6	Abs. Concrete	WAR-75	-5.02	6.95	2.46	7	0.080
7	Earthen	CUY-480	-4.67	3.34	1.18	7	0.005*
8	Earthen	MIA-75	-4.20	5.66	2.00	7	0.074
9	Hol. Fiberglass	CUY-71	-6.51	6.36	2.25	7	0.023*
10	Hol. Fiberglass	CUY-90	-1.26	5.33	1.89	7	0.526
11	RF Fiberglass	GRE-675	-2.20	4.23	1.49	7	0.183
12	Steel	FRA-71	-2.00	5.56	2.10	6	0.379
13	Steel	FRA-670	-2.38	4.34	1.53	7	0.165
14	Wood	FRA-70	-0.92	4.66	1.90	5	0.650
15	AFF	FRA-161	-4.35	4.50	1.84	5	0.064
16	AFF	HAM-75	-0.08	2.77	1.13	5	0.946
17	AFF	HAM-126	-3.07	2.23	0.91	5	0.020*

*Significant Difference at 95% Level of Confidence

Of the 17 comparisons, five site comparisons were found to have statistically significant differences between the measured (field) and predicted (TNM) A-weighted noise levels. The TNM 2.5 model can be very useful in select situations. TNM 2.5 can account for many things such as vehicle volume and class, site topography, and metrological conditions. The model cannot account for parameters such as pavement temperature, wall thickness, or wall material, which all can contribute to noise levels experienced. Not having these types of parameters can skew the results and not correctly represent the noise levels produced at the site. Therefore, due to the limitations of the TNM model, such as inability to model material types, age of material (to replicate quality or degradation), it was found that the TNM model over predicts noise levels at the receptor as compared to the measured noise levels.

8.2. *Comparison of Absorptive and Reflective Noise Wall Materials*

Previous tests have confirmed the capability of the system to function in the presence of noise from other sources. However, during the tests for this project it was found that the levels of concurrent traffic noise severely challenged the capabilities of the system. This unanticipated result was due to two factors. First, the microphones, being located on the highway side of the noise walls, were in close proximity to the roadway. Second, very high noise levels often occurred during tests due to the pass-by of closely spaced heavy trucks. These two factors led to an extremely inverted signal-to-noise ratio, coupled with the limited dynamic range of the recording system, which together proved difficult for the system to accurately process. While the problem appeared during the field tests, it was in the data reduction and analysis phase that the problem was fully realized. As one indicator, the analysis program produced an estimate of the distance traveled by a reflected sound wave. Relatively large errors in this estimated distance were present for a number of tests. Therefore, these tests were disqualified subsequent to the analysis phase.

The difference in noise levels of the test signals received at the microphone for the absorptive noise walls was to be compared with the corresponding differences for a reflective barrier. However, the problem described above showed up in various sites, including tests at the reflective site. To avoid confounding the results for the absorptive noise wall sites with any errors in the reflective noise wall tests, which were to be the basis for comparison, the noise level differences from measurements made previously at reflective walls in the absence of high traffic noise were chosen to serve as the basis of comparison for this study. These measurements, which had a mean value of 6.4 dB, were both consistent with each other, and they matched well with acoustic theory.

The resulting Relative Average Values (RAVs), by site, which are calculated as described in the data reduction and analysis section above, are shown in Table 8.3. As stated in the previous section on the field procedures, the RAV is the difference in test signal levels, Absorptive DL-RL minus Reflective DL-RL, where DL is the direct level measured and RL is the reflective level measured.

All values in the table are positive, indicating that all the test noise walls absorbed more sound energy than a standard reflective barrier. The measured relative values (relative to a reflective barrier) in Table 8 ranged from as small as 1.1 dB at Site 2 to as much as 6.3 dB at Site 5. The smallest relative average value (RAV) of 1.6 dB occurred at Site 2, while the largest RAV of 4.5 dB occurred at Site 5. Overall, the mean RAV for all absorptive noise walls was 3.0 dB, correlating to a just barely perceptible level differential by the human ear.

Table 8.3. Absorptive and Reflective Material Comparison

Site Number	RAV (dB)	Range (dB)	Manufacturer
1-Franklin	3.6	2.1 to 5.0	Faddis
2-Franklin	1.6	1.1 to 1.9	Mack
3-Franklin	2.0	1.8 to 2.1	Durisol
4-Franklin	3.3	2.7 to 3.6	Durisol
5-Hamilton	4.5	1.3 to 6.3	Soundcore
Mean	3.0		

Taken at face value, these results indicate that all the absorptive noise walls are absorbing sound energy compared with reflective noise walls. Further, these results indicate that there is variation in the amount of absorption within sites and between sites. However, these indications can be questioned, due to the problems with the test system, described above. In other words, the variations (or a portion of the variations) could in fact be due to the problems encountered with the test system. The significance of this possibility warrants further development of the system before it can be considered a viable and accurate in-situ method to evaluate absorptive noise wall material effectiveness.

Note, the application of the results, even if there were no problems with the test system, would be limited to the comparison of the relative absorption of noise wall materials, and the following limitations and cautions would be advised:

- The measurement results are indicative of the energy absorbed for sound waves with angles of incidence and reflection occurring perpendicular to the surface of the noise wall in the frequency range of 200 Hz to 2 KHz. For sound waves with other angles of incidence, a typical occurrence for residents receiving reflected noise, the amount of energy absorbed can vary.
- RAVs cannot be used as a predictor of the reduction in noise levels at typical receiver locations due to the installation of absorptive materials to control multiple reflections between parallel reflective noise walls. Both the increased noise levels caused by multiple reflections and the reductions in level due to absorptive materials are variable quantities that depend on the geometric relationships between roadways, noise walls, and receivers.
- Measurements were not taken opposite the freeway for the comparison of absorptive and reflective walls due to the minor and barely perceptible differences in front the wall nearest the sound transmission. It was anticipated that evaluating the results of the noise on the opposite side of the freeway would produce lower levels of differential.

8.3. Comparison of Noise Wall Materials

The purpose for evaluating the noise barriers was to compare the materials and find a material or materials that performed significantly better than the others. 17 total sites were analyzed, and the noise recordings taken at each site were between 30 and 60 minutes. Special consideration was taken to ensure that each site had documentation regarding noise-influencing factors such as vehicle volume and classification, microphone positioning, and weather data, among others. Topography, atmospheric data, volume and vehicle class, and noise wall characteristics were all collected for each site. Sites 11(wooden) and 14(rubber filled fiberglass) were left out of the field comparisons because there was only one location for each of these materials; however the noise data collected has been provided.

8.3.1. Material Advantages and Disadvantages

In order to thoroughly understand the effectiveness of each material tested, the advantages and disadvantages for each material was collected.

The clear panels are generally made of either a glass panel or a clear plastic product, such as Plexiglas or Acrylic. Regardless of type, they have tremendous advantages in the reduction of visual impacts from traditional noise walls based upon their ability to prevent hiding scenic views or retail areas. When driving through scenic areas, the driving public would prefer to view the scenery than traditional noise abatement; the same is true for residents living in a scenic area. The clear panels allow both the driving public and residents to view the scenic area without the confinement of a traditional noise abatement wall. In addition, in populous area where retail establishments are located, the business owners would prefer the driving public to see the nearby facilities in order to support their businesses. The clear panels, allow the driving public to view the retail establishments without the usage of billboards or other visual distractive signage. The clear panels also tend to be shatter resistant. Depending upon the type of clear panel, the disadvantages range. Regardless of the type of panel, the clear panels tend to be more expensive than most of the other types of noise wall materials mainly due to the size of the panels (in an effort to reduce the number of posts) and the stresses than can develop when erecting the clear panels. Some of the types of clear panels are sensitive to ultraviolet light and may be susceptible to glare from other sources and damage from debris along the roadway. The panels may also require frequent cleaning; however, technology has improved the quality of the clear panels and this issue is greatly reduced in recent years. If damaged, the clear panels cannot be repaired, they must be replaced to provide a consistent viewing area. In terms of sustainability, acrylic clear walls utilize a petroleum-based product in production.

Concrete wall materials are widely used across the nation. Concrete is a very durable material that is able to withstand severe temperatures and conditions, such as sunlight, moisture, ice, and salt. Concrete noise walls tend to take the appearance of many forms depending on the desired appearance of the state or local municipality; therefore, their versatility in appearance can improve the highway roadside for both the driving public and residents. Concrete has a high structural strength and is resistant to vehicle impact damage. Concrete materials are also sustainable. Installation of the concrete walls varies but may require the use of cranes, other erection equipment and even a lane closure during installation. In addition to the installation, there are size limitations associated with the concrete panels due to delivery constraints. In terms of sustainability, Portland concrete cement accounts for approximately ten percent of the carbon dioxide production annually worldwide.

Earthen berms are the most aesthetically appealing and lowest cost of construction of any noise wall material. Unfortunately, their installation requires substantial land to develop the height necessary for noise abatement due to side slope restrictions for recoverable roadway departures of vehicles and constructability. Adequate drainage must also be considered at the base of the berm in terms of conveyance as well as depth of storage in case of a rollover crash. The earthen berm will also require landscaping or at least frequent mowing maintenance.

Fiberglass walls are similar to concrete in terms of versatility and the ability to take the appearance of many forms. Fiberglass is also a lightweight material and generally shatter resistant in the case of vehicle impact. However, the fiberglass material may shrink and leave cracks in the wall, thereby limiting the noise reduction potential. Fiberglass can also deteriorate rapidly creating concerns with the surface appearance and material strength. The fiberglass panels, similar to the clear panels, cannot be repaired and must be replaced to maintain a consistent appearance. Fiberglass is also flammable and the fumes associated with such an event could be potentially toxic.

Steel is a lightweight, common metal that is generally readily available. The material is durable and able to withstand severe temperatures and conditions, such as sunlight, moisture, ice and salt, with a proper coating. If left uncoated, the steel can rust with weathering. Steel noise abatement walls have an industrial appearance and may be susceptible to glare from opposing light sources. They may be electrically conductive which could create a substantial issue near electrical components. Residents living near steel walls may be impacted as their landscaping will not survive next to the wall due to the heat generated by the material with sun exposure. The walls, which require scaffolding or a crane for erection, may also be climbable. There are also sustainability concerns with steel products as their production does create greenhouse gases.

Wood walls are constructed with a sustainable material that blends in with a natural or residential background. They are easily erected as well as dismantled. Wood is not as structurally sound as other materials and may shatter upon vehicle impact. With time, the wood will warp and shrink leaving cracks in the wall which limit noise reduction potential. Another possibility for introducing holes or additional cracks in the wood walls is the potential for insect damage in wood walls. While most wood walls are treated with a chemical preservative, those that are not tend to decay with exposure to moisture. With the modifications in chemical preservative in treated lumber, it has been determined that fasteners tend to react with the chemical preservative and in time, decay. Another concern with the chemical preservative is the toxic fumes emitted when exposed to fire, which is a concern as wood is extremely flammable.

The acoustic fabric fence is relatively easy to construct, simply use ties to connect the material to an existing fence through grommets in the fabric fence. The fence fabric is also relatively inexpensive. A concern with the acoustic fabric fence is the need of a fence in which to hold it in place. In areas with consistent wind events, the acoustic fabric fence may need a fence on either side of the fabric to hold it in place. Regardless of which fence the fabric is adhered to, consideration must be given to wind load issues when constructing the posts of the fence. The fabric has a 6-foot height and would require overlapping to achieve heights greater than 6 feet. While the general acoustic fabric fence is black and relatively unattractive compared to other noise abatement wall materials, there are photographed landscape attachments that can be added as an additional layer to the acoustic fence material.

8.3.2. Field Measurement Analysis

With each site differing in vehicle volume and class as well as site geometry, it is impossible to have a direct comparison of decibel levels. There were essentially two groups of microphones utilized in the field, those in front of or above the wall and those behind the wall. A one-way analysis of variance (ANOVA) was utilized to examine the differences in the two groups of microphones. For example, Microphones 1, 7 and 8 were compared to determine if the noise levels recorded were similar or not. The same was done for Microphones 2 through 6. It was found that at a 95% level of confidence there was no difference among the groups. Therefore, the noise levels recorded at Microphone 1 were similar to Microphones 7 and 8 by site. In addition, the noise levels recorded at Microphones 2 through 6 produced similar levels by site. Therefore, in order make the sites comparable to each another, the data from each site was normalized by taking the decibel reading at Microphones 1, 7 and 8 (now considered the before abatement field measured noise levels) and subtracting the decibel readings at Microphones 2 through 6 (now considered the after abatement field measured noise levels). This new value would be considered the noise reduction due to the wall or the field determined insertion loss and would be comparable from site to site. Table 8.4 provides a summary of the field data by site including the insertion loss.

Table 8.4 Insertion Loss Results

Site No.	County	Route	Material	Wall Height	Distance from Pavement	STC	Temp. (F)	% Rel. Humidity	Insertion Loss (dB)
1	Franklin	I-71	Clear	12’	40’	37	76	32	16.74
2	Franklin	I-71	Clear	16’	35’	37	85	51	16.51
3	Greene	I-675	Refl.Concrete	13’	35’	53	70	40	19.59
4	Montgomery	I-75	Abs. Concrete	15’	40’	53	95	32	17.54
5	Stark	I-77	Abs. Concrete	17’	60’	53	75	70	18.52
6	Warren	I-75	Abs. Concrete	15’	80’	53	84	74	18.53
7	Cuyahoga	I-480	Earthen Berm	8’	60’	23	75	45	7.91
8	Miami	I-75	Earthen Berm	8’	80’	23	68	50	17.95
9	Cuyahoga	I-71	Hol. Fiberglass	18’	50’	28	78	45	18.39
10	Cuyahoga	I-90	Hol. Fiberglass	13’	65’	28	70	45	16.65
11	Greene	I-675	RF Fiberglass	13’	35’	37	80	65	16.65
12	Franklin	I-71	Steel	17’	60’	33	76	35	17.4
13	Franklin	I-670	Steel	12’	35’	33	74	40	21.72
14	Franklin	I-70	Wood	18’	30’	26	68	35	13.60
15	Franklin	SR-161	AFF	13’	25’	28	78	64	13.19
16	Hamilton	I-75	AFF	6’	40’	28	80	87	11.02
17	Hamilton	SR-126	AFF	4’	45’	28	70	100	10.65

Due to the differential in the independent variables (material, wall height, distance from pavements, vehicular volume, vehicular speed, STC rating, temperature, and humidity), a partial correlational analysis was conducted to determine if any of the independent variables impacted the insertion loss. The partial correlational analysis allows control of the other variables in order to determine the unique relationship between a single independent variable and the dependent variable (insertion loss). Table 8.5 summarizes the partial correlational analysis.

Table 8.5. Partial Correlational Analysis for Insertion Loss

Dependent Variable	Independent Variable	Correlation	Unique Contribution	Significance (2-tailed)
Insertion Loss	Material Type	0.978	1.0%	0.978
	Wall Height	0.148	2.2%	0.682
	Distance From Roadway	0.303	9.2%	0.395
	STC Rating	0.356	12.7%	0.313
	Temperature	0.064	0.4%	0.860
	Humidity	-0.294	-8.6%	0.410
	Total Volume	-0.371	-13.8%	0.291
	Average Speed	0.056	0.3%	0.878

Based upon the correlational analysis, there are no significant correlations at a level of confidence of 95% for any of the relationships with insertion loss. The amount of variability in insertion loss totals 48.2 percent, which is simply the sum of the unique contributions by independent variable. Therefore, 51.8 percent of the variability is due to data that was not analyzed. The relationship between the variables indicates that all have non-significant positive relationships with insertion loss, except for humidity and total volume, which have a non-significant negative relationship. This indicates that as the humidity or total vehicular volume increases, the insertion loss decreases. The analysis also indicates that volume and STC rating contribute most to the variation in insertion loss, which is an accurate representation of noise theory. The basic reason for the lack of statistical significance is related to the scatter among the data set. Figures 8.3 through 8.5 indicate graphical relationships for insertion loss with wall height, STC rating and distance from the edge of pavement.

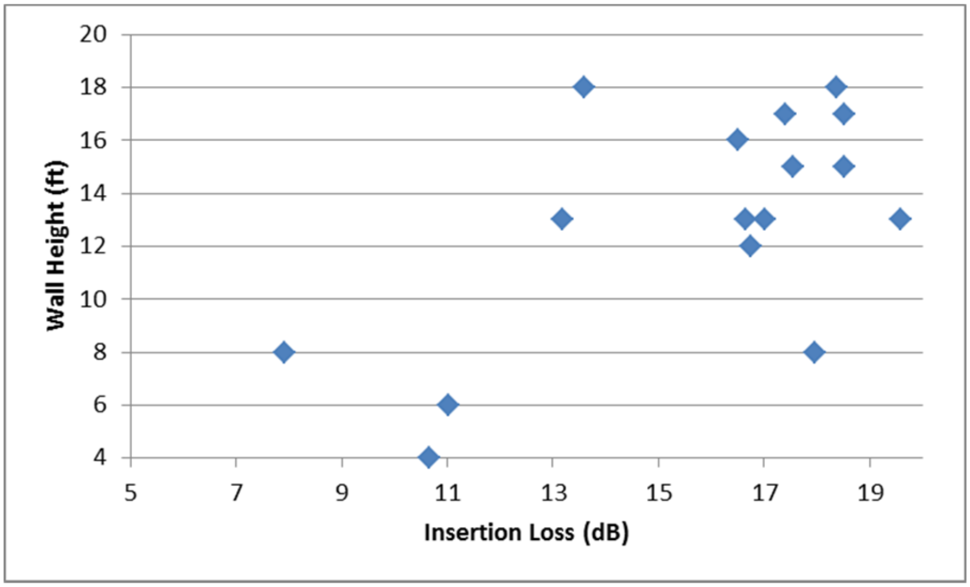

Figure 8.3. Scatter Plot of Insertion Loss and Wall Height

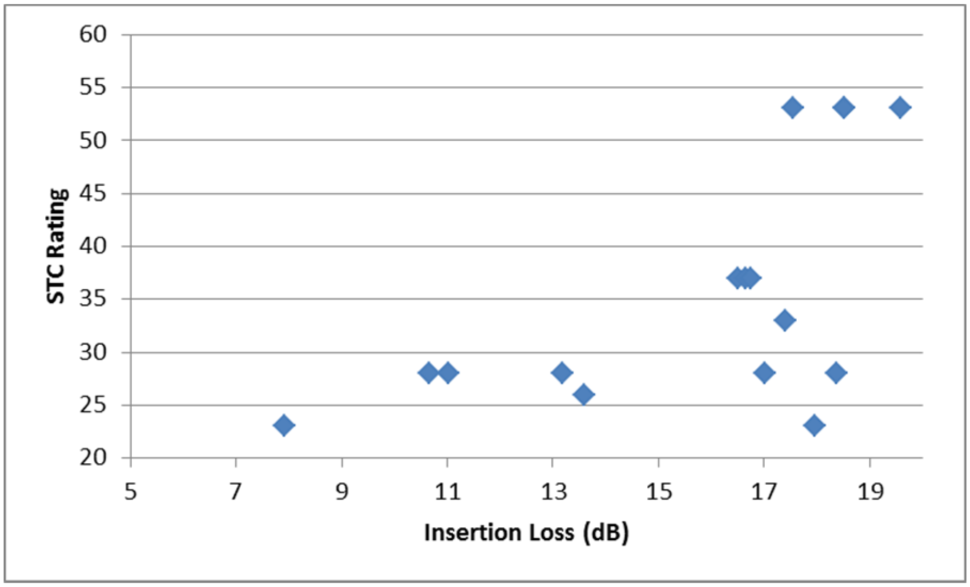

Figure 8.4. Scatter Plot of Insertion Loss and STC Rating

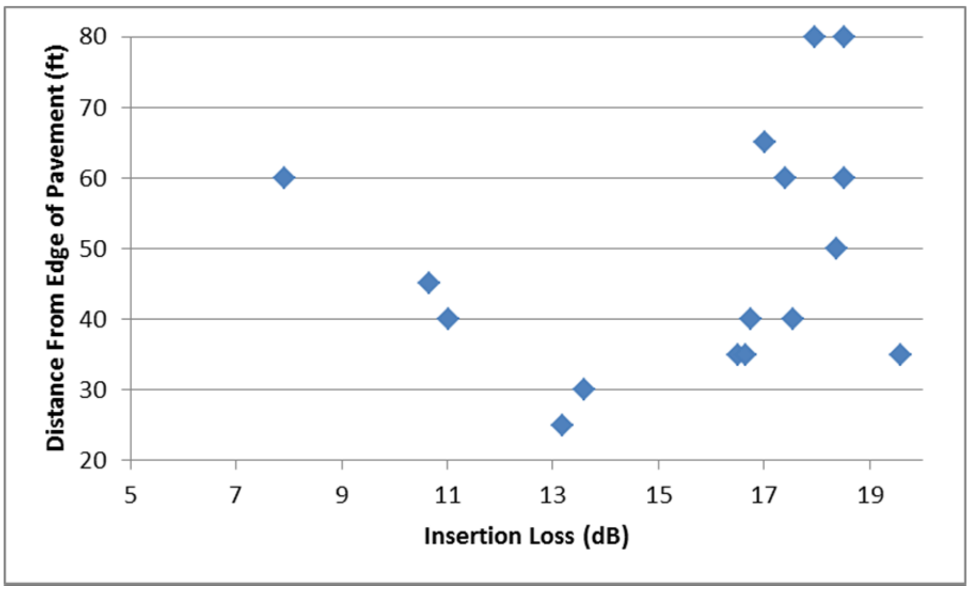

Figure 8.5. Scatter Plot of Insertion Loss and Distance from the Edge of Pavement

In order to further understand the variability within the dataset, a review of the data organized by insertion loss provides additional insight and is shown in Table 8.6.

Table 8.6. Sorted Insertion Loss

Site No.	County	Route	Material	Wall Height	Distance from Pavement	STC	Insertion Loss (dB)	Material Std. Dev.
13	Franklin	I-670	Steel	12	35	33	21.72	4.71
3	Greene	I-675	Refl. Concrete	13	35	53	19.59	1.40
6	Warren	I-75	Abs. Concrete	15	80	53	18.53	1.40
5	Stark	I-77	Abs. Concrete	17	60	53	18.52	1.40
9	Cuyahoga	I-71	Hol. Fiberglass	18	50	28	18.39	0.49
8	Miami	I-75	Earthen Berm	8	80	23	17.95	7.10
4	Montgomery	I-75	Abs. Concrete	15	40	53	17.54	1.40
12	Franklin	I-71	Steel	17	60	33	17.40	4.71
10	Cuyahoga	I-90	Hol. Fiberglass	13	65	28	17.00	0.49
1	Franklin	I-71	Clear	12	40	37	16.74	1.49
11	Greene	I-675	RF Fiberglass	13	35	37	16.65	0.49
2	Franklin	I-71	Clear	16	35	37	16.51	1.49
14	Franklin	I-70	Wood	18	30	26	13.60	N/A
15	Franklin	SR-161	AFF	13	25	28	13.19	0.86
16	Hamilton	I-75	AFF	6	40	28	11.02	0.86
17	Hamilton	SR-126	AFF	4	45	28	10.65	0.86
7	Cuyahoga	I-480	Earthen Berm	8	60	23	7.91	7.10

Upon review of the above table, the insertion loss by material does not track with the STC rating of the material. This is explainable by the fact that STC ratings, while similar for similar material types, do have variability within the material type. For example, the two steel walls tested have a standard deviation of 4.71 indicating there is a difference in the insertion loss measured by that material by 4.71 dB. Another interesting finding is that of the earthen berm data with a 7.10 standard deviation even though the walls were at similar heights. Although material samples were not taken at the sites, one could induce that the material comprising the earthen berm at site 8 was a denser material than that of site 7. Those materials with relatively low standard deviations, tended to bunch together in terms of insertion loss indicating minimal variation in material and thereby noise reduction potential.

A one-way analysis of variance (ANOVA) was utilized to examine the difference in the wall materials to ascertain which materials yielded the greatest noise reduction. Due to only one wood wall represented in the data set, the wood wall was removed from the analysis. In addition, the one rubber-filled fiberglass and two hollow fiberglass walls were combined and labeled as fiberglass; this was similarly done for the reflective and absorptive walls. Table 8.7 summarizes the descriptive data for the various wall materials by material type.

Table 8.7. Descriptive Data for Noise Wall Material

Wall Material Type	Sample Size	Field Mean Insertion Loss (dB)	Standard Deviation (dB)
Clear	2	16.62	0.163
Concrete	4	18.54	0.835
Reflective Concrete	1	19.59	N/A
Absorptive Concrete	2	18.20	0.565
Earthen	2	12.93	7.102
Fiberglass	3	17.35	0.917
Hollow Fiberglass	2	17.69	0.977
Rubber Filled Fiberglass	1	16.65	N/A
Wood	1	13.60	N/A
Steel	2	19.56	3.056
Acoustic Fabric Fence	3	11.62	1.371
Total	16	16.05	3.596

The ANOVA indicated significant differences between materials and the Games Howell post hoc test (conducted due to the lack of homogeneous variances and unequal sample sizes) indicated that the concrete wall material and fiberglass wall material were significantly different than the acoustic fabric fence. In a review of the mean noise reduction among the wall material types, it is obvious that the acoustic fabric fence does not perform at the same level as the other wall material types. The other material types were statistically similar in terms of noise reduction.

8.3.3. Life Cycle Cost Analysis

Based upon data gathered from sources such as, Morgan et. al [Morgan et. al, 2001], the life cycle cost analysis was conducted. Service life in terms of year was utilized based upon manufacturer information for each type of material for noise abatement walls. The cost of installation, maintenance and replacement costs were established by dollar per square foot of wall based upon 2000 dollars. In order to adjust the values to 2014, the gross domestic product in 2000 and 2014 were utilized to determine a dollar increase of 1.84 percent annually, or an overall 1.29 factor increase. Lastly, the performance differential was considered in two ways; (1) life cycle cost per reduction in dollars per decibel and (2) the reduction in decibels per dollar of life cycle cost. The life cycle cost analysis was conducted on a 50 year period, which required the replacement of the walls with service lives less than 50 to be replaced at the end of their service life. The acoustic fabric fence was not included in the analysis as service life and costs were not available through the manufacturer. The life cycle cost analysis is summarized in Table 8.8, sorted by the insertion loss per dollar.

Table 8.8. Life Cycle Cost Analysis

Material	Service Life (yrs)	Installation Costs ($/ft^2)	Maintenance and Replacement Costs ($/ft^2)	Life Cycle Cost, 2000 ($/ft^2)	Life Cycle Cost, 2014 ($/ft^2)	Field Measured Insertion Loss (dB)	Performance Differential (LCC/IL) ($/dB)	Performance Differential (IL/LCC) (dB/$)
Earthen Berm	50+	10.33	3.6	13.93	17.97	12.93	1.39	0.72
Concrete	50	19.67	4.03	23.7	30.57	18.54	1.65	0.61
Fiberglass	50	25.33	4.65	29.98	38.67	17.35	2.23	0.45
Clear	25	19.67	14.14	33.81	43.61	16.62	2.62	0.38
Wood	25	16.7	11.35	28.05	36.18	13.6	2.66	0.38
Steel	25	27.67	12.19	39.86	51.42	19.56	2.63	0.38

The life cycle cost analysis indicates that the earthen berm provides the greatest insertion loss per dollar of installation, maintenance and replacement cost. Concrete materials have the second highest performance differential in terms of insertion loss per dollar cost.

9. CONCLUSIONS

Multiple noise barrier materials and the TNM 2.5 were evaluated as a part of this study. These tests were conducted in order to identify the noise barrier material that produces the best noise reduction and determine whether the model produces comparable results to the field. The conclusions gathered from this study are discussed in the following sections.

9.1. TNM Model Evaluation

The noise model evaluation portion of this study was conducted to determine how accurately the FHWA model can replicate results that would be obtained in the field. Each site that was field tested was entered into the model and the resulting noise levels were recorded. There were 17 total comparisons for this section of the study.

A statistical analysis was performed to determine if there was a significant difference between the model and the field results. With the model being a replica of the filed site a paired t-test was used to compare the two results from each site. The results from this analysis showed that in the 17 comparisons five of them had a significant difference between the noise reduction in the model and field. The model cannot account for parameters such as pavement temperature, wall thickness, or wall material, which all can contribute to noise levels experienced. Not having these types of parameters in the model can skew the results and not correctly represent the noise levels produced at the site in the field. Therefore, due to the limitations of the TNM model, such as inability to enter material types, age of material (to replicate quality or durability), it was found that the TNM model over predicts noise levels at the receptor as compared to the measured noise levels for both broadband and 1/3 octave levels at a level of confidence of 95 percent. There are concerns that if the TNM over predicts noise levels at the receptor location, the noise abatement capability of the wall may not be accurately represented. For instance if the TNM predicts a receptor noise level of 69.26 dB and the threshold for abatement is 67 dB or greater, the designed would modify the wall design. However, in the field the actual noise level at the receptor would have been 62.11 dB, below the threshold of 67 dB. Therefore, the additional cost of the wall based upon the TNM prediction would not have been necessary. Thus, the model should be reserved for planning uses and field measurements alone should be used for field evaluations of various materials.

9.2. Absorptive and Reflective Wall Comparison

An experimental system was used as a secondary approach to augment the traditional approach to the evaluation of absorptive versus reflective noise walls. However, during the tests it was found that the levels of concurrent traffic noise severely challenged the capabilities of the system. Therefore, the test results and conclusions are presented with the disclaimer that they contain error that has not been quantified. It was found that all the test noise walls absorbed more sound energy than a standard reflective barrier. The Relative Average Values (RAVs), for energy absorption by the absorptive noise walls compared to the reference reflective noise wall, ranged from 1.6 dB to 4.5 dB, with an overall mean value of 3.0 dB for all absorptive noise walls tested. Therefore, no statistical difference found in concrete noise wall manufacturer's absorptive capabilities at a 95 percent level of confidence. Further development of the experimental system is needed before it can be considered a viable and accurate in-situ method to evaluate absorptive noise wall material effectiveness. Overall, the cost for the absorptive barriers may be prohibitive given the average differential in noise level of 3 dB, which is just barely perceptible to the human ear.

9.3. Noise Wall Material Comparison

The goal for this portion of the study was to identify the noise barrier material that produced the greatest noise reduction. There were seven different materials tested: acoustic fabric, clear, concrete, earthen berm, hollow fiberglass, rubber-filled fiberglass, and steel. These materials were tested in a field setting on existing interstates and highways. There were 17 total sites used for the study.

The noise data collected at each of the 17 sites was collected in the same fashion. The acoustic fabric sites used six microphone sets, while all other sites used eight sets. The microphones at each site were set up in an array formation behind the wall, and recording sessions at lasted between 30 and 45 minutes. Once the recording sessions were finished, the tapes were replayed through the Larson Davis RTA and a spreadsheet was developed. The spreadsheets were organized by microphone number with a minute by minute decibel reading for each A-weighted octave band. These decibel readings were then converted to a single decibel reading for each microphone and this value was used for all future comparisons.

A statistical analysis was done to determine if there were any significant differences in the noise reduction between the noise barrier materials. Because each site has different characteristics compared to the others, the one-way analysis of variance was used to analyze the data. The results showed that the acoustic fabric material had significantly less noise reduction than the other materials. There was no statistical difference between the remaining materials. In regards to other material types, there were durability concerns with all but two of the concrete walls. The worst case was the wooden wall which was heavily warped with large gaps in the middle of the wall. The remaining sites experienced soil eroding from the base of the wall and the physical structure of the wall facing the roadway deteriorating. The life cycle cost analysis indicated that the earthen berm and concrete wall material provided the greatest noise reduction potential per cost.

Based upon the noise reduction statistical analysis, the durability of the wall materials and the life cycle cost analysis, it is recommended that ODOT continue to utilize concrete materials for noise abatement and minimize the use of other materials.

A summary for each of the materials tested is provided in the following sections.

9.3.1. Clear Wall Materials

- Clear noise abatement walls yielded a mean insertion loss of 16.62 dB.
- Clear wall material noise levels yielded a standard deviation of 0.163, indicating very low variability between wall materials meaning the materials were consistent among the two sites sampled.
- The life cycle cost analysis found that clear noise abatement walls produce a 0.38 insertion loss per dollar of cost. This is among the lowest of the materials tested.
- Acrylic clear panels utilize a petroleum-based product in production which may cause sustainability concerns.
- Clear noise abatement wall have tremendous advantages in the reduction of visual impacts based upon their ability to prevent hiding scenic views or retail areas.
- Due to the life cycle analysis, clear walls should continue to be used when there are scenic areas of interest to the driving population or residents or at the request of retail establishments. If retail establishments request a clear wall instead of the standard ODOT noise abatement wall, ODOT may want to consider charging the retail establishments for the differential in the cost of the wall.

9.3.2. Concrete Wall Materials

- Concrete noise abatement walls yielded a mean insertion loss of 18.54 dB.
- Concrete wall material noise levels yielded a standard deviation of 0.835, indicating some variability between wall materials meaning the materials were somewhat consistent among the three sites sampled, two of which were absorptive wall and one was a reflective wall. The standard deviation for the two absorptive walls was lower at 0.565 which still indicates some variability between materials.
- In terms of sustainability, Portland concrete cement accounts for approximately ten percent of the carbon dioxide production annually worldwide.
- Concrete is a very durable material that is able to withstand severe temperatures and conditions, such as sunlight, moisture, ice, and salt.
- Concrete noise walls tend to take the appearance of many forms depending on the desired appearance of the state or local municipality; therefore, their versatility in appearance can improve the highway roadside for both the driving public and residents.
- Concrete has a high structural strength and is resistant to vehicle impact damage.
- The life cycle cost analysis found that concrete noise abatement walls produce a 0.61 insertion loss per dollar of cost. This is the second highest of the materials tested.
- Due to the performance, durability and life cycle cost analysis, concrete walls should continue to be used widely across the State of Ohio.

9.3.3. Earthen Berms

- Earthen berm noise abatement walls yielded a mean insertion loss of 12.93 dB.

- Earthen berms noise levels yielded a standard deviation of 7.10, indicating vast variability between wall materials meaning the materials were not consistent among the two sites sampled.
- The life cycle cost analysis found that earthen berm noise abatement walls produce a 0.72 insertion loss per dollar of cost. This is the highest of the materials tested.
- Earthen berm installation requires substantial land to develop the height necessary for noise abatement due to side slope restrictions for recoverable roadway departures of vehicles and constructability.
- The earthen berms require landscaping or at least frequent mowing maintenance.
- Earthen berms should be further evaluated to determine a consistent material for construction to reduce the variability in the noise reduction at the receptor.
- Due to the performance, durability and life cycle cost analysis, earthen berms should be utilized where rights-of-way are adequate to support the land necessary to appropriately develop the height required for noise reductions.

9.3.4. Fiberglass Wall Materials

- Fiberglass noise abatement walls yielded a mean insertion loss of 17.35 dB.
- Fiberglass wall material noise levels yielded a standard deviation of 0.917, indicating variability between wall materials meaning the materials were somewhat consistent among the three sites sampled.
- Fiberglass is also a lightweight material, generally shatter resistant in the case of vehicle impact and has the ability to take the appearance of many forms.
- Fiberglass material may shrink and leave cracks in the wall, thereby limiting the noise reduction potential. Fiberglass can also deteriorate causing concerns to rise with appearance and material strength.
- Fiberglass is also flammable and the fumes associated with such an event could be potentially toxic.
- The life cycle cost analysis found that fiberglass noise abatement walls produce a 0.45 insertion loss per dollar of cost.
- Due to the performance, durability and life cycle cost analysis, there are other noise abatement wall materials that have better performance and durability at a lower cost than fiberglass walls.

9.3.5. Wood Wall Materials

- Wood noise abatement walls yielded a mean insertion loss of 13.60 dB.
- The life cycle cost analysis found that wood noise abatement walls produce a 0.38 insertion loss per dollar of cost. This is among the lowest of the materials tested.
- Wood walls are constructed with a sustainable material that blends in with a natural or residential background.
- With time, the wood will warp and shrink leaving cracks in the wall which limit noise reduction potential. They are also susceptible to insect damage.
- Wood walls are treated with a chemical preservative that emits a toxic fume when on fire. Given the flammability of the material, this is a concern.

- Due to the performance, durability and life cycle cost analysis, there are other noise abatement wall materials that have better performance and durability at a lower cost than wood walls.

9.3.6. Steel Wall Materials

- Steel noise abatement walls yielded a mean insertion loss of 19.56 dB.
- Steel wall material noise levels yielded a standard deviation of 3.06, indicating variability between wall materials meaning the materials were not consistent among the two sites sampled.
- The life cycle cost analysis found that steel noise abatement walls produce a 0.38 insertion loss per dollar of cost. This is among the lowest of the materials tested.
- Steel is durable and able to withstand severe temperatures and conditions, such as sunlight, moisture, ice and salt, with a proper coating.
- Steel walls may be electrically conductive and generate heat with sun exposure which prohibits landscaping from growing near the wall.
- Due to the performance, durability and life cycle cost analysis, there are other noise abatement wall materials that have better performance and durability at a lower cost than steel walls.

9.3.7. Acoustic Fabric Fence Materials

- Acoustic fabric fence noise abatement walls yielded a mean insertion loss of 11.62 dB.
- Acoustic fabric fence noise levels yielded a standard deviation of 1.37, indicating variability between wall materials meaning the materials were somewhat consistent among the three sites sampled.
- Acoustic fabric fence is relatively easy to construct, simply use ties to connect the material to an existing fence through grommets in the fabric fence.
- In areas with consistent wind events, the acoustic fabric fence may need a fence on either side of the fabric to hold it in place. Regardless of which fence the fabric is adhered to, consideration must be given to wind load issues when constructing the posts of the fence.
- Due to the performance, durability and life cycle cost analysis, the acoustic fabric fence, while not necessarily appropriate for permanent noise abatement, would reduce noise impacts from construction sites or other temporary noise nuisances and should be considered.

9.4. Recommendations

1. Based on the results found in this study, a couple of issues for future research should be considered. The first recommendation would be to increase the sample size; however, atmospheric conditions and costly state-wide travel limit the feasibility of such improvements to the study. Secondly, a controlled environment would be more suitable to pinpoint the advantages and disadvantages to strictly the noise reduction potential of each material type. In a controlled environment, the researcher could control all factors so that the only difference between the noise barriers will be the material. However, the concerns with constructability and maintenance throughout the life of the wall could substantially alter the results of such a study.
2. The TNM, version 2.5, is an acceptable tool to predict noise levels for planning purposes as it does under-predict noise reductions beyond the wall as compared to the field

conditions. However, using the model for field evaluations should be restricted due to the under-prediction.

3. Absorptive wall materials seem to offer an advantage over reflective wall materials and should continue to be utilized for noise abatement if the cost is justifiable. Overall, the cost for the absorptive barriers may be prohibitive given the average differential in noise level of 3 dB, which is just barely perceptible to the human ear. This finding support research conducted by Watts where the reflective barrier increased noise levels by 3.1 dB and absorptive treatments decreased noise levels by 2.7 dB. The data also falls within the FHWA guidelines for a wall width-to-height ratio for 10:1 to 20:1 where a 0 to 3 dB insertion loss was expected.
4. Earthen berms should be further evaluated to determine a consistent material for construction to reduce the variability in the noise reduction at the receptor.
5. The acoustic fabric fence did not provide substantial noise reductions and was outperformed by the other noise wall materials. However, due to its portability, the acoustic fabric fence would be a suitable product for use in a temporary situation, such as construction work zones to reduce noise impacts in residential areas.
6. Based upon the acceptable levels of noise reduction, life cycle cost analysis, and the durability of the product, the concrete noise walls seem to perform better than the other noise wall materials.

9.5. Implementation

It is recommended that the ODOT procedures for noise analysis incorporate the use of the TNM as strictly a planning tool, recommend the use of absorptive noise wall materials, when cost is justifiable, as well as the use of concrete walls for noise abatement.

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APPENDIX A

Project Equipment List

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., down arrow to set level to 94.0 dB). 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.

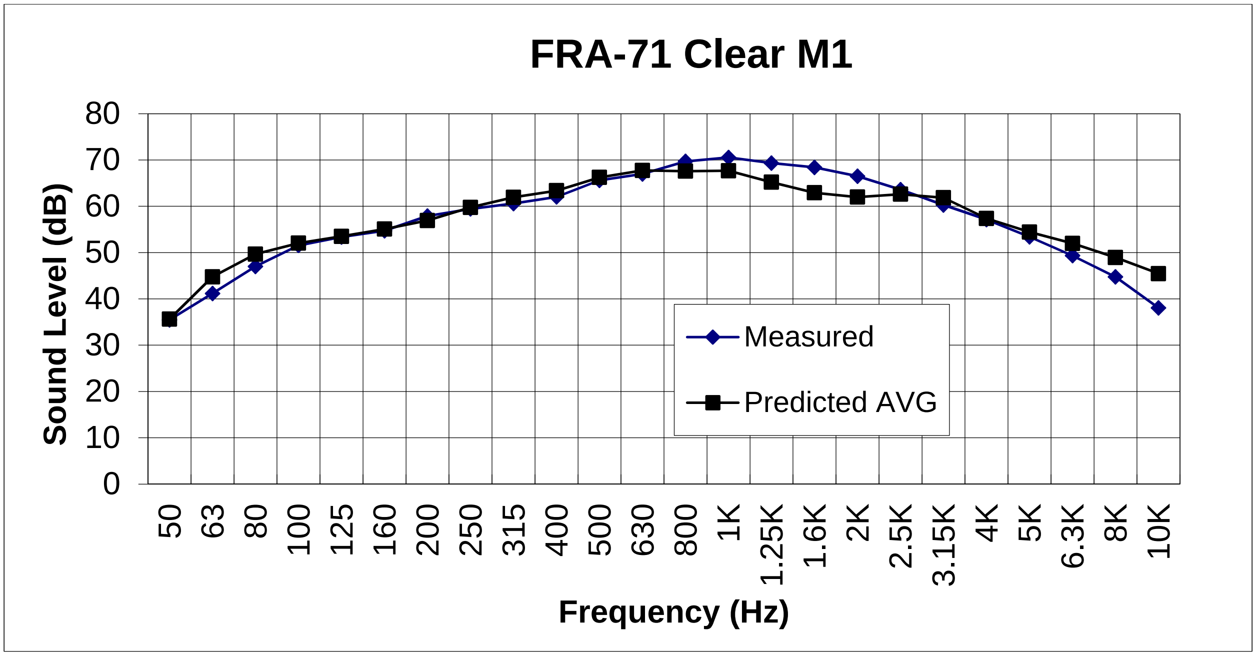
A file created in the FILES menu will contain data created, and the user setups present in RAM, while that file name appears in the lower left hand corner of the main menu. Each data set stored with the STORE key or automatically by AUTOSTR adds a “record” under the file name that can be confirmed by 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.

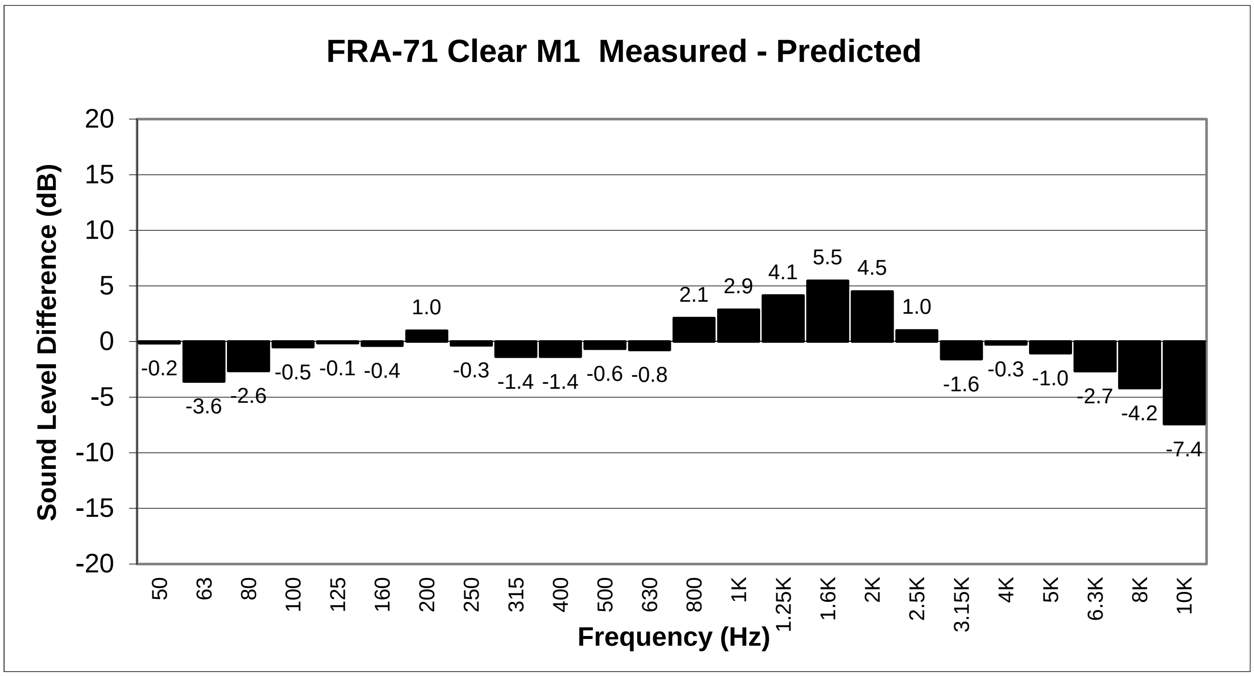
Note on DAT AC power supplies. Plugging the power supply cable into the DAT disconnects the internal battery. If the power supply isn’t live, the DAT time-of-day clock will reset after a few seconds.

APPENDIX C

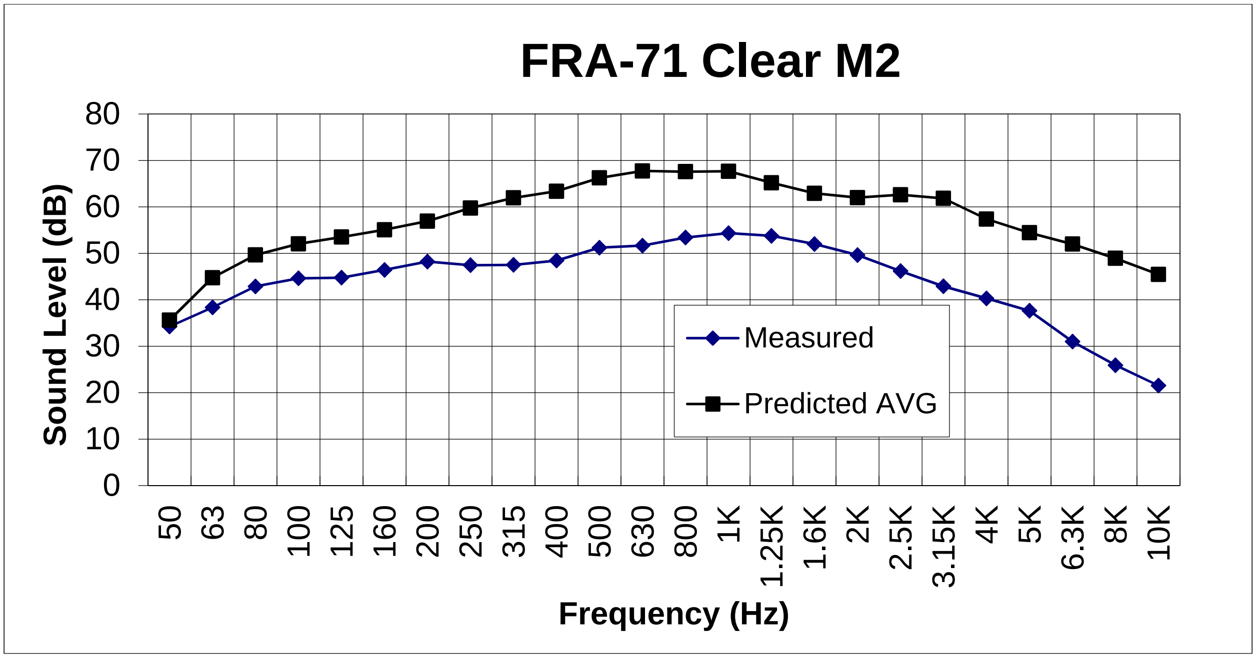
One-Third Octave Band Frequency Levels by Site and Microphone Location

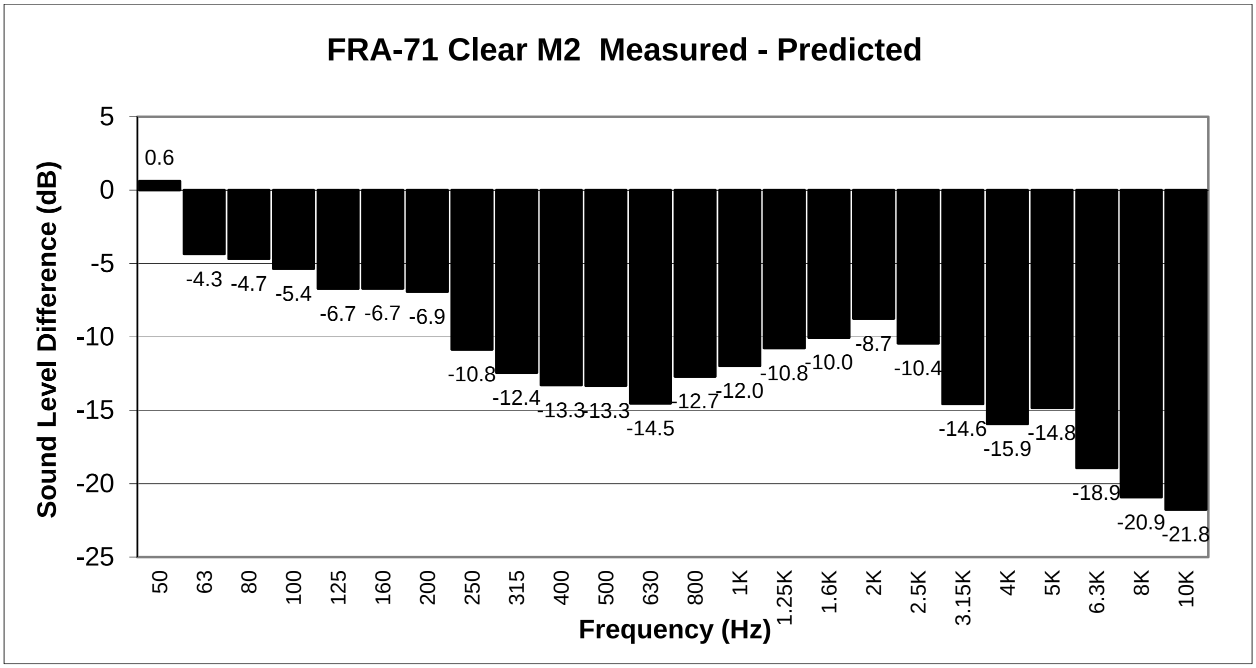
Site 1: Franklin County, I-71 by Lighthouse Church; Clear Wall





Site 1: Franklin County, I-71 by Lighthouse Church; Clear Wall





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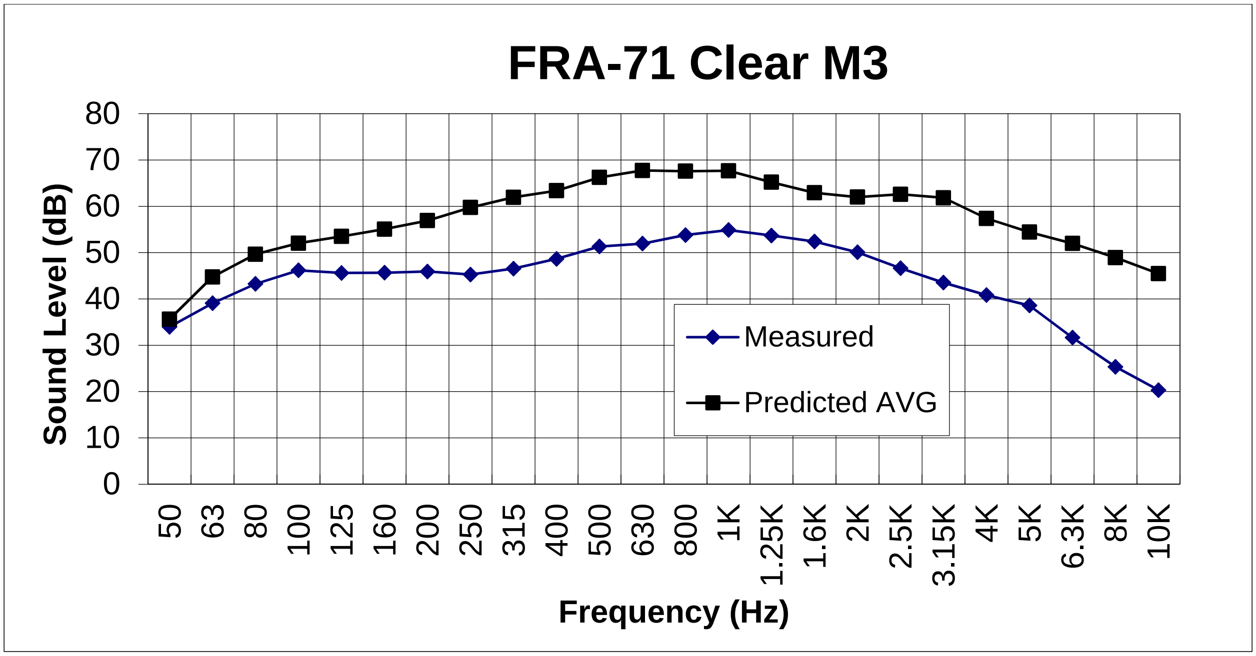

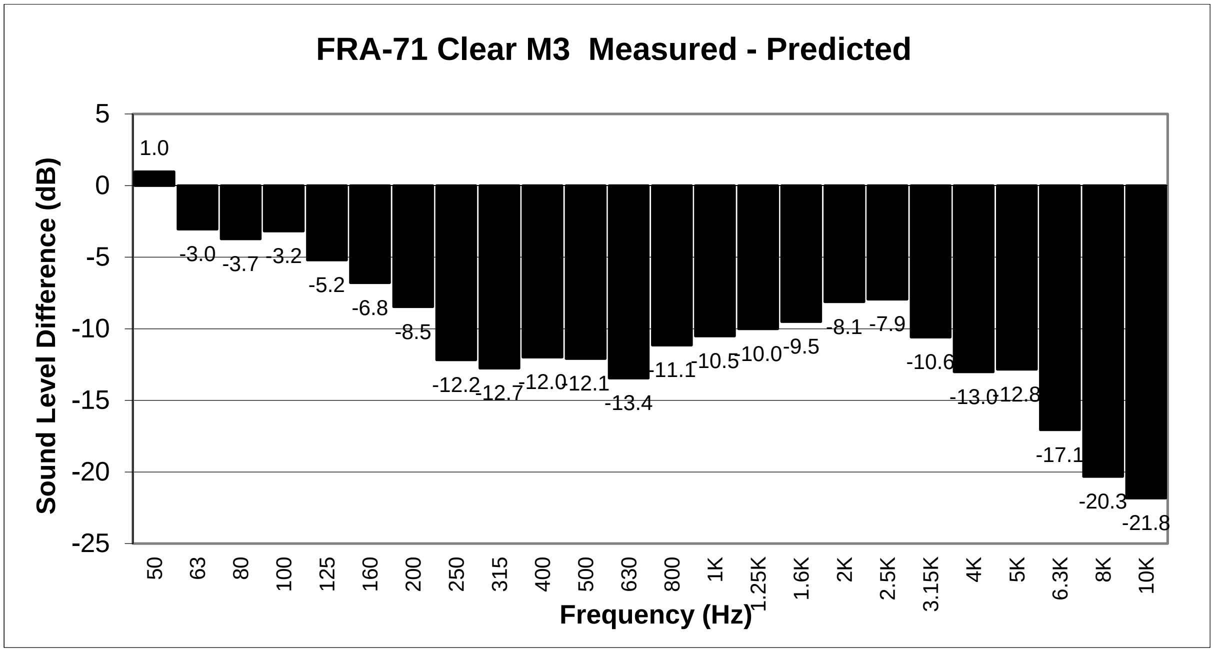

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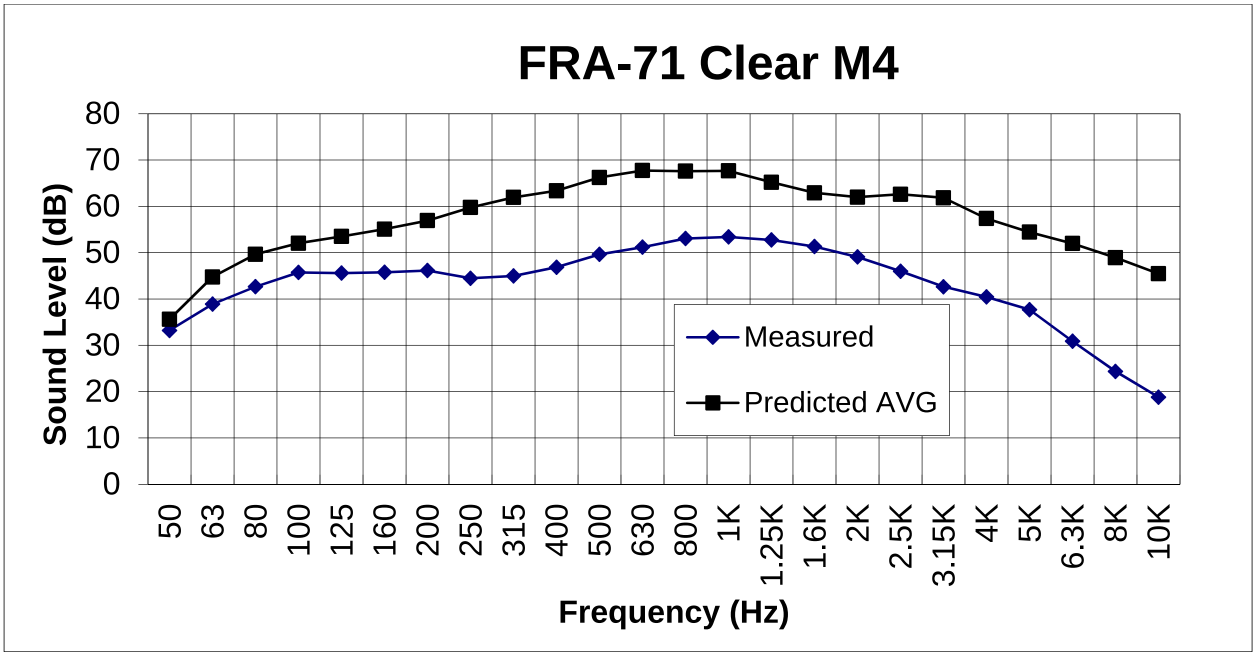

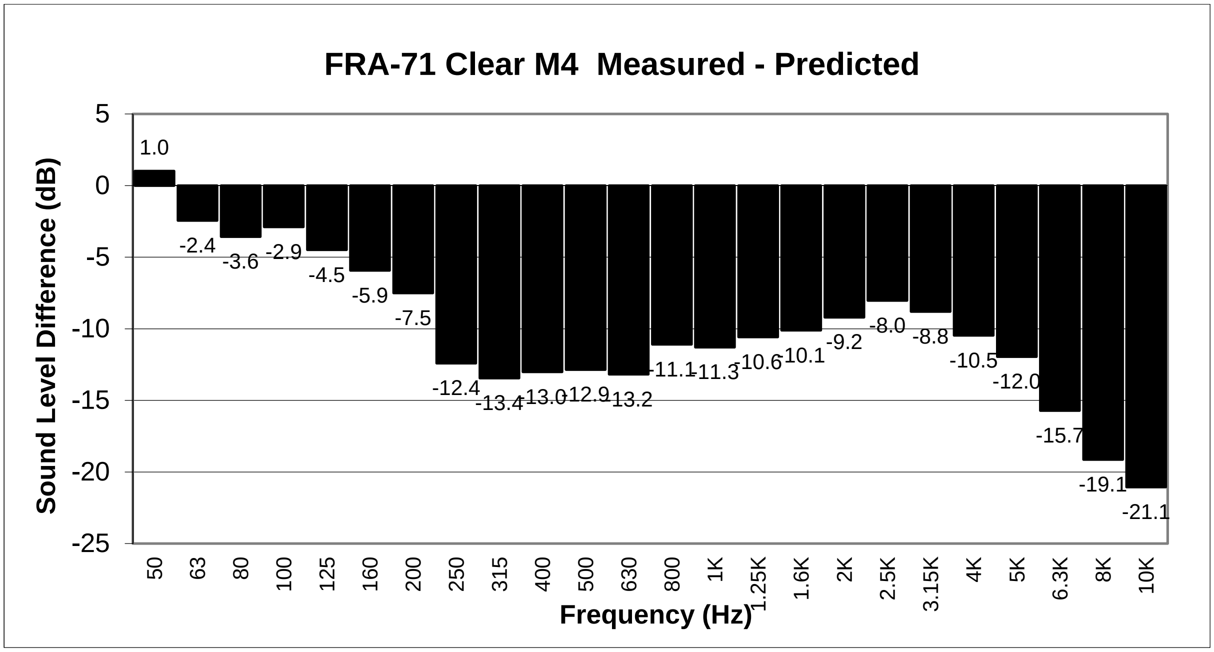

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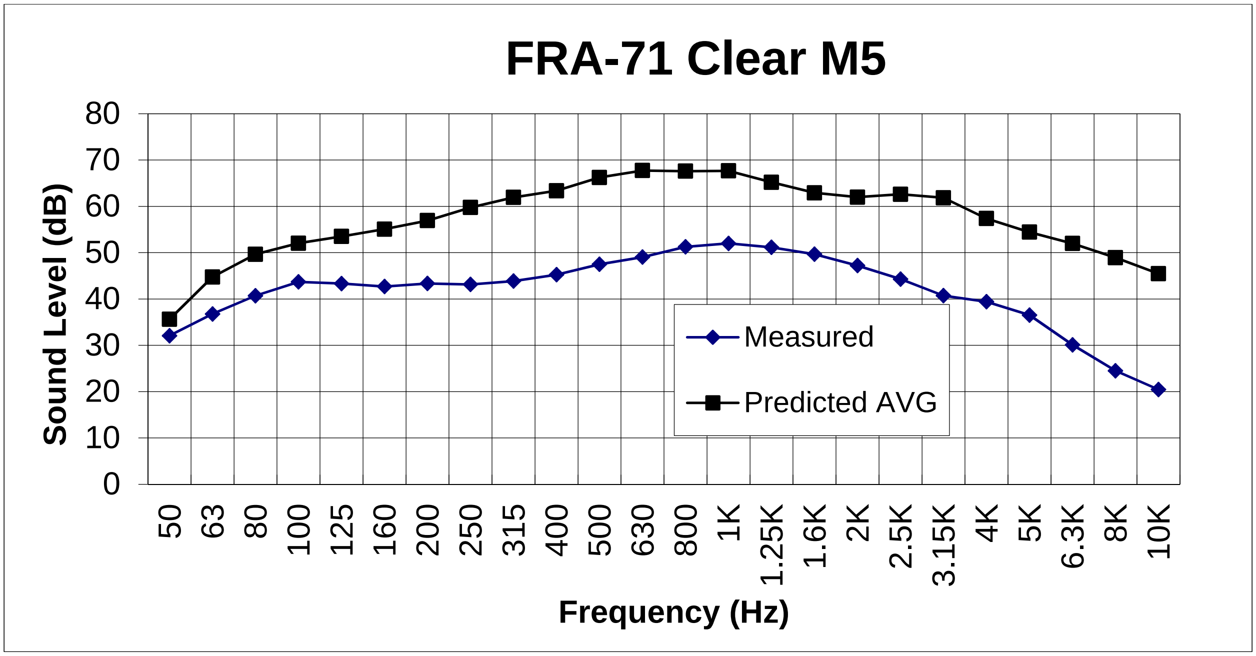

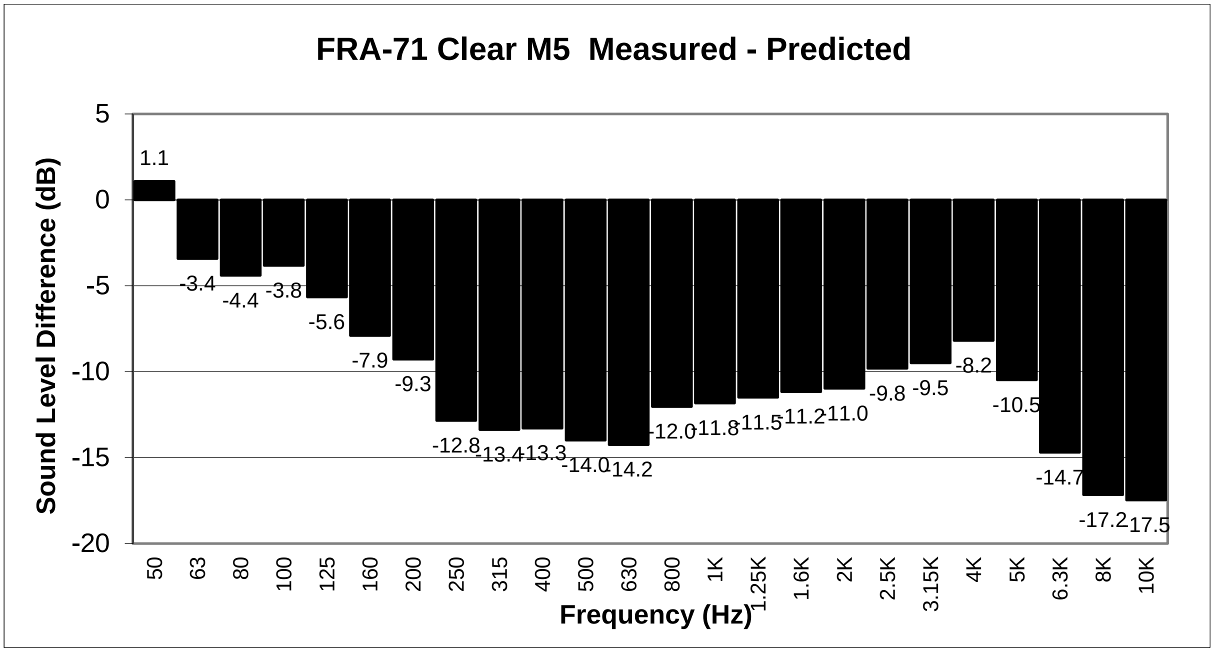

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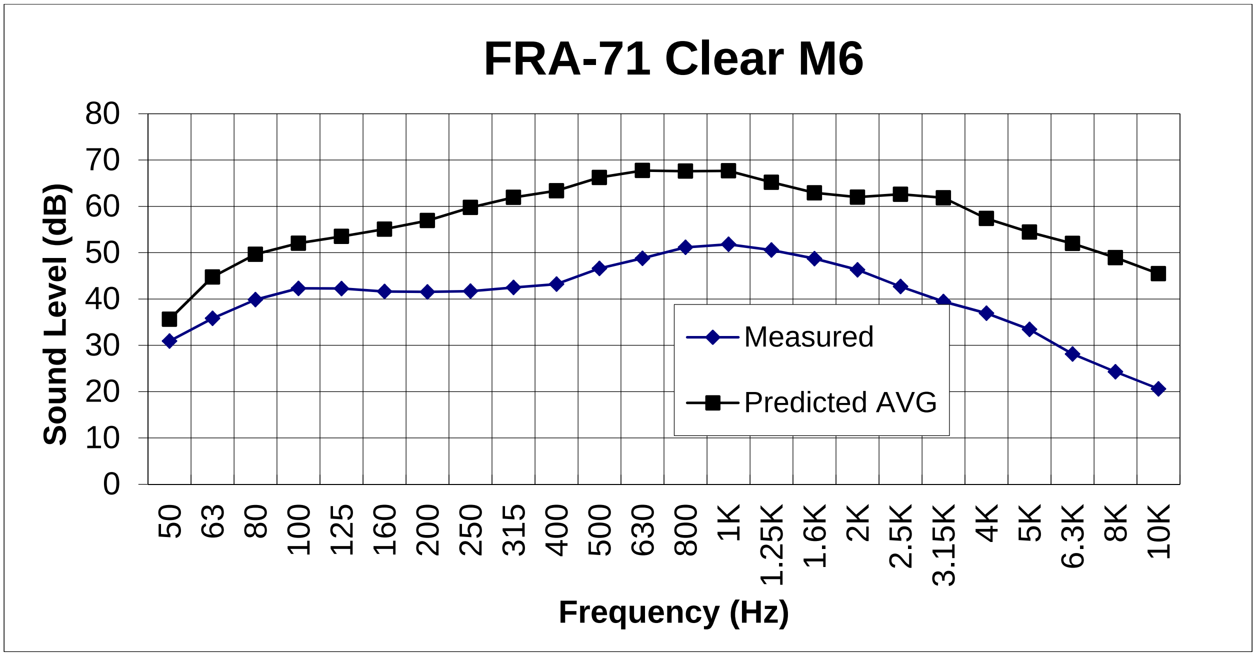

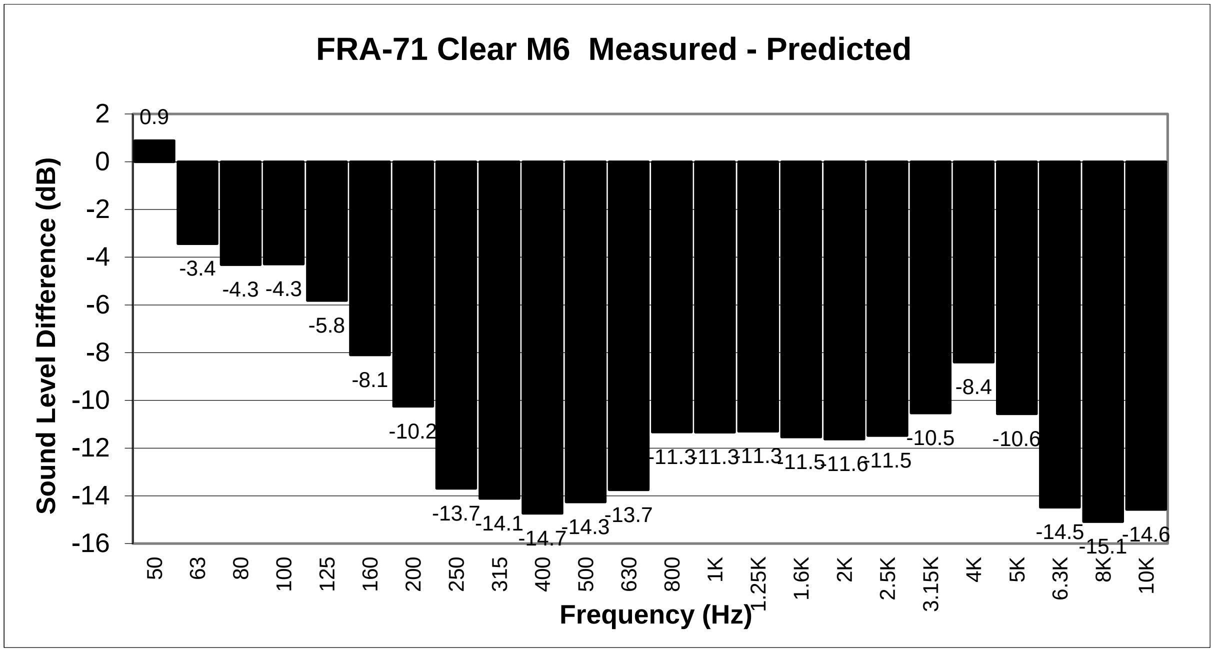

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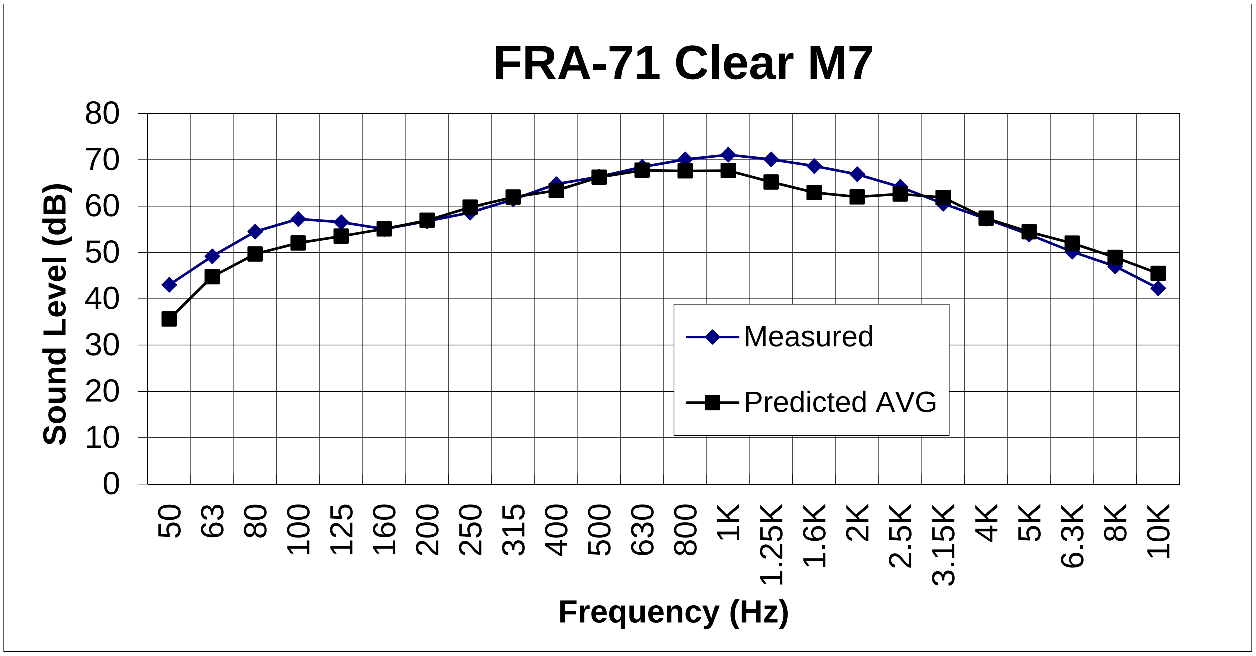

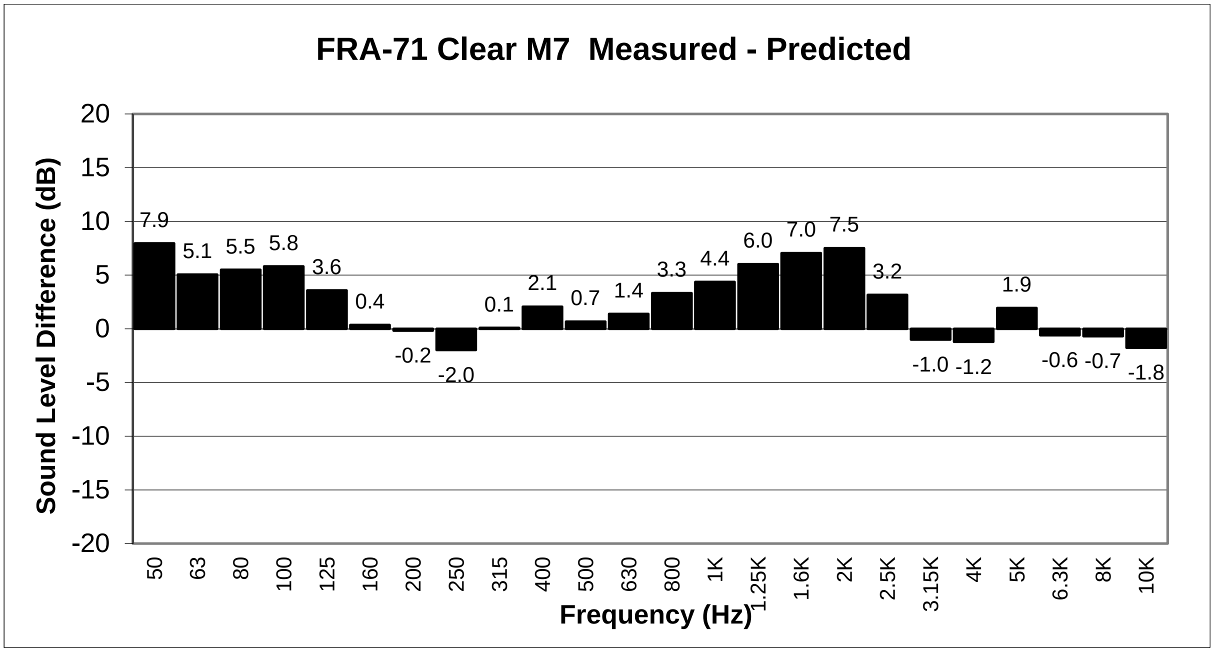

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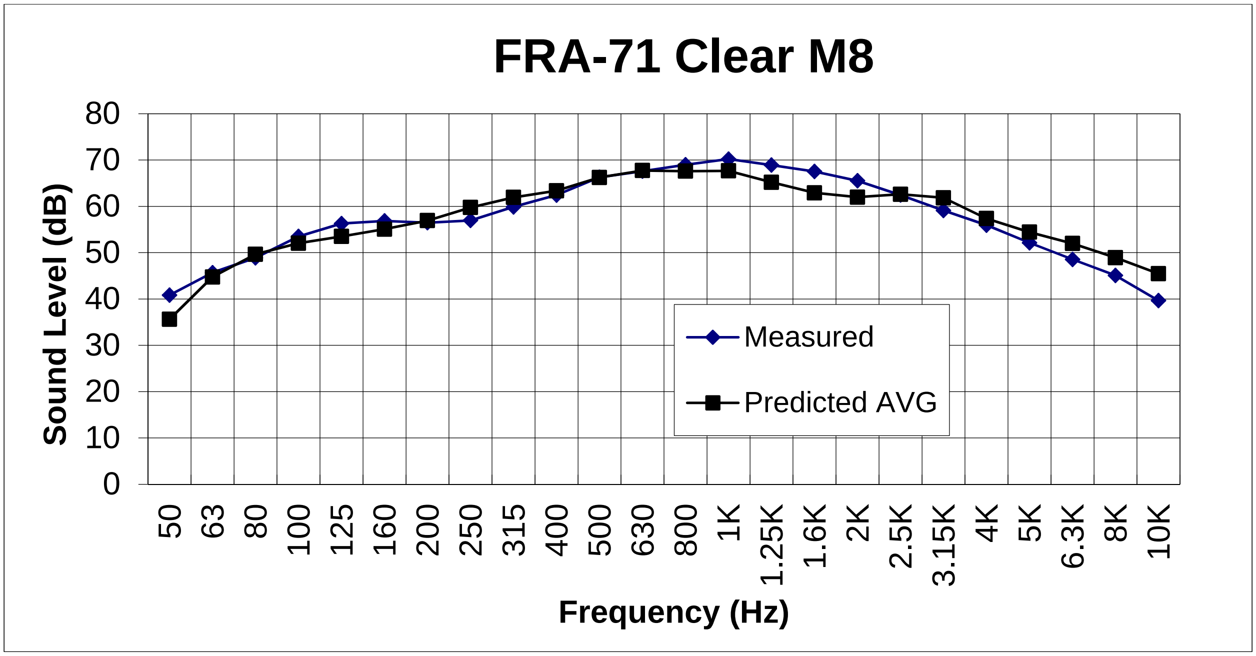

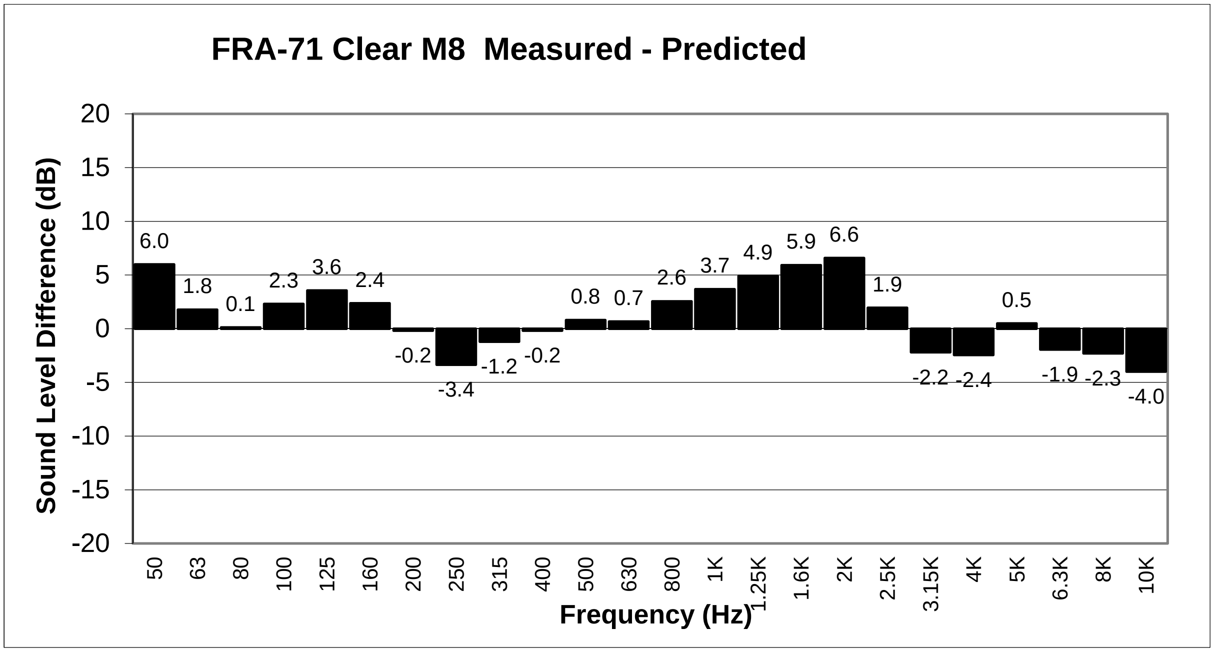

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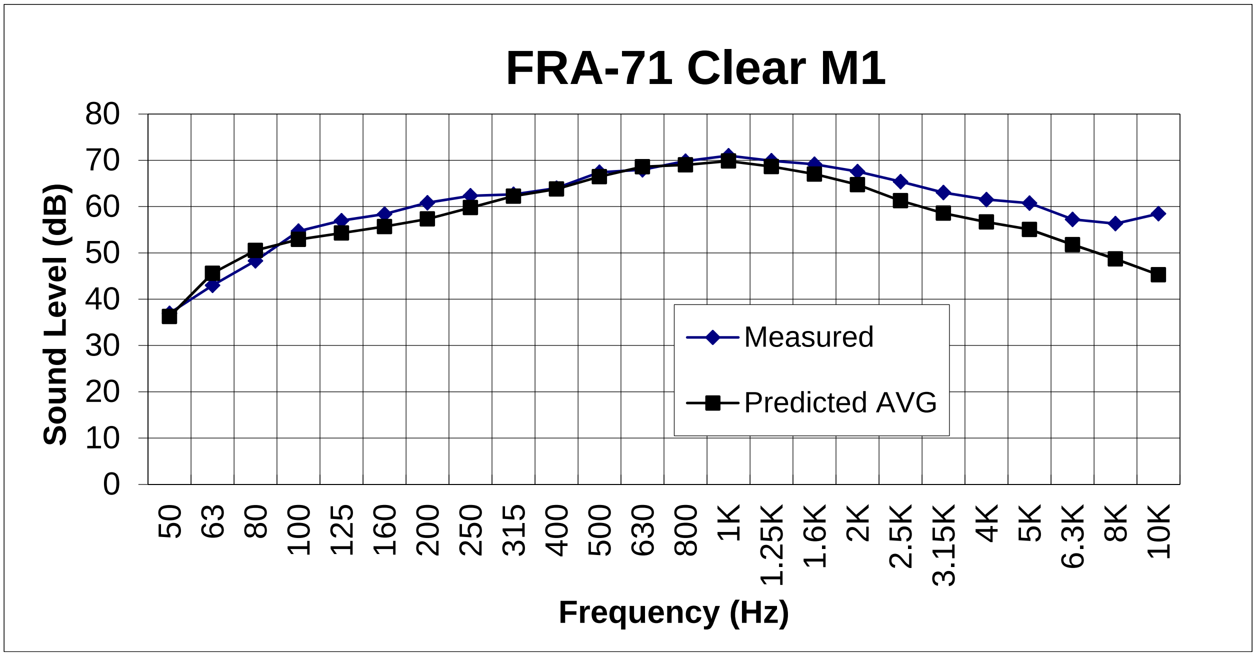

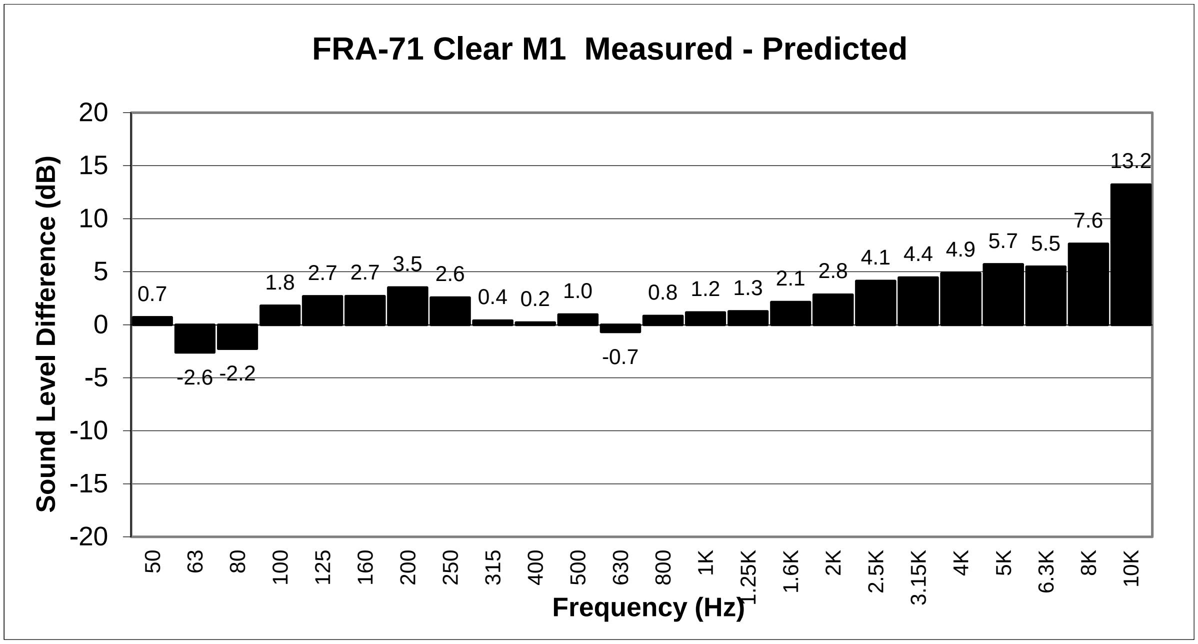

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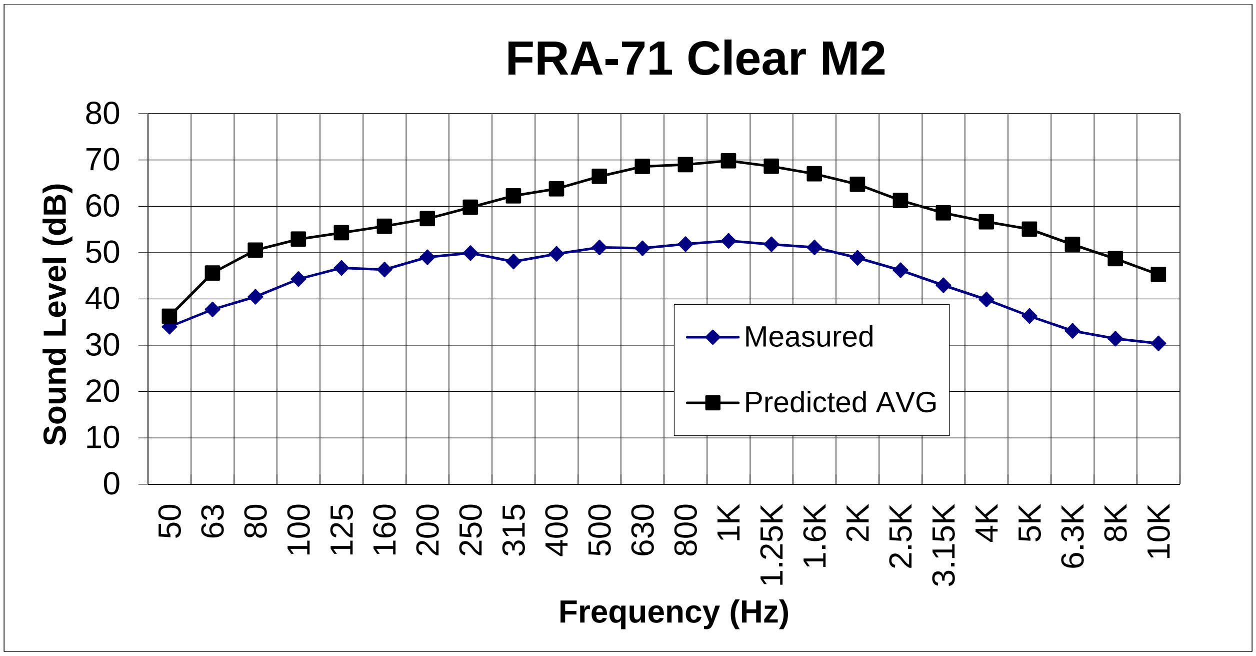

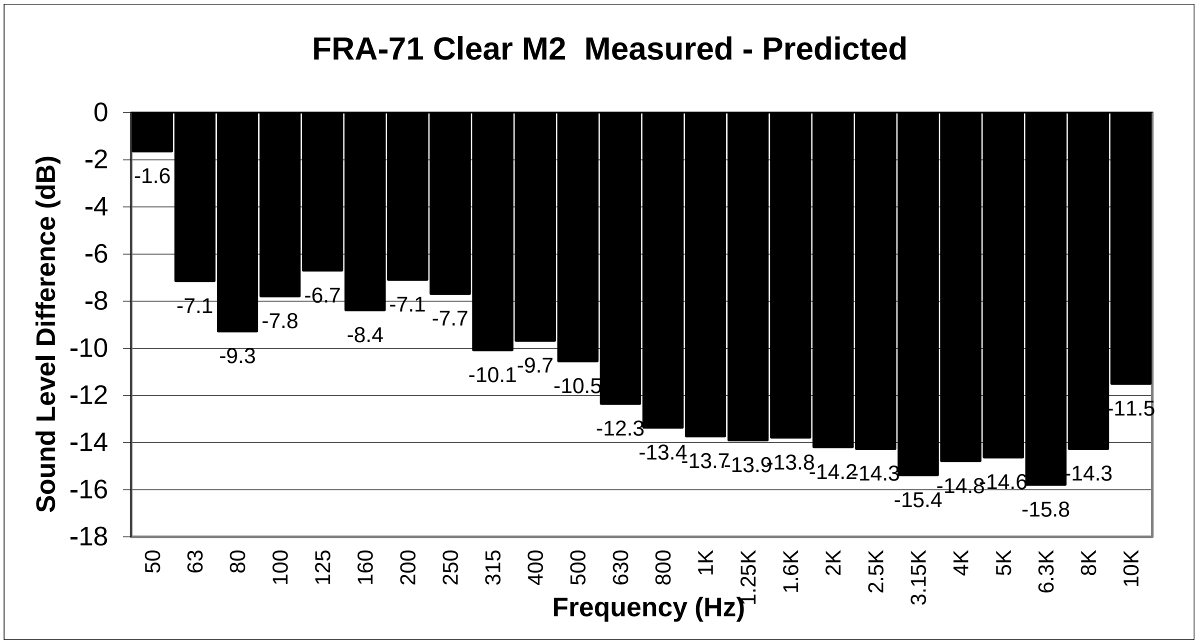

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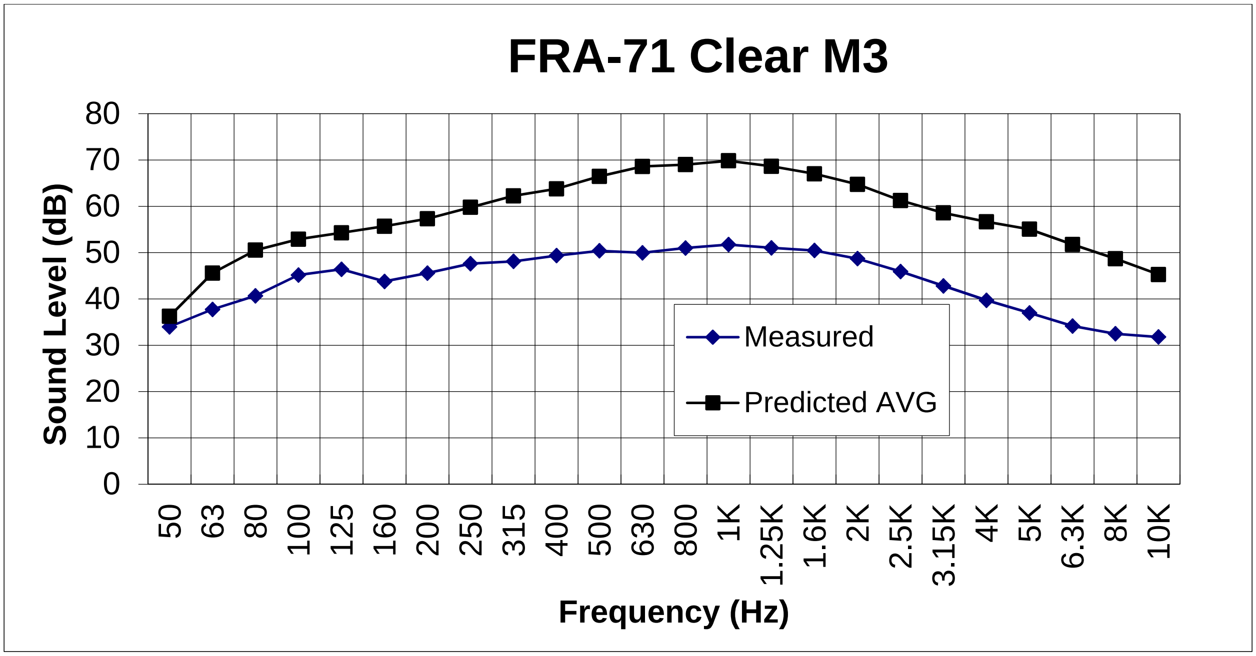

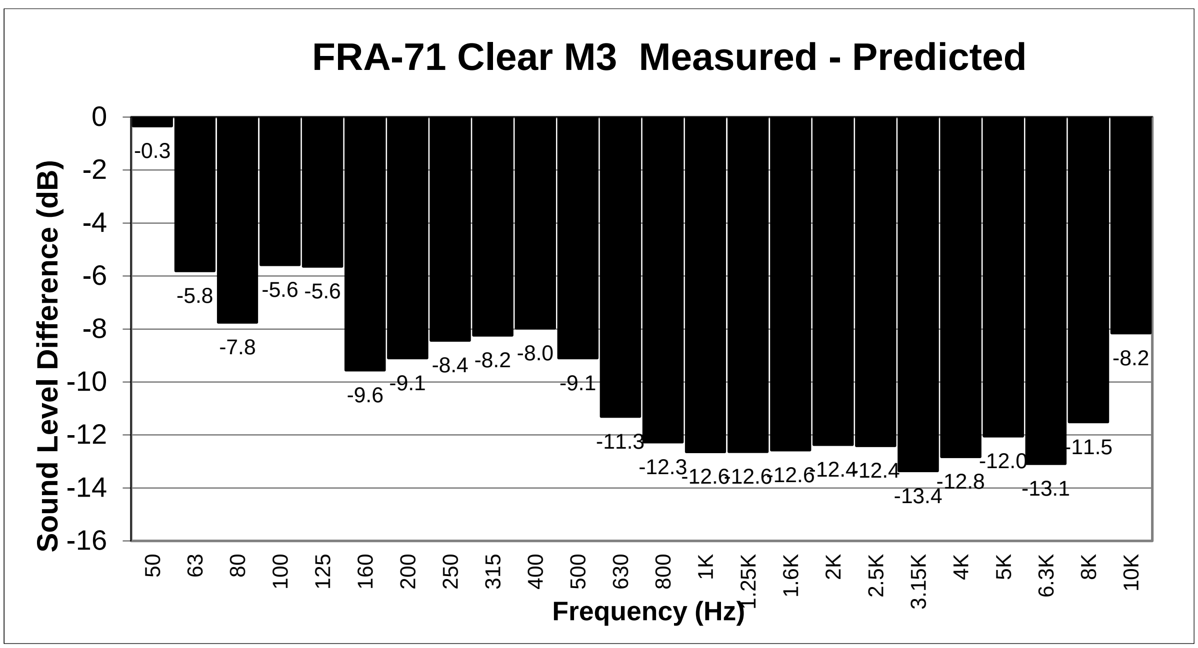

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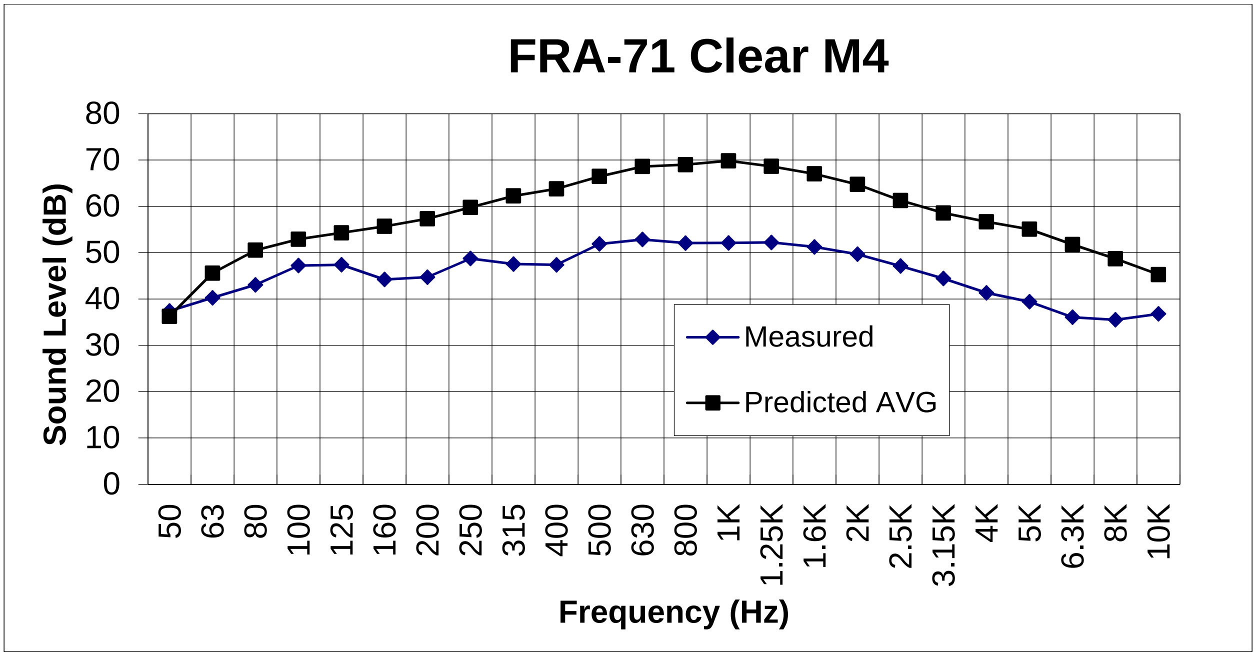

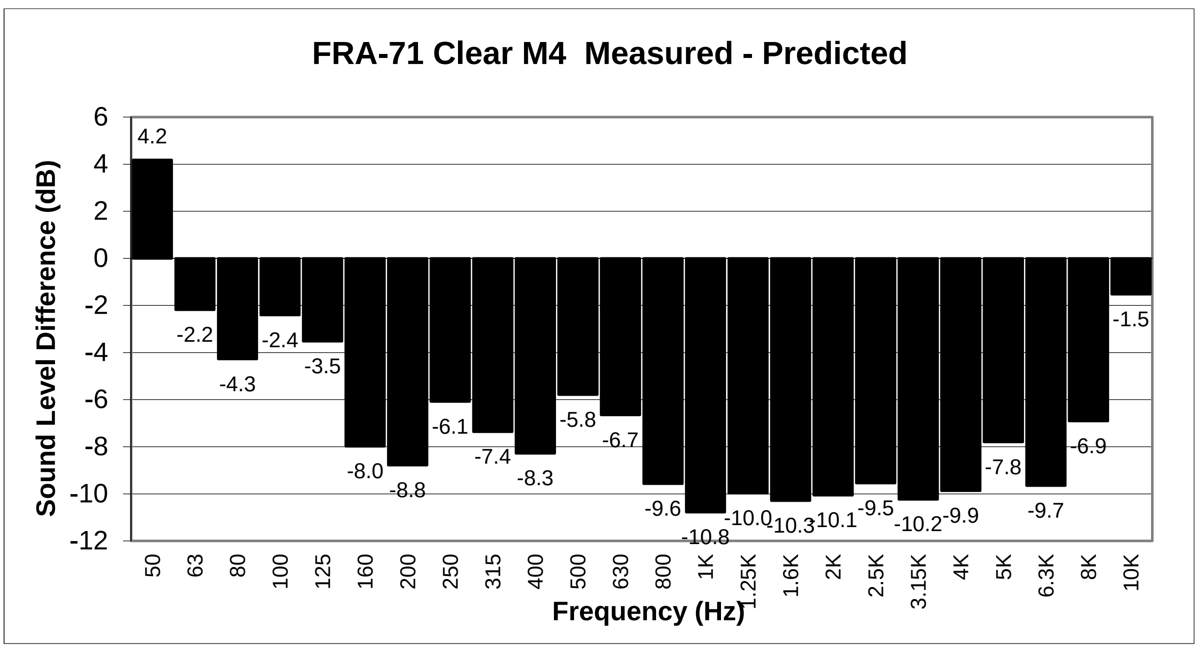

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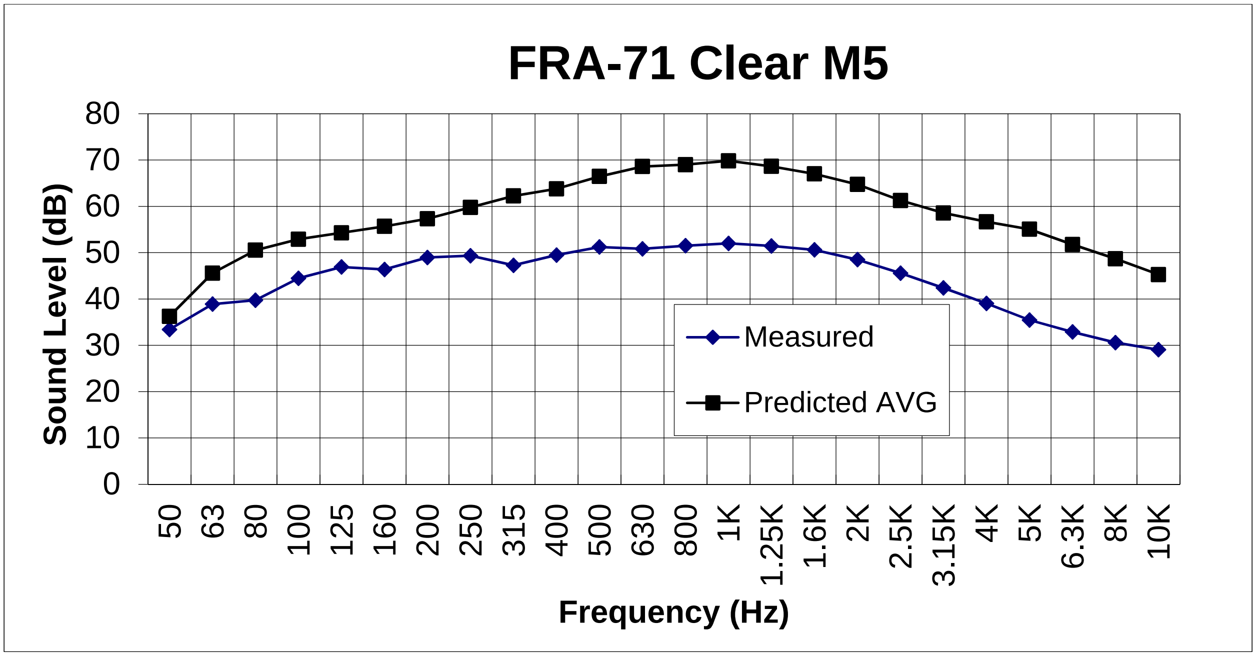

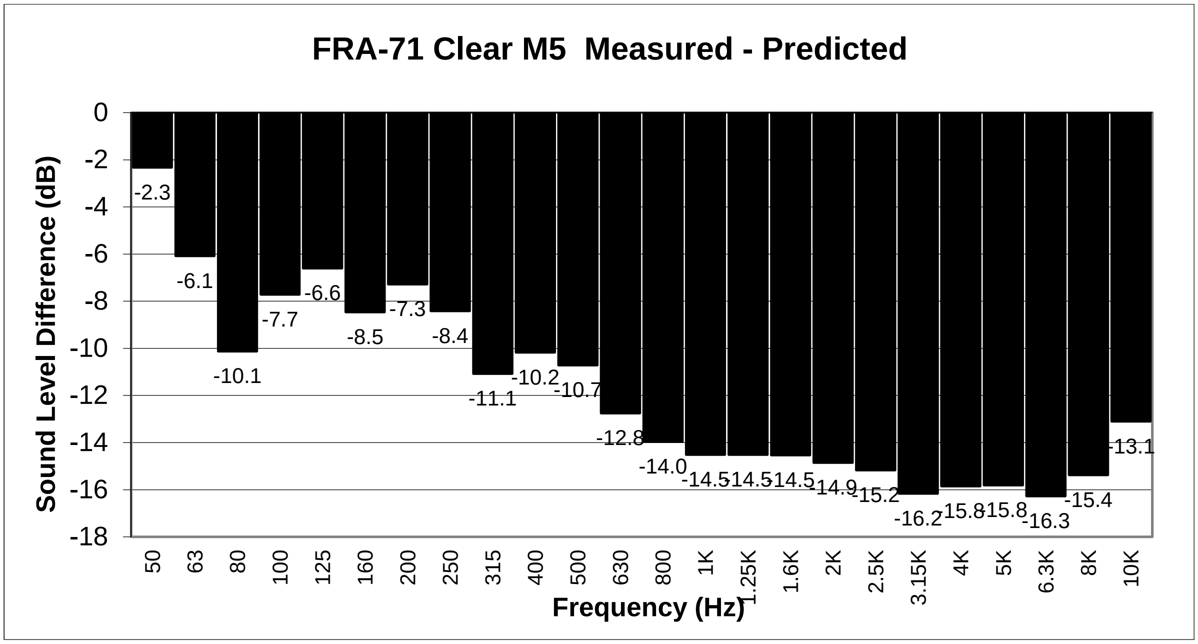

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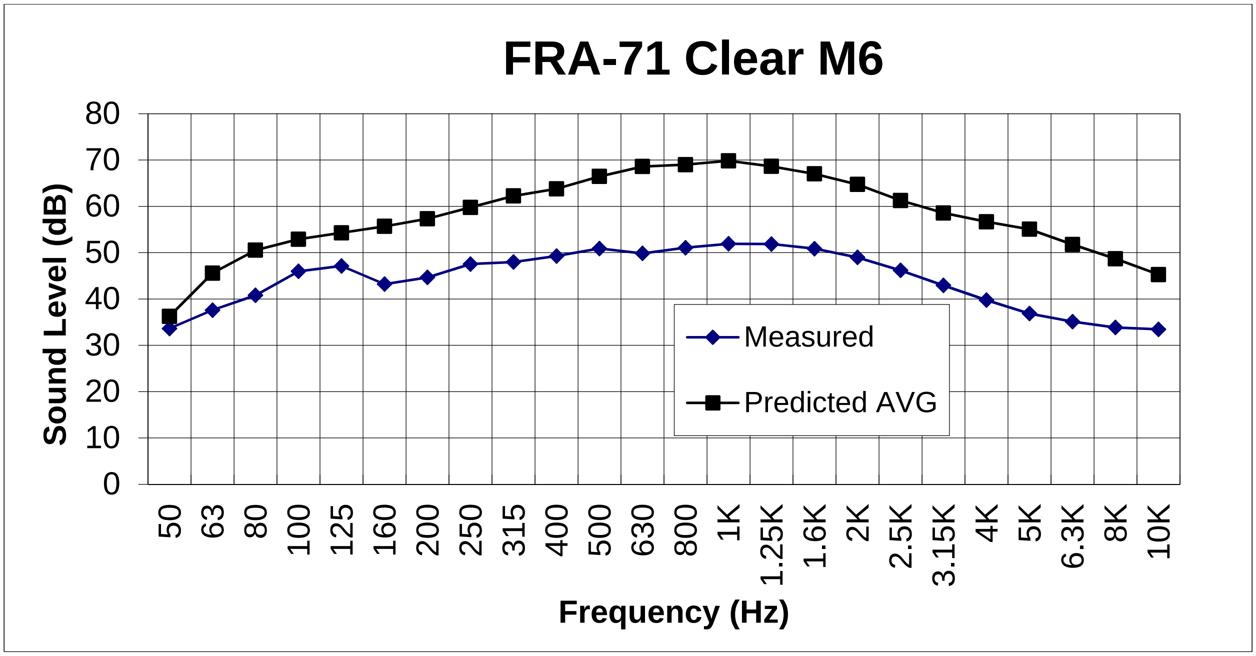

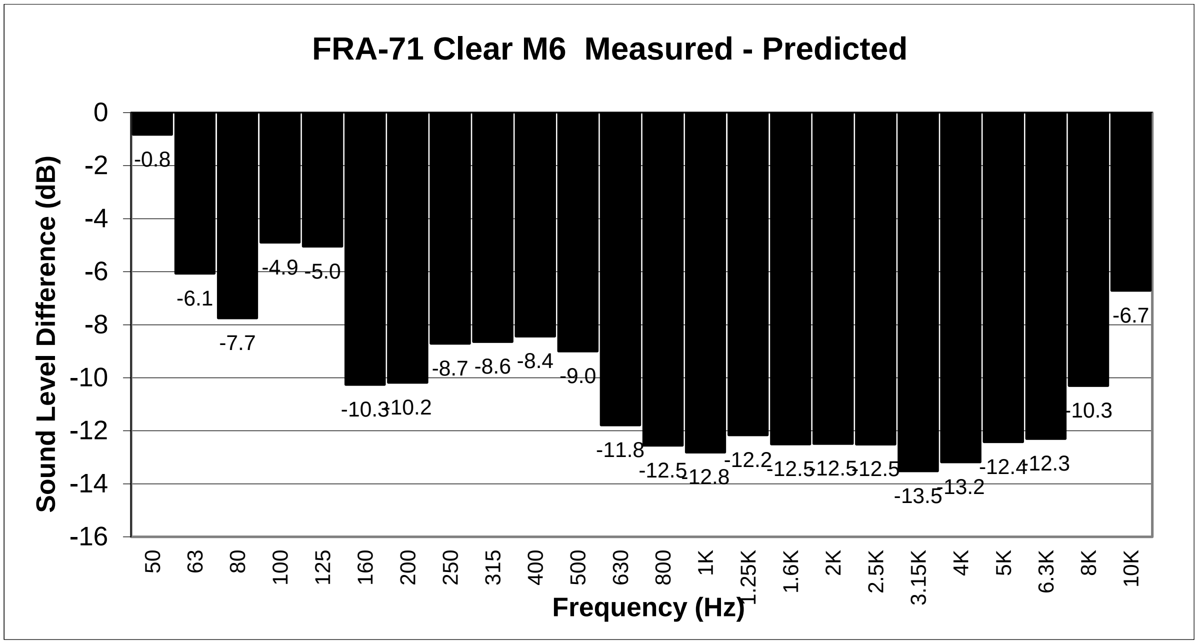

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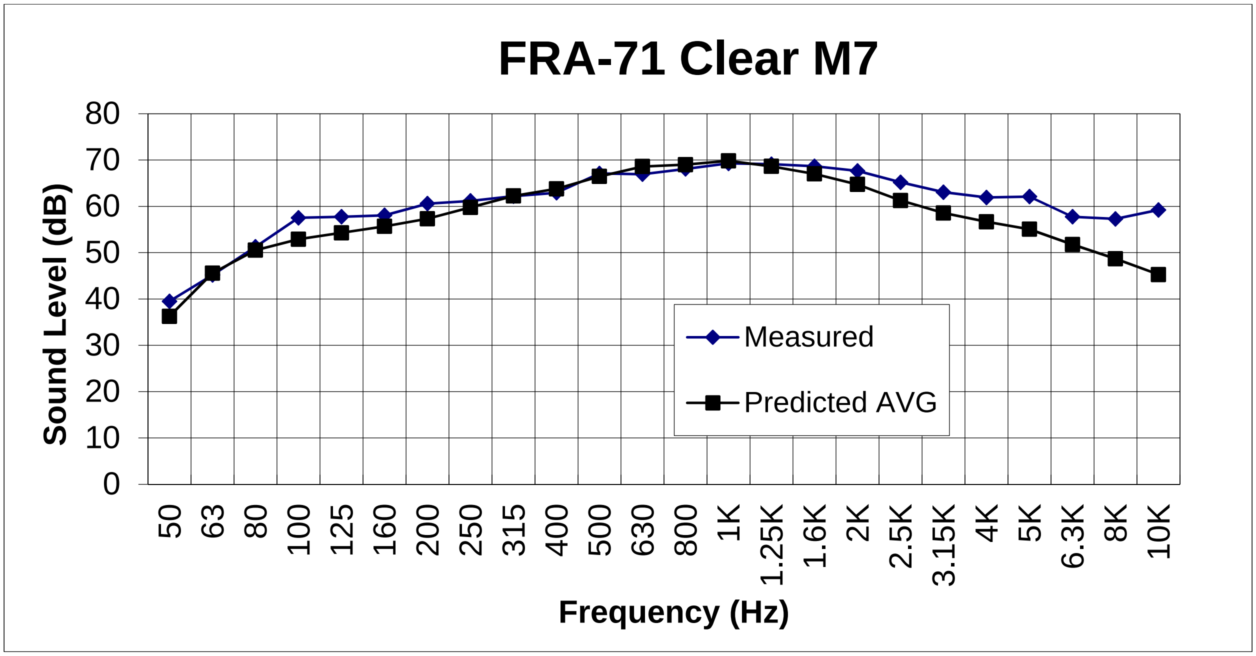

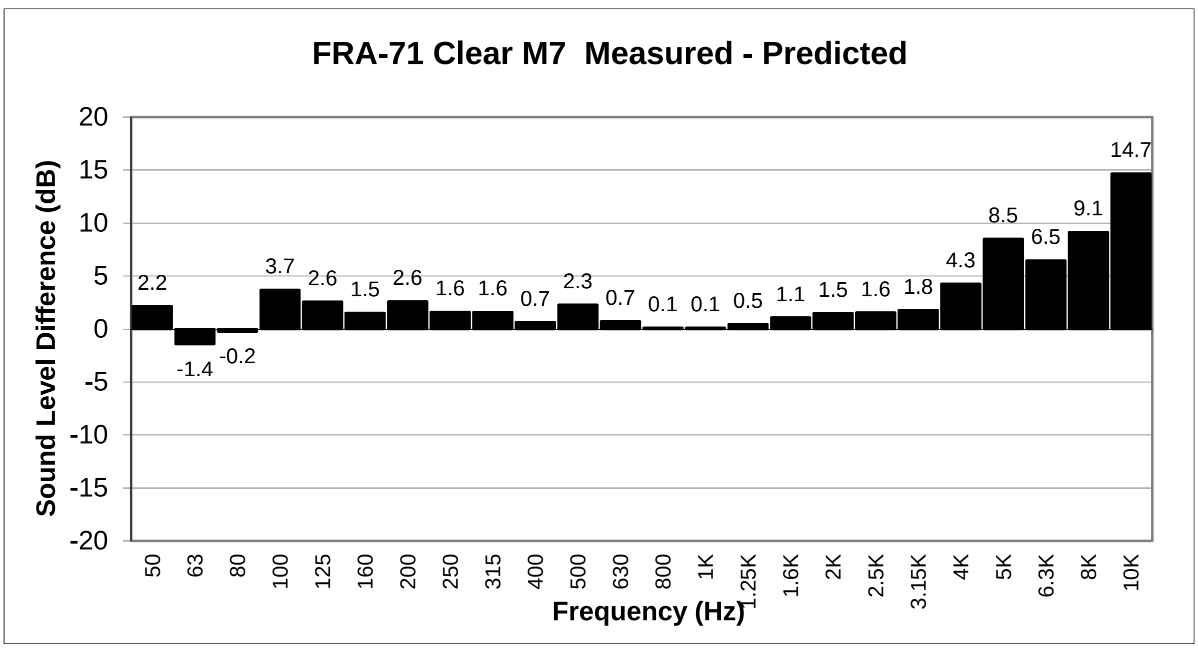

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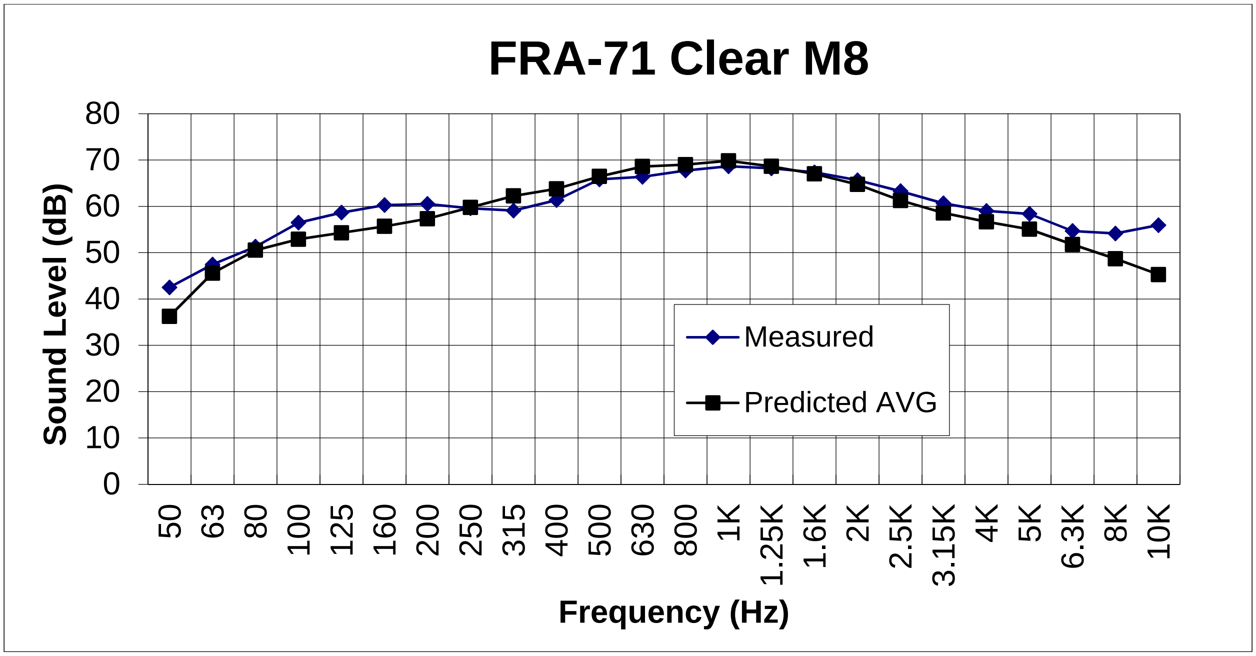
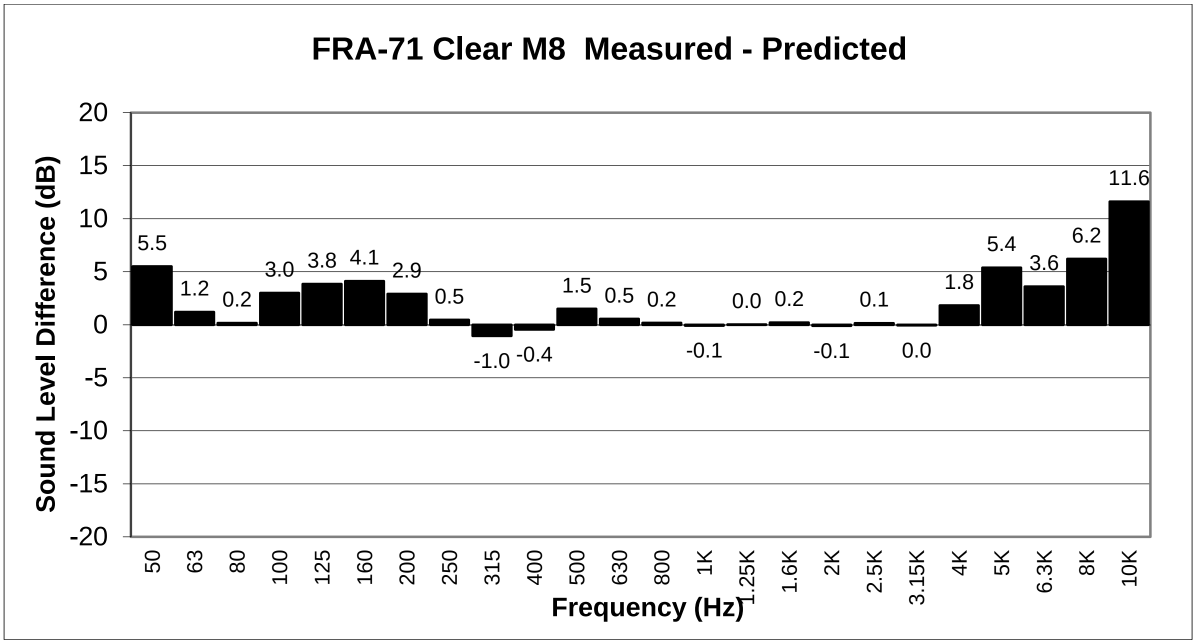
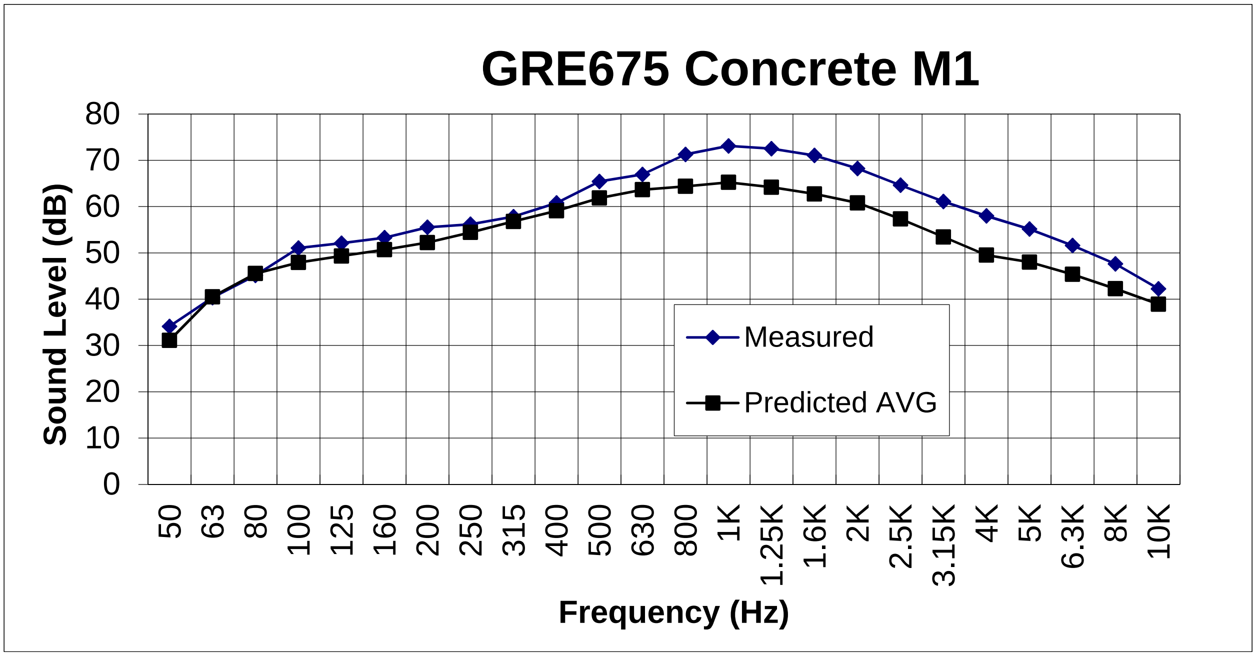
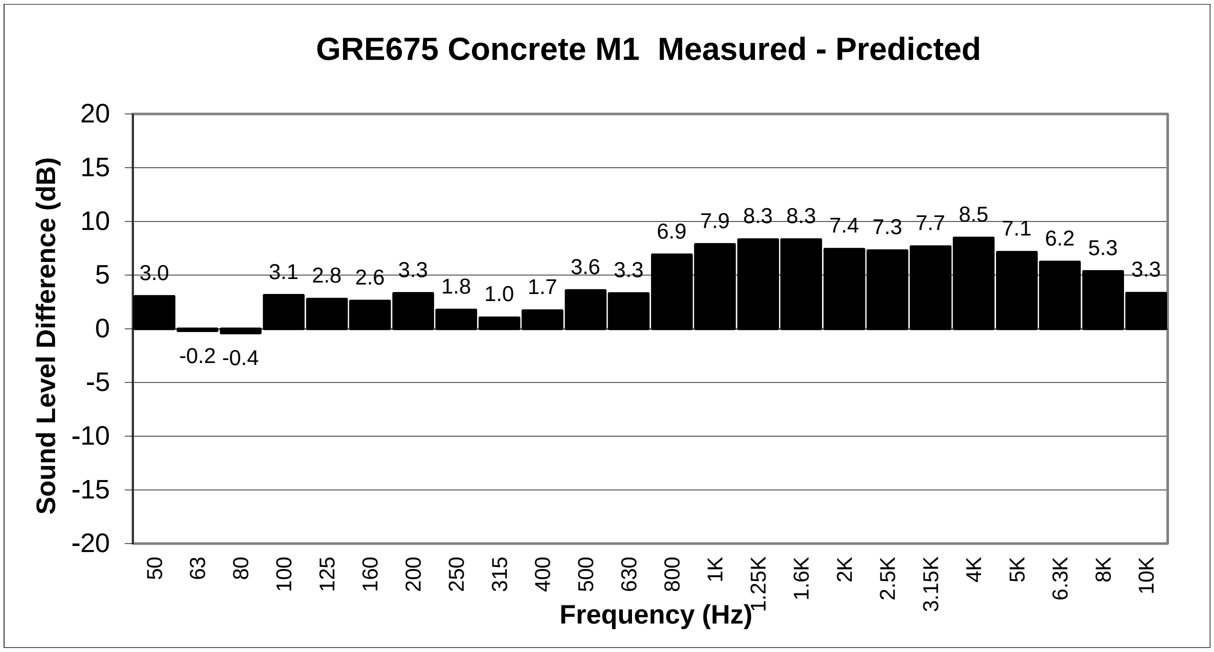




Site 3: Greene County, I-675; Reflective Concrete Wall





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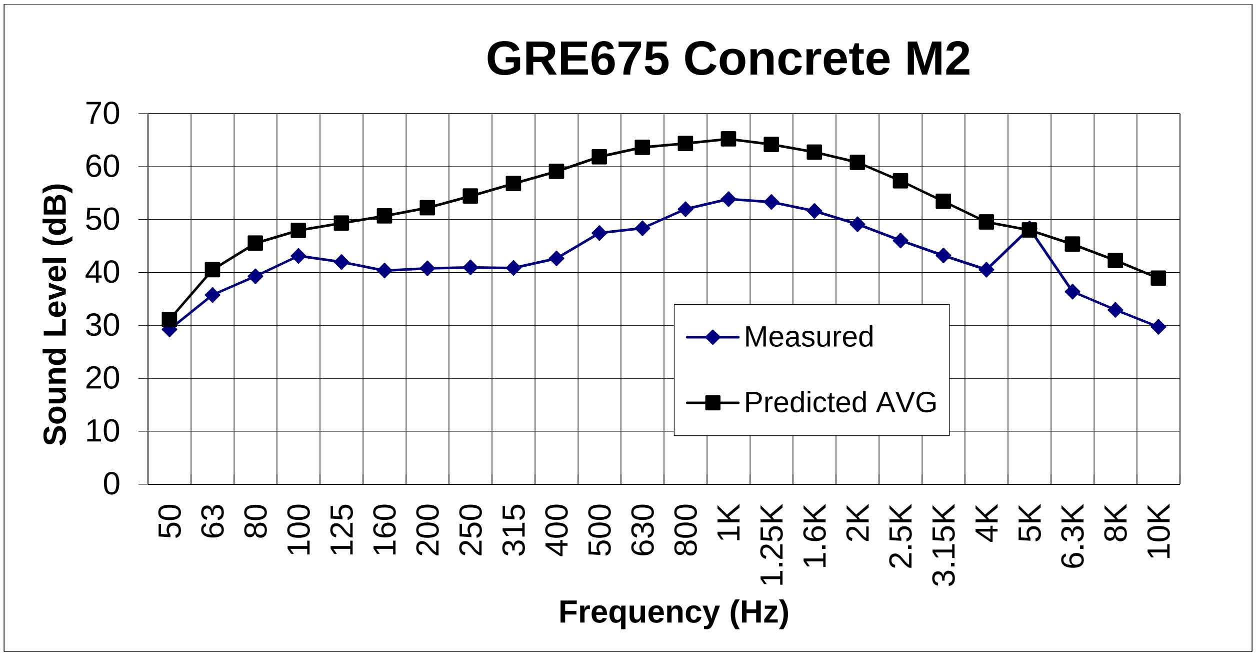

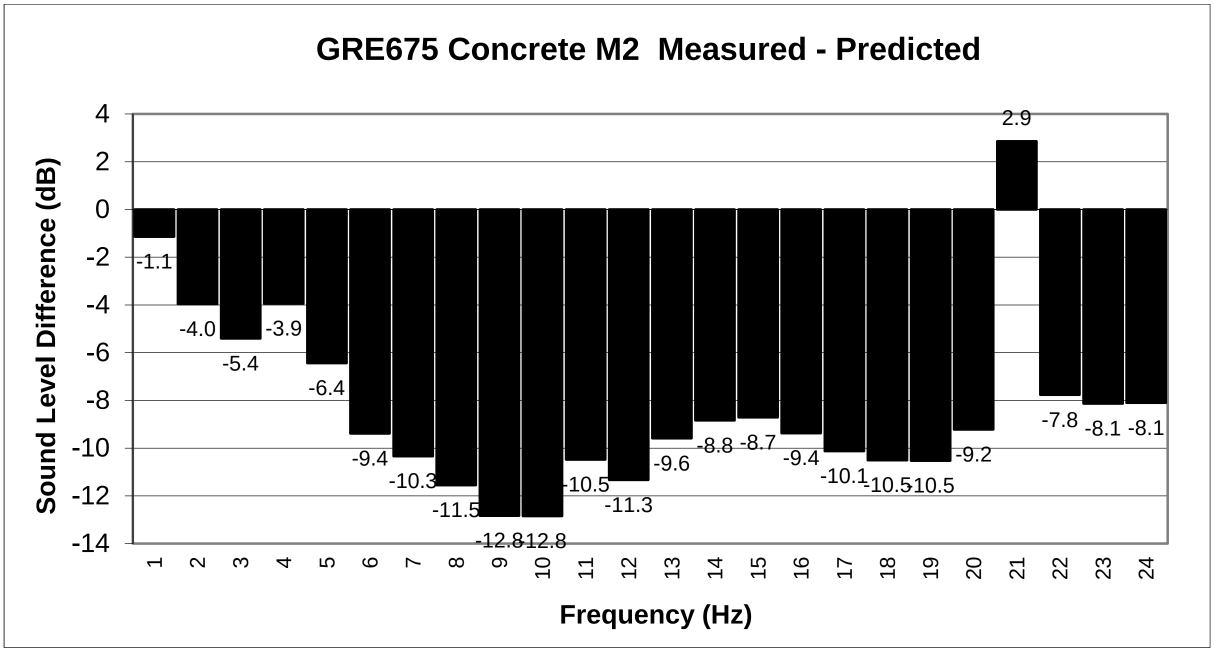

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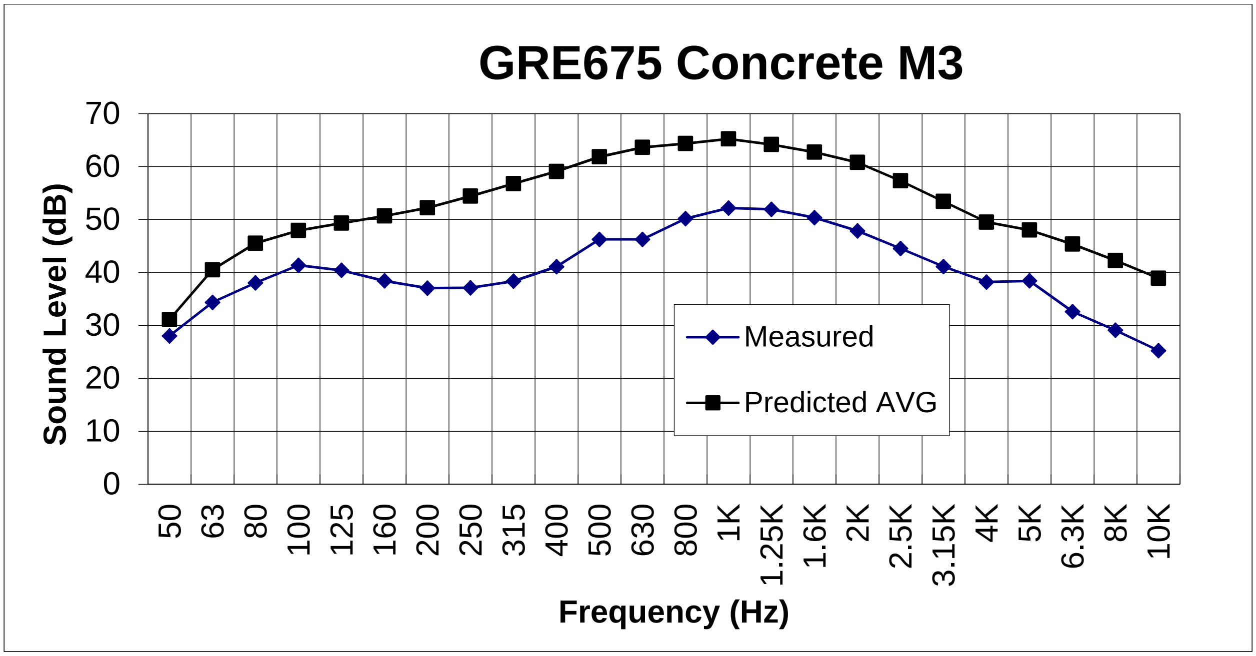

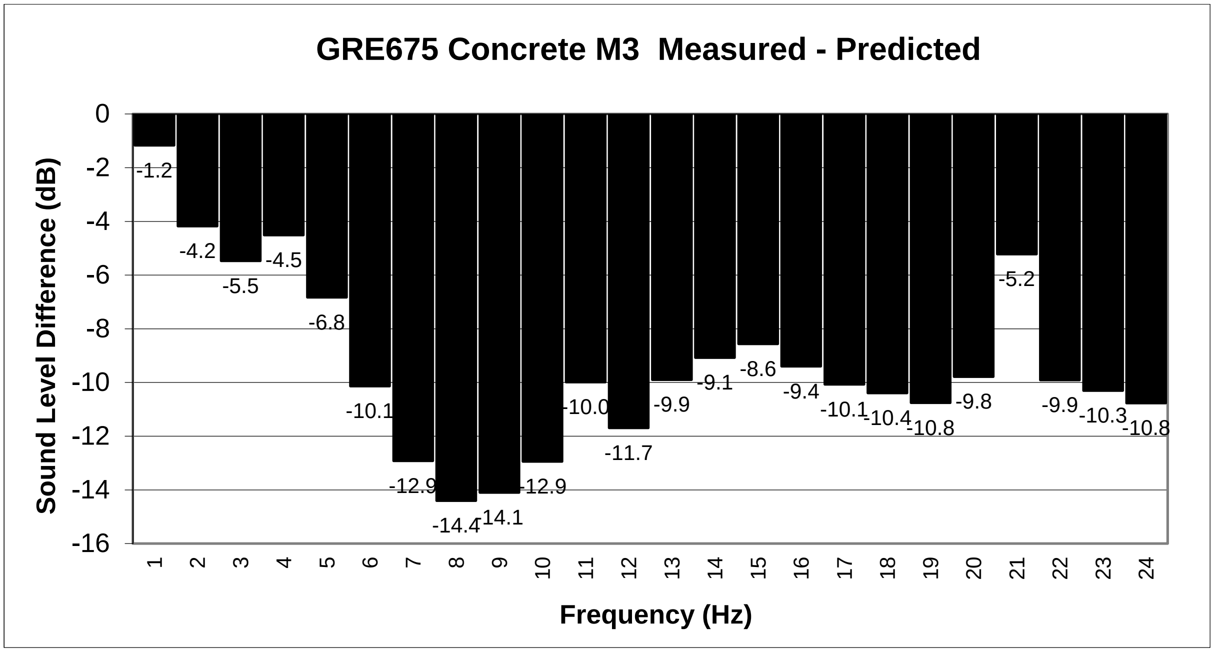

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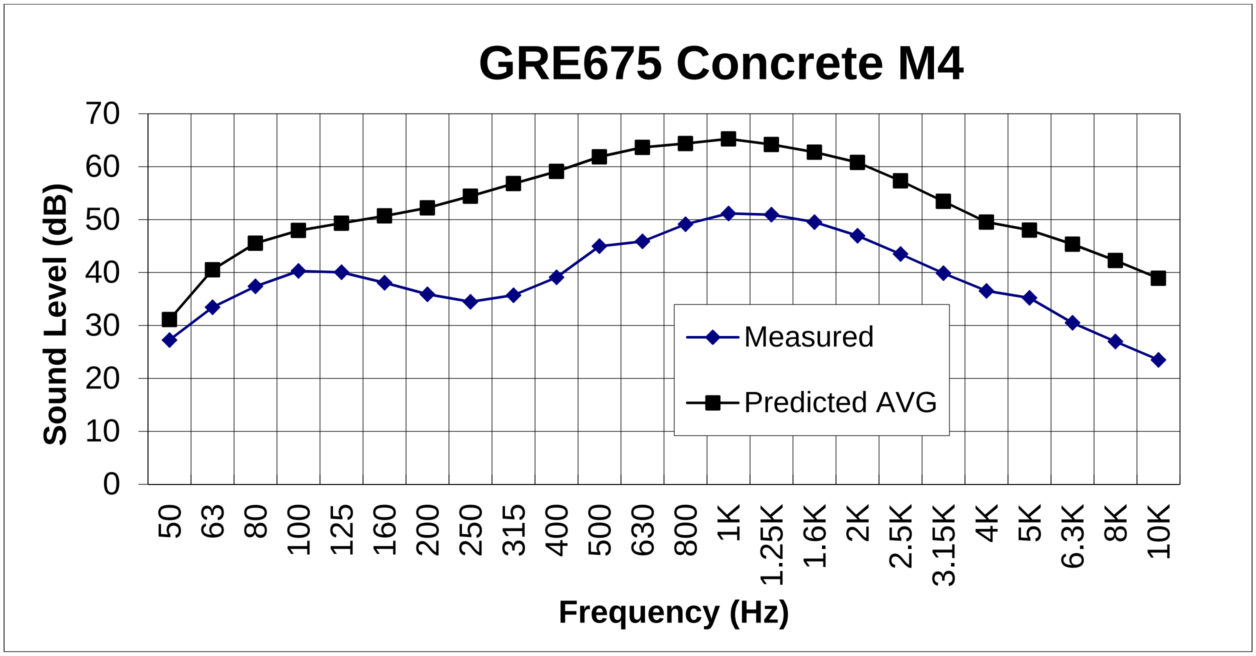
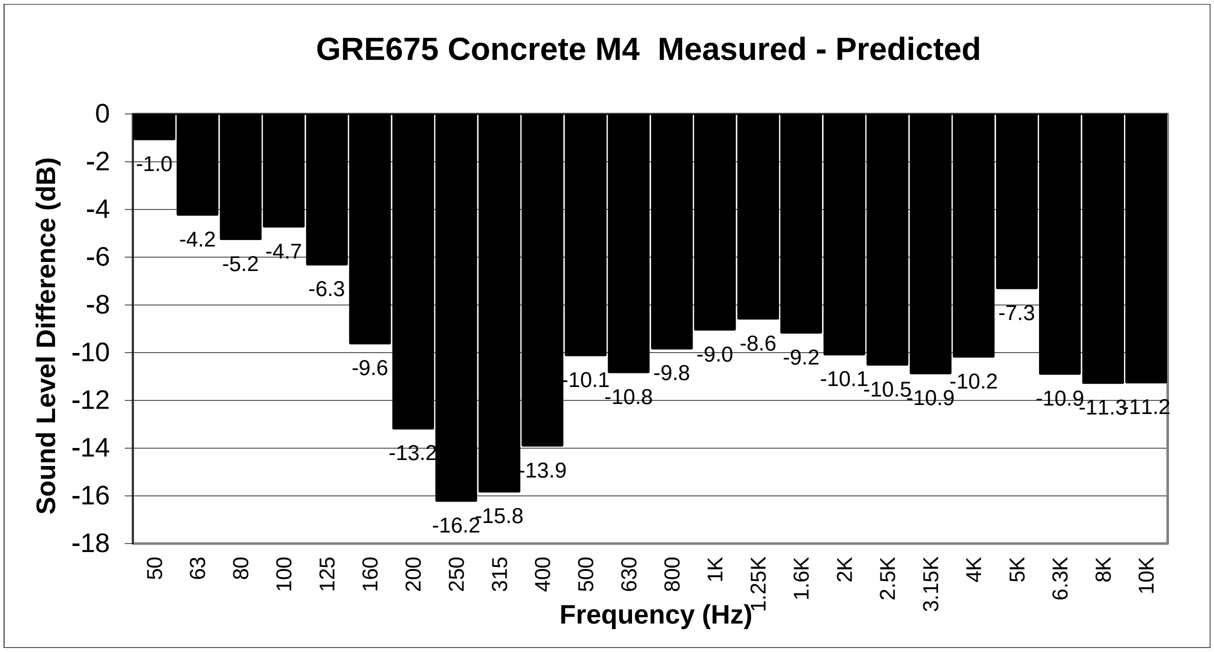
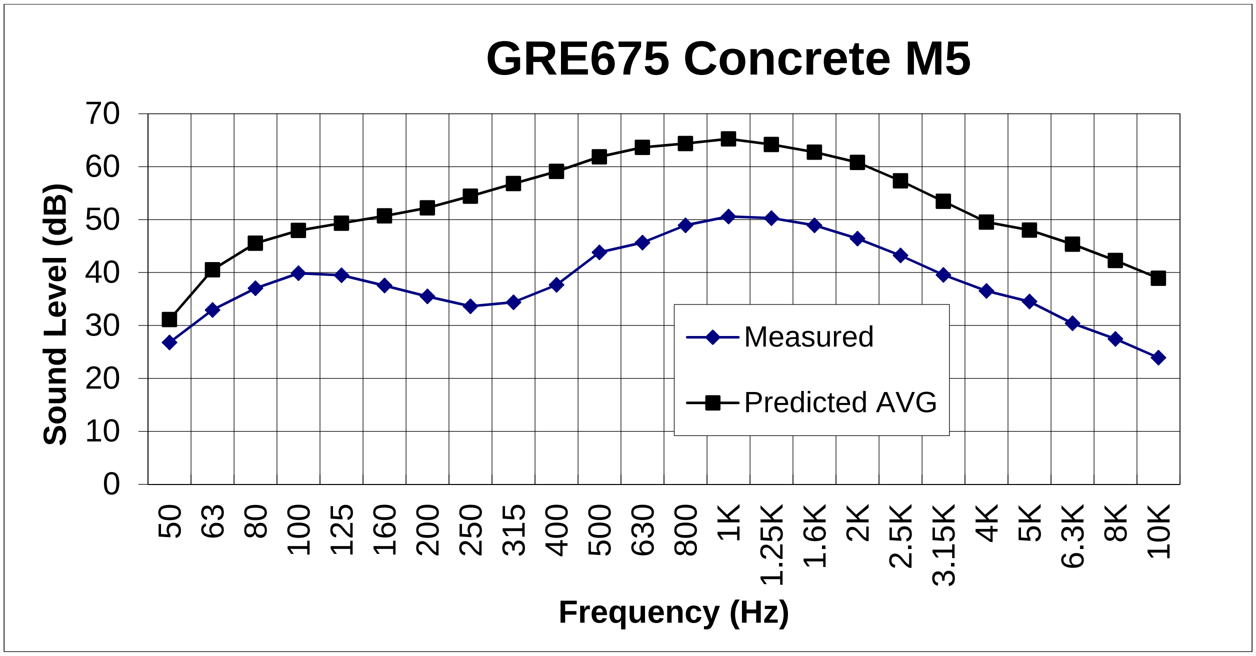
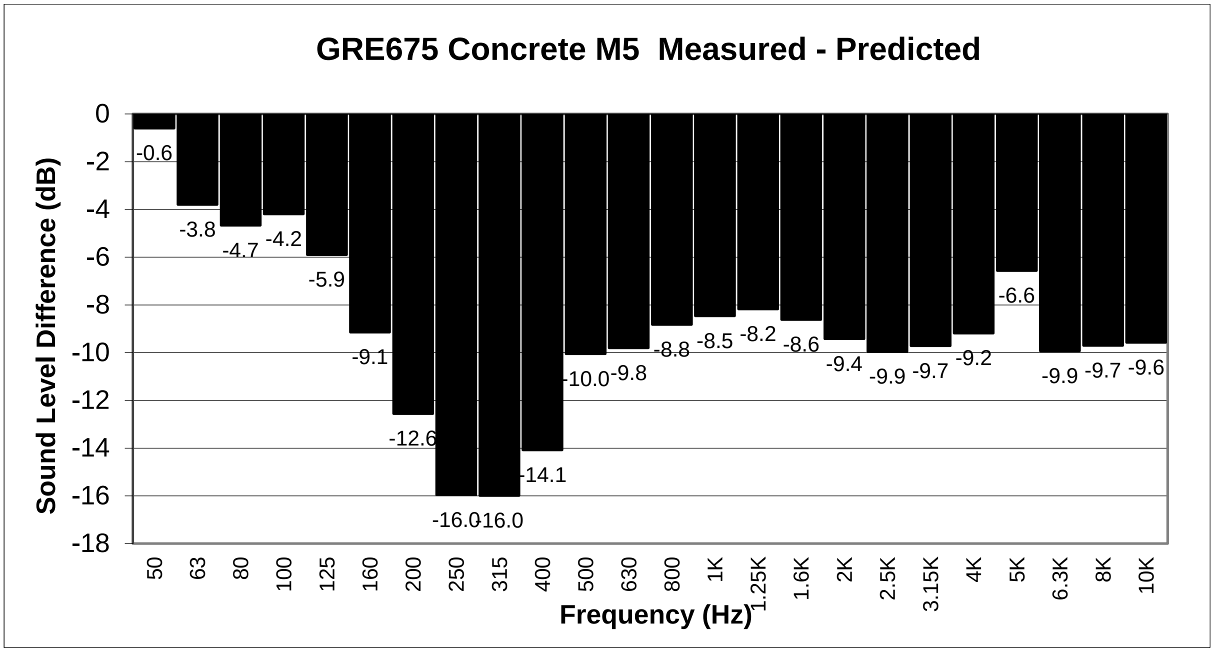


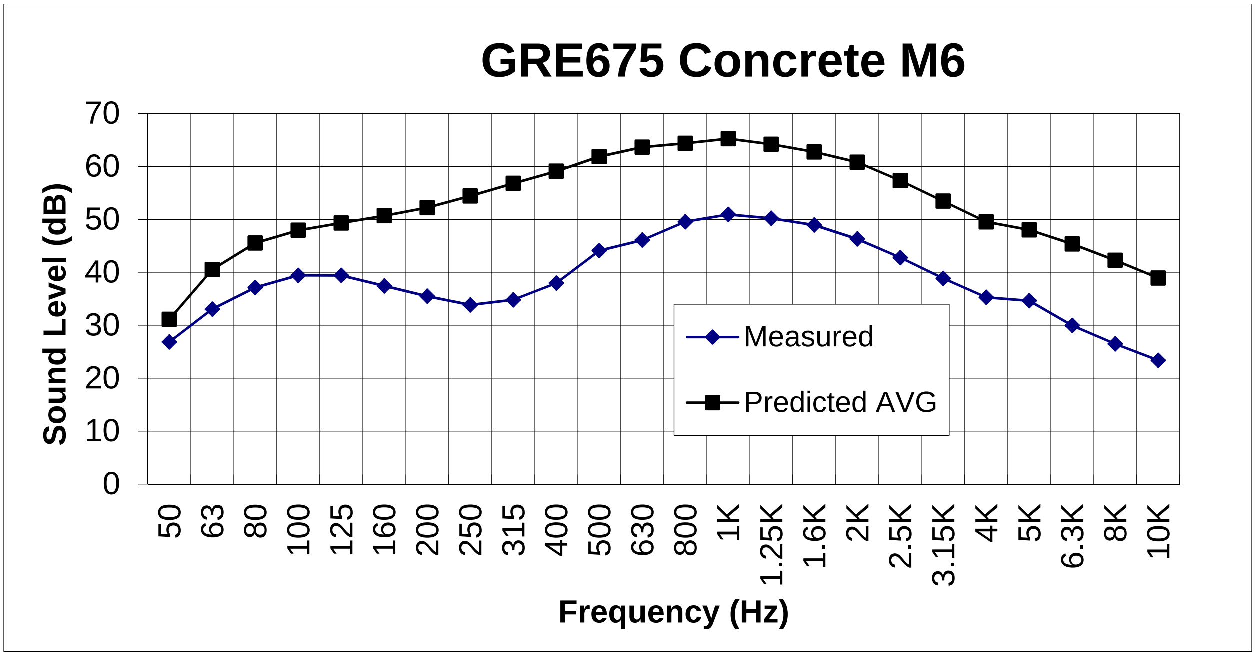


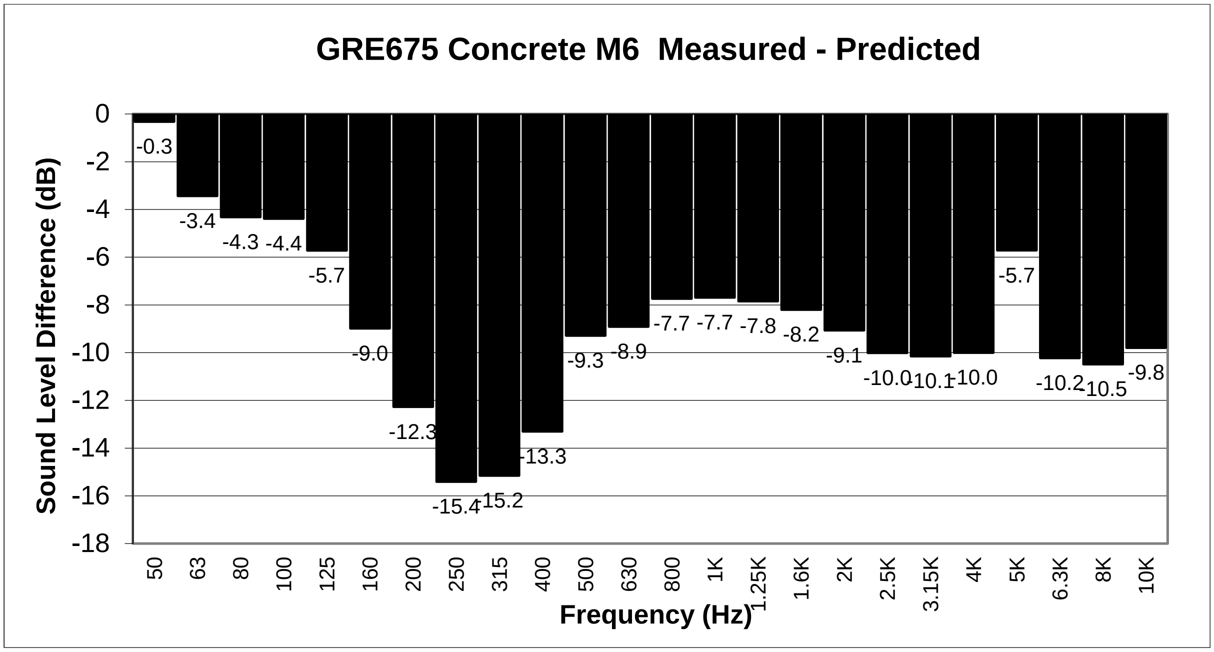
Site 3: Greene County, I-675; Reflective Concrete Wall



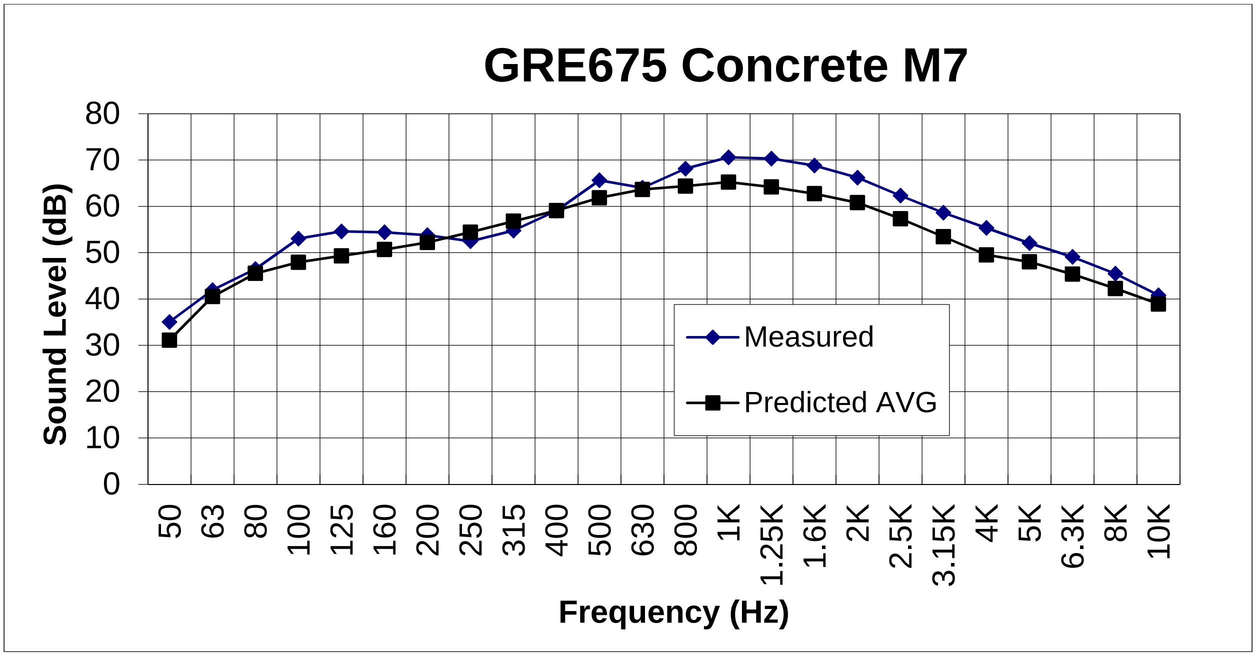


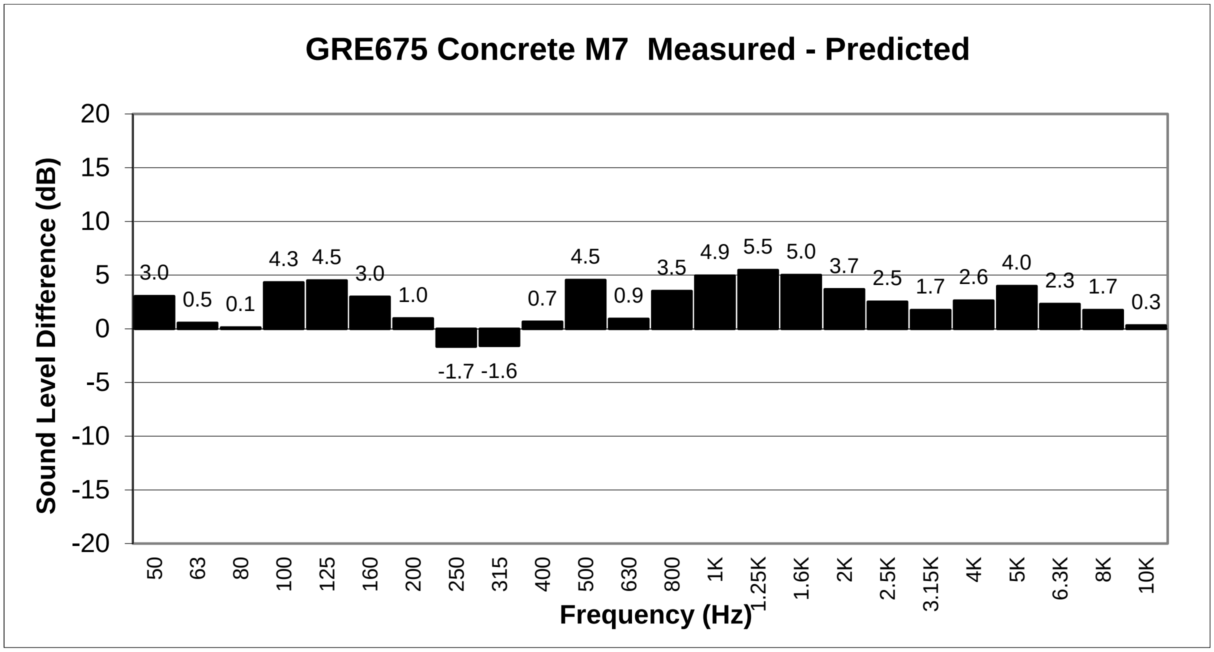
Site 3: Greene County, I-675; Reflective Concrete Wall



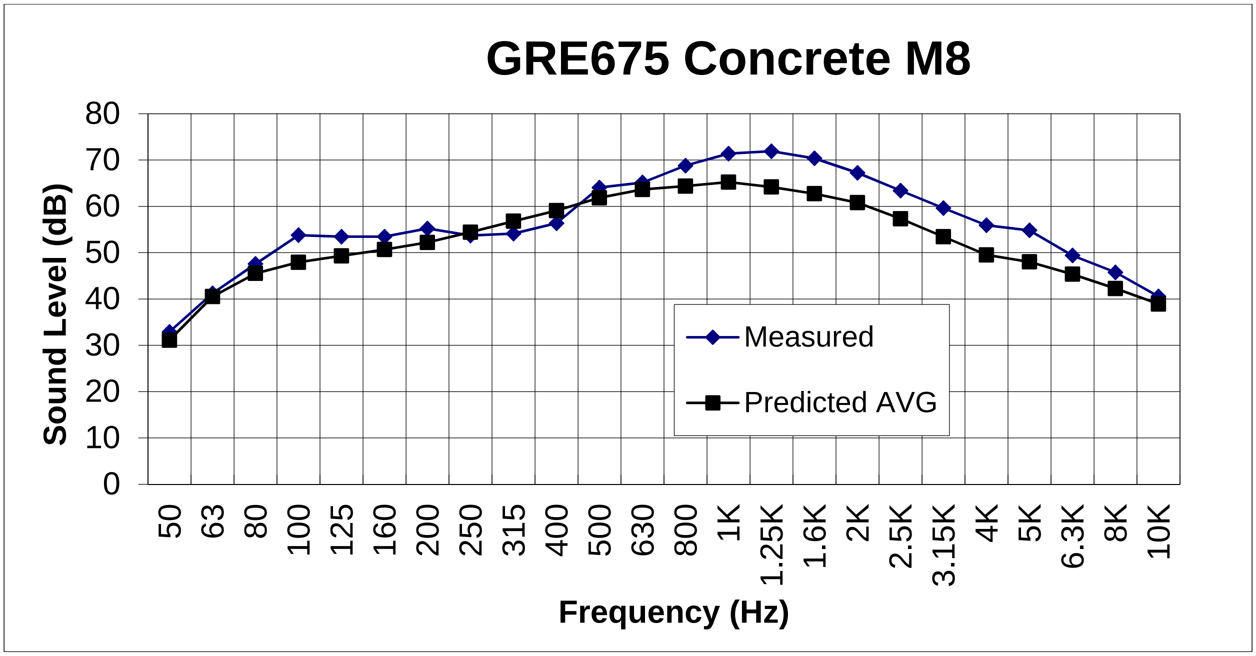


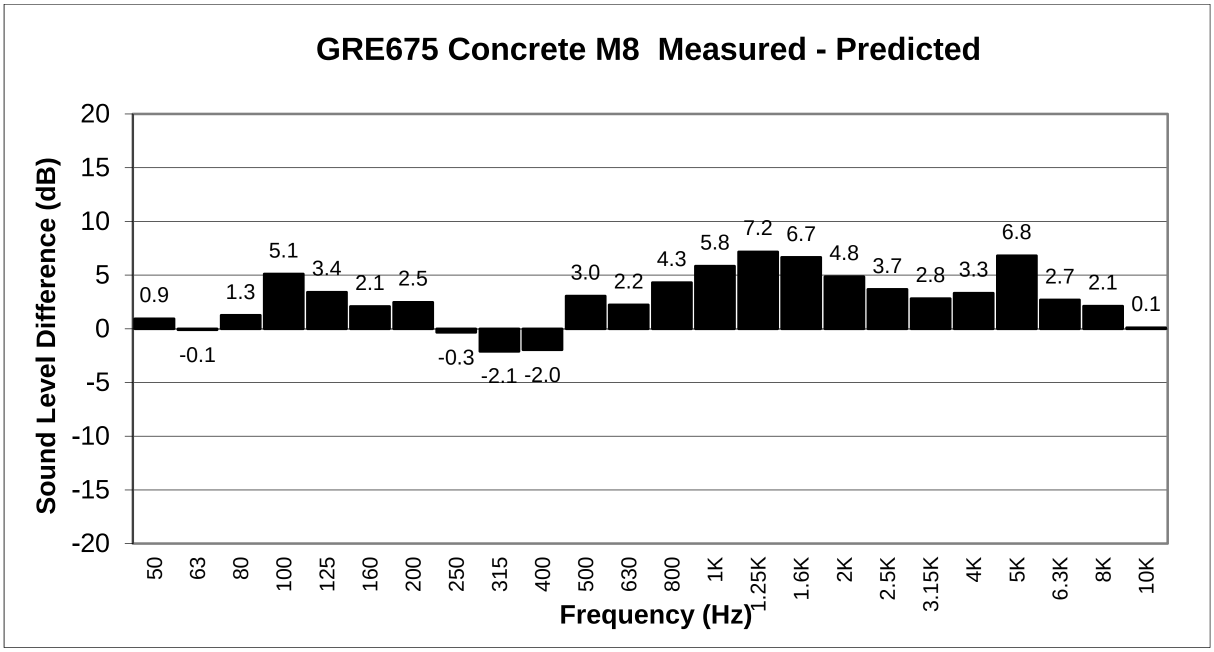
Site 3: Greene County, I-675; Reflective Concrete Wall





Site 3: Greene County, I-675; Reflective Concrete Wall





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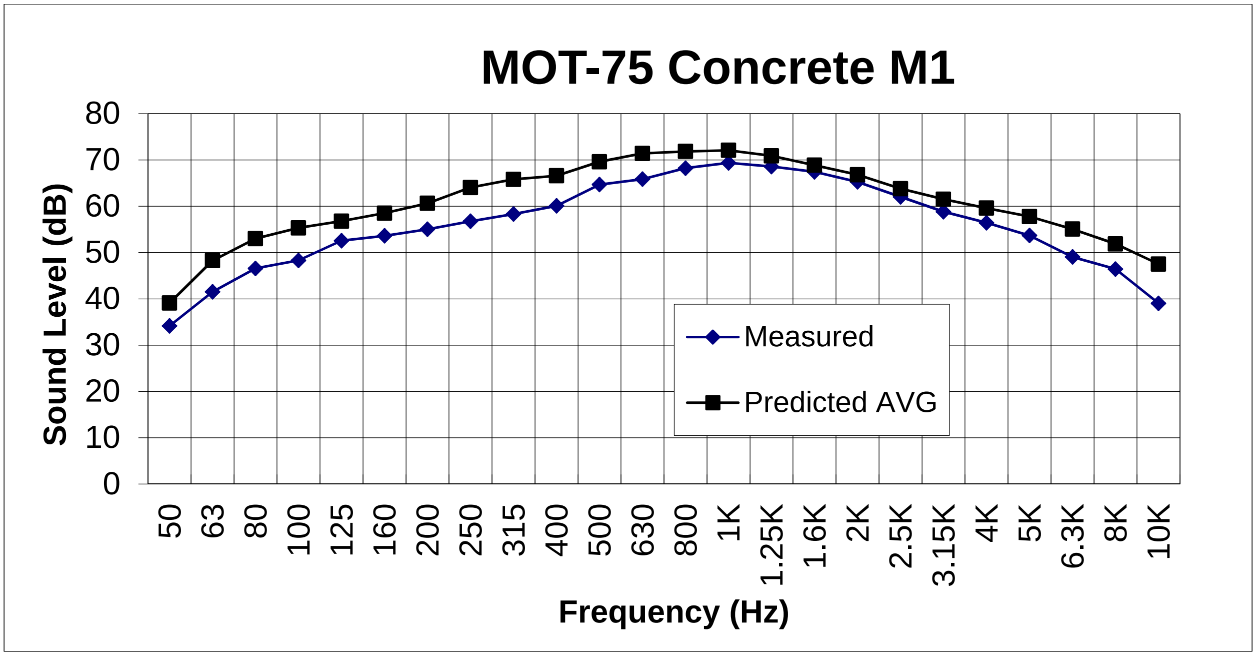
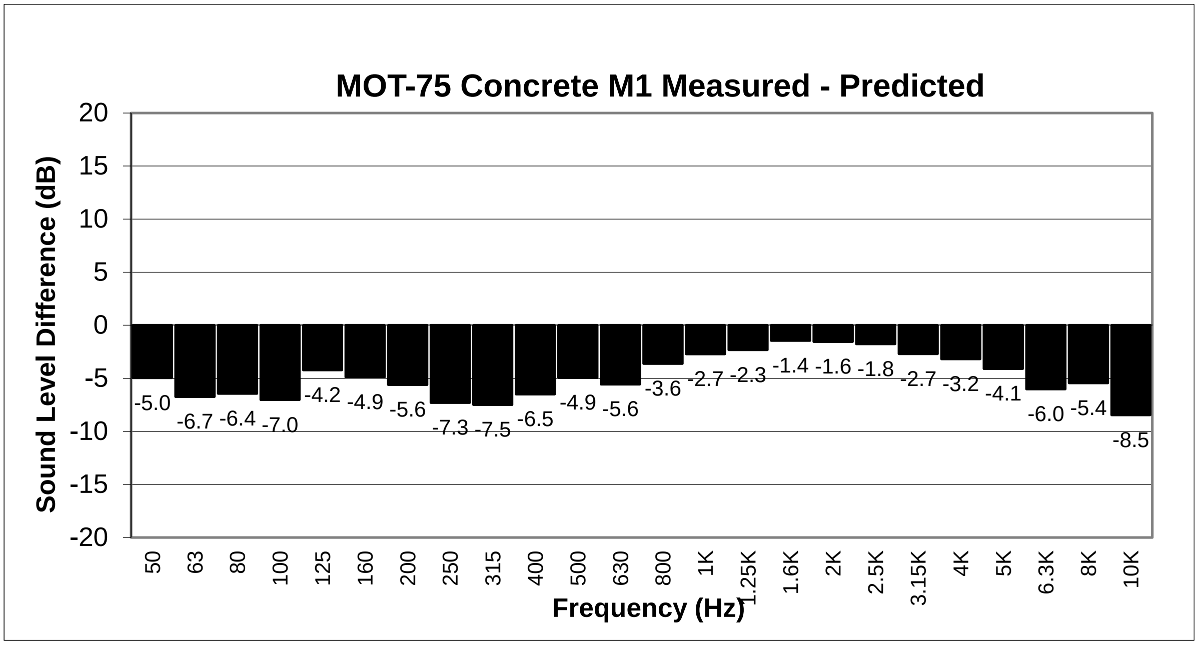
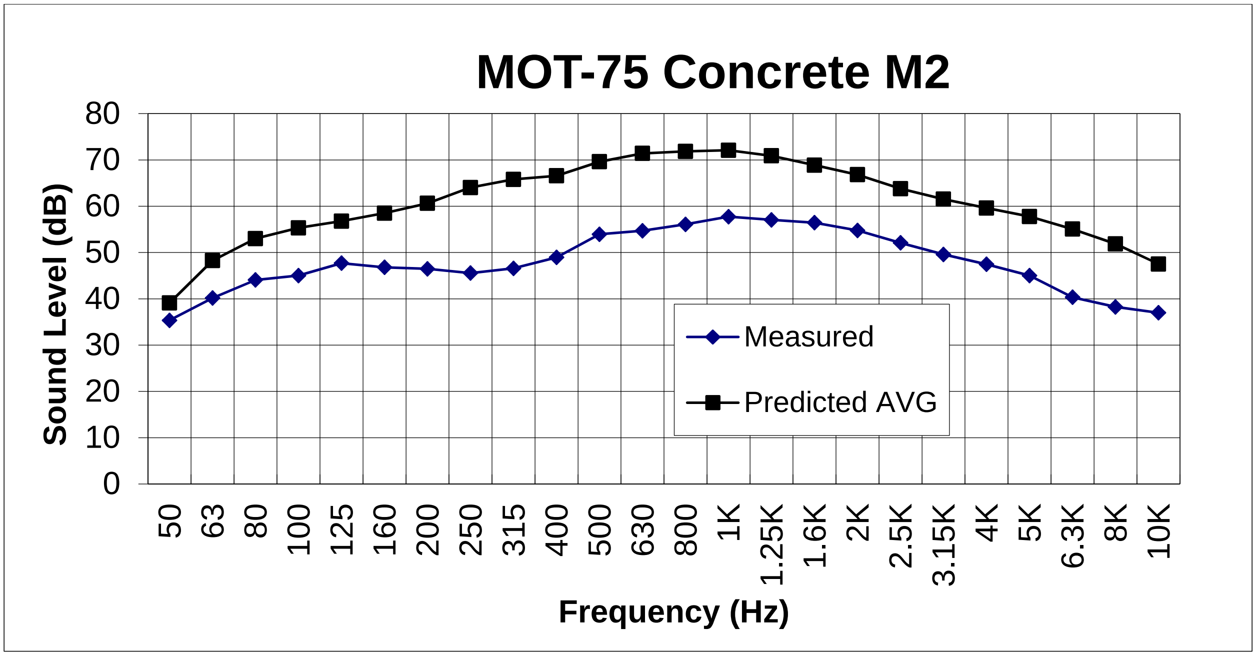
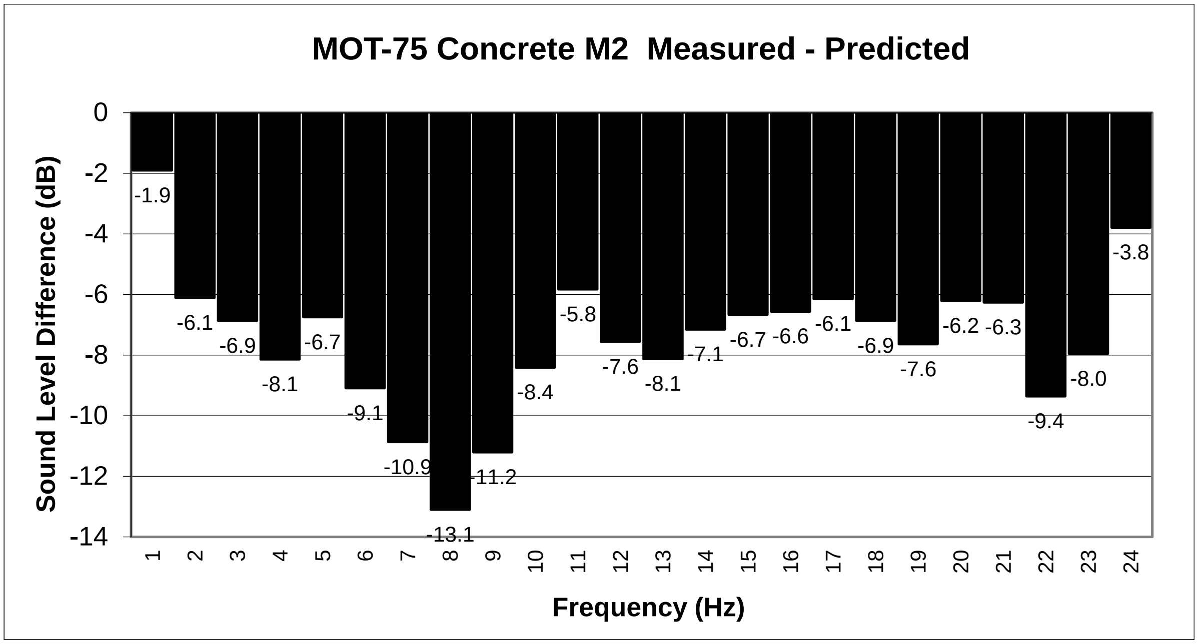


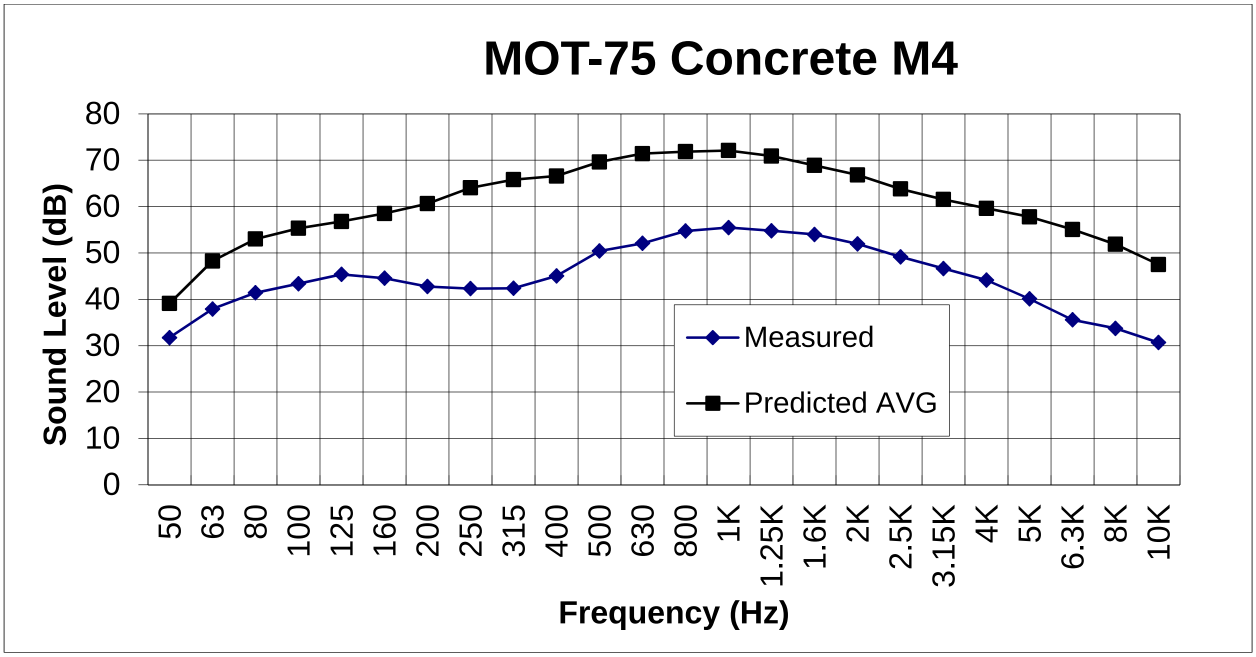


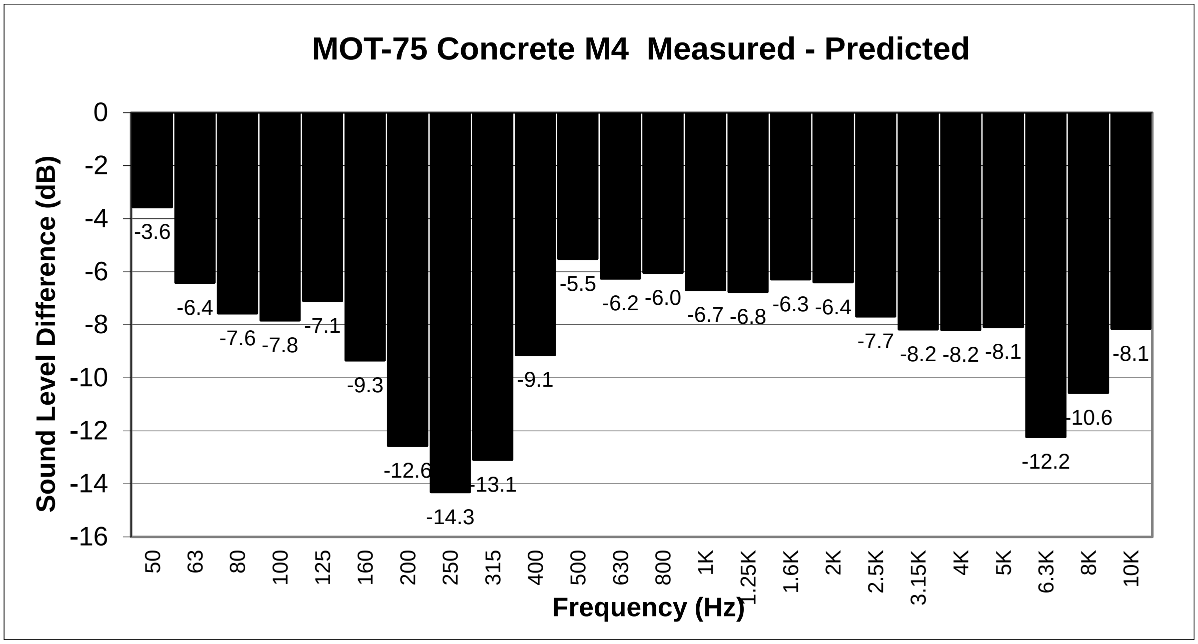
Site 4: Montgomery County, I-75; Absorptive Concrete Wall



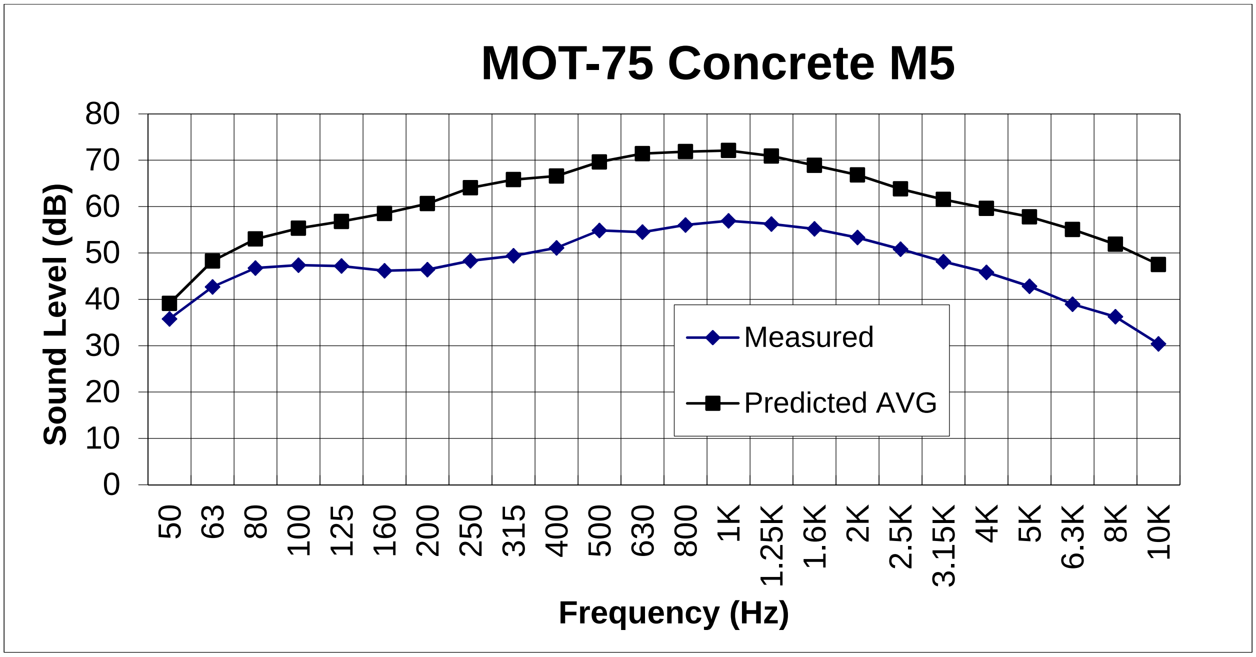


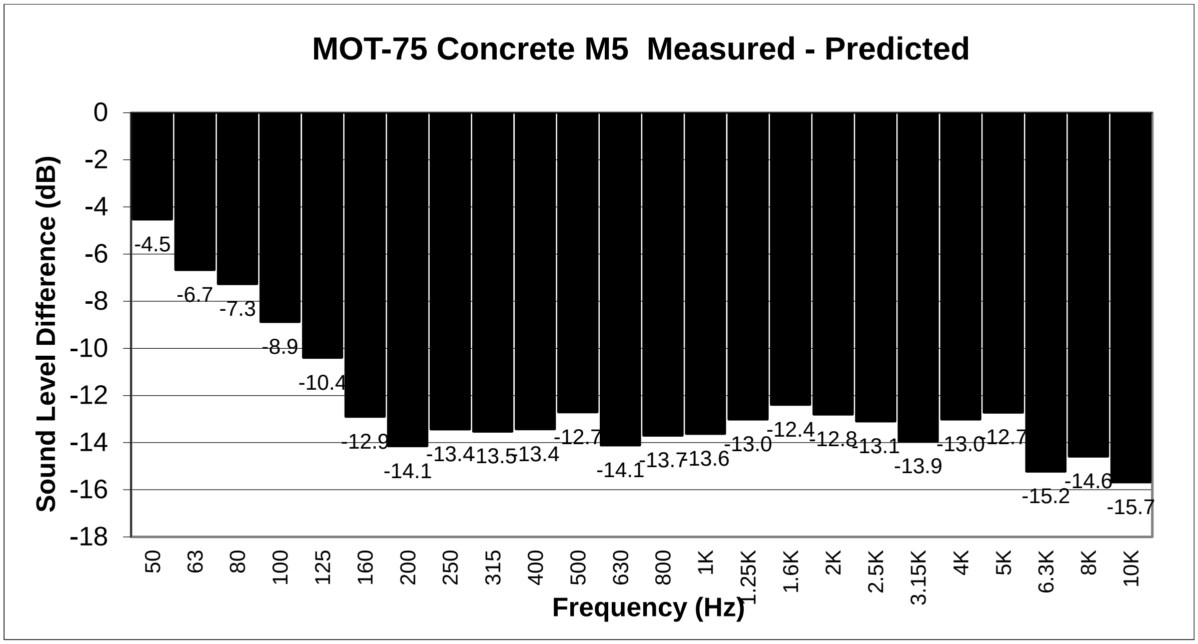
Site 4: Montgomery County, I-75; Absorptive Concrete Wall



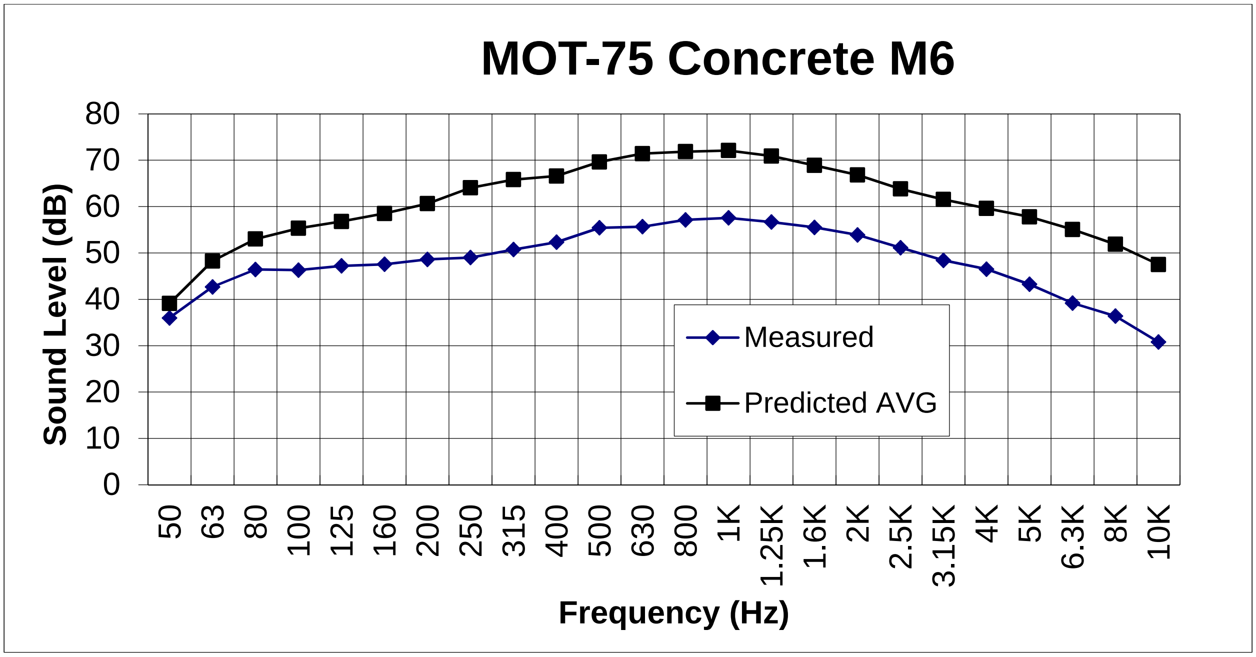


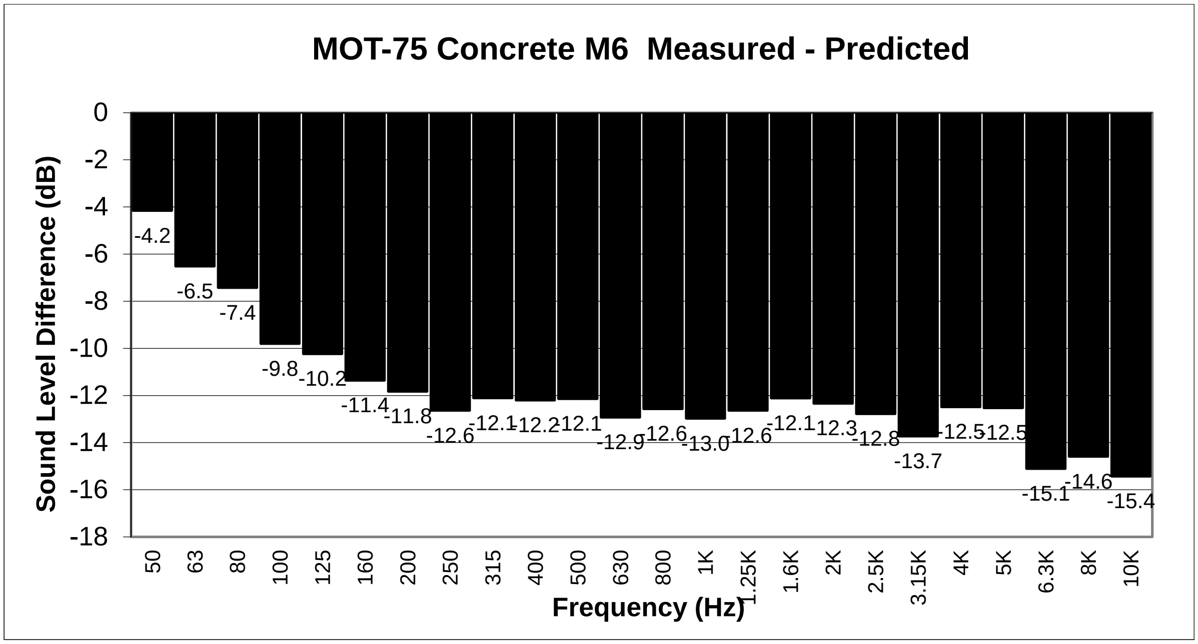
Site 4: Montgomery County, I-75; Absorptive Concrete Wall



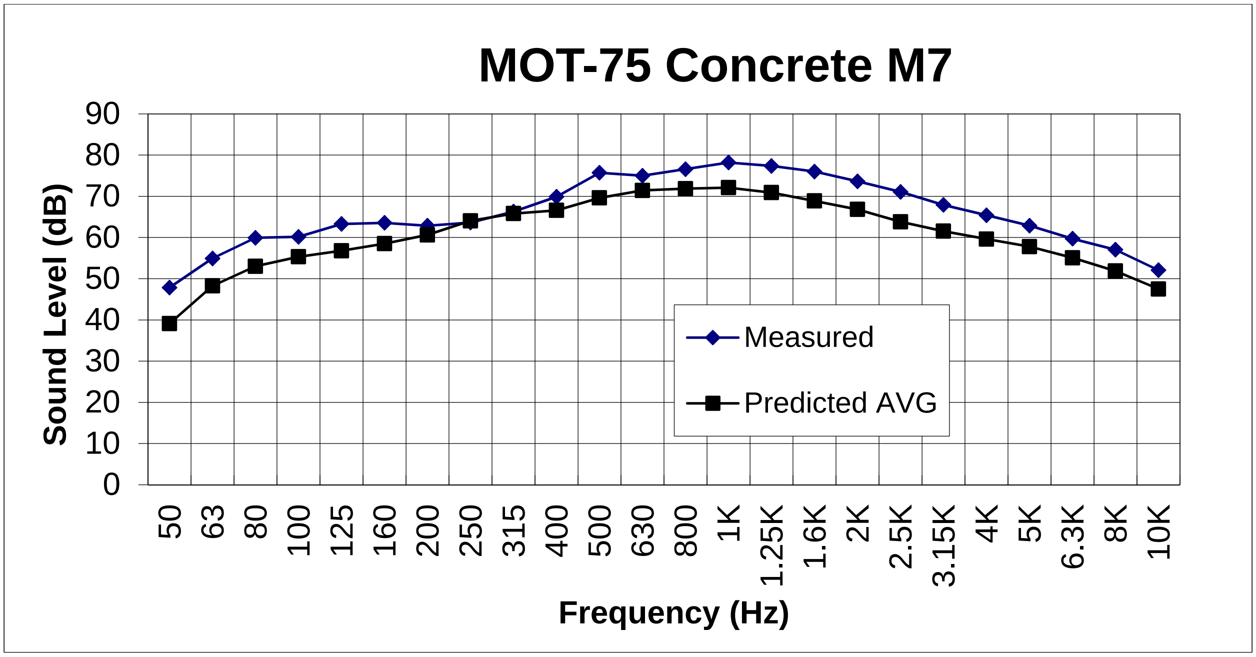


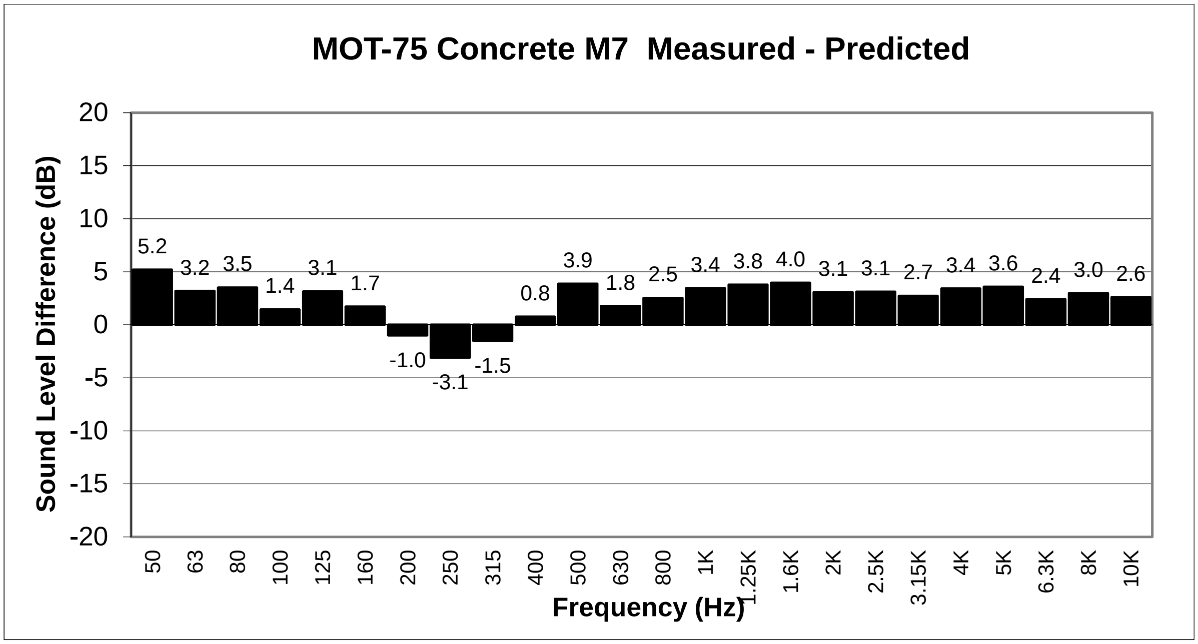
Site 4: Montgomery County, I-75; Absorptive Concrete Wall



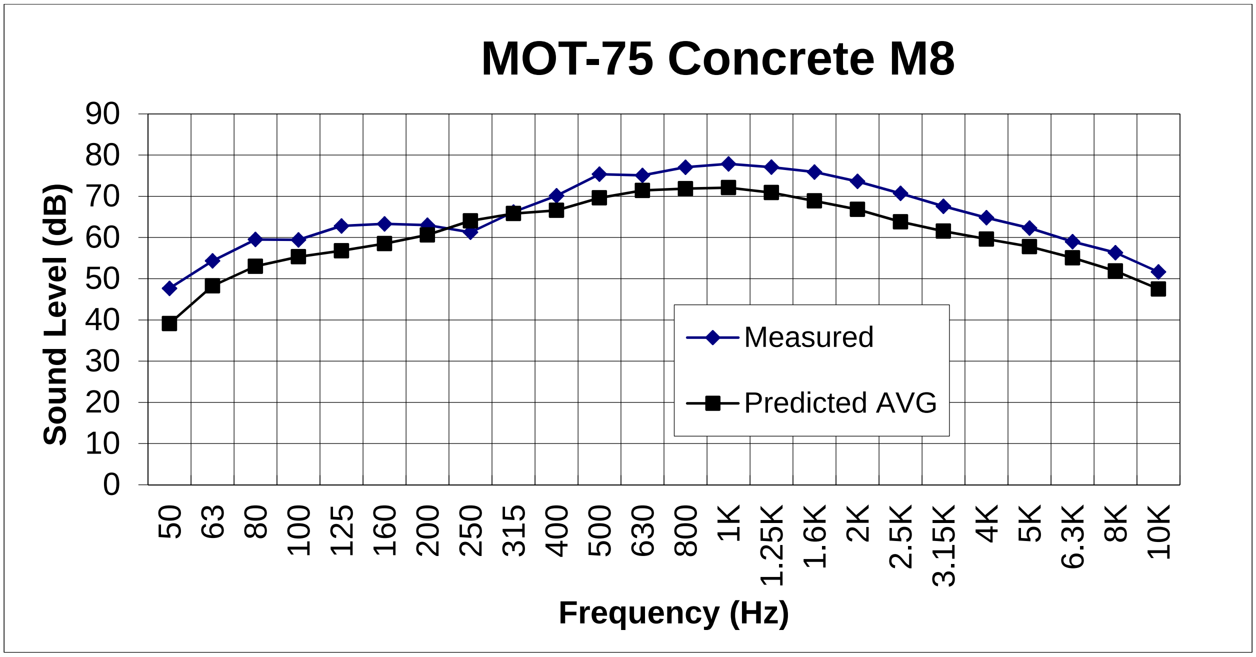


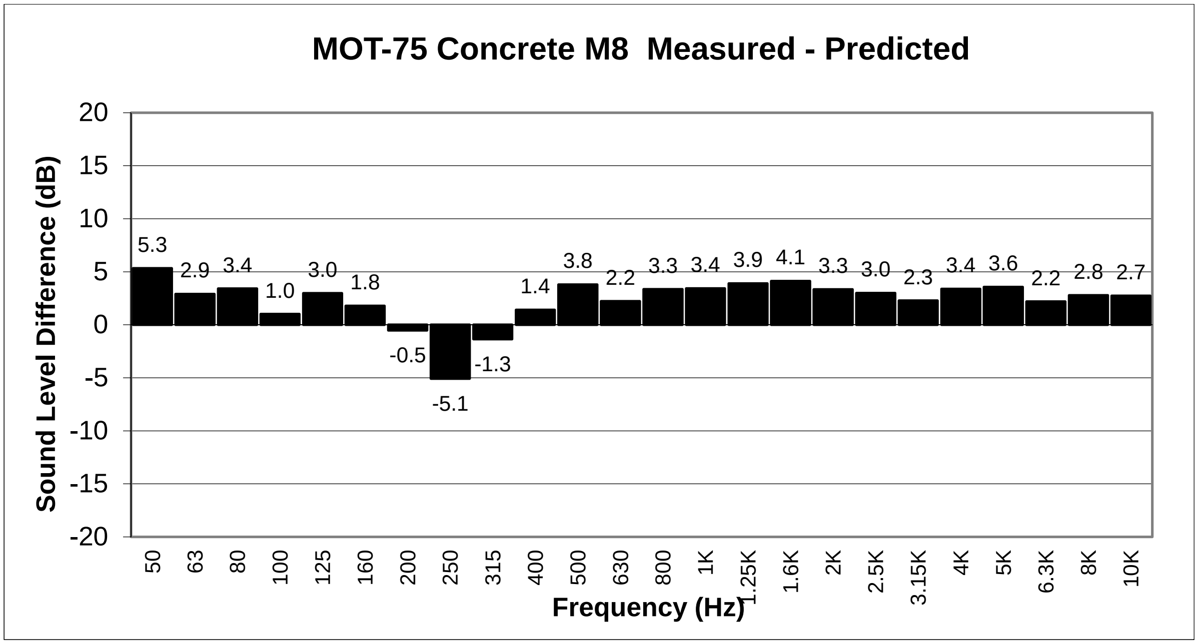
Site 4: Montgomery County, I-75; Absorptive Concrete Wall



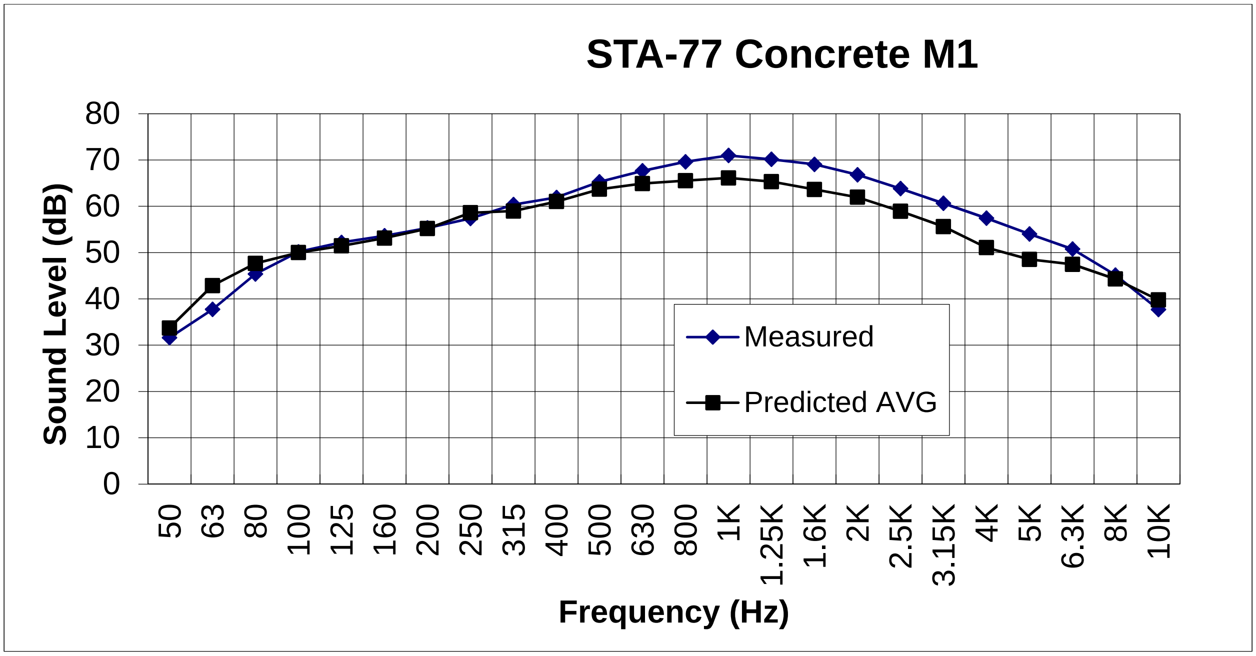


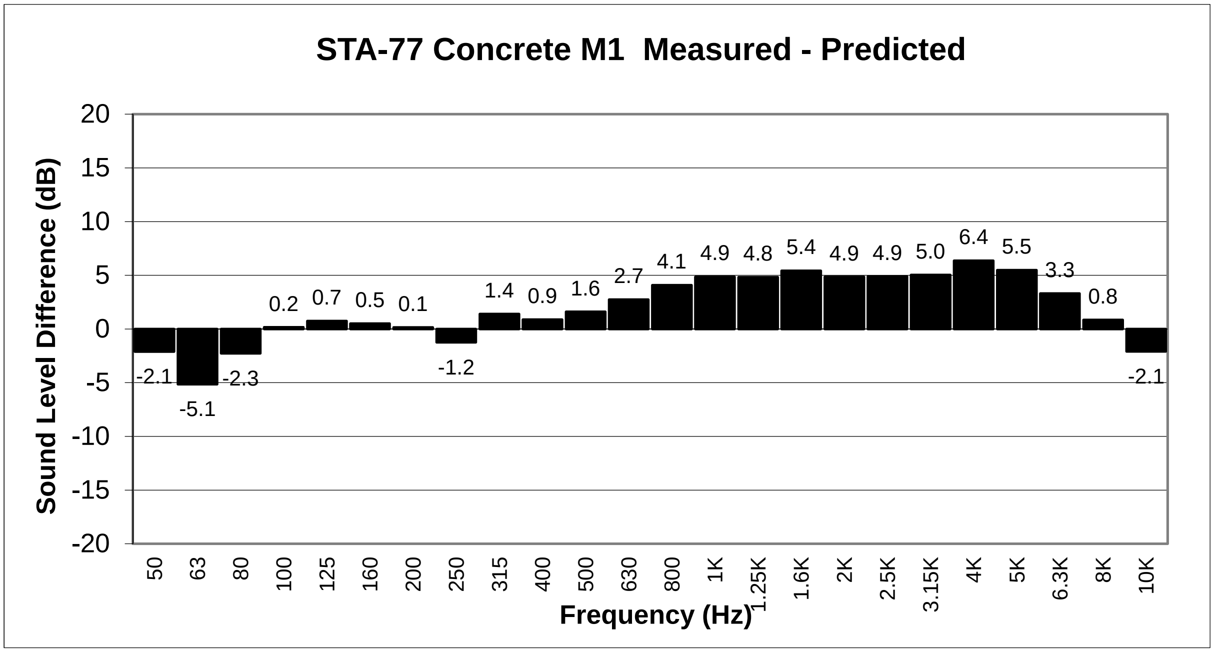
Site 4: Montgomery County, I-75; Absorptive Concrete Wall



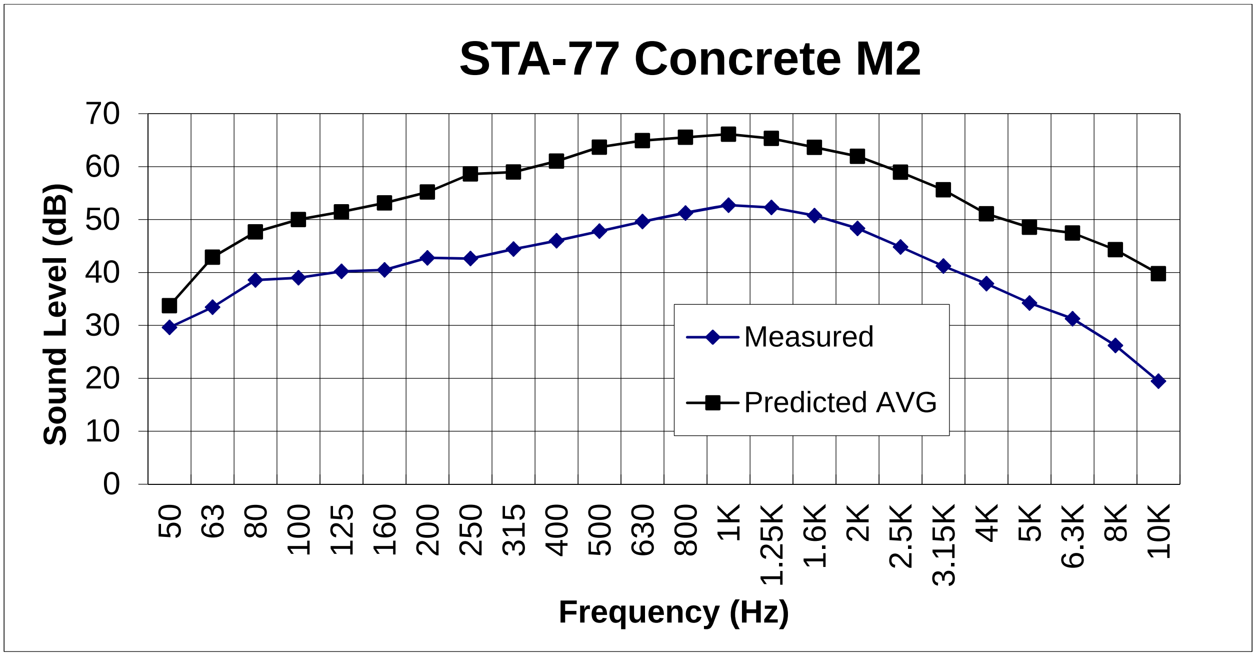


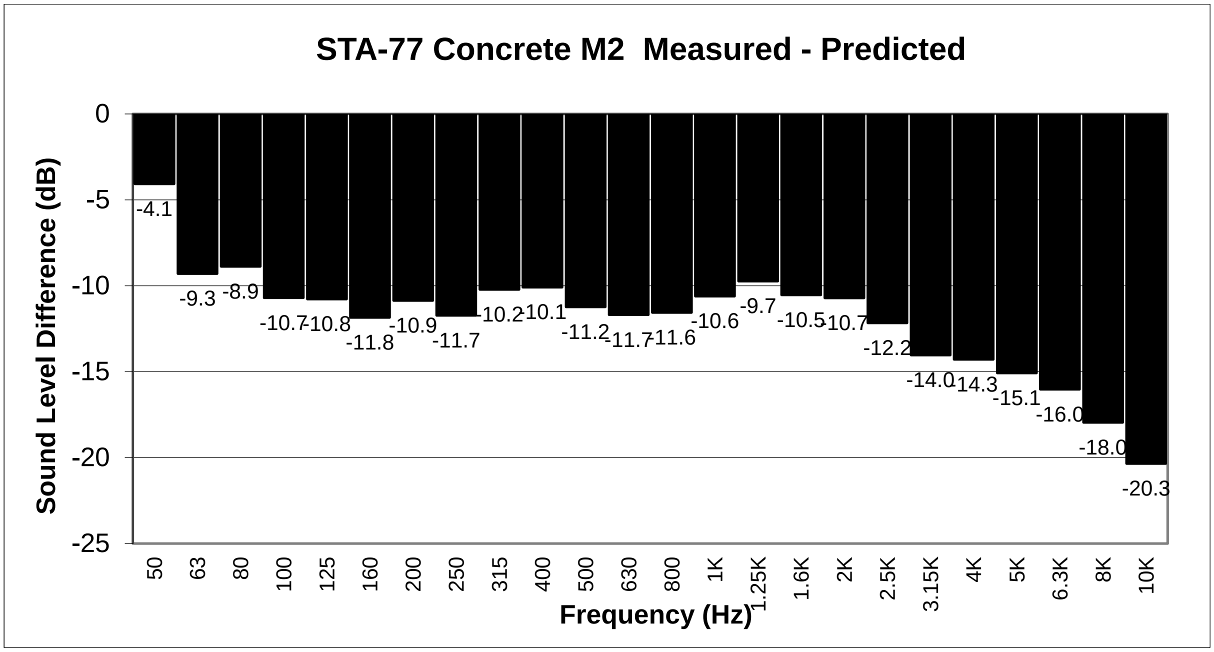
Site 5: Stark County, I-77; Absorptive Concrete Wall



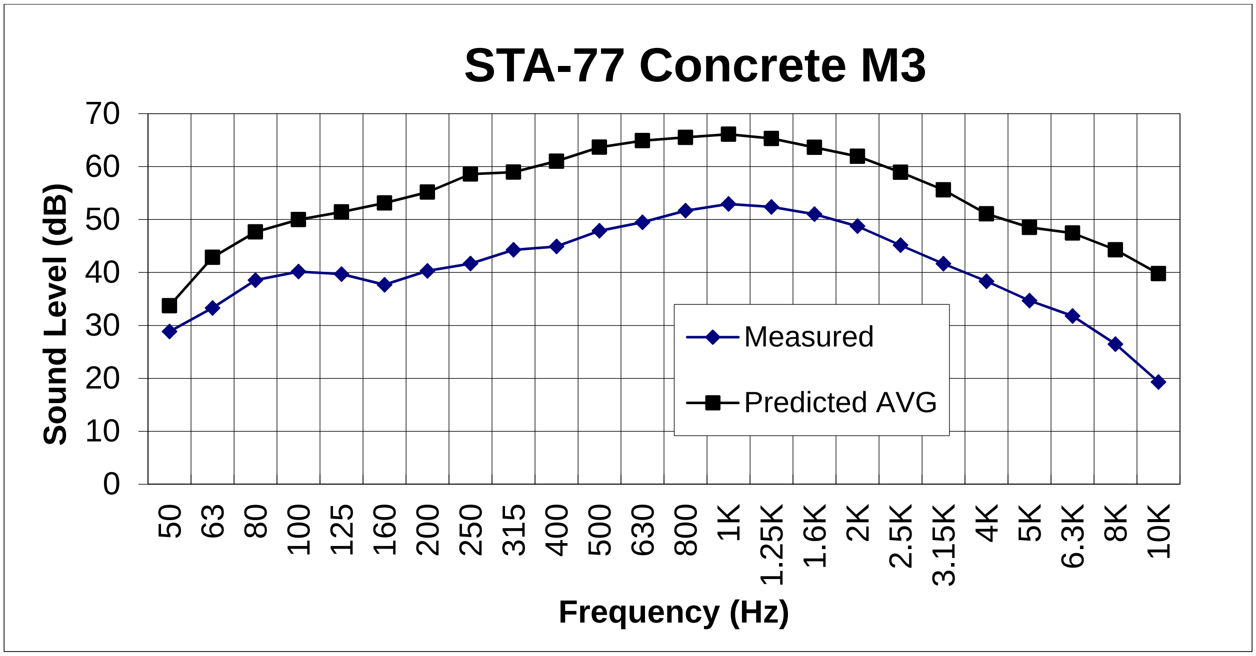


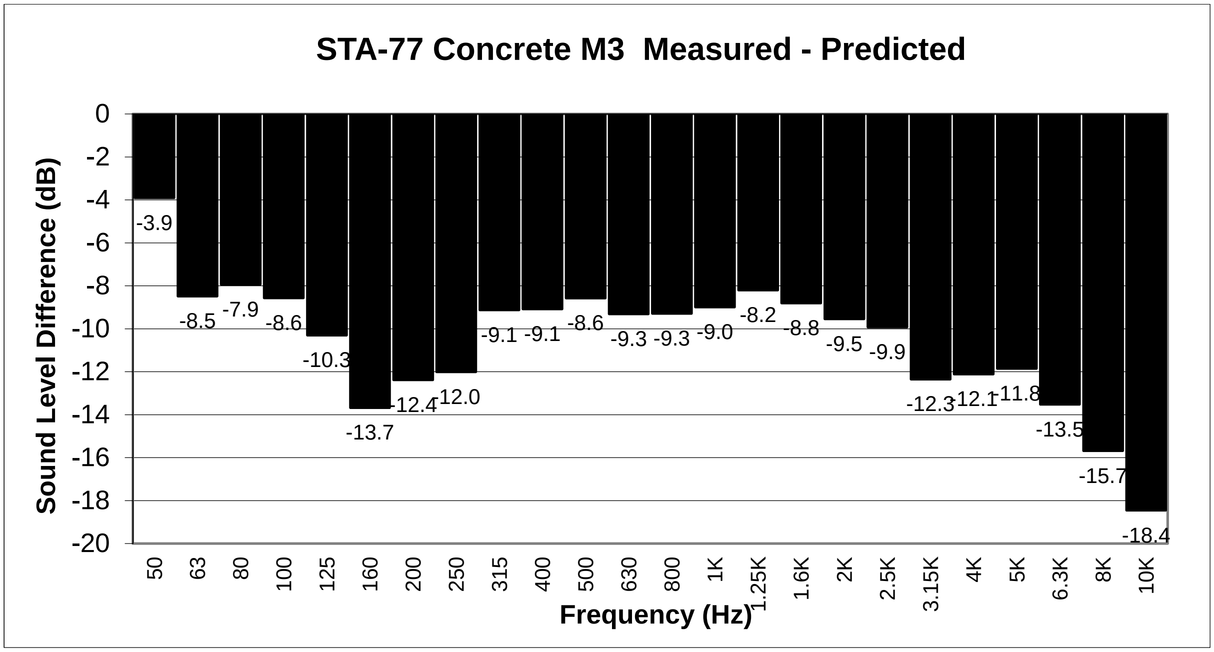
Site 5: Stark County, I-77; Absorptive Concrete Wall





Site 5: Stark County, I-77; Absorptive Concrete Wall





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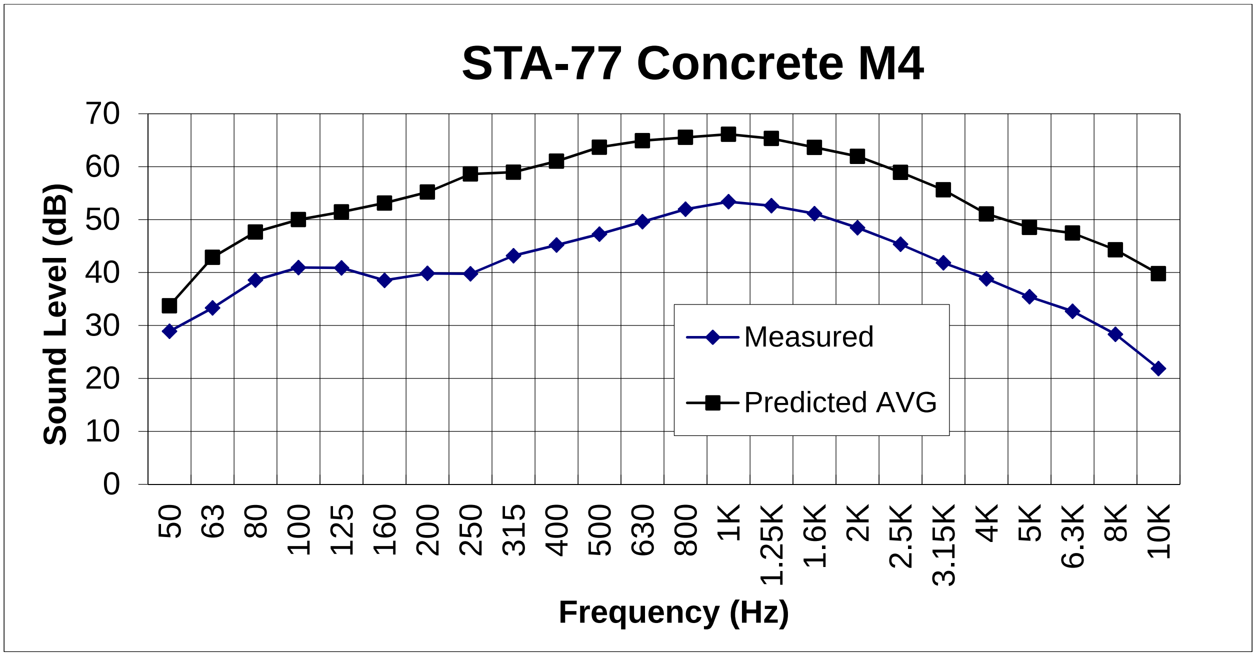

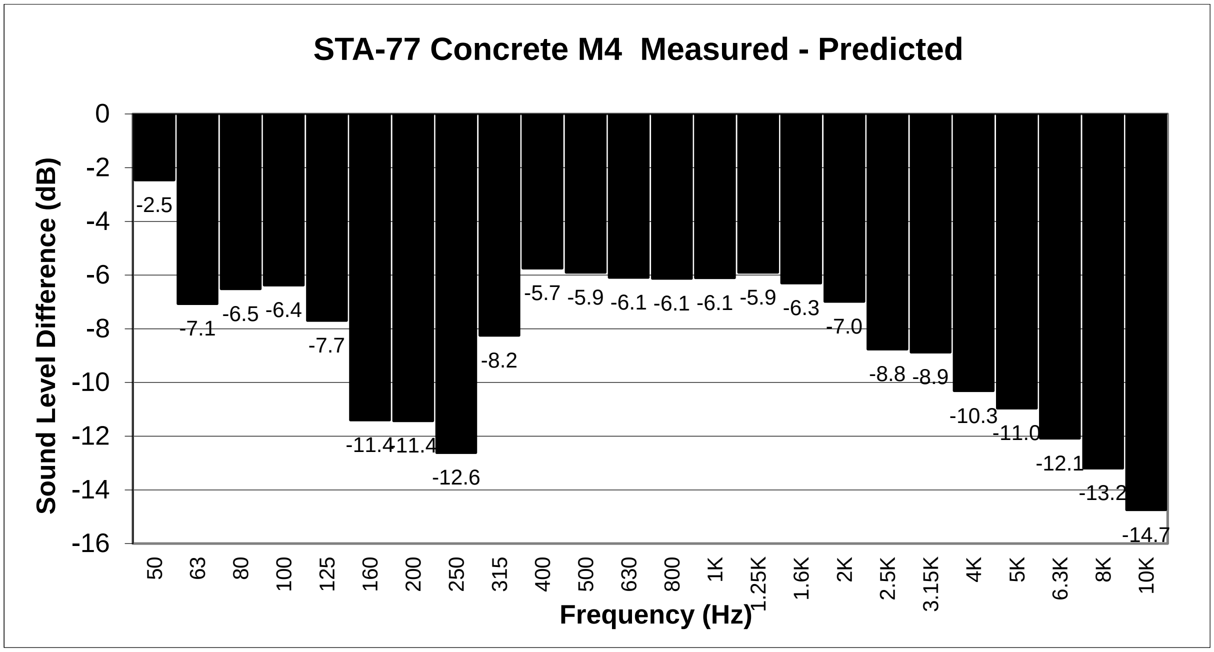

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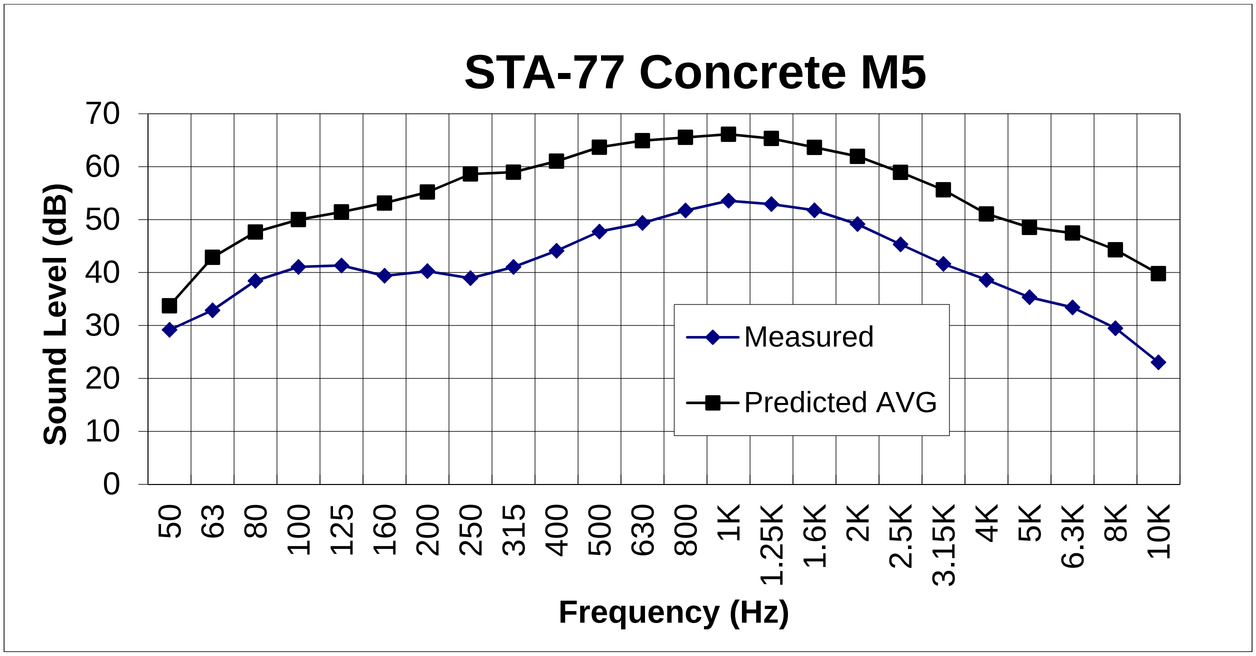
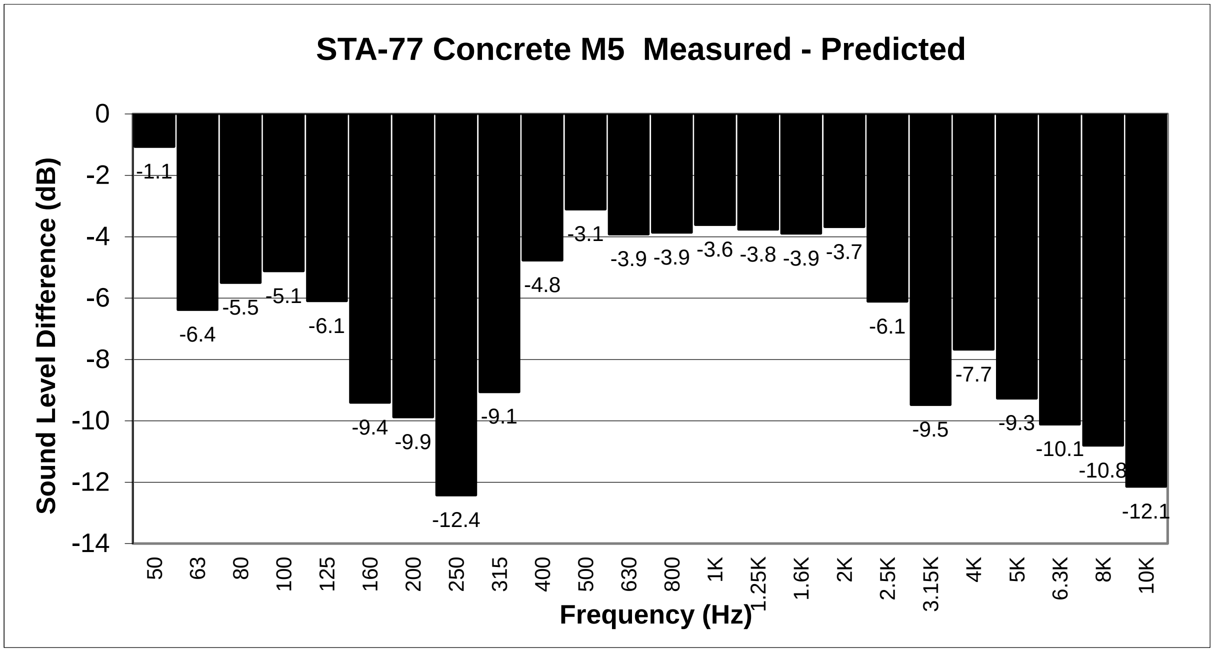
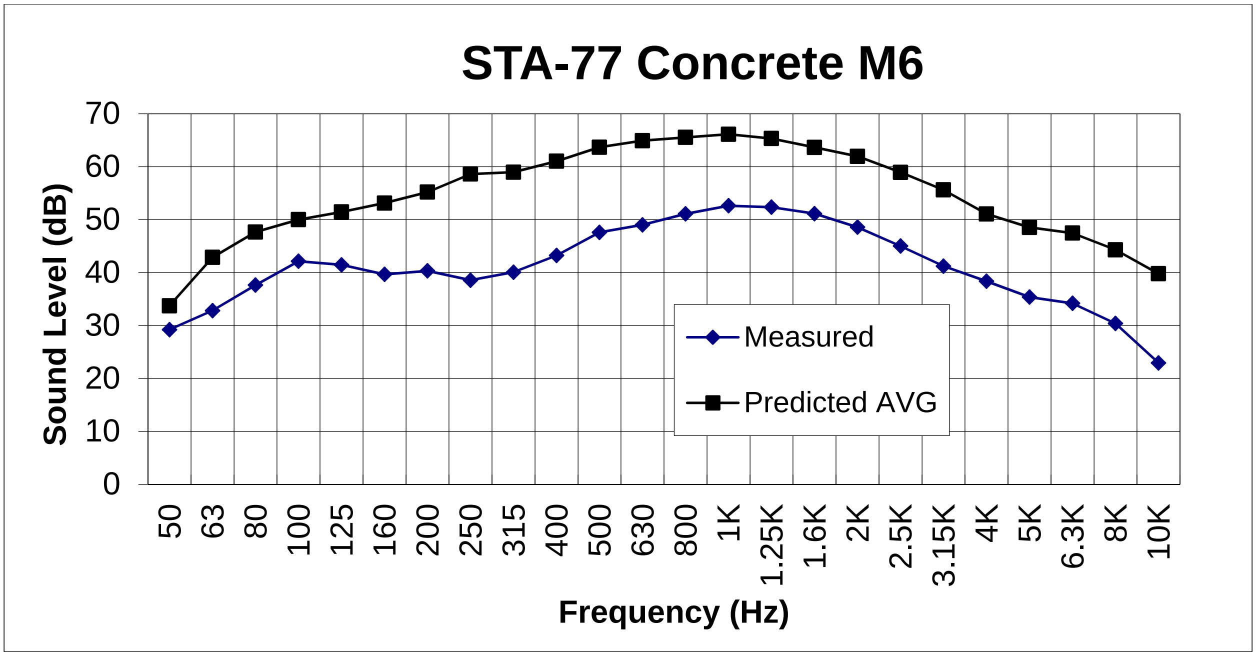
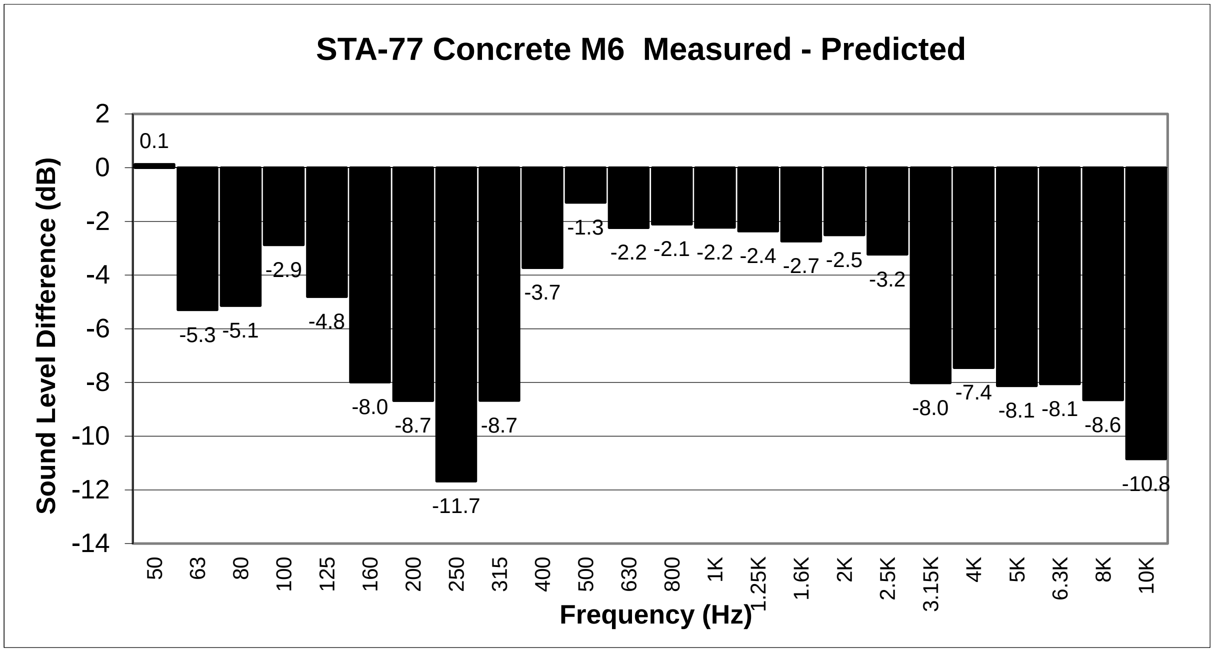




Site 5: Stark County, I-77; Absorptive Concrete Wall





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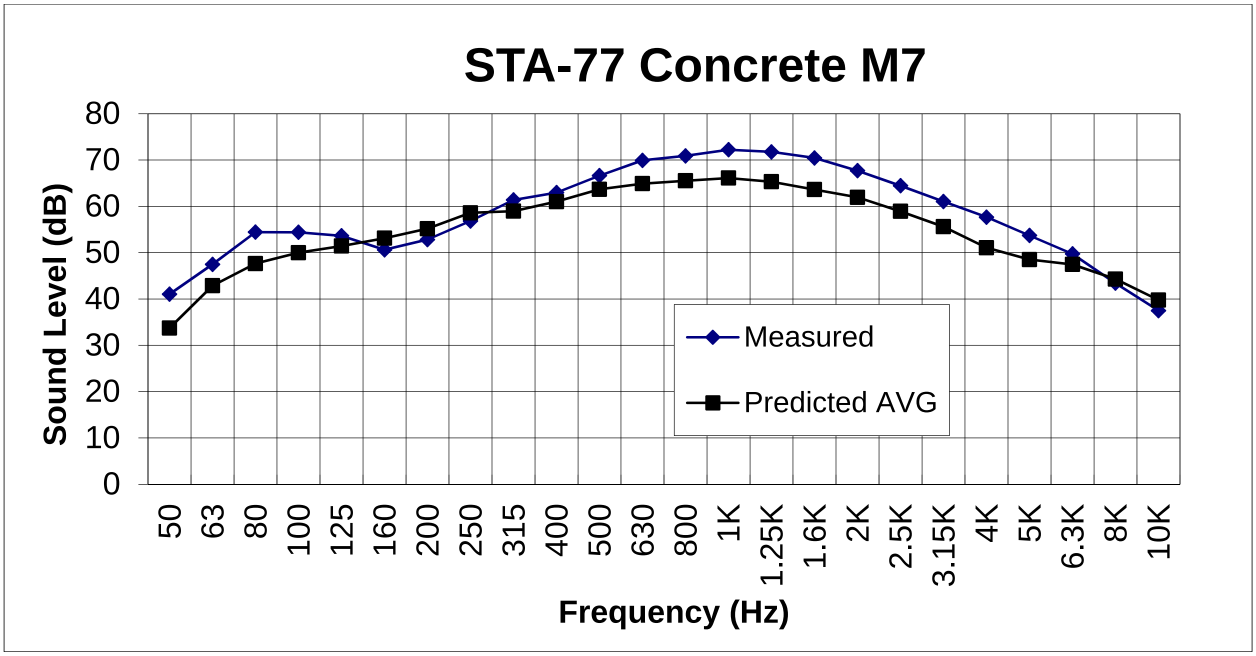
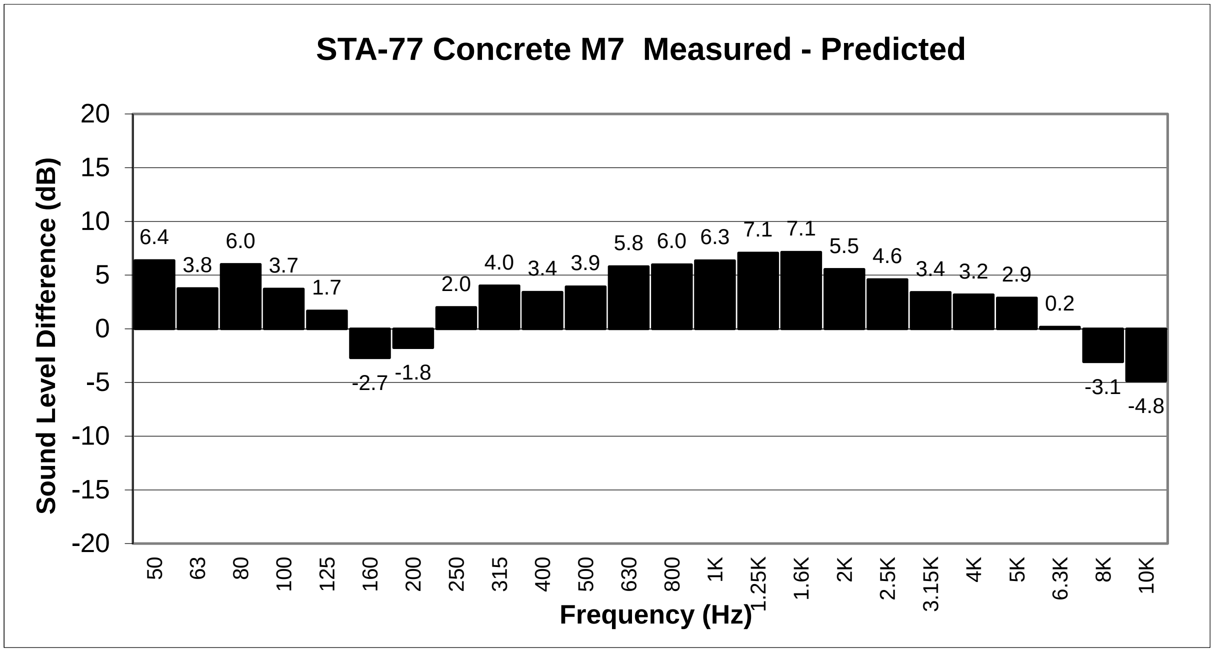
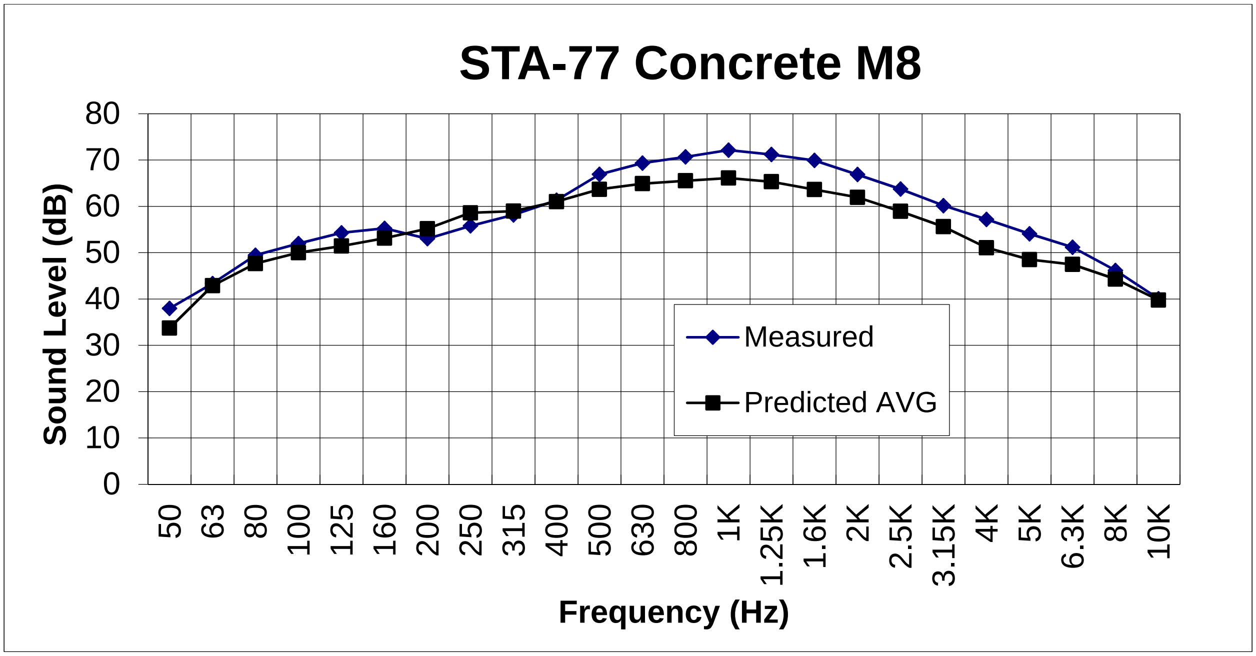
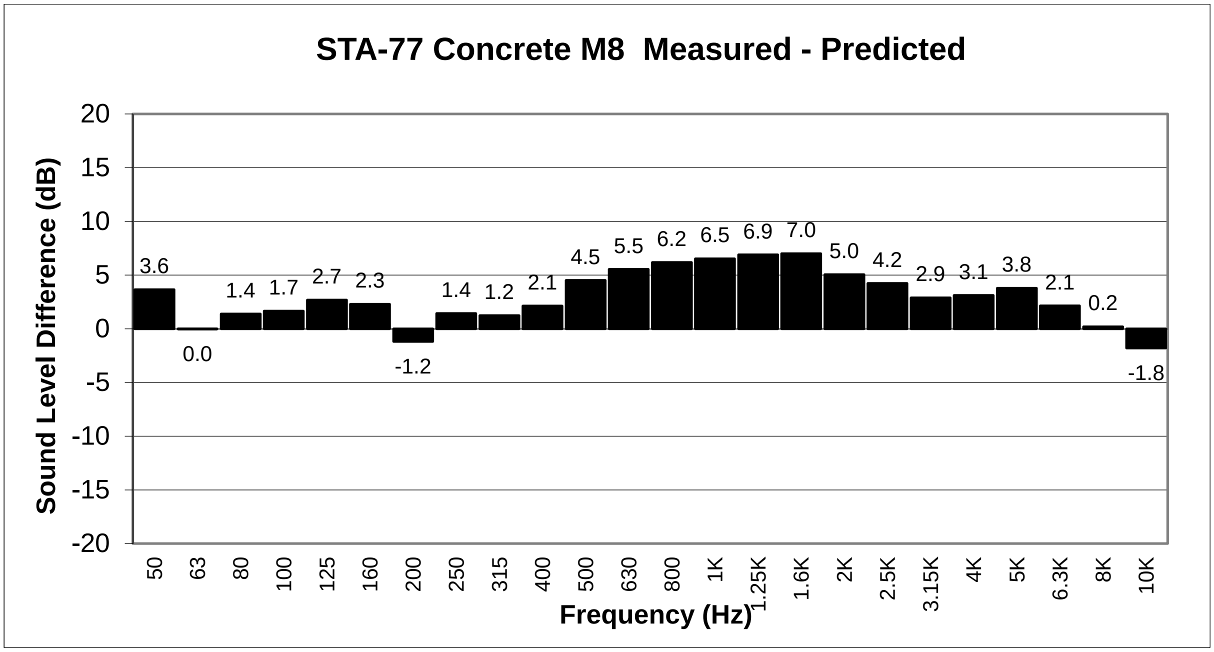


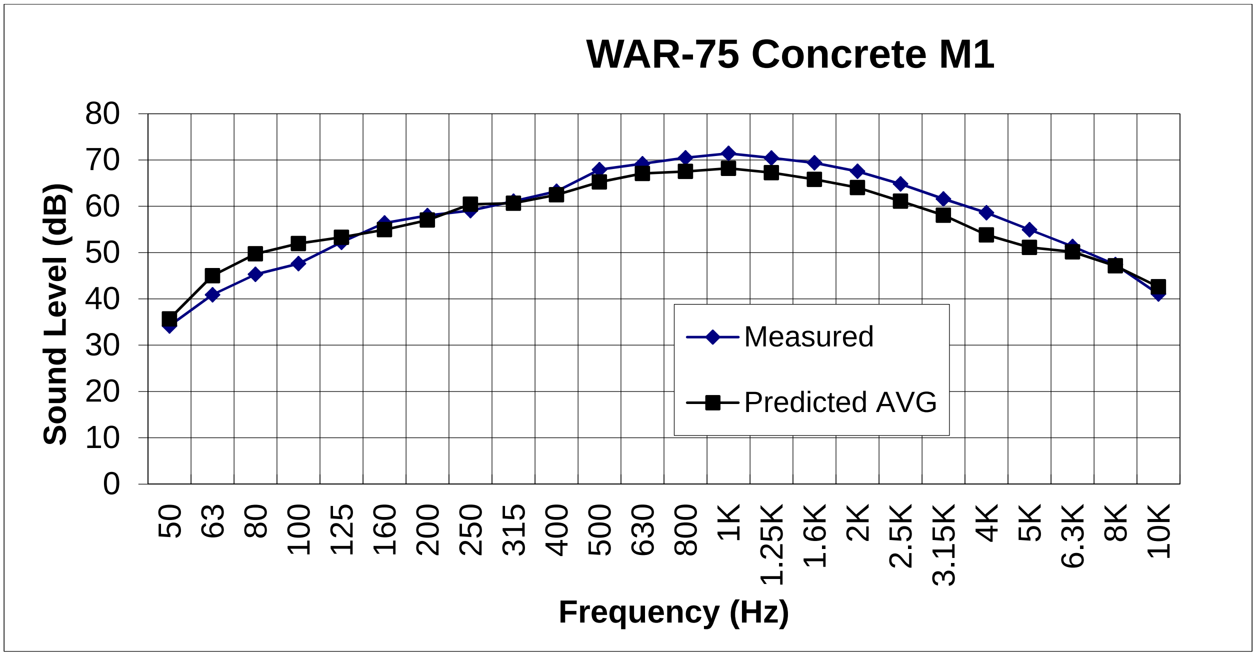


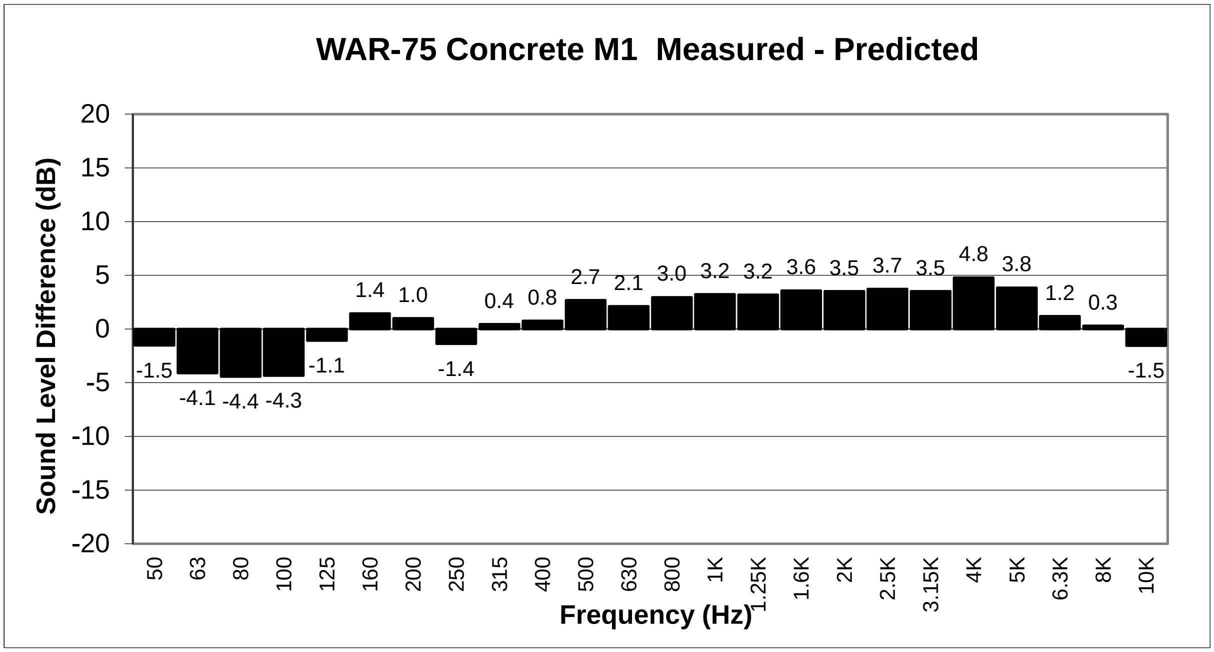
Site 5: Stark County, I-77; Absorptive Concrete Wall





Site 6: Warren County, I-75; Absorptive Concrete Wall





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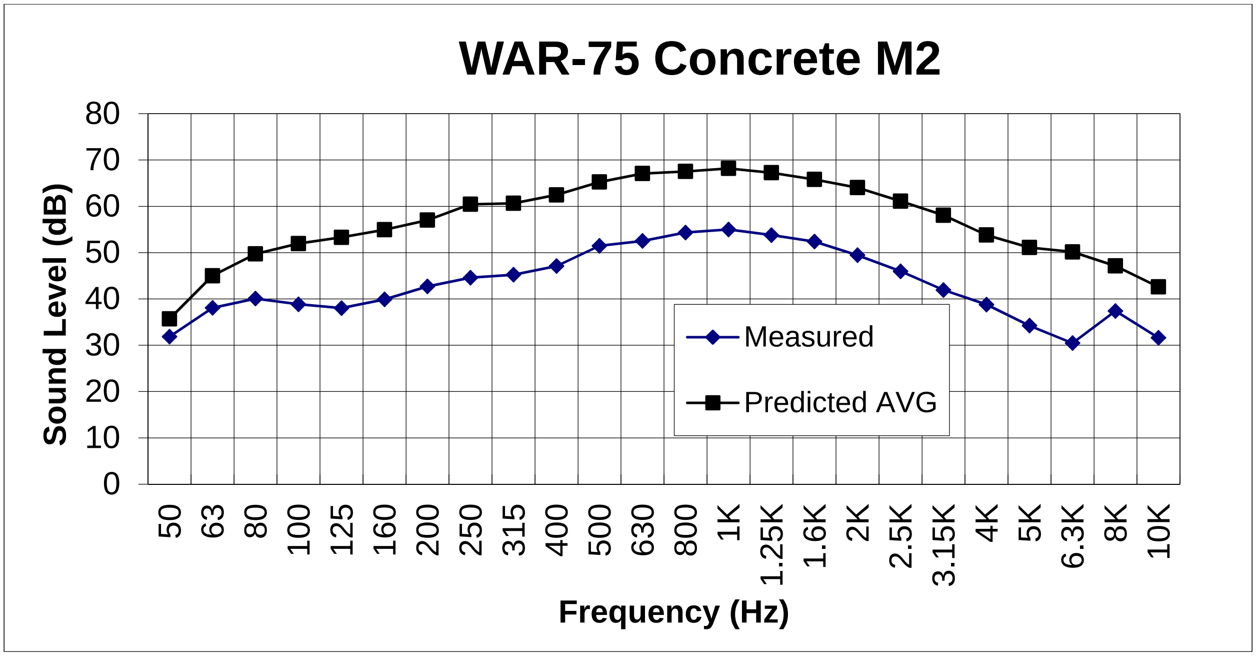

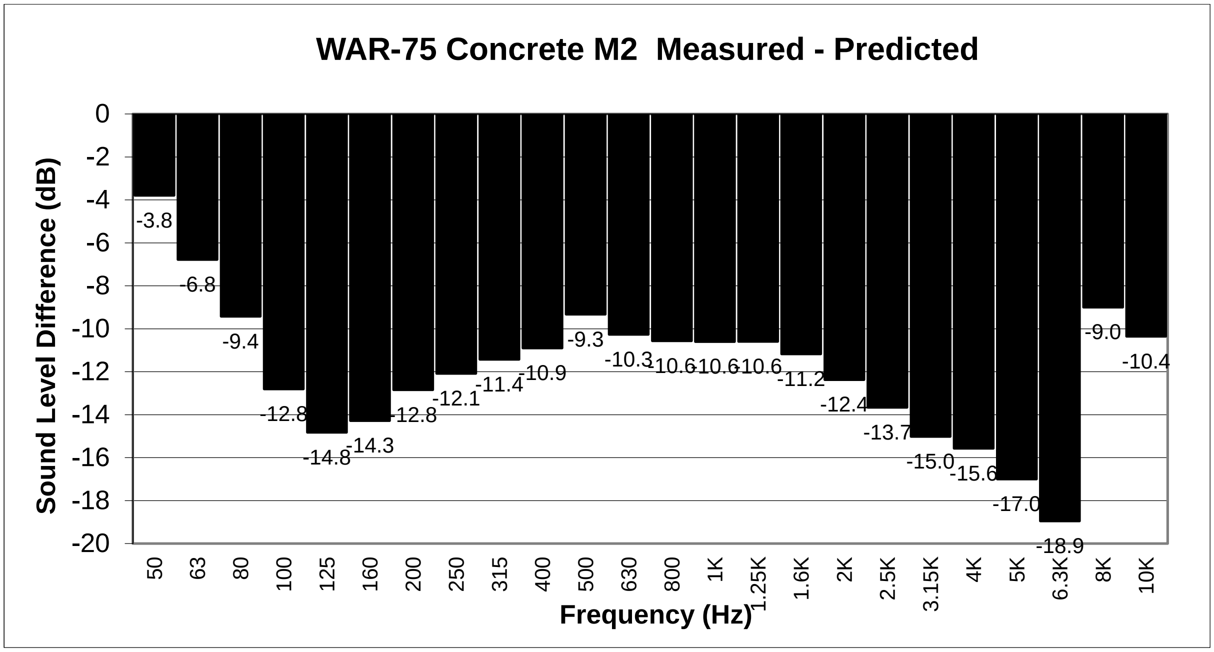

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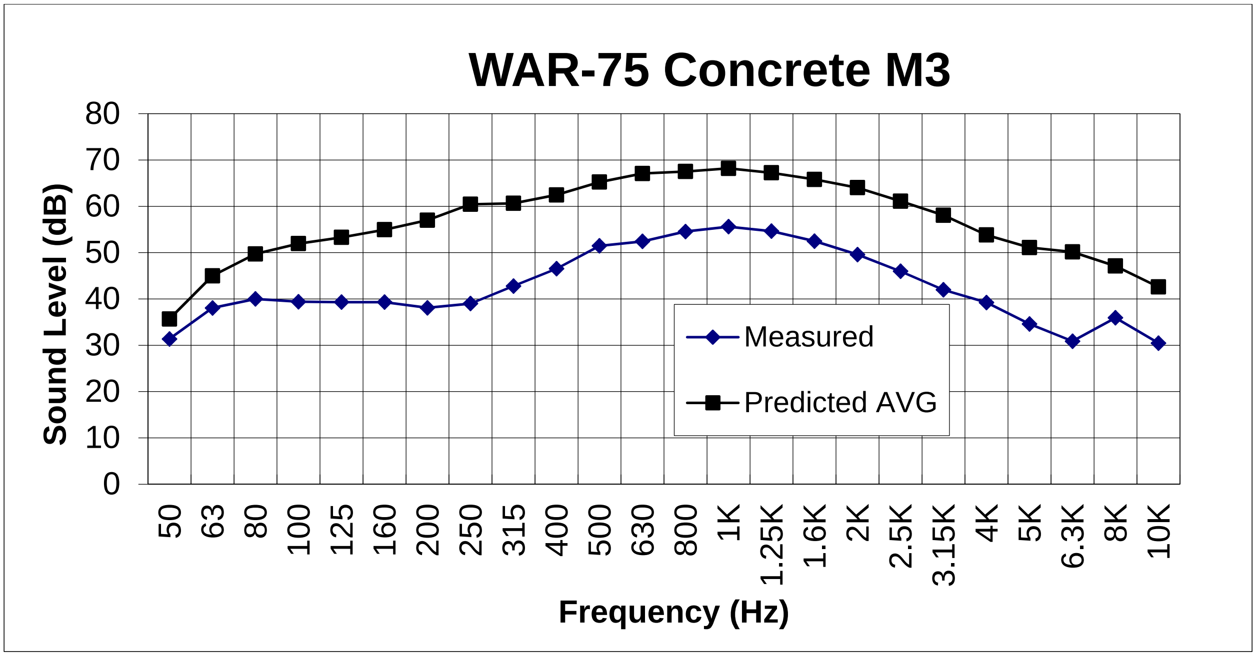

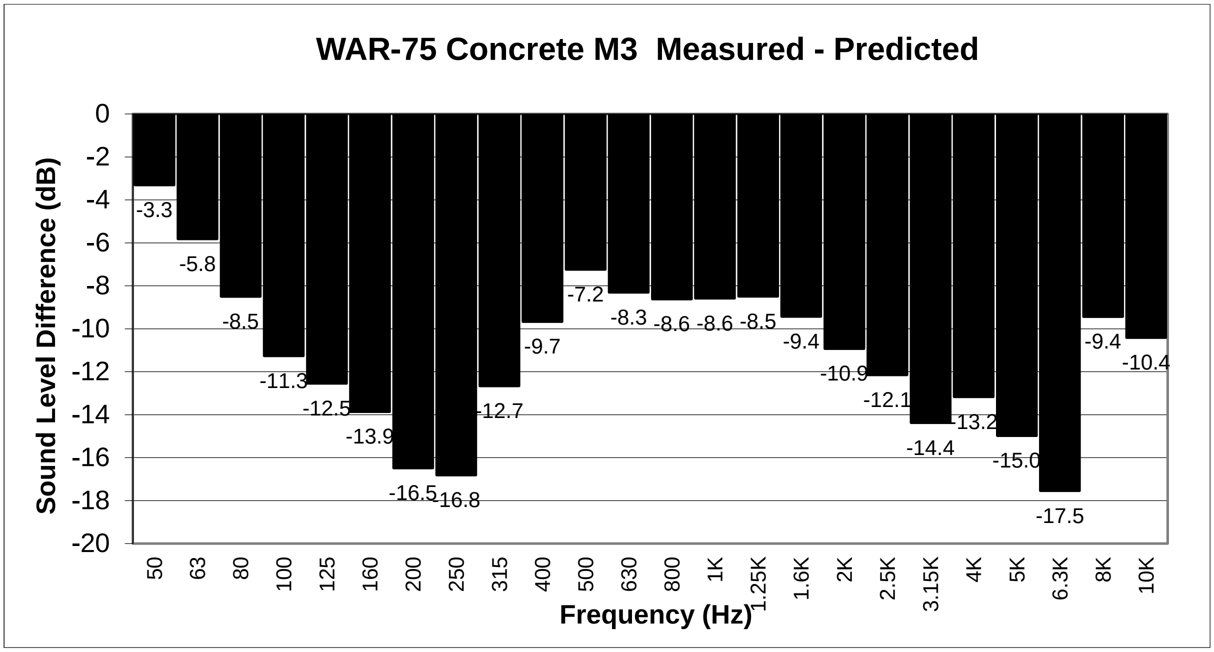

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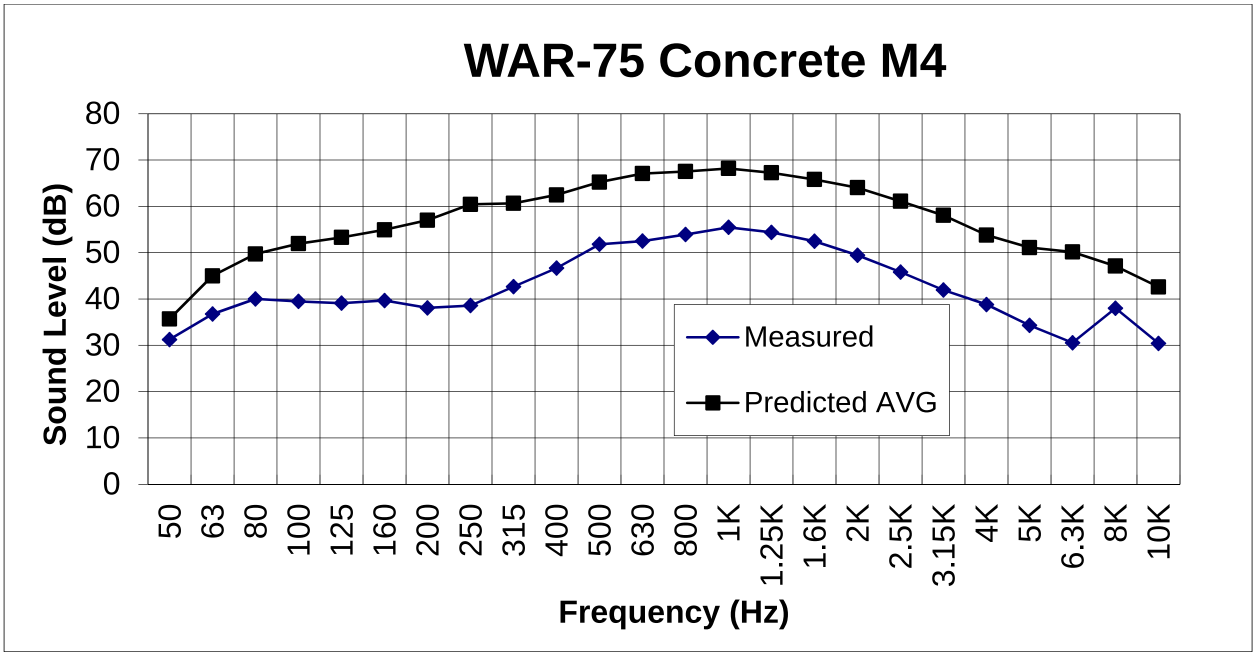

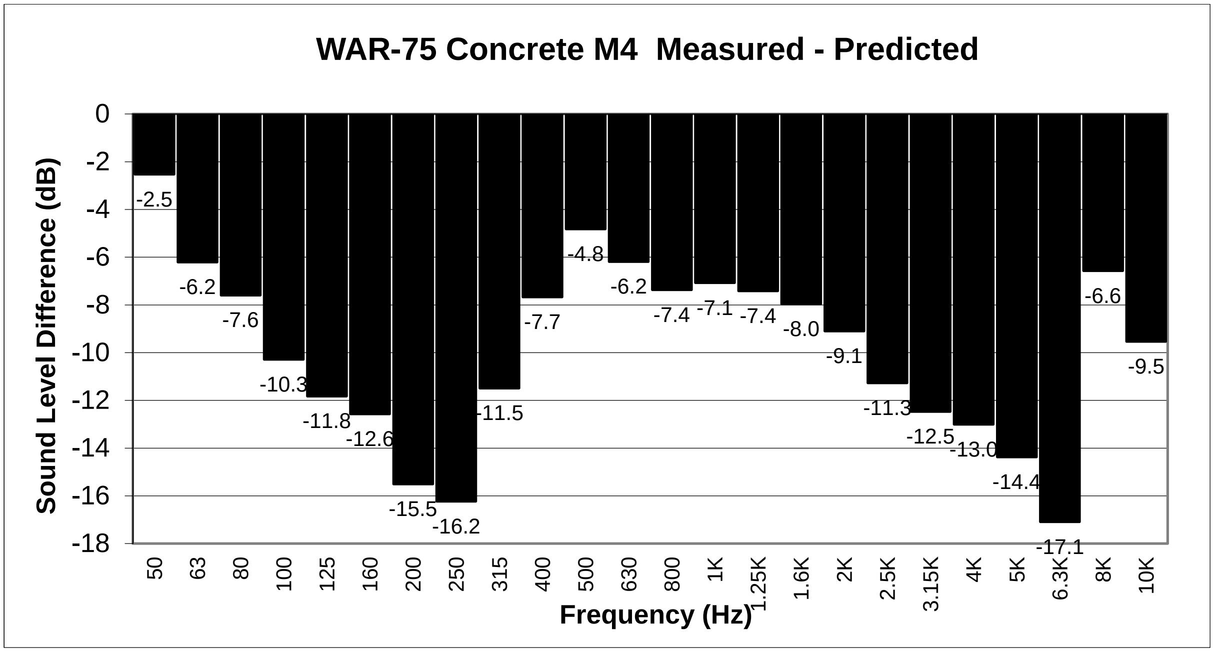

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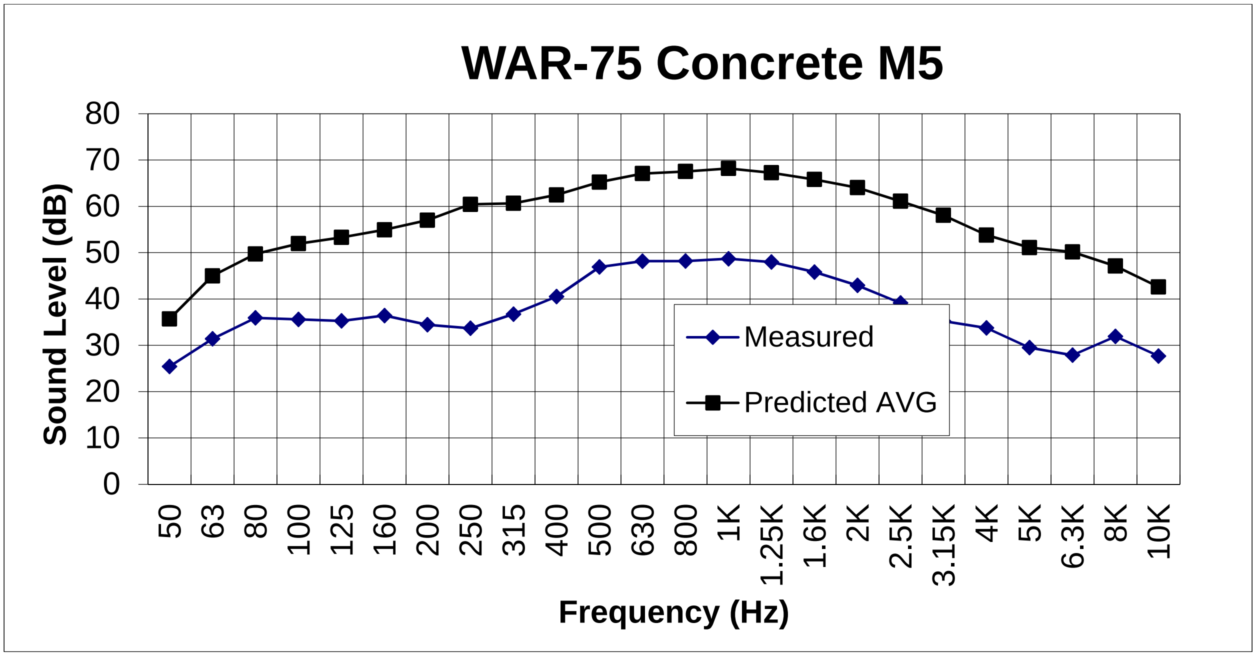

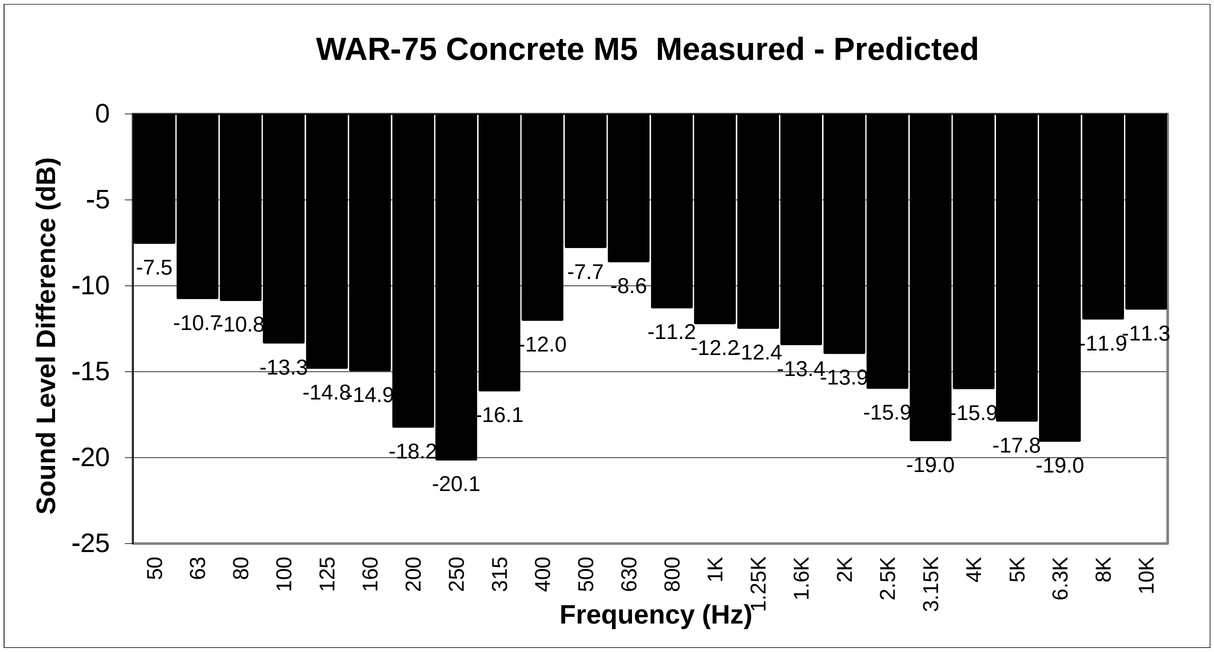

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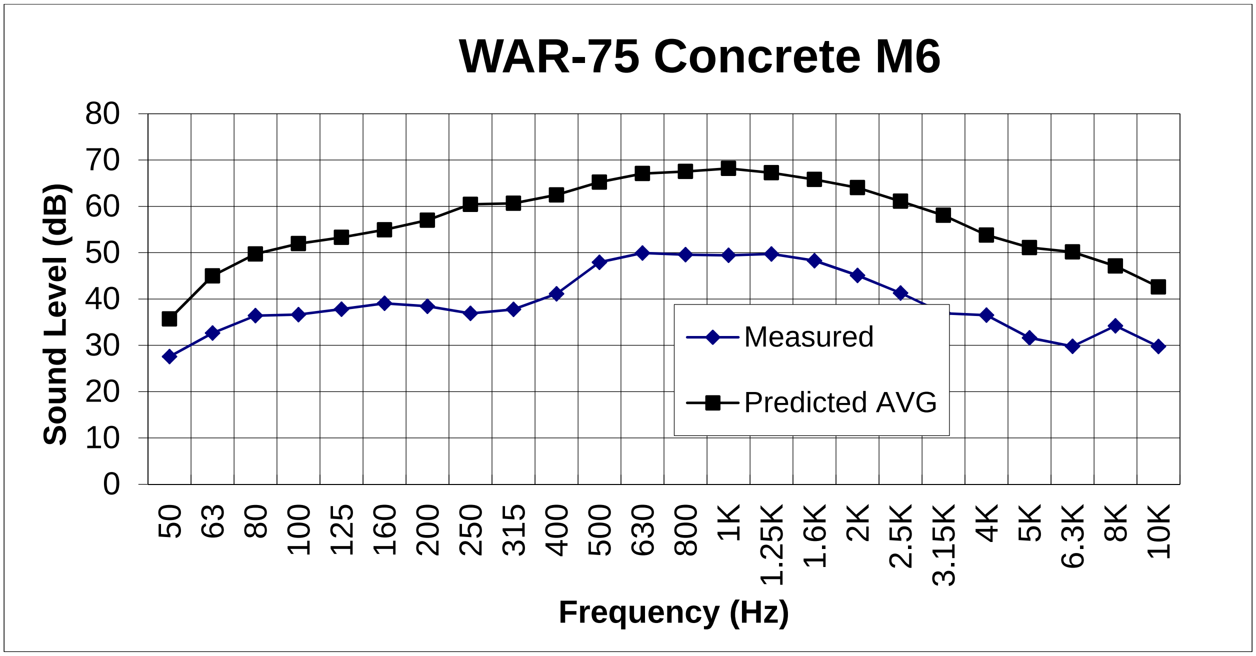

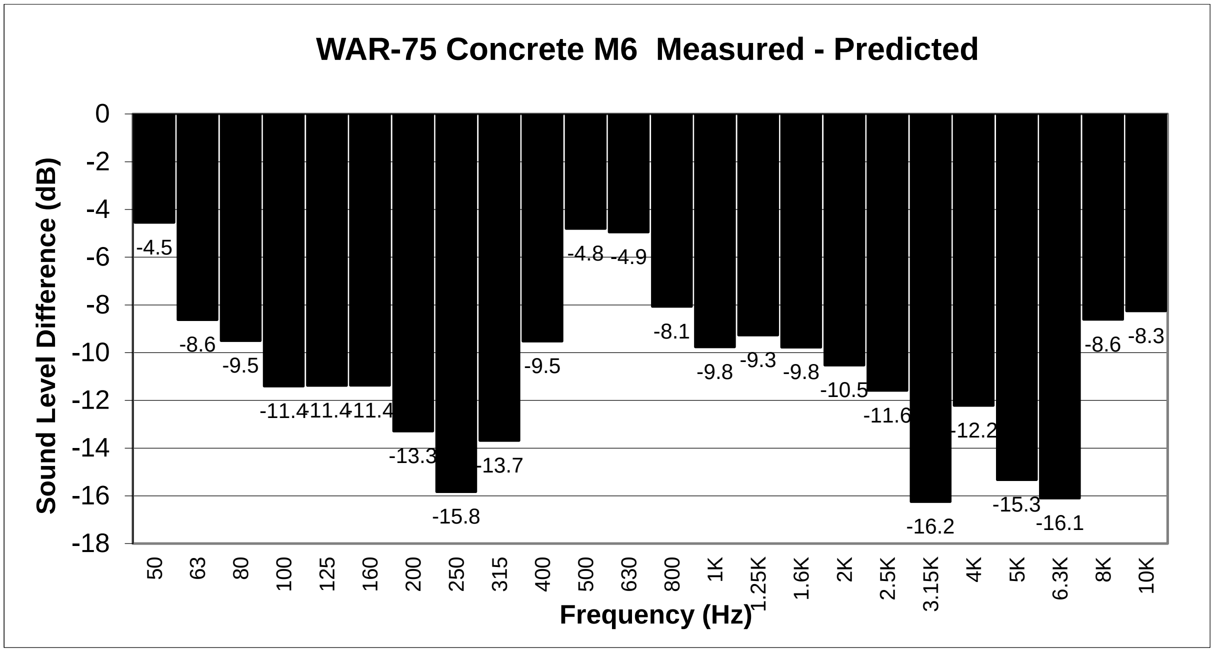

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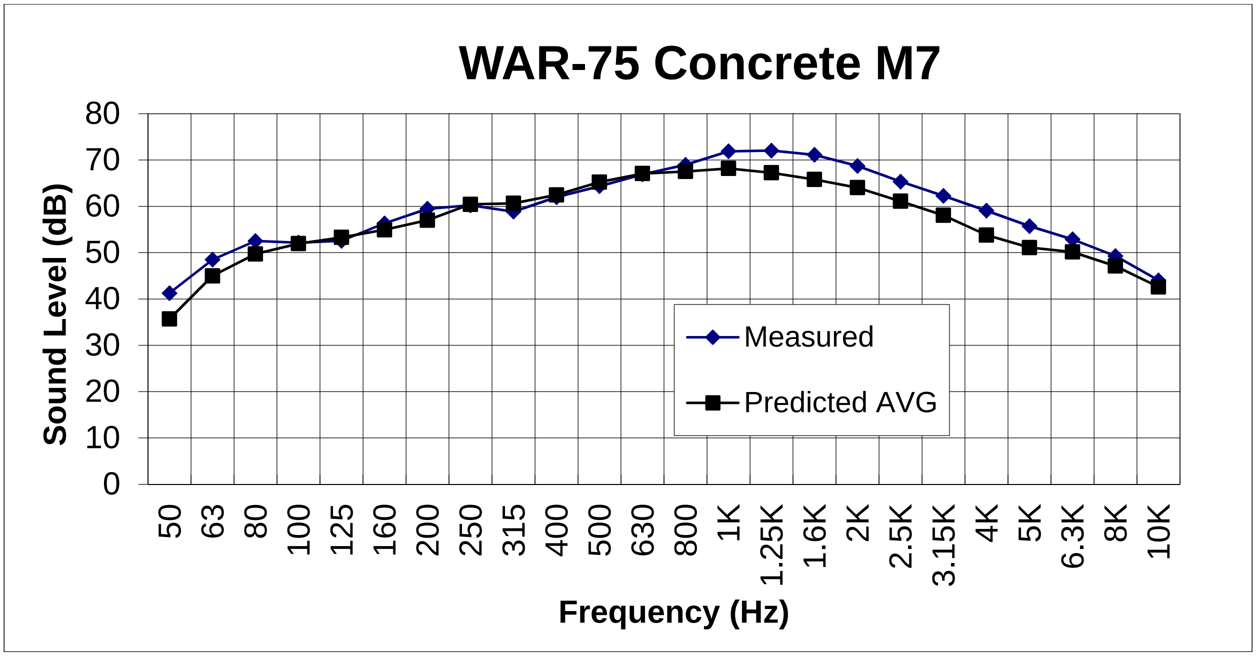

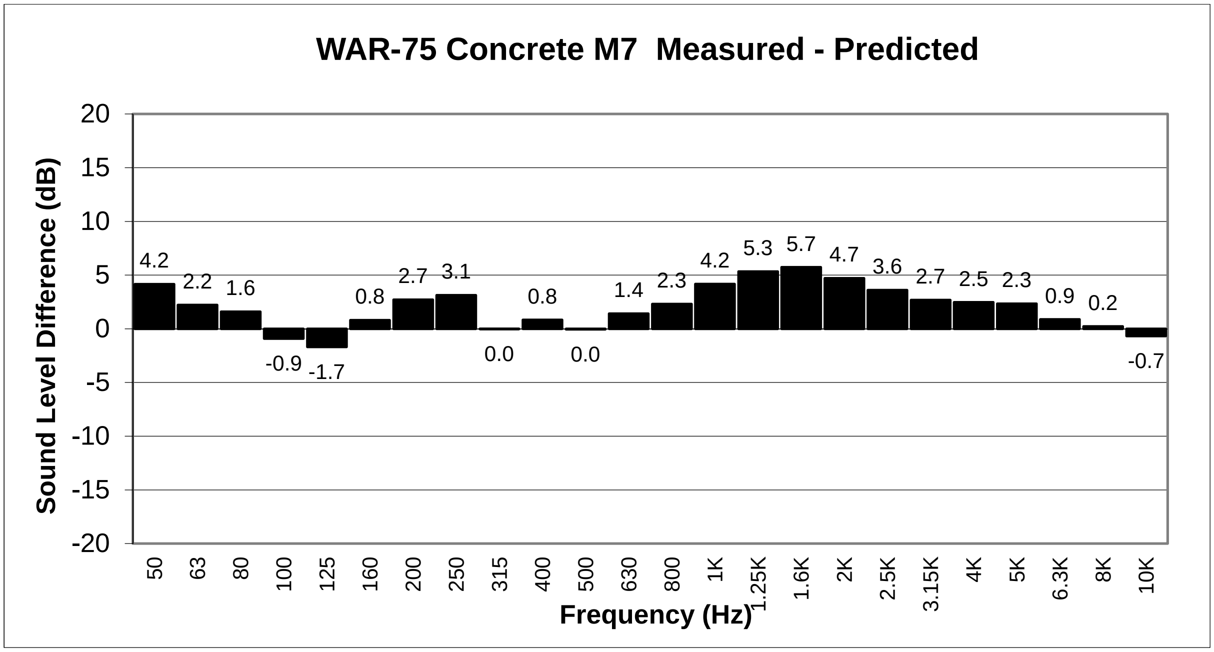

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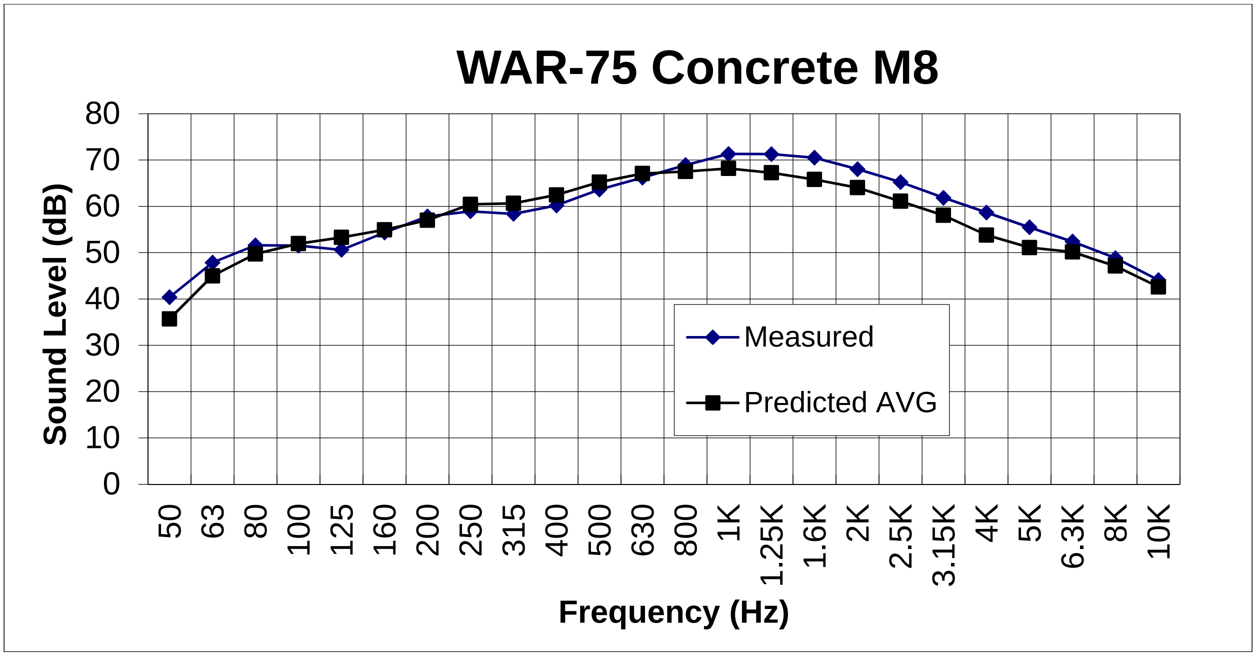
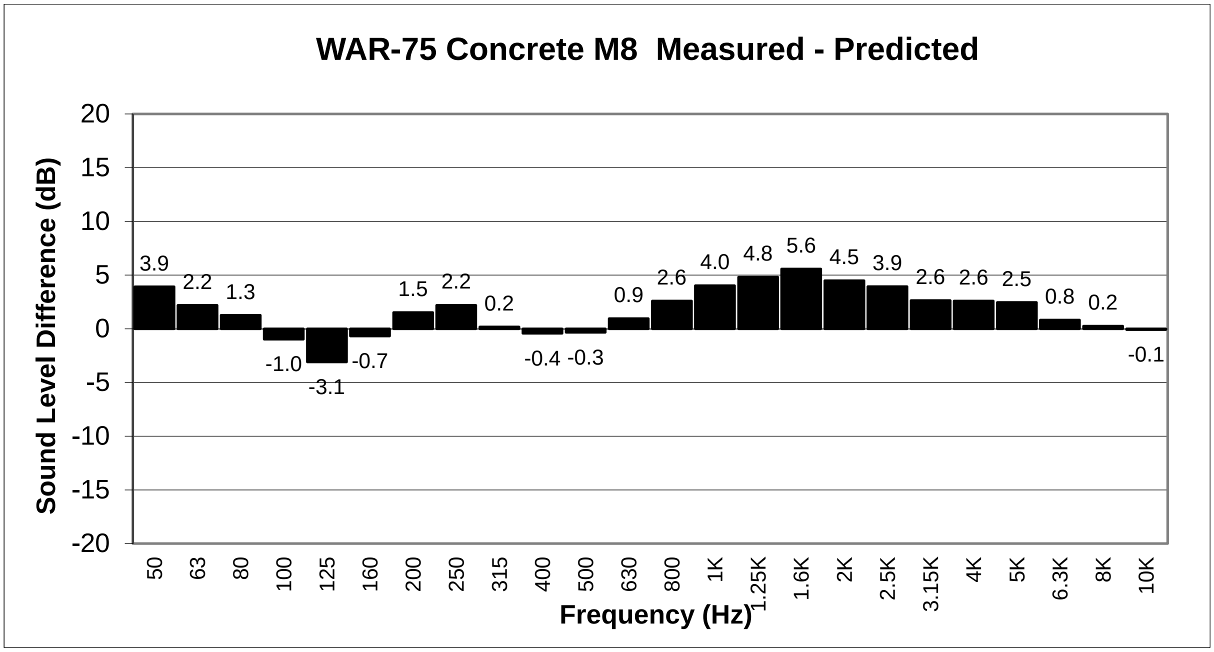
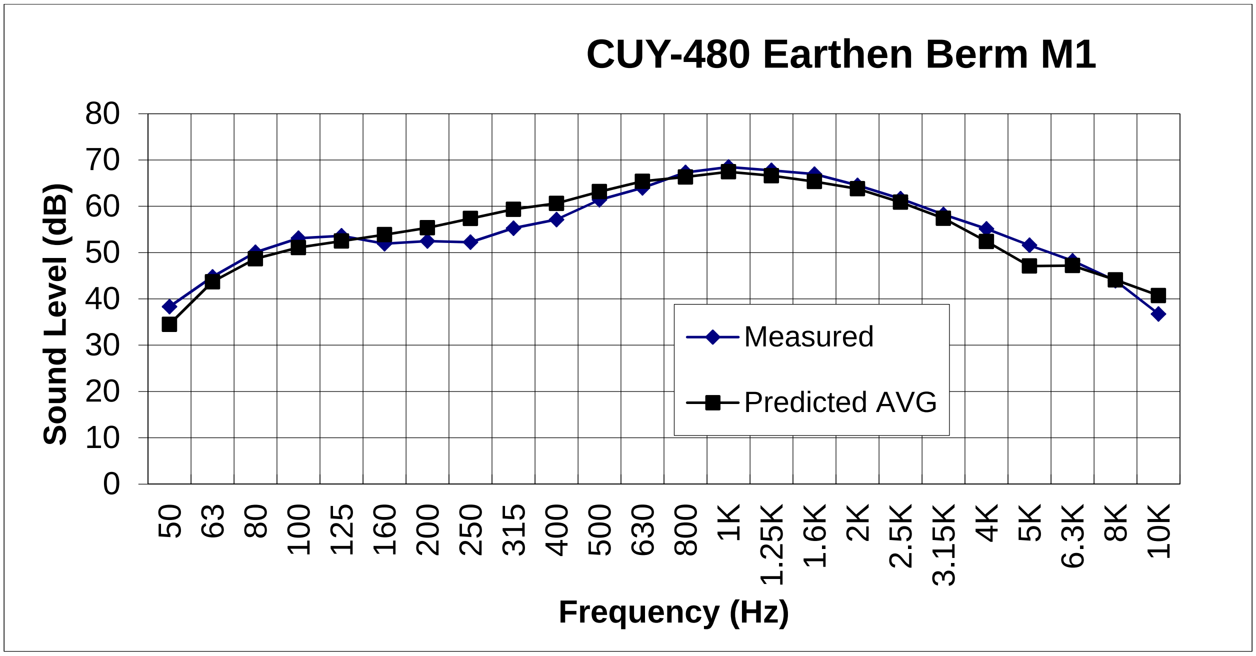
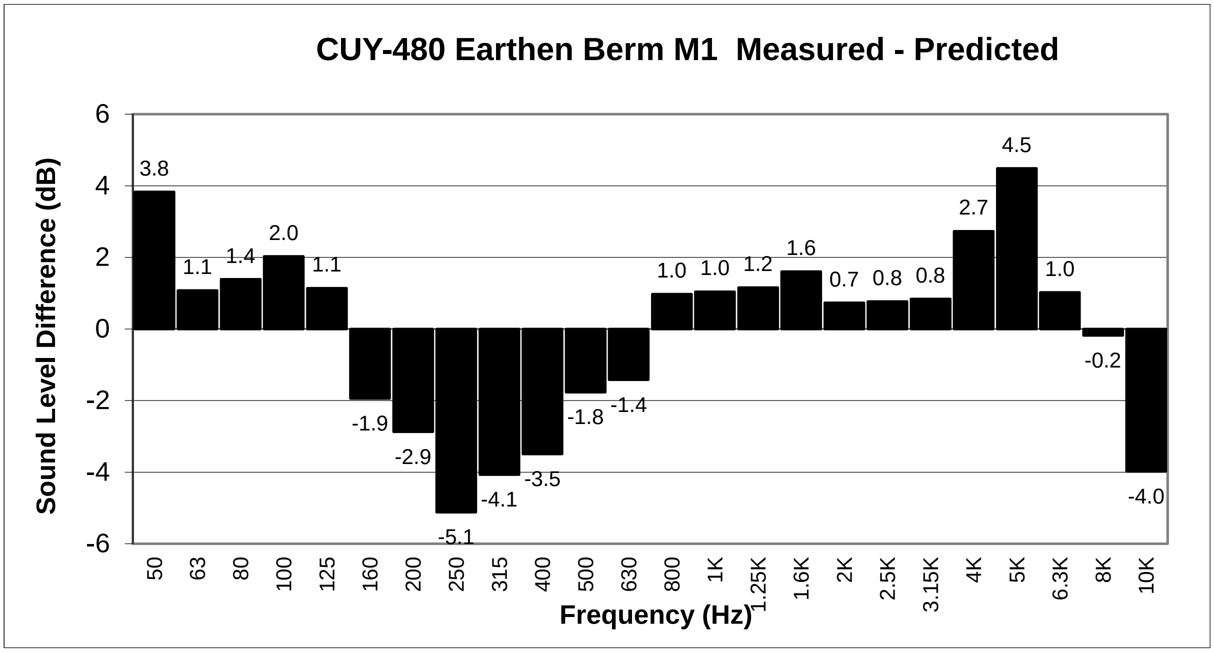


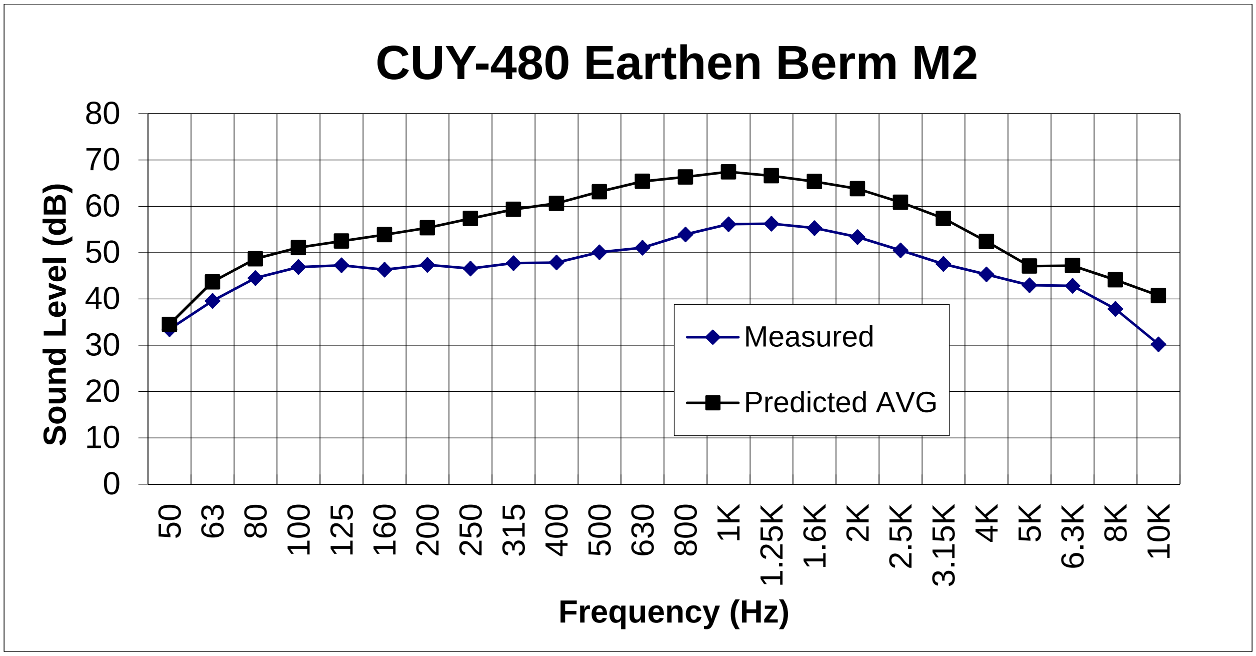


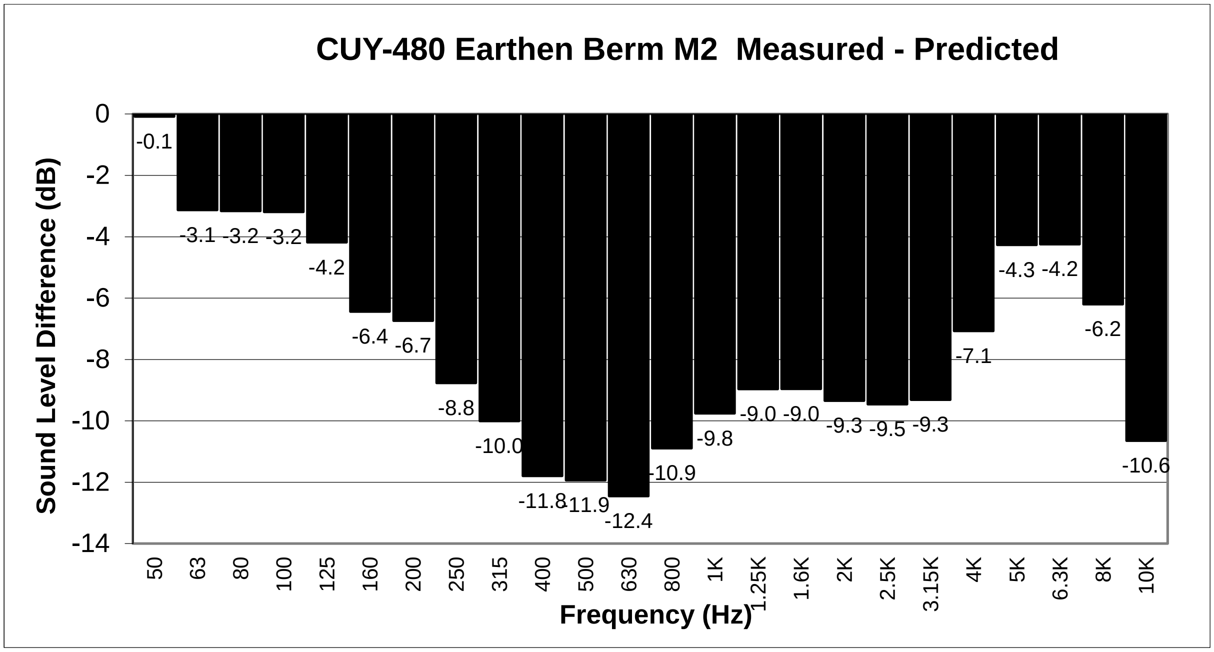
Site 7: Cuyahoga County, I-480; Earthen Berm



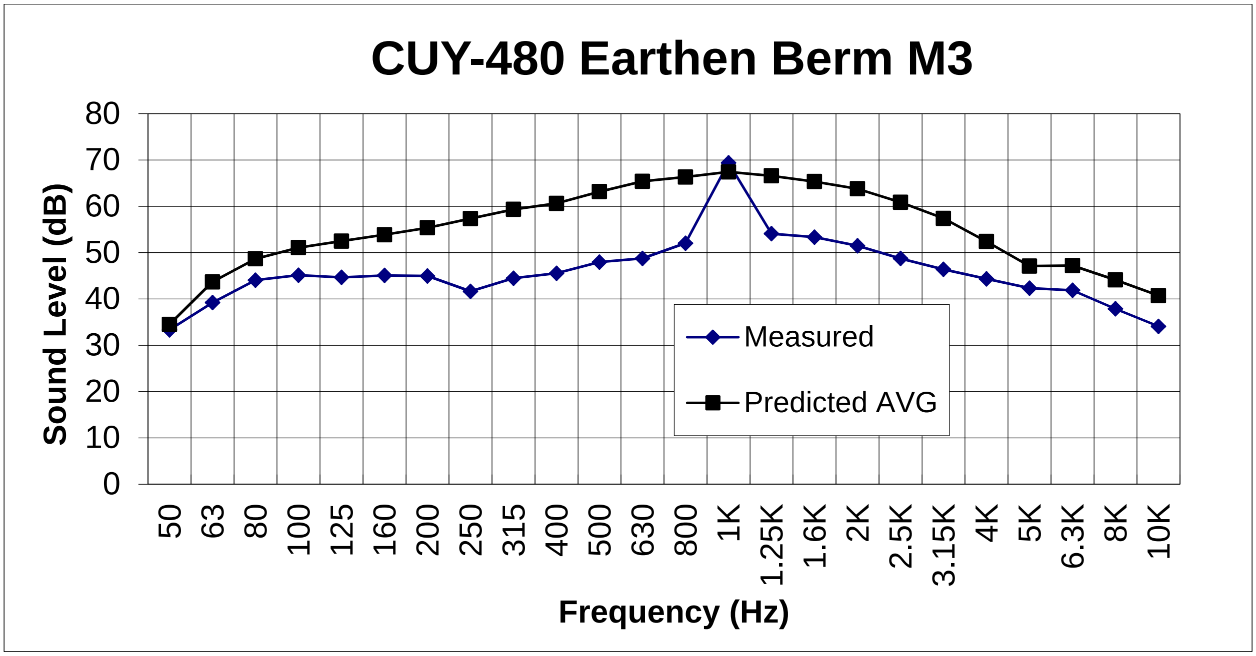


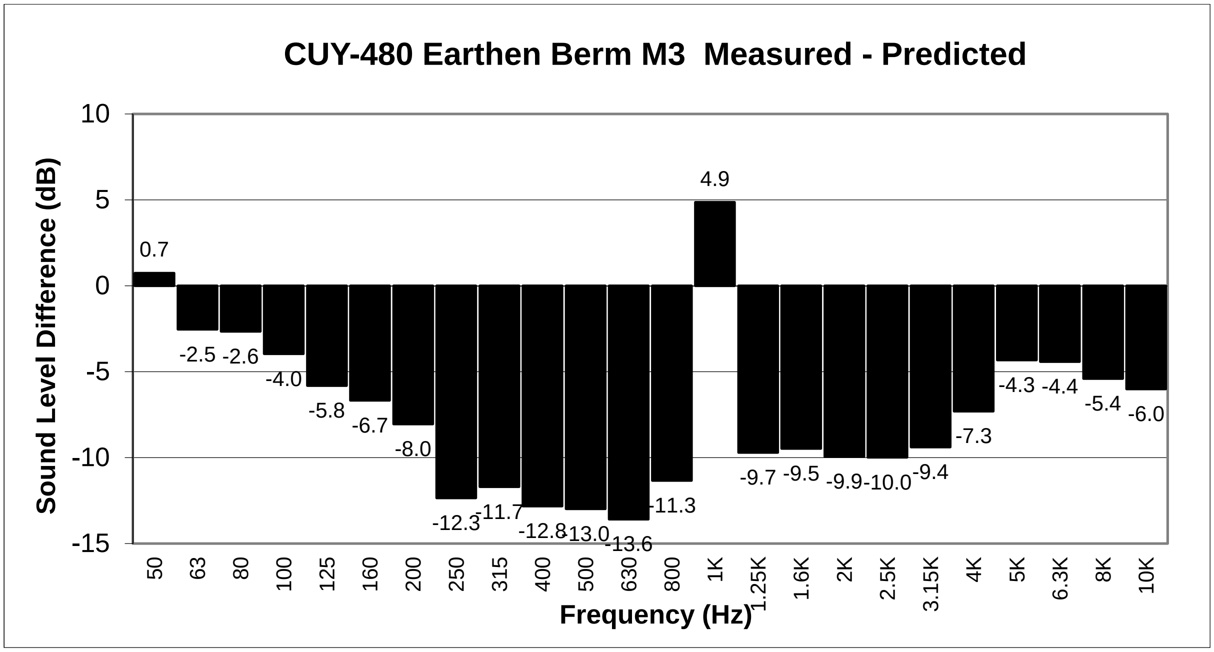
Site 7: Cuyahoga County, I-480; Earthen Berm





Site 7: Cuyahoga County, I-480; Earthen Berm





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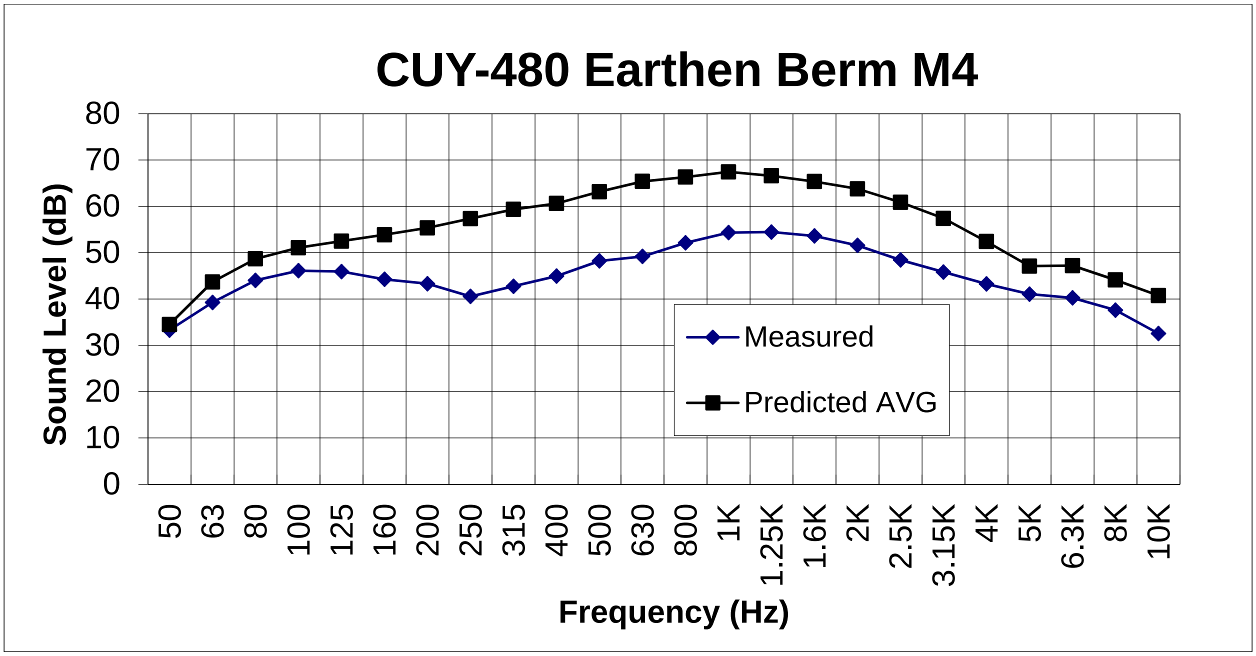
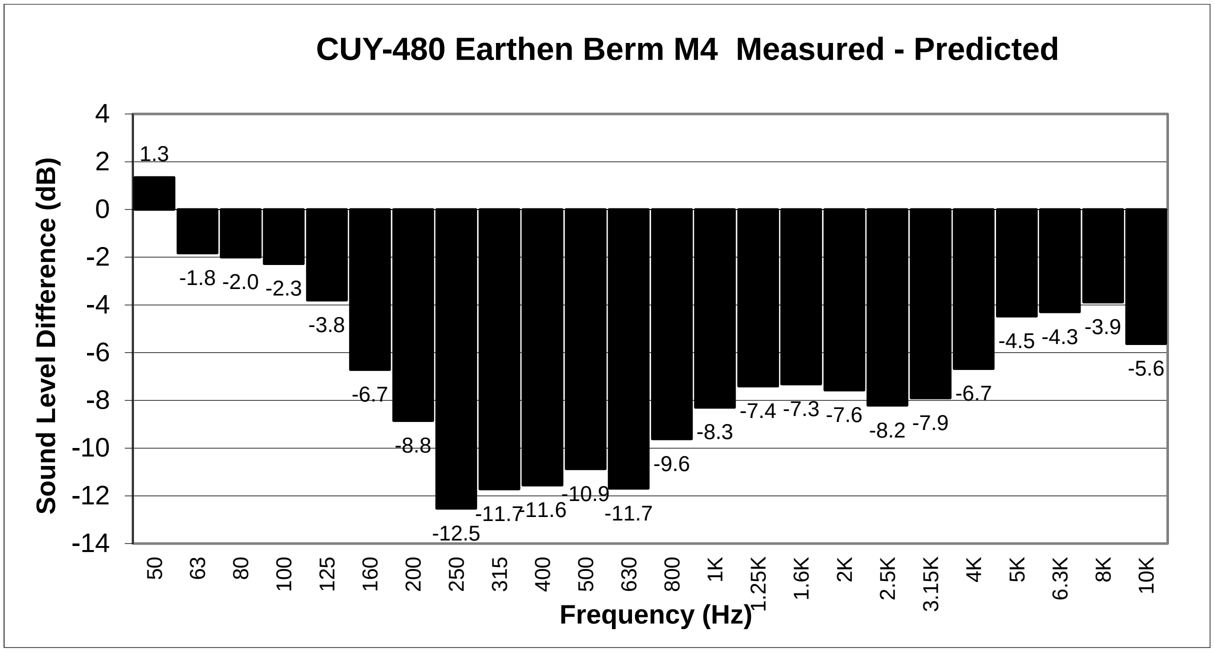
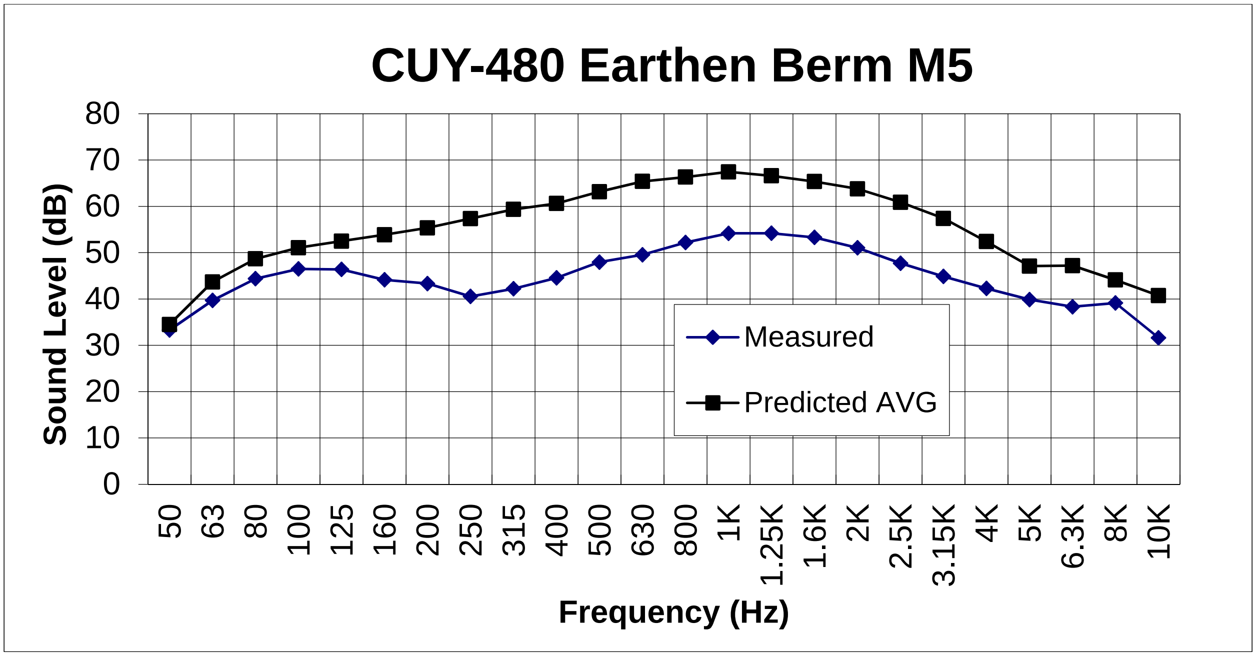
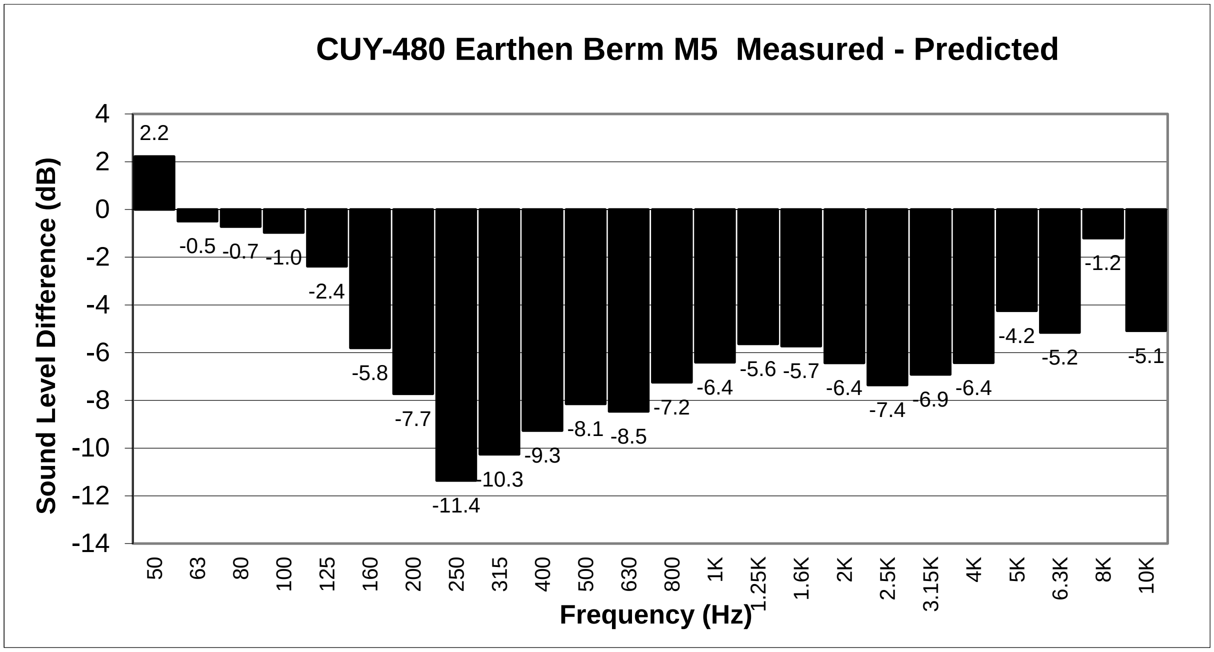


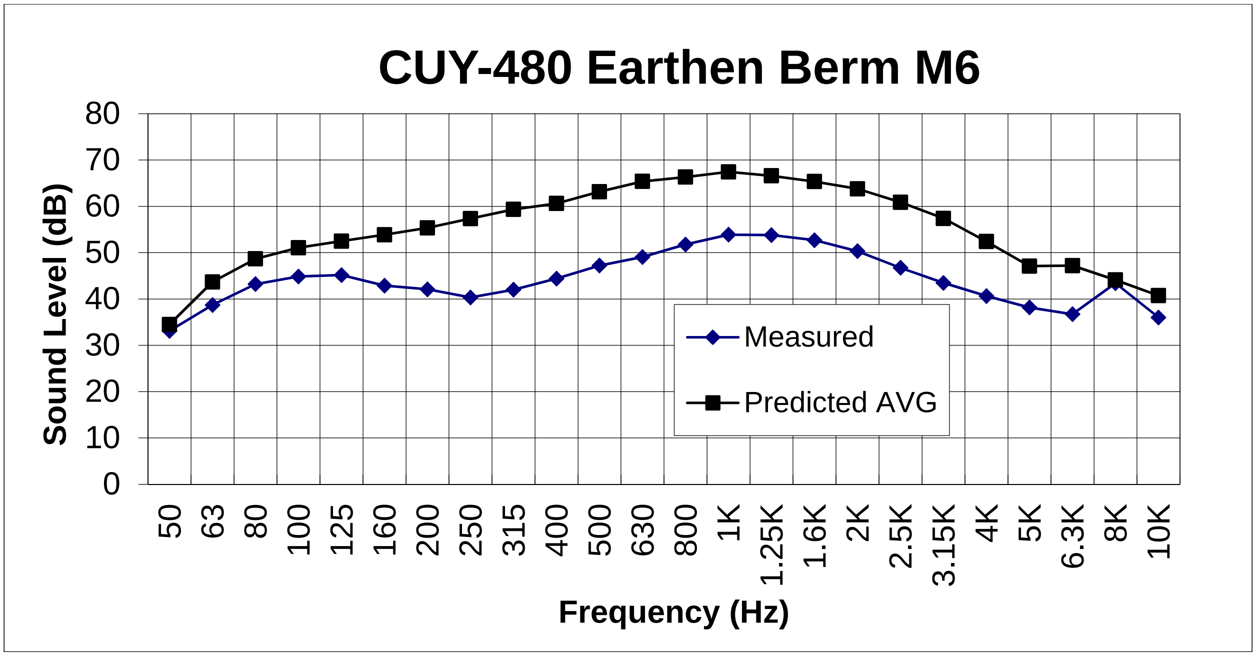


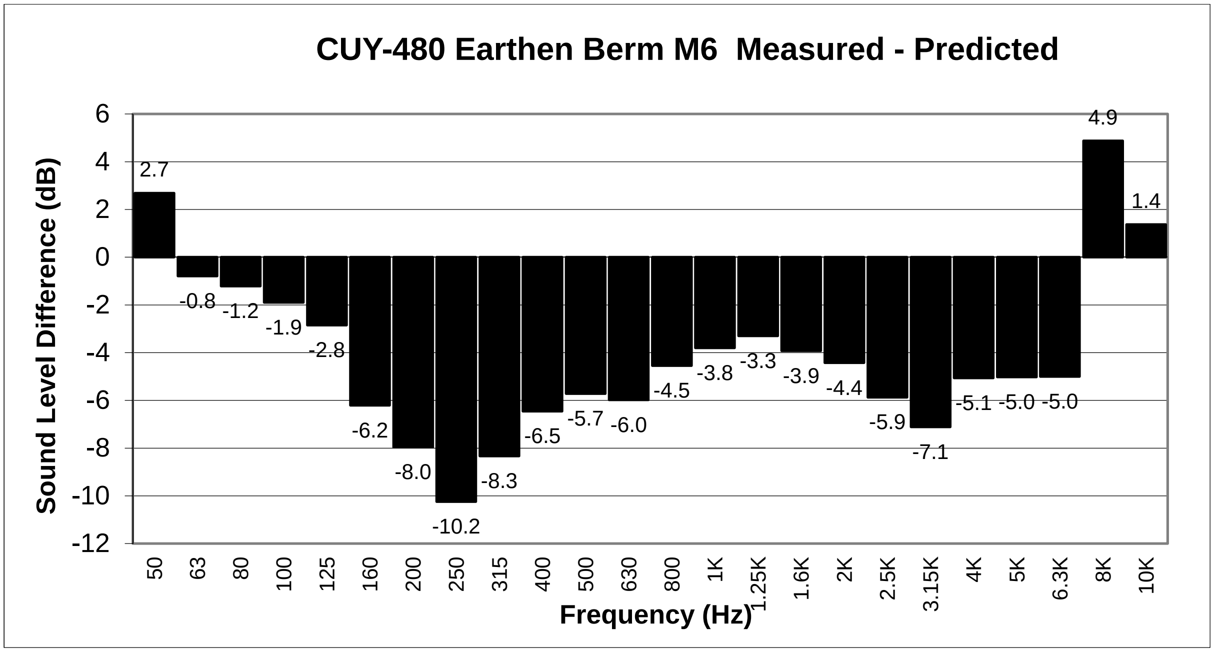
Site 7: Cuyahoga County, I-480; Earthen Berm





Site 7: Cuyahoga County, I-480; Earthen Berm





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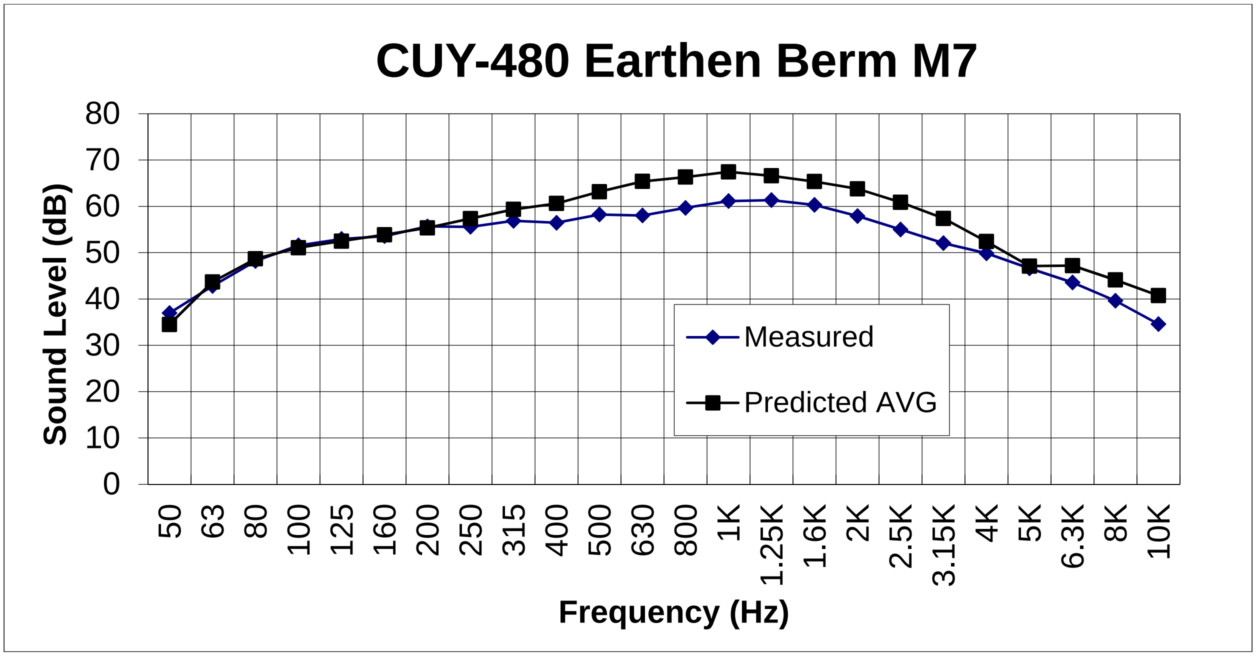
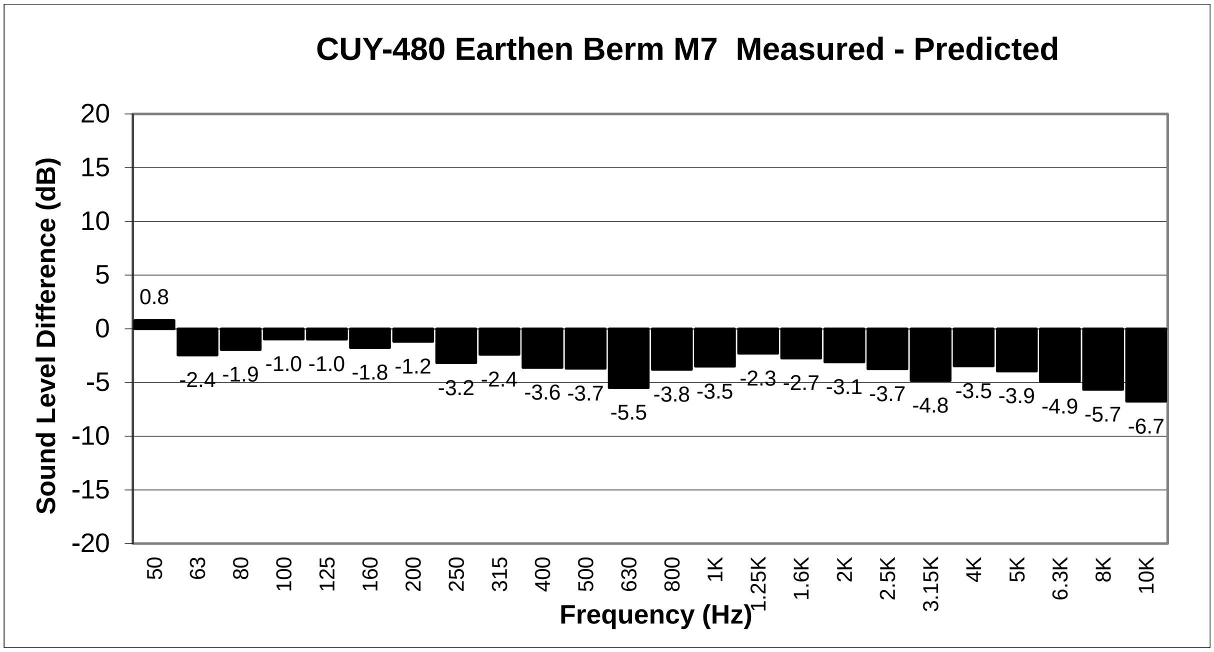
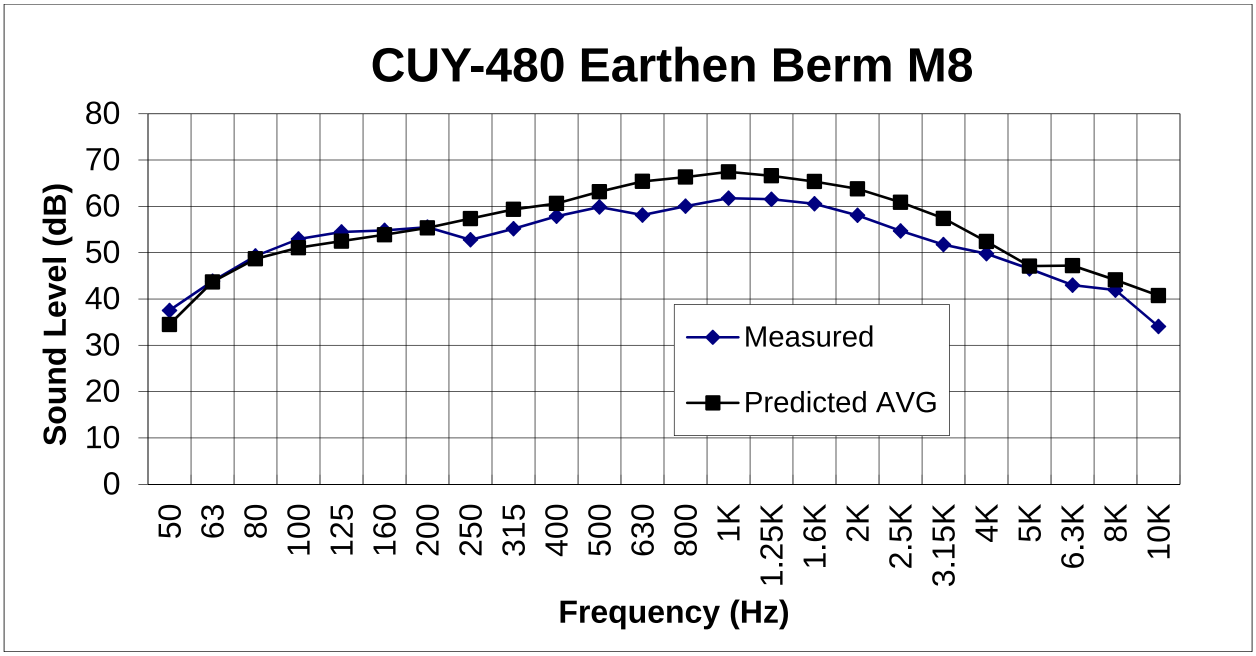
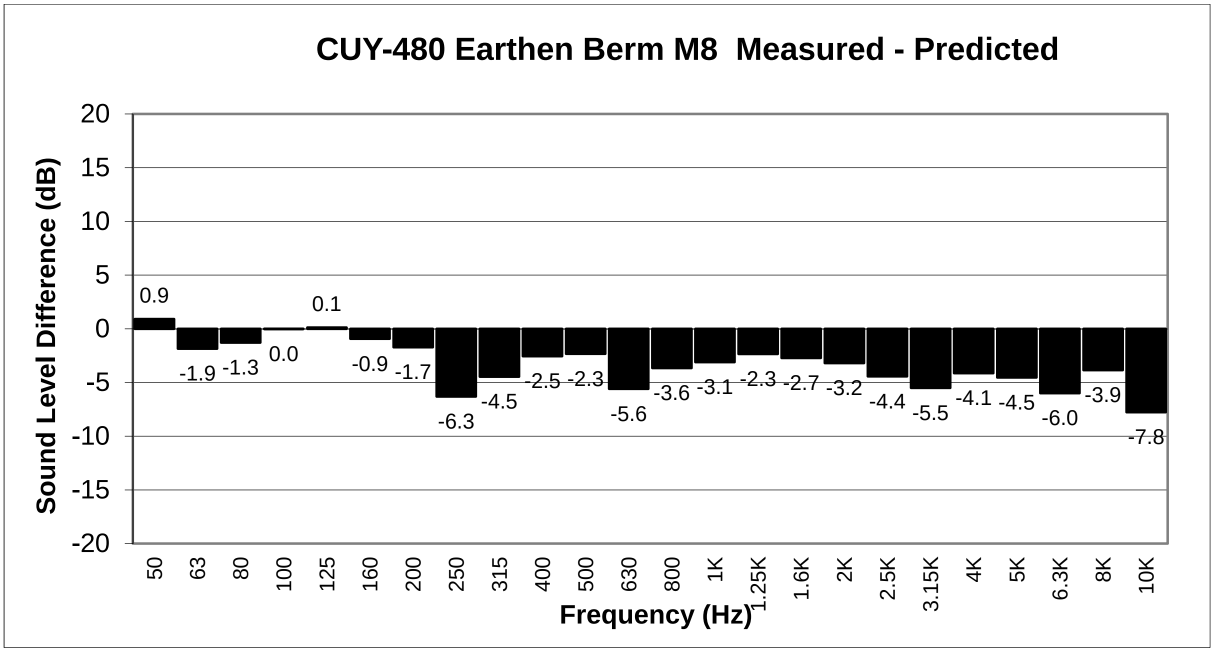


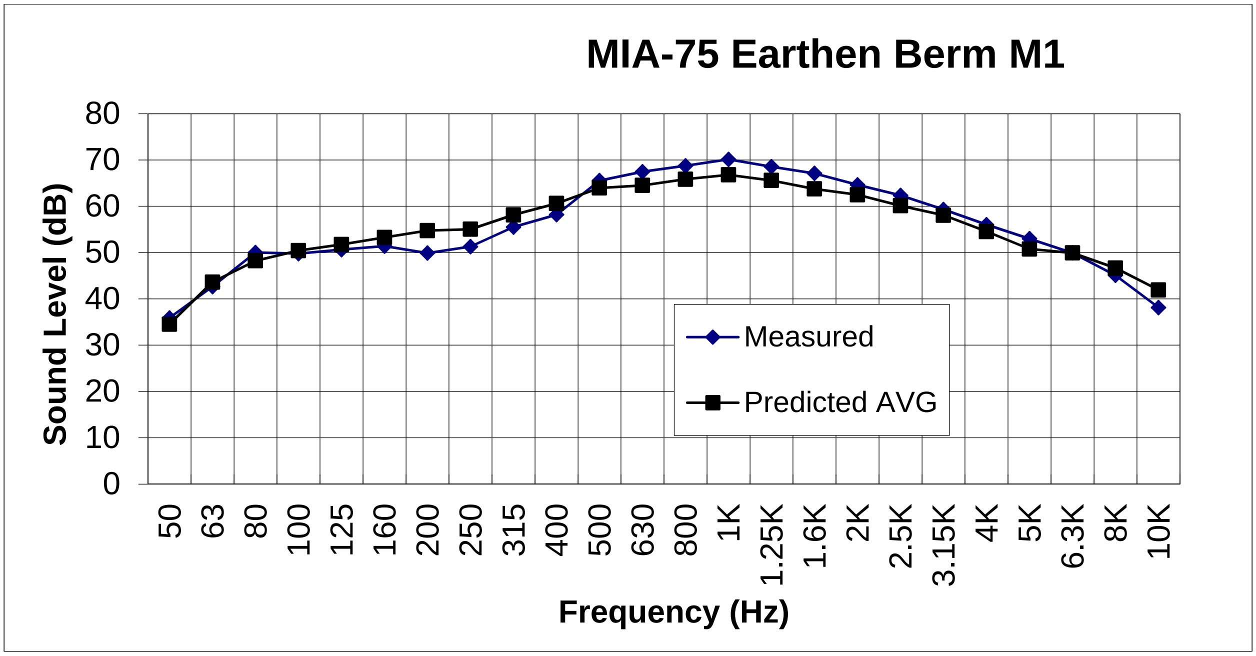


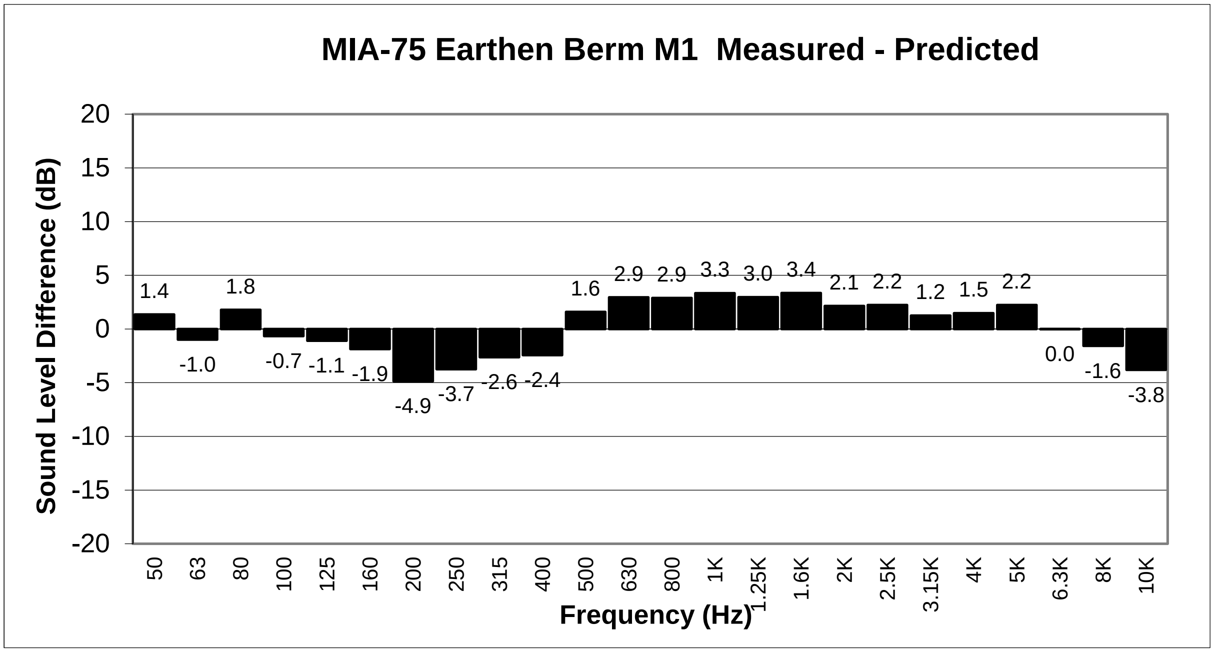
Site 7: Cuyahoga County, I-480; Earthen Berm



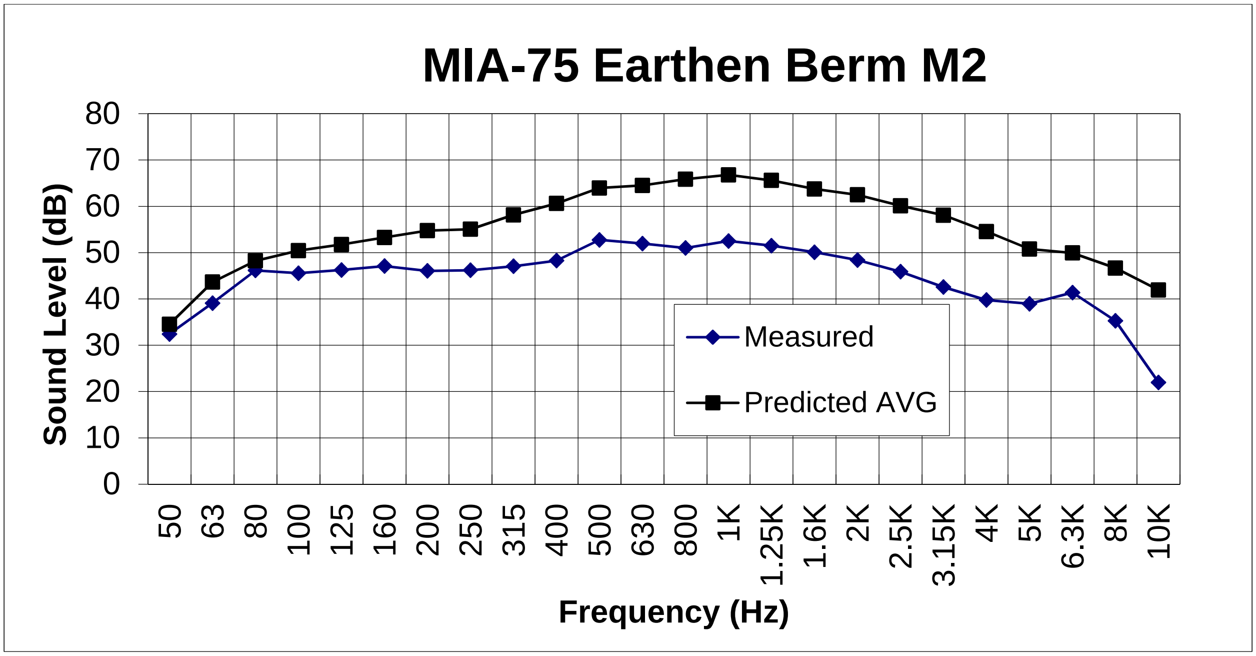


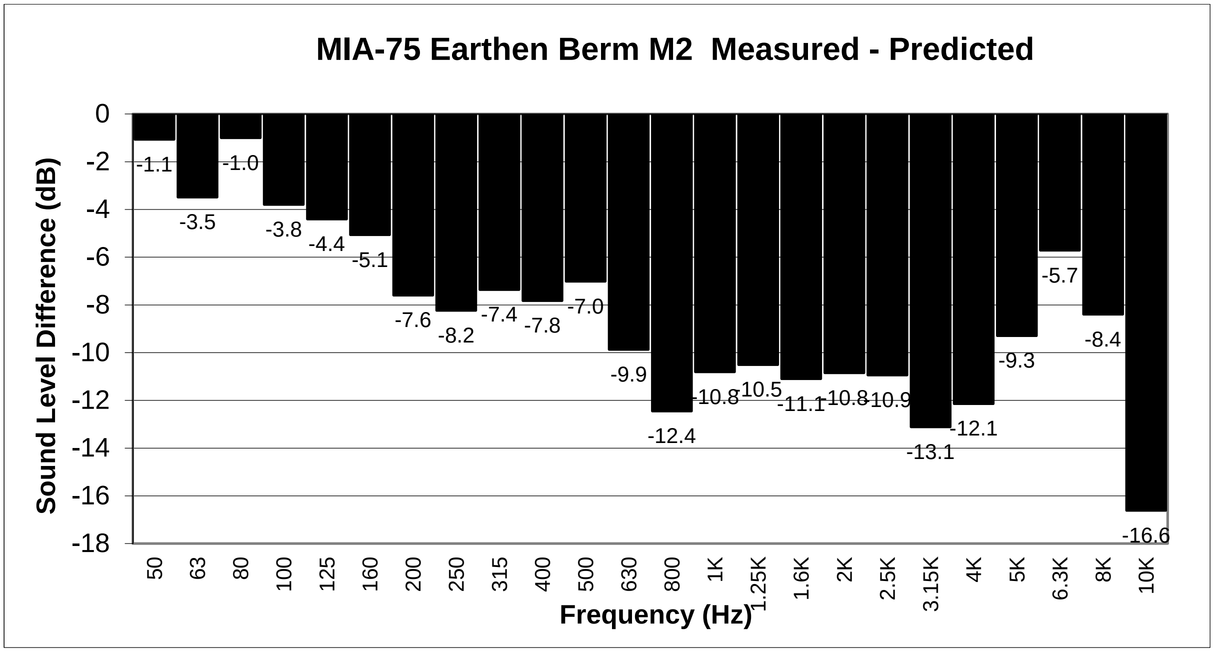
Site 8: Miami County, I-75; Earthen Berm



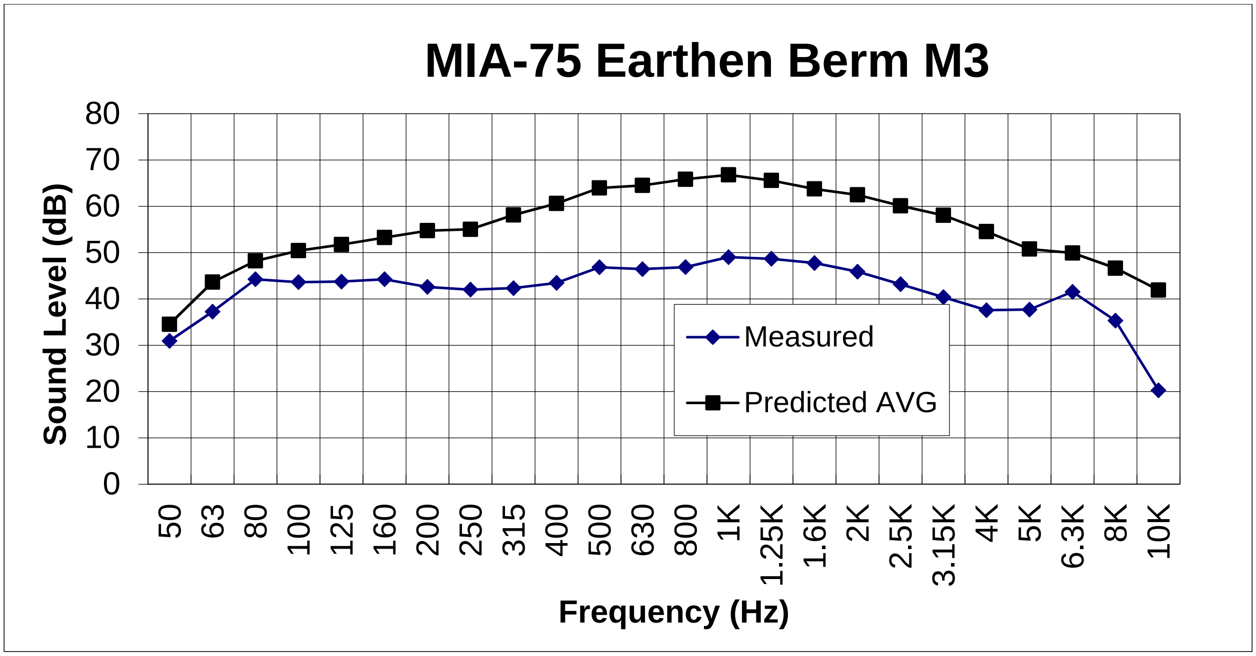


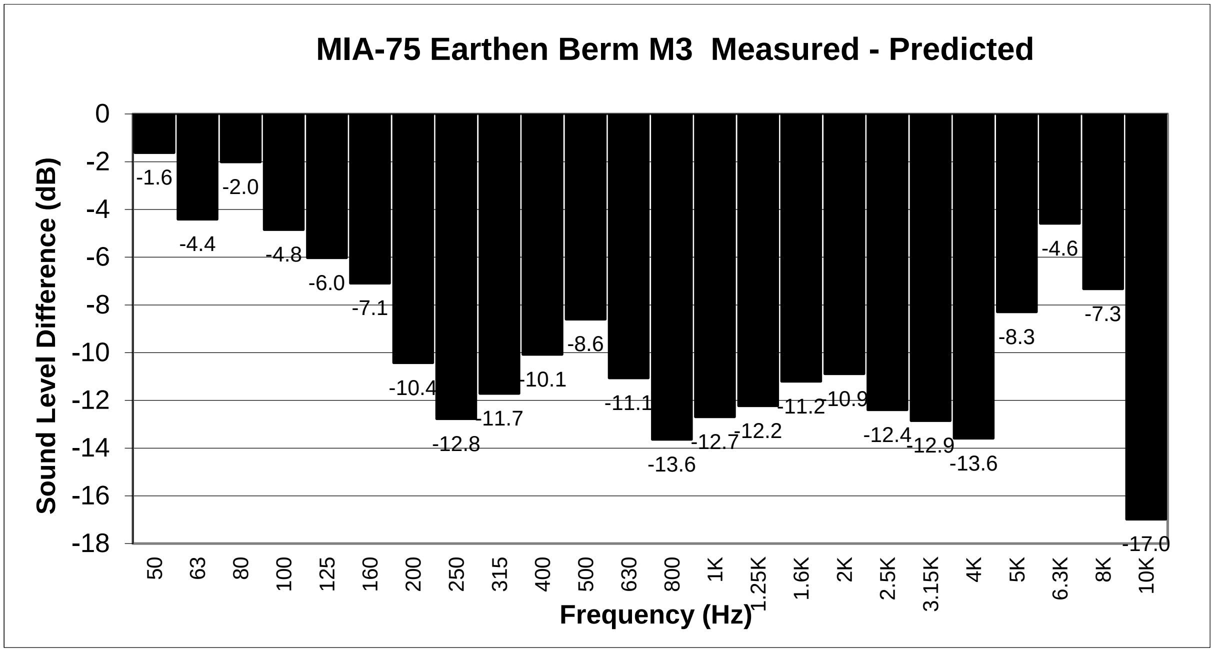
Site 8: Miami County, I-75; Earthen Berm



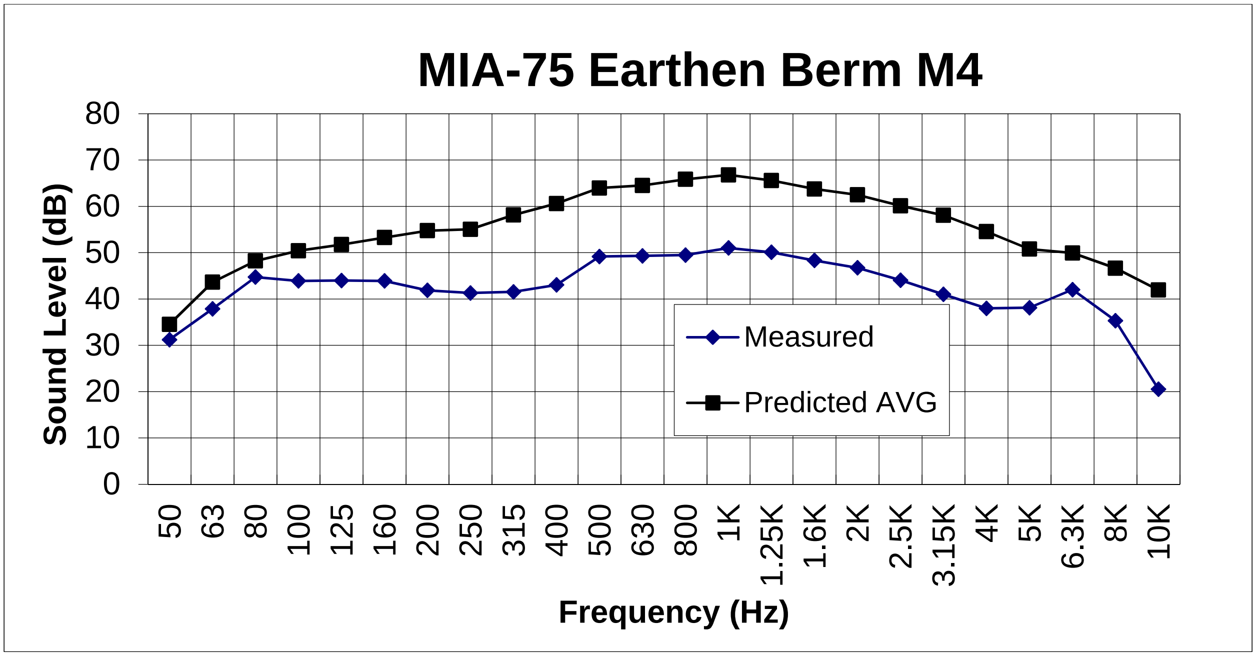


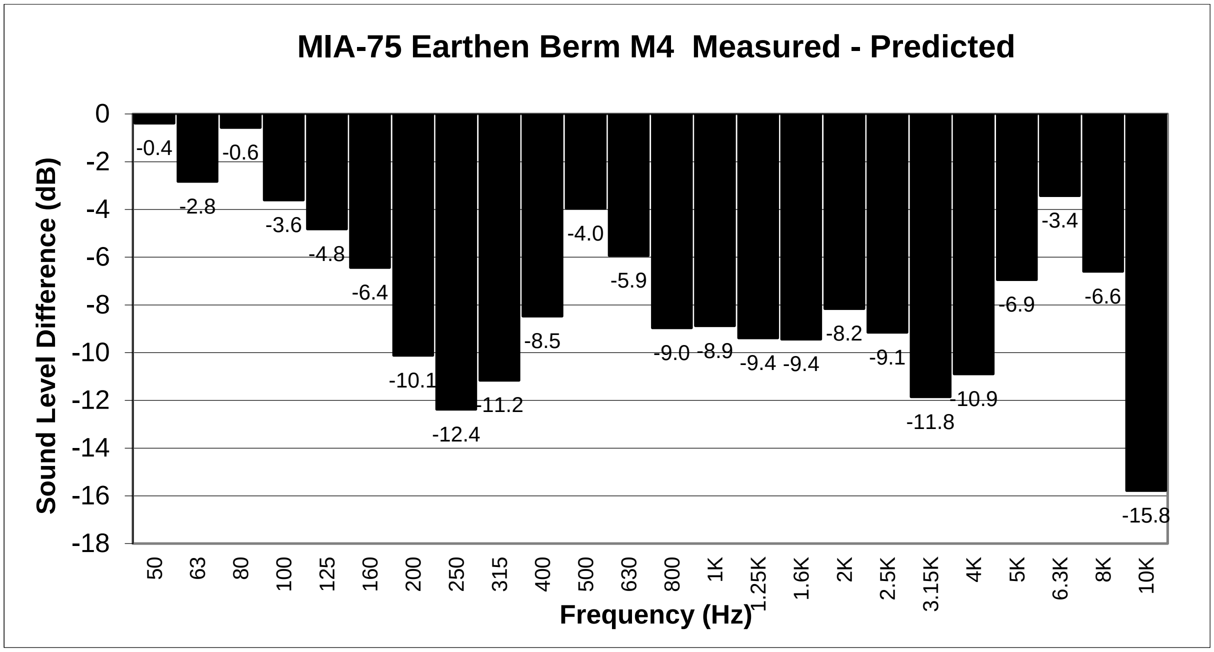
Site 8: Miami County, I-75; Earthen Berm



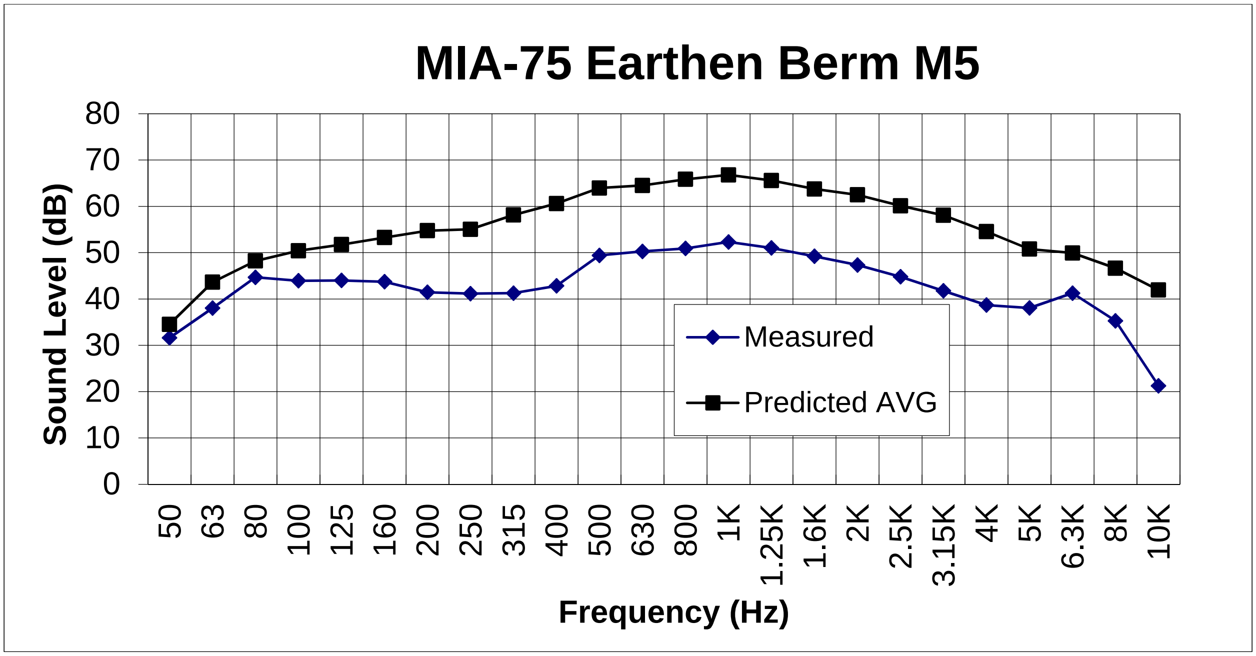


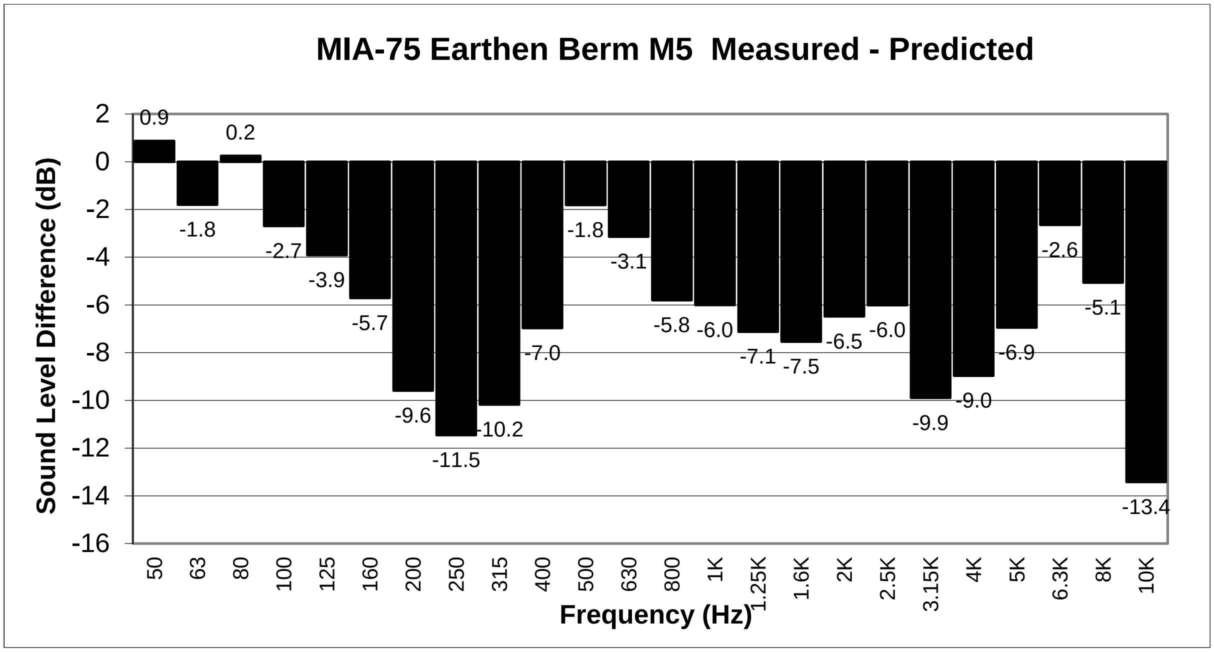
Site 8: Miami County, I-75; Earthen Berm





Site 8: Miami County, I-75; Earthen Berm





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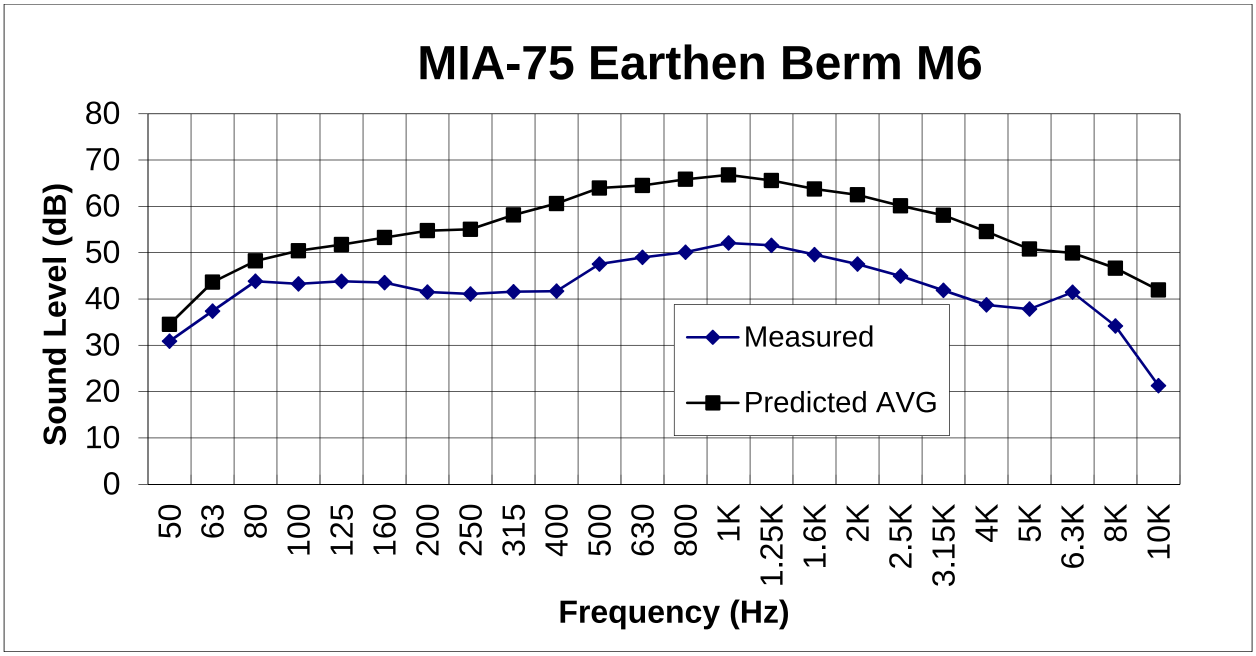

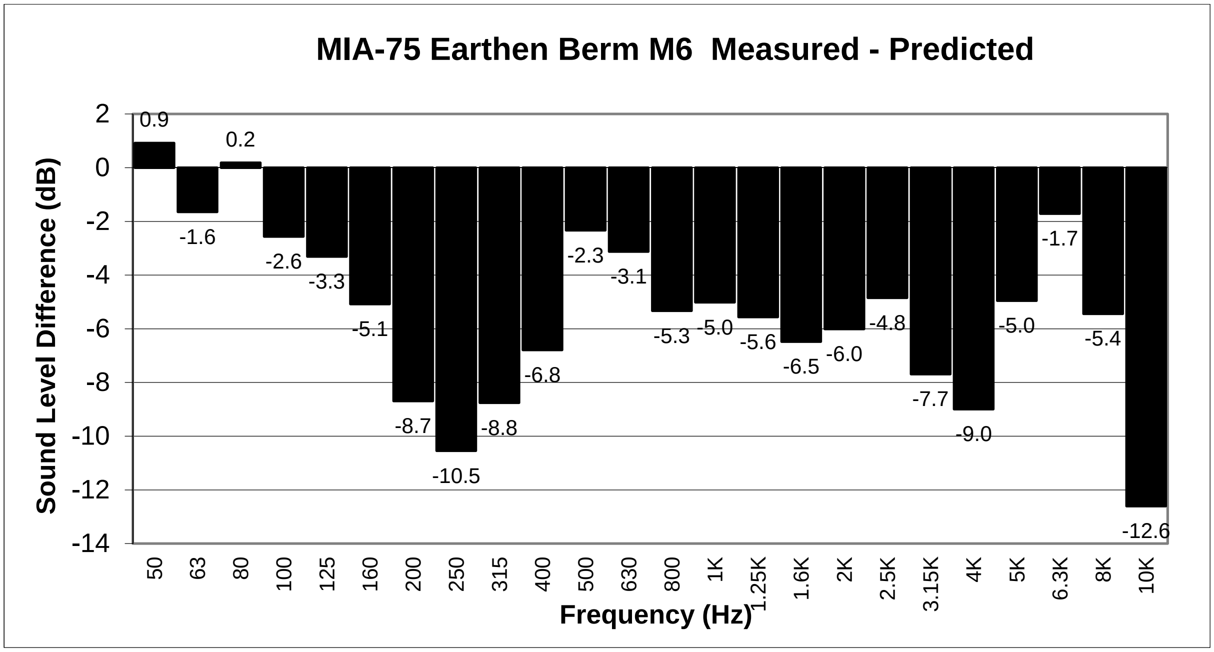

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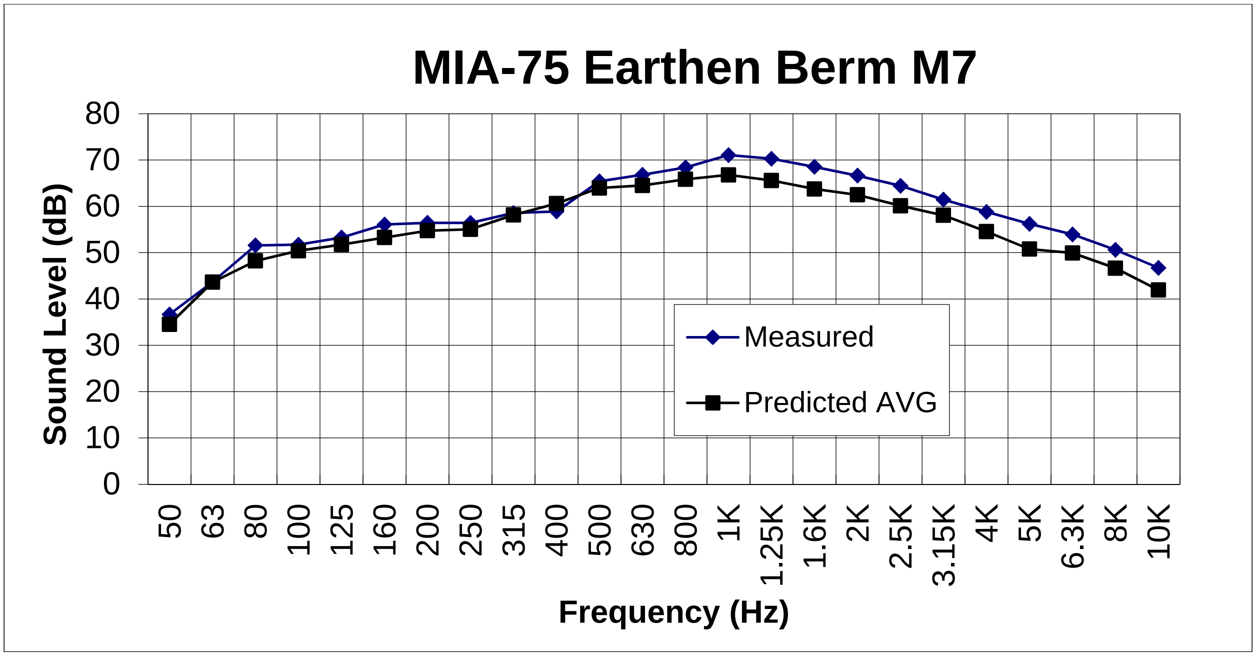
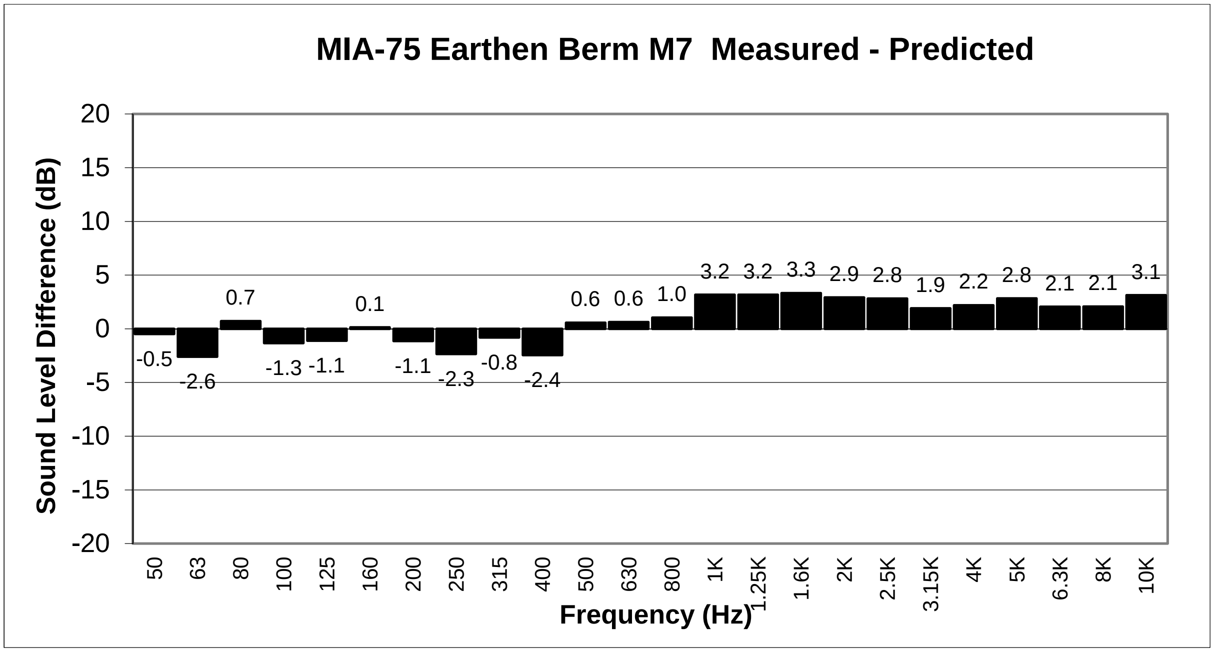
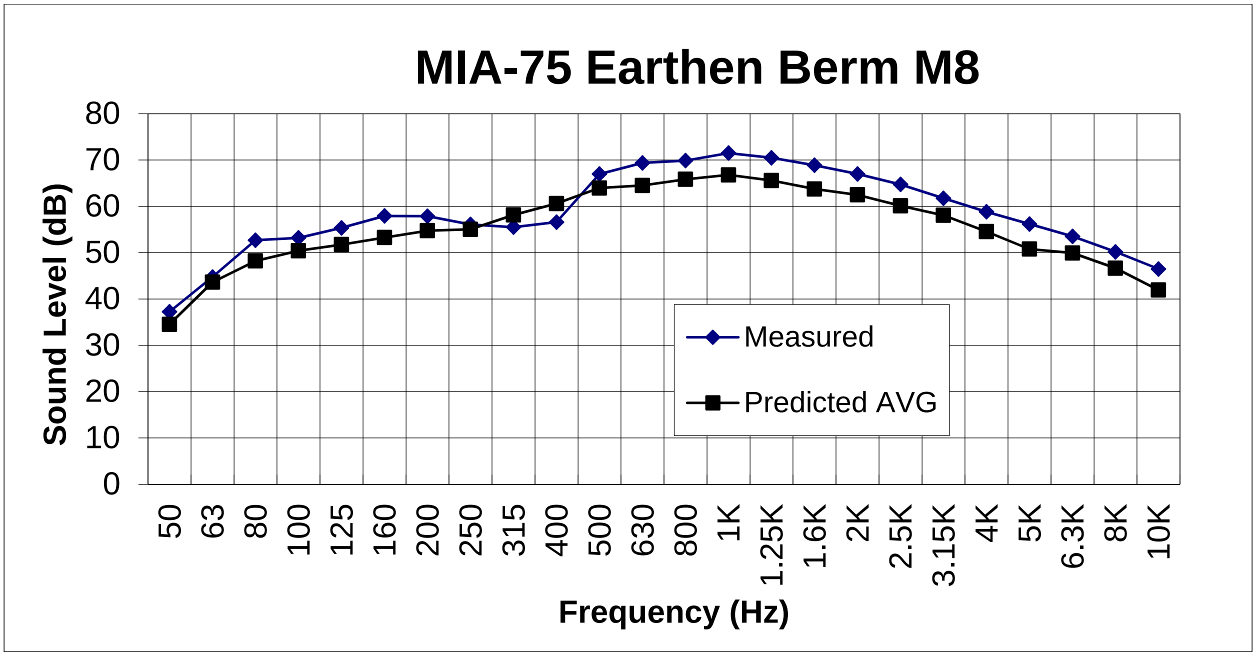
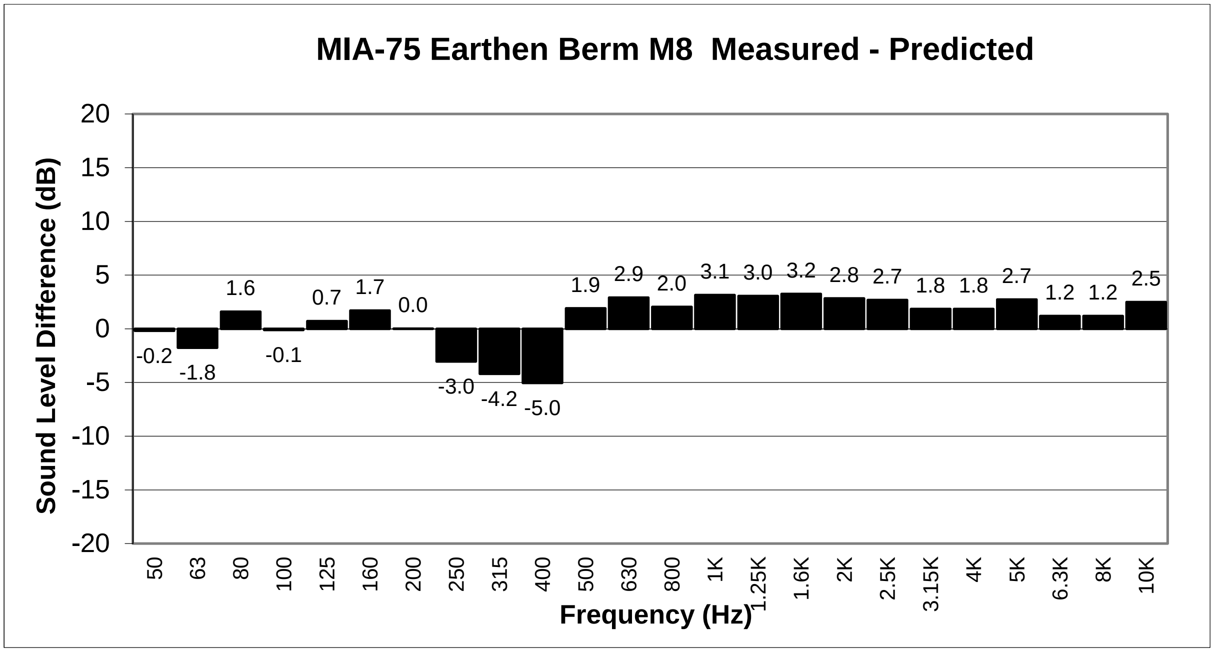


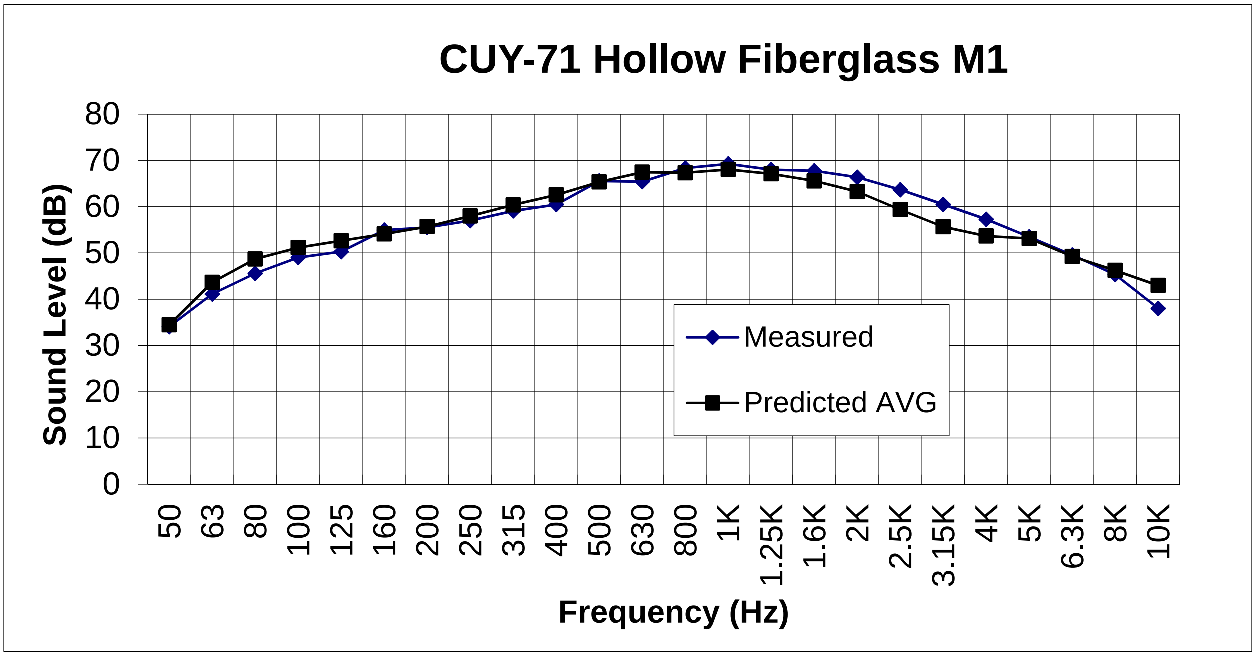


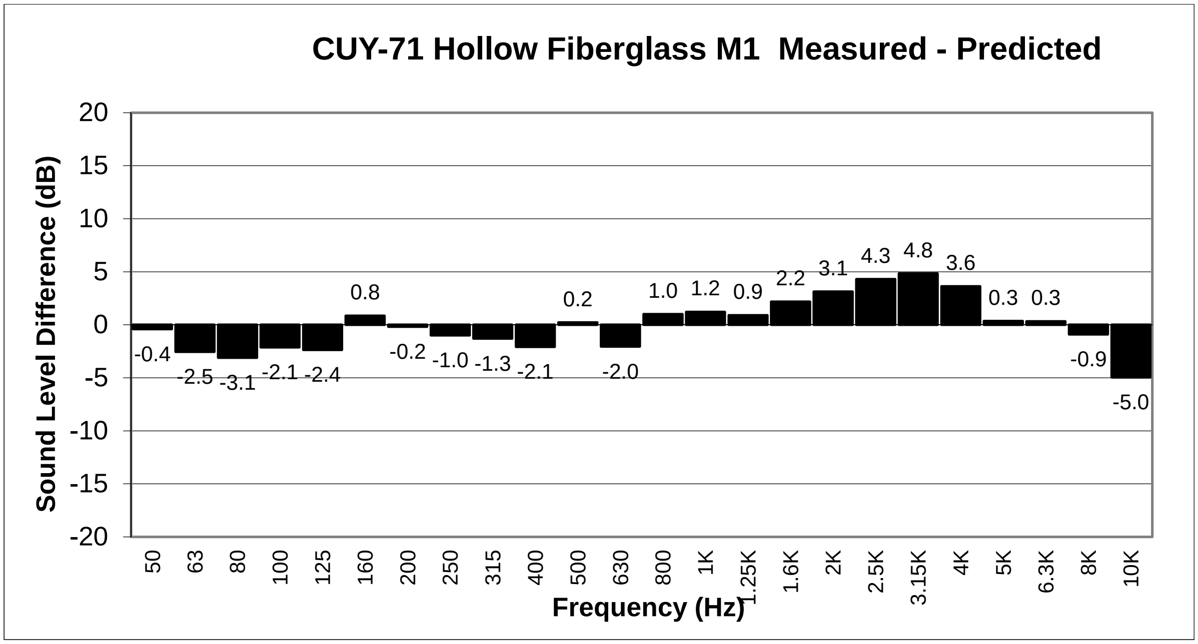
Site 8: Miami County, I-75; Earthen Berm



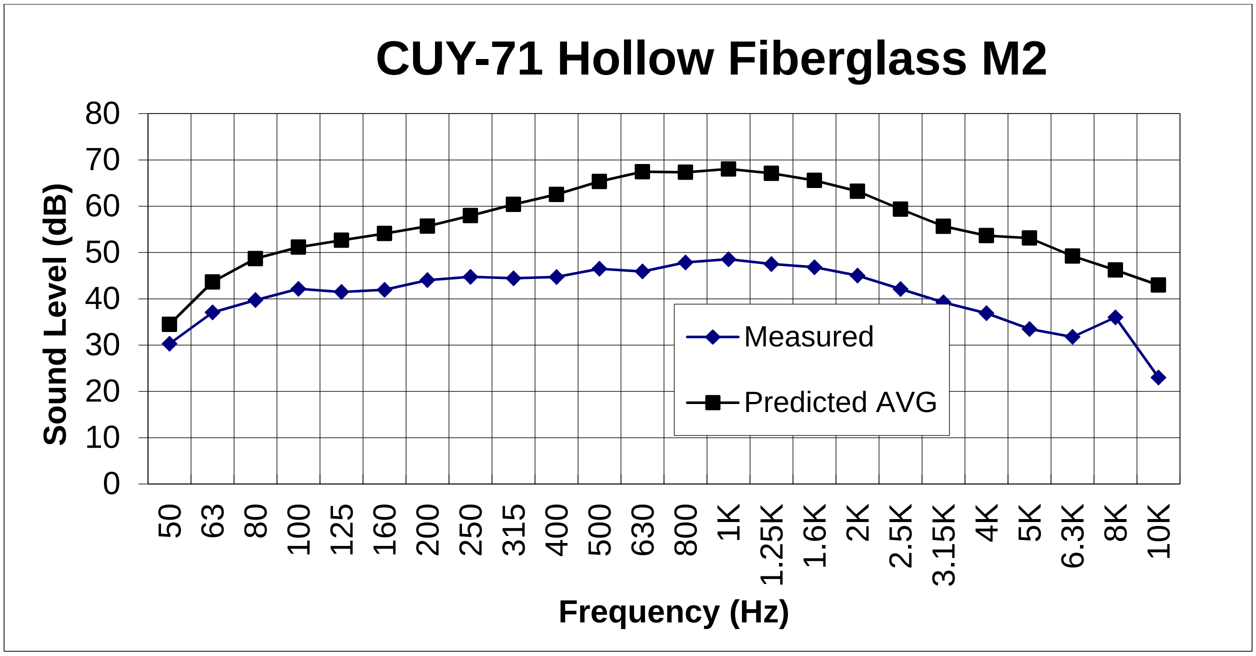


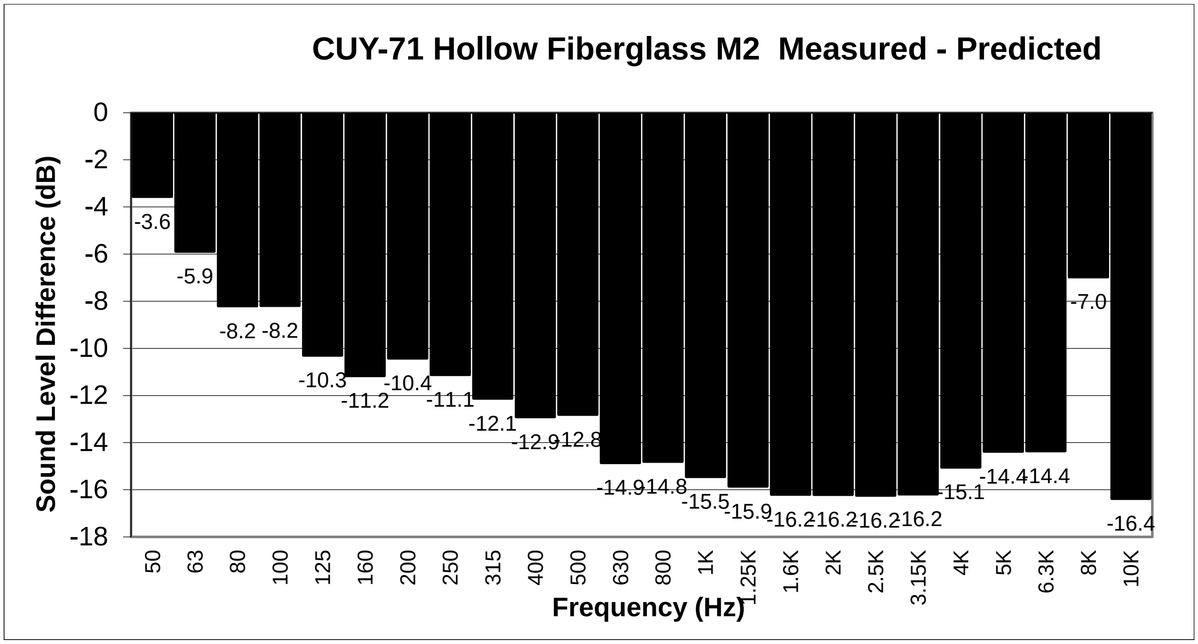
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



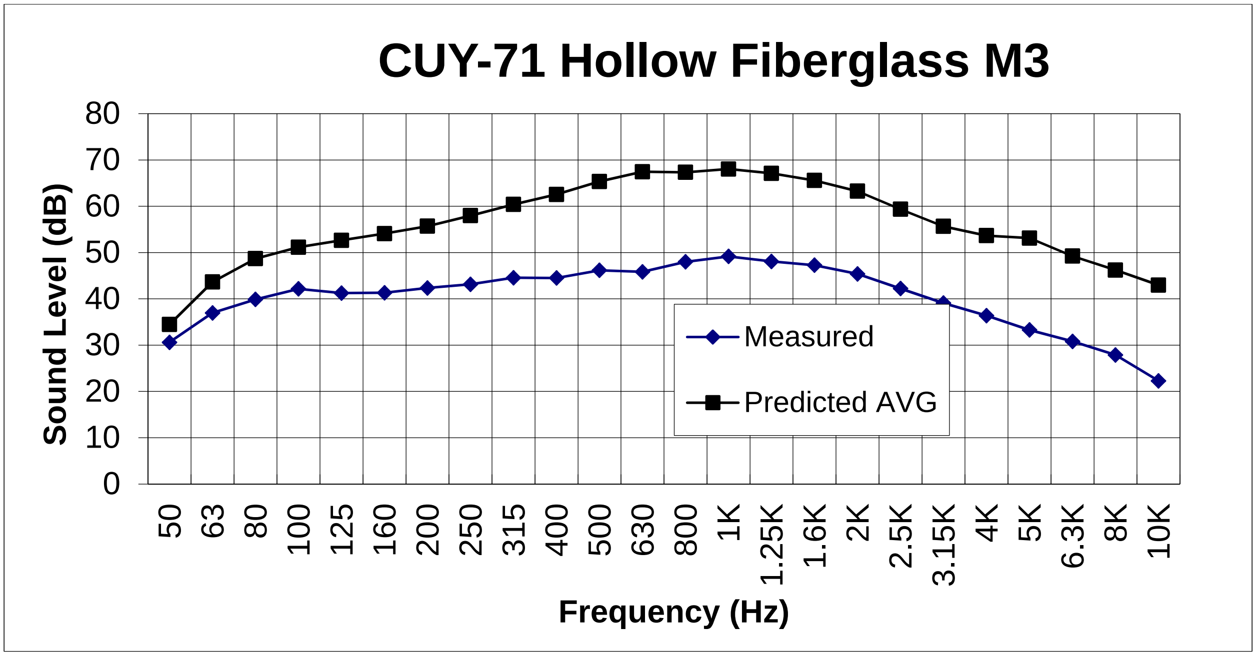


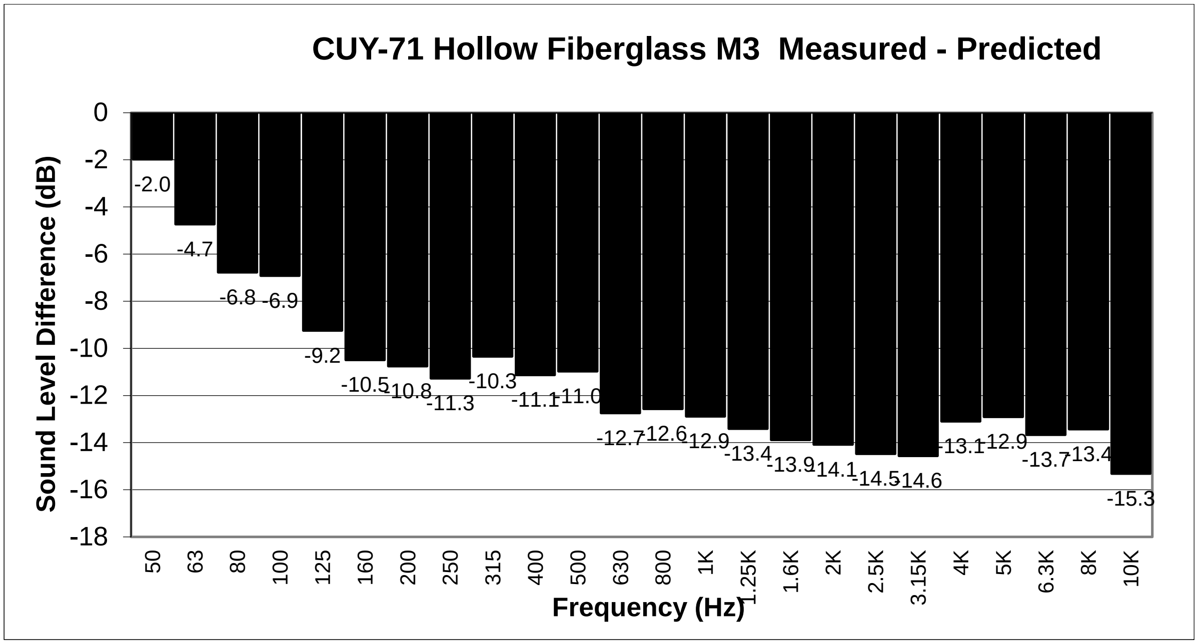
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



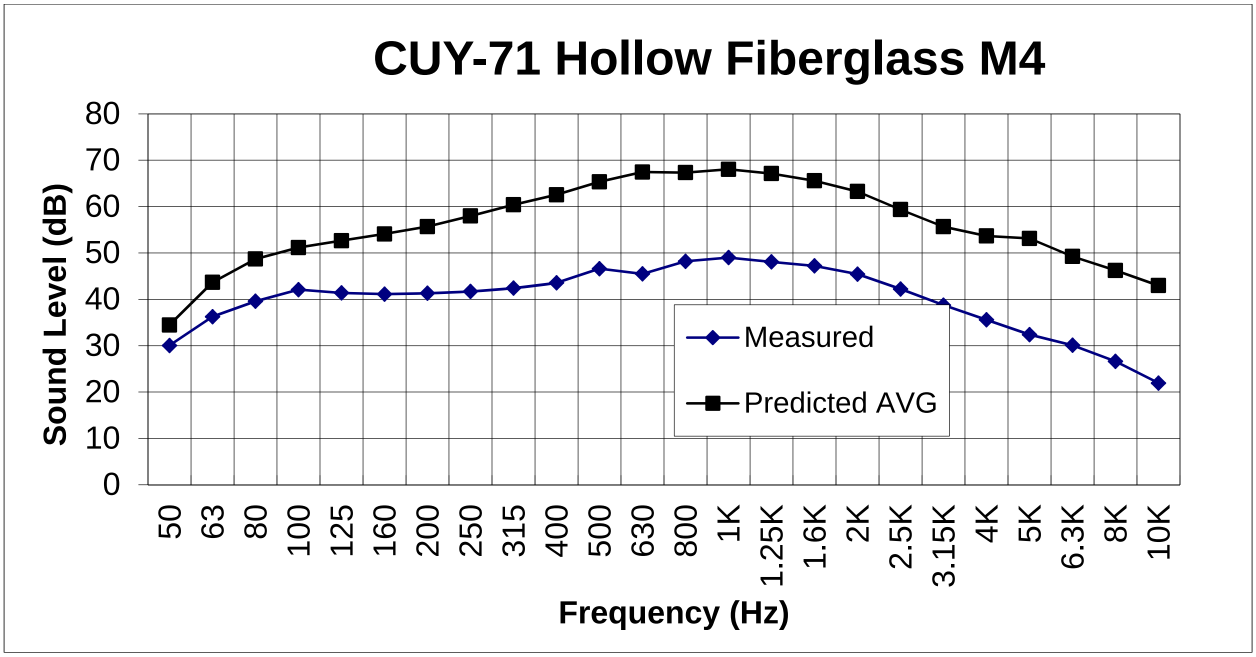


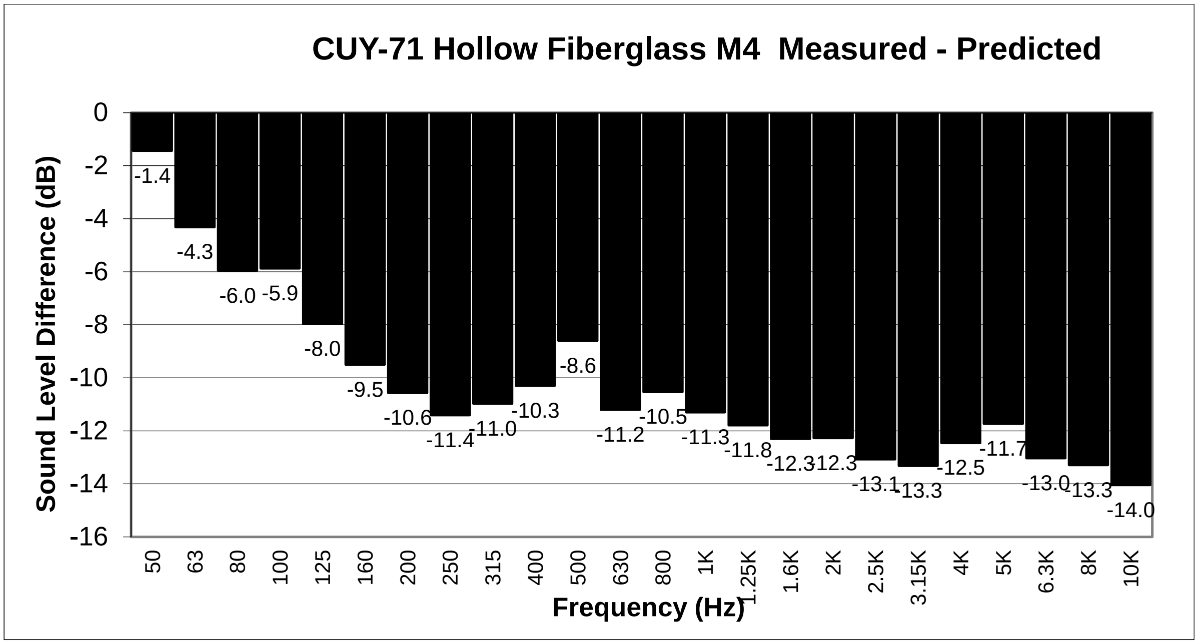
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



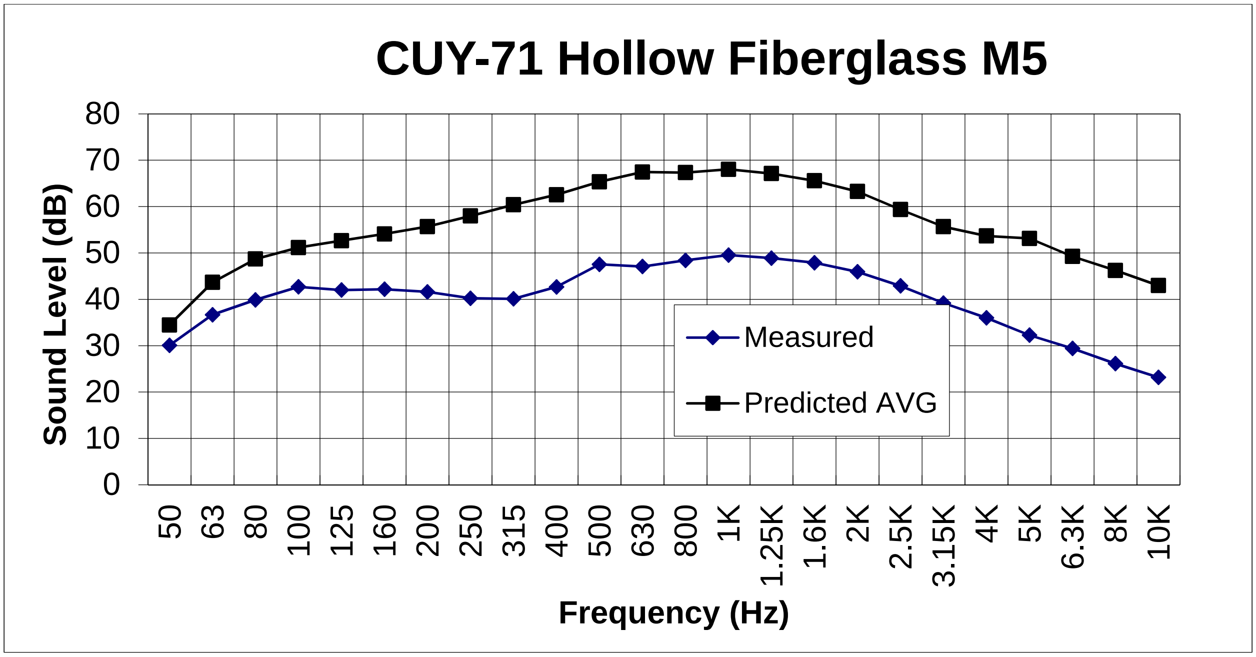


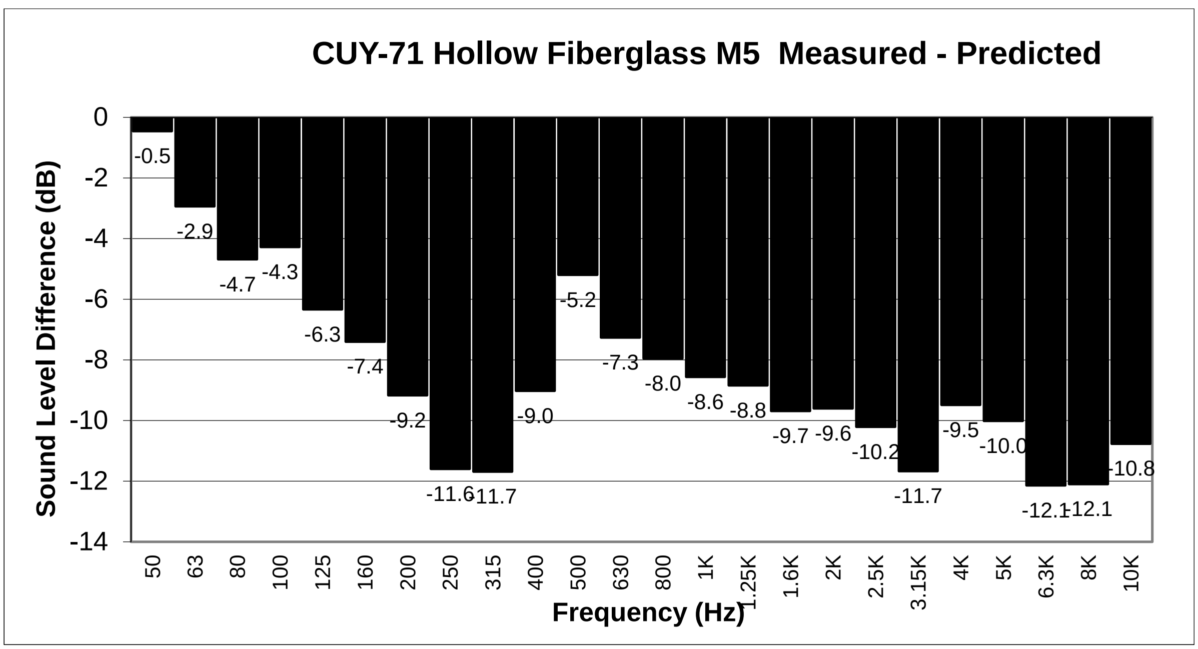
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



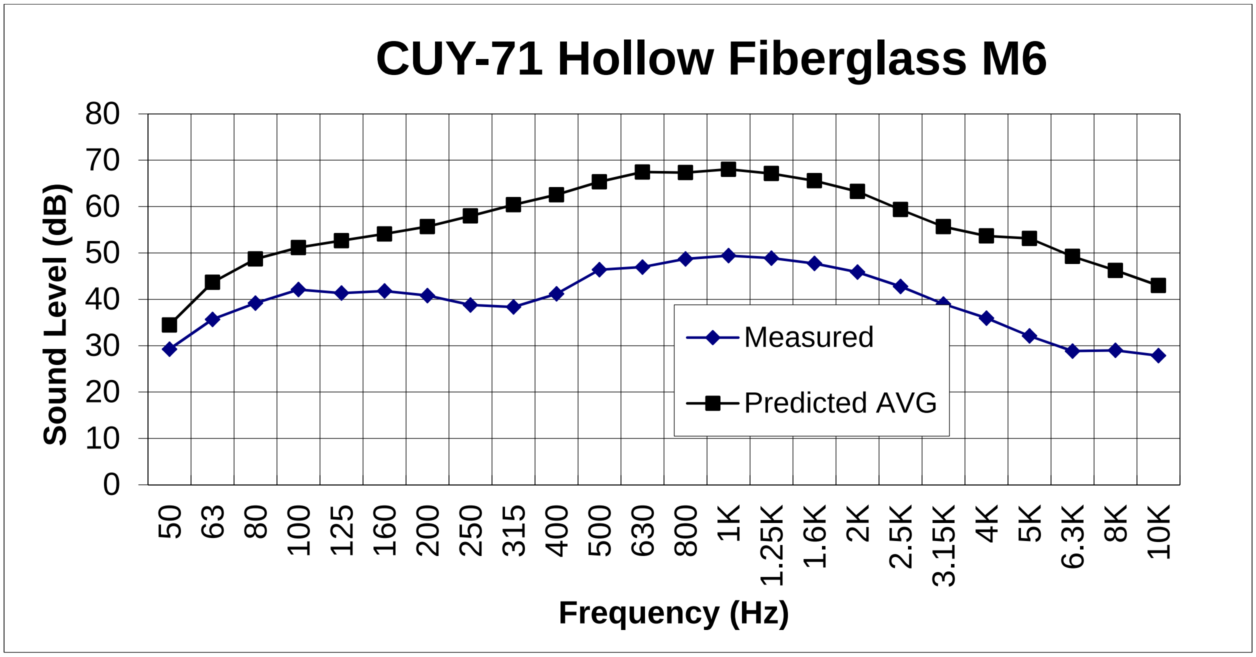


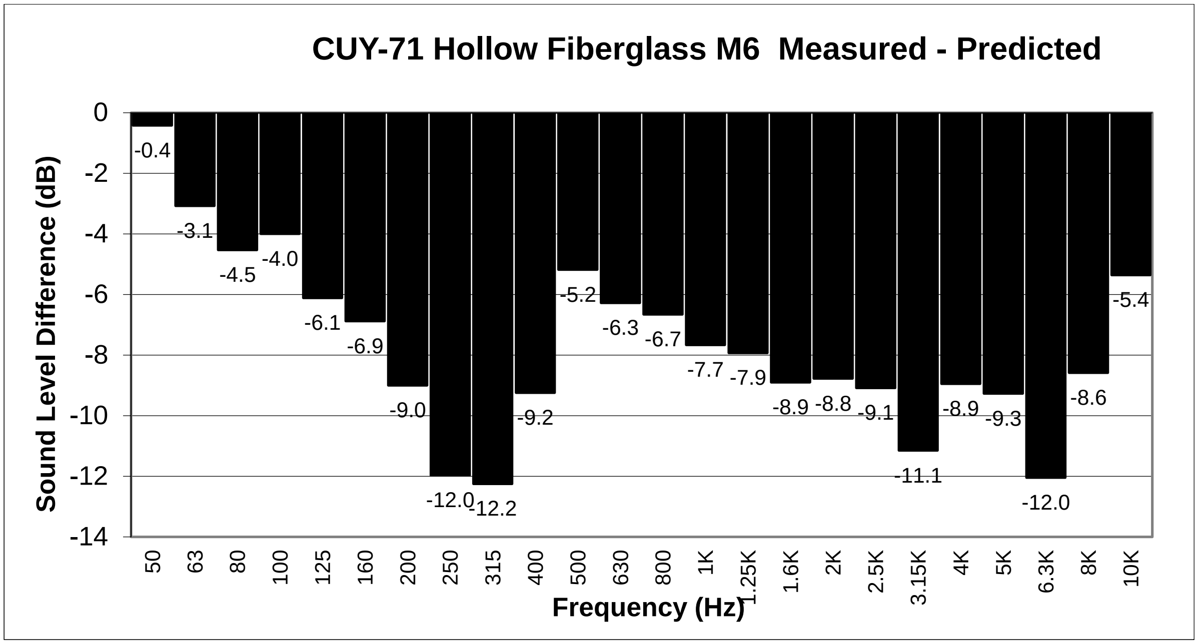
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



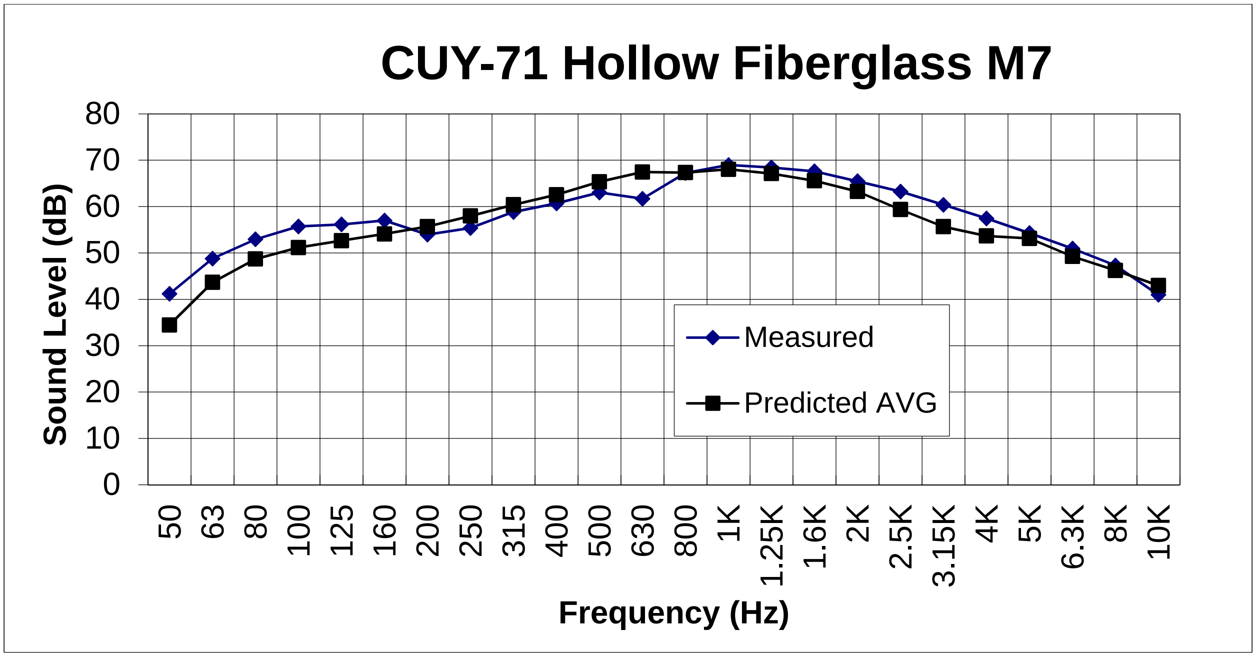


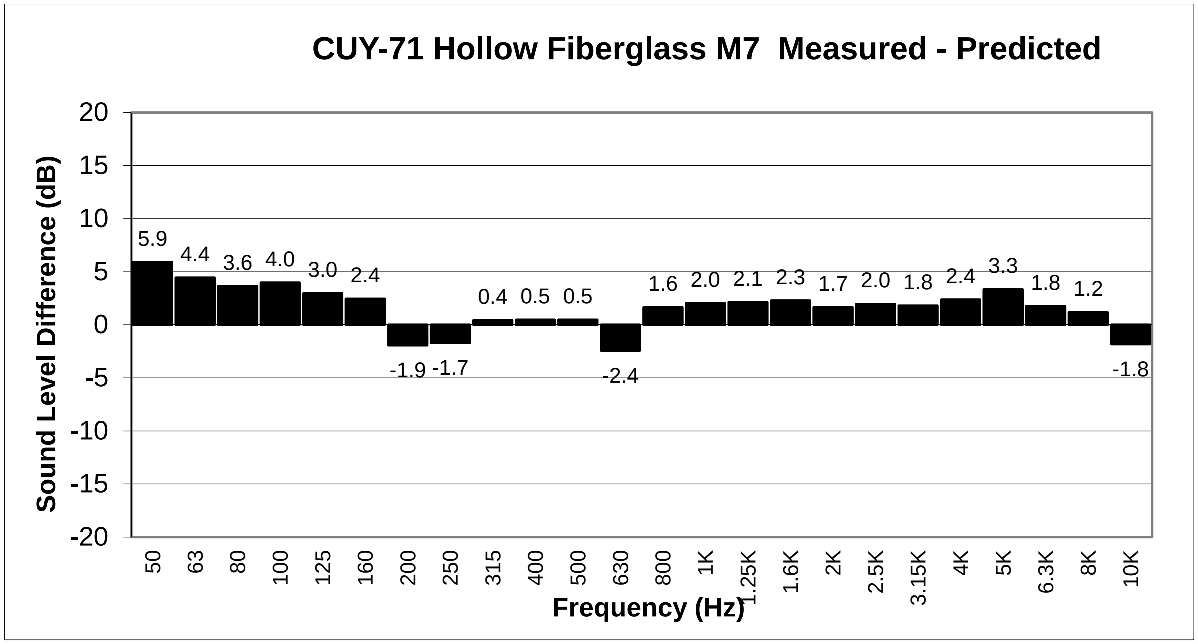
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



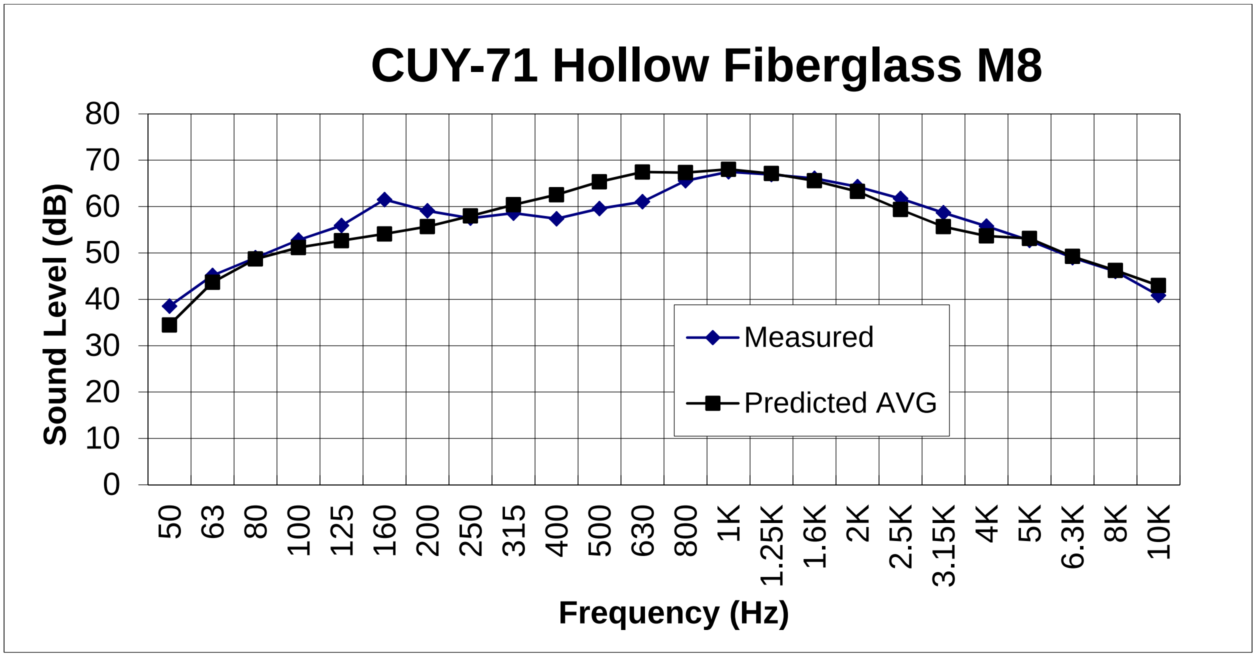


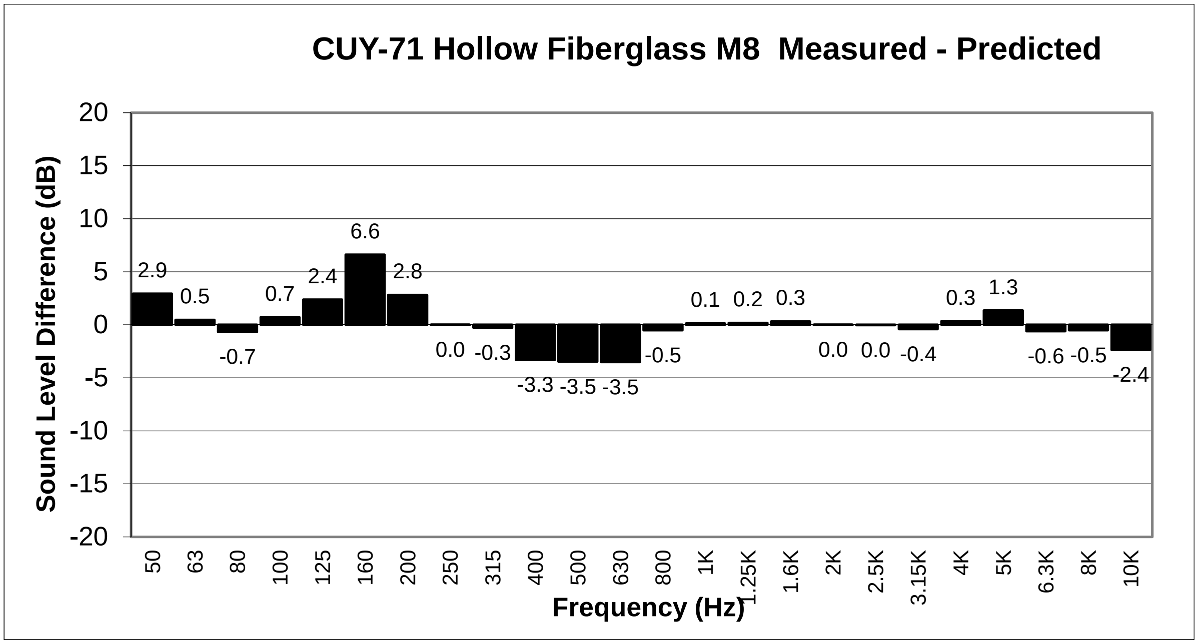
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



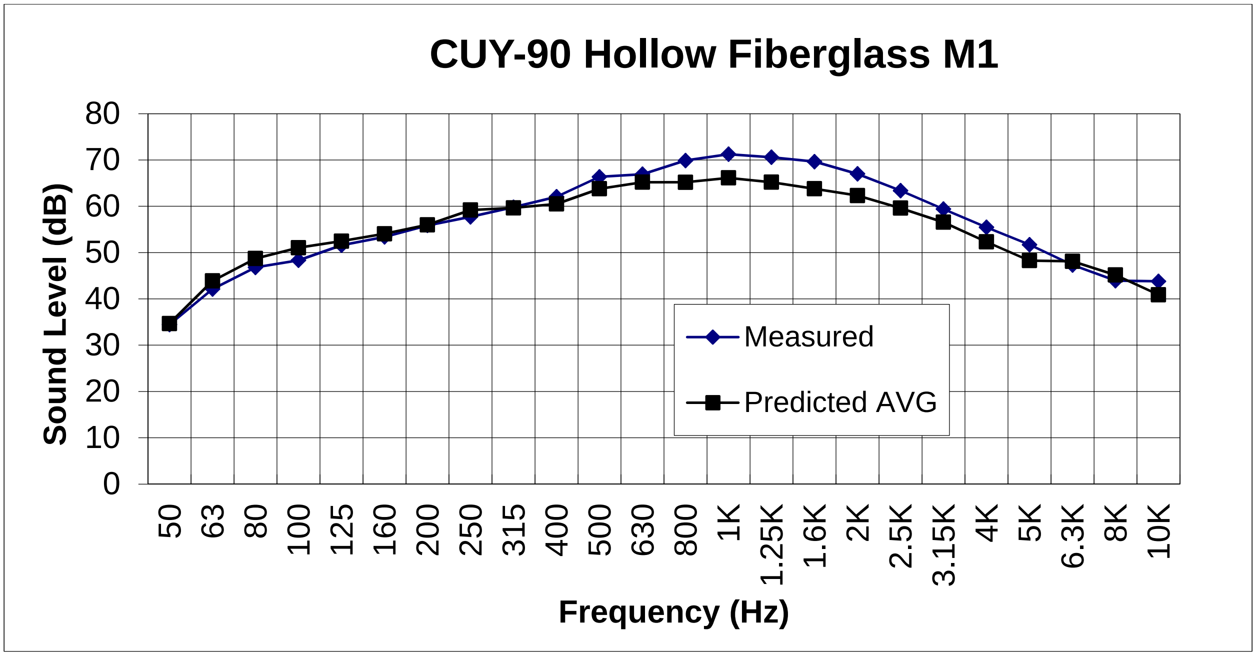


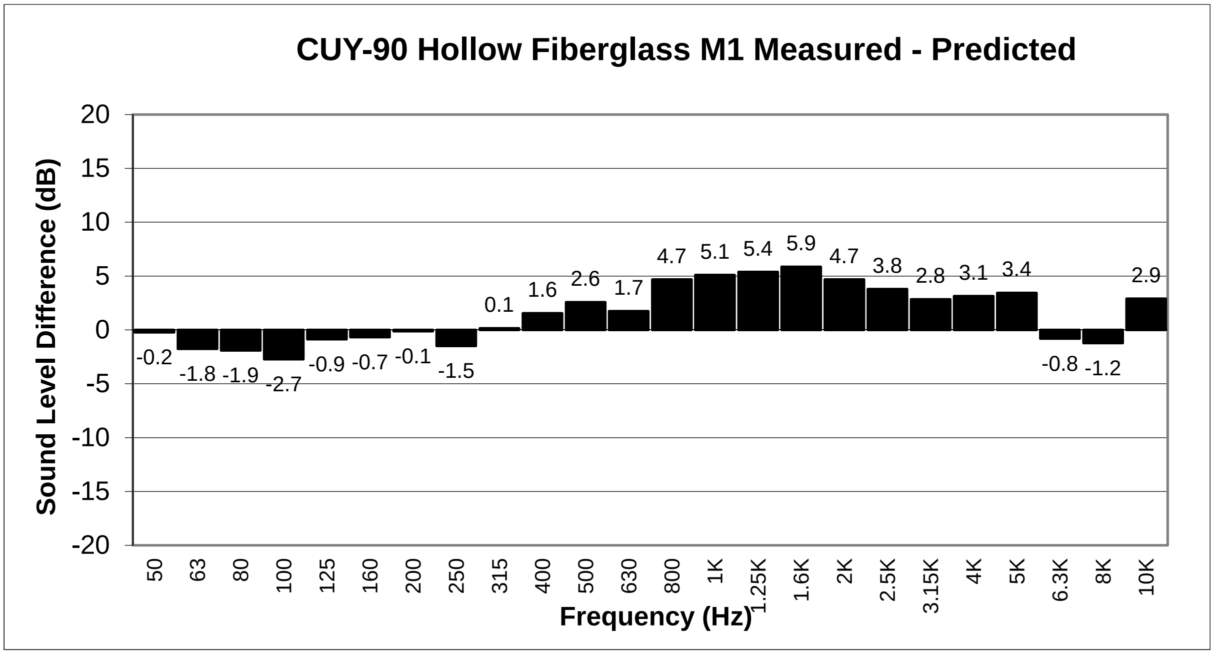
Site 9: Cuyahoga County, I-71; Hollow Fiberglass Wall



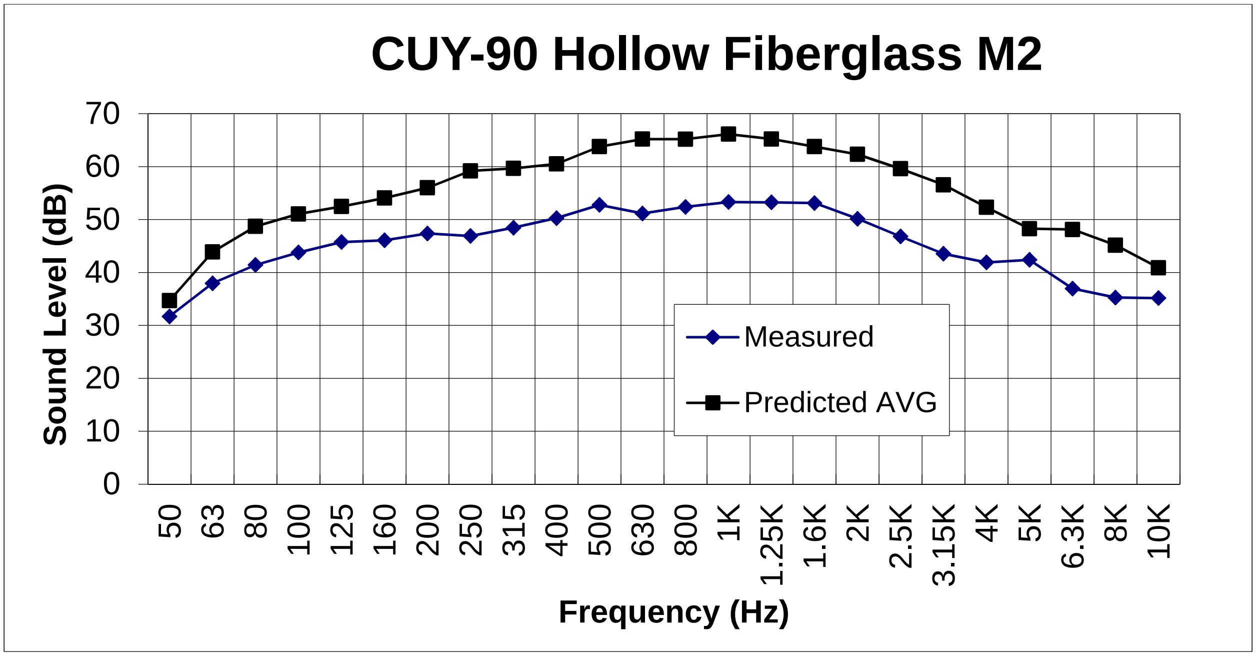


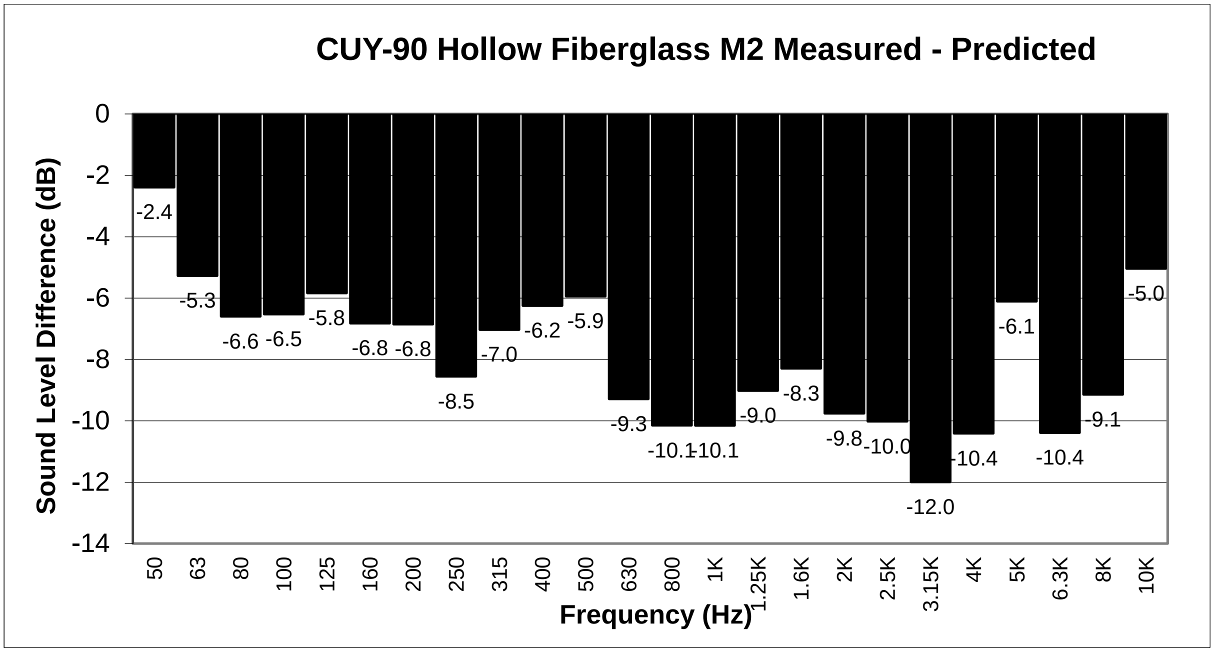
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



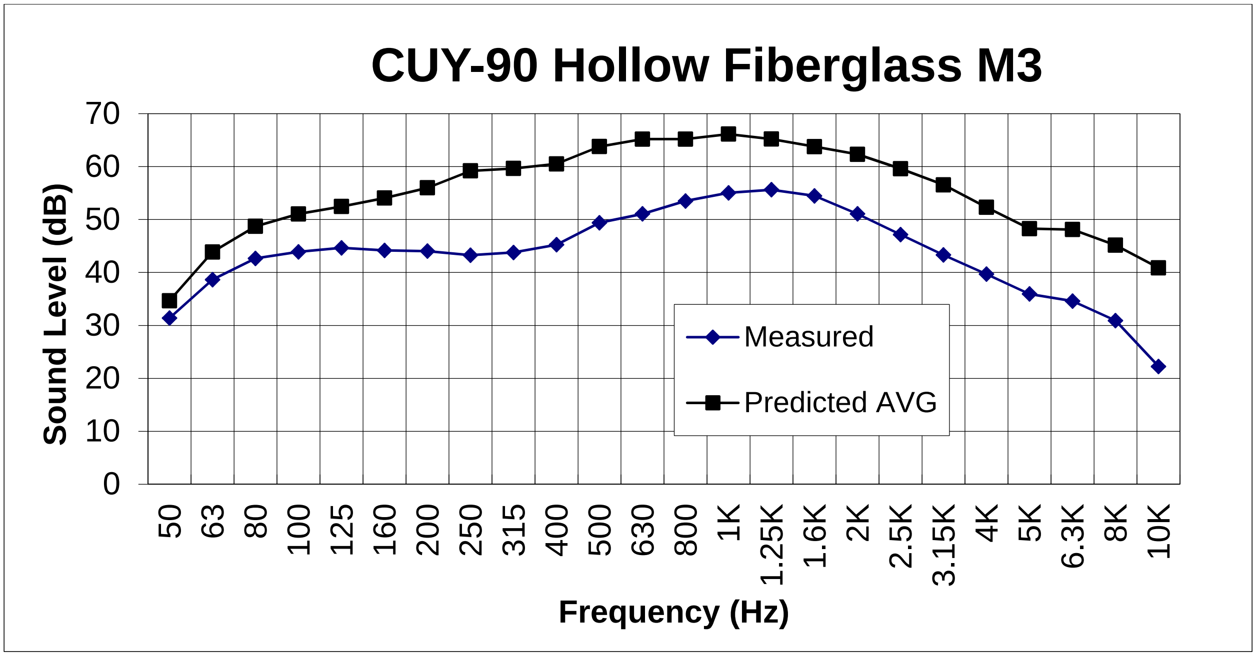


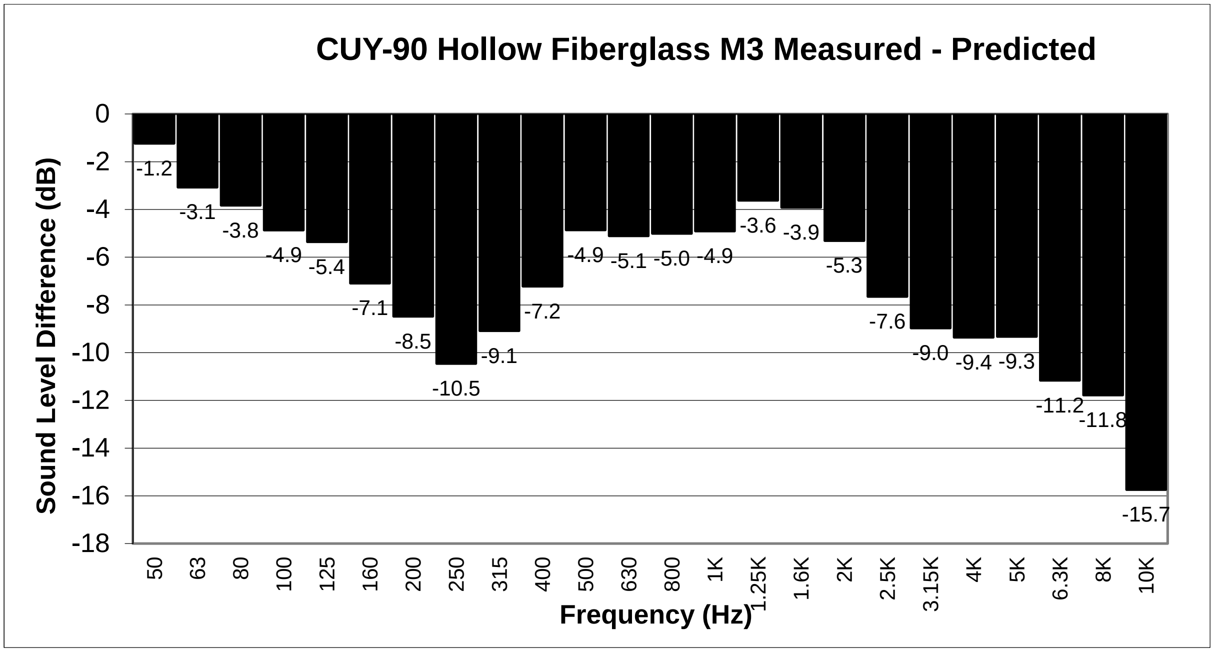
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



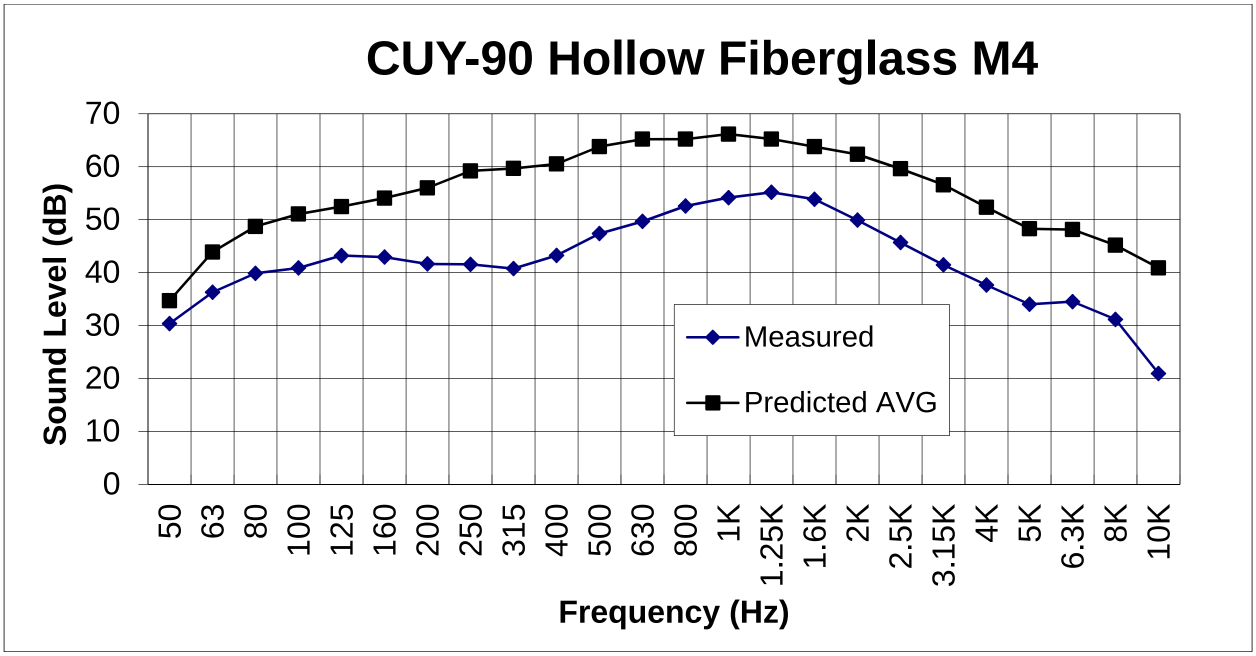


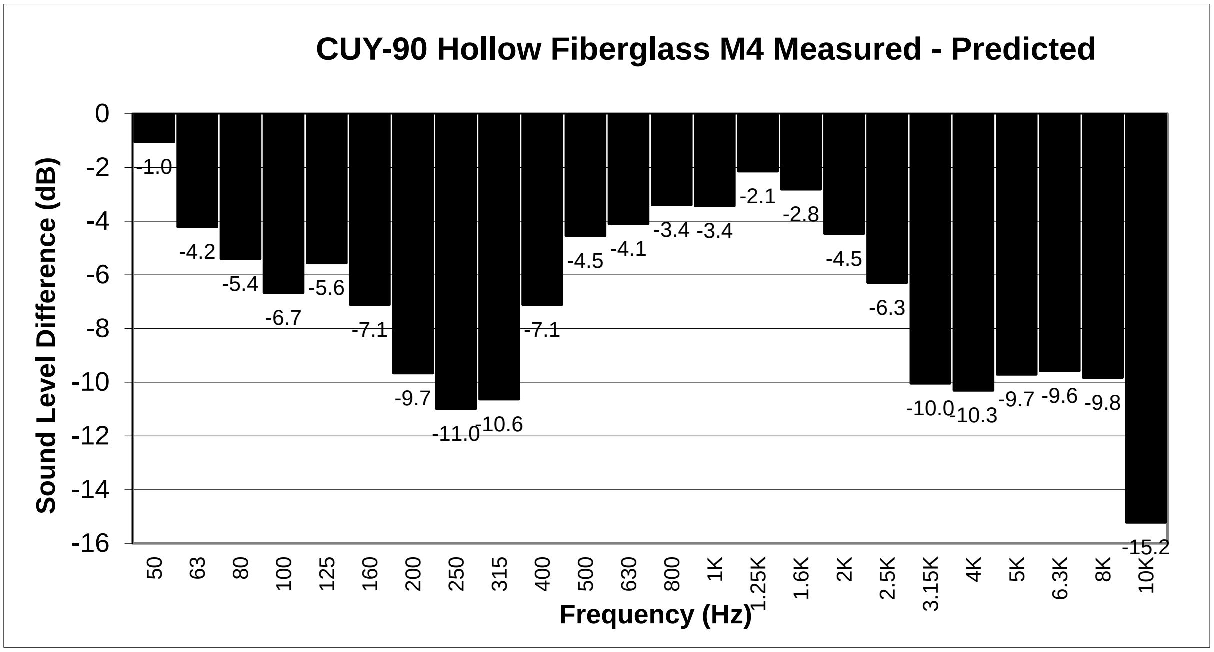
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



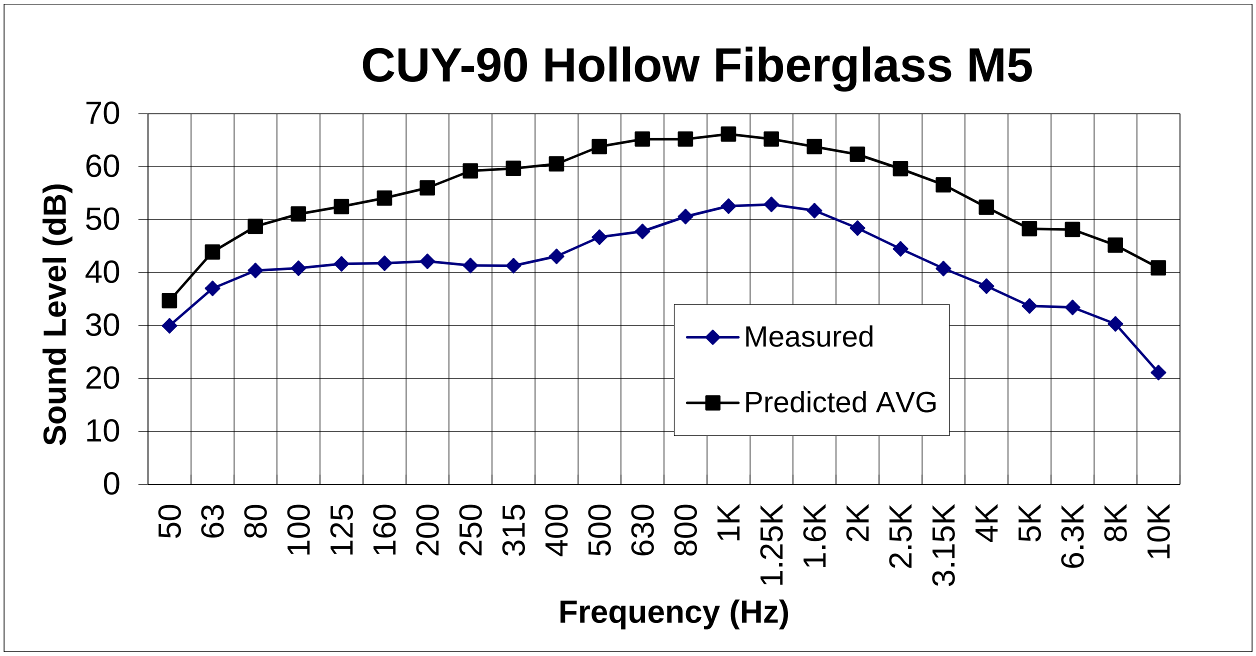


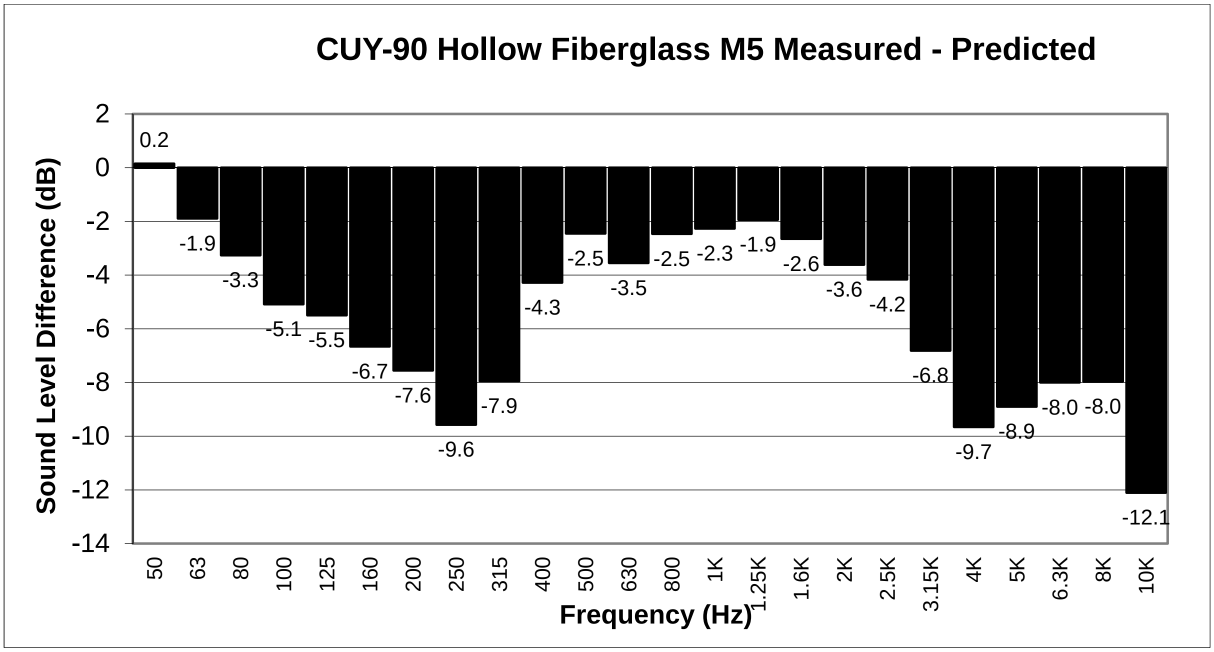
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



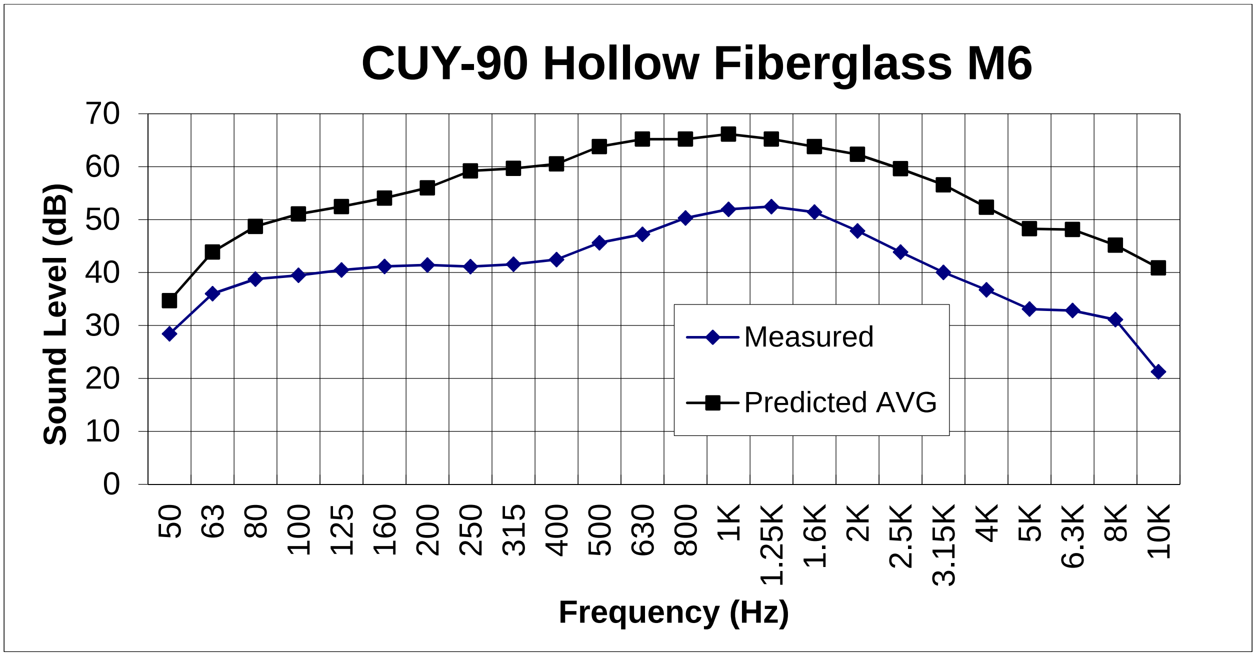


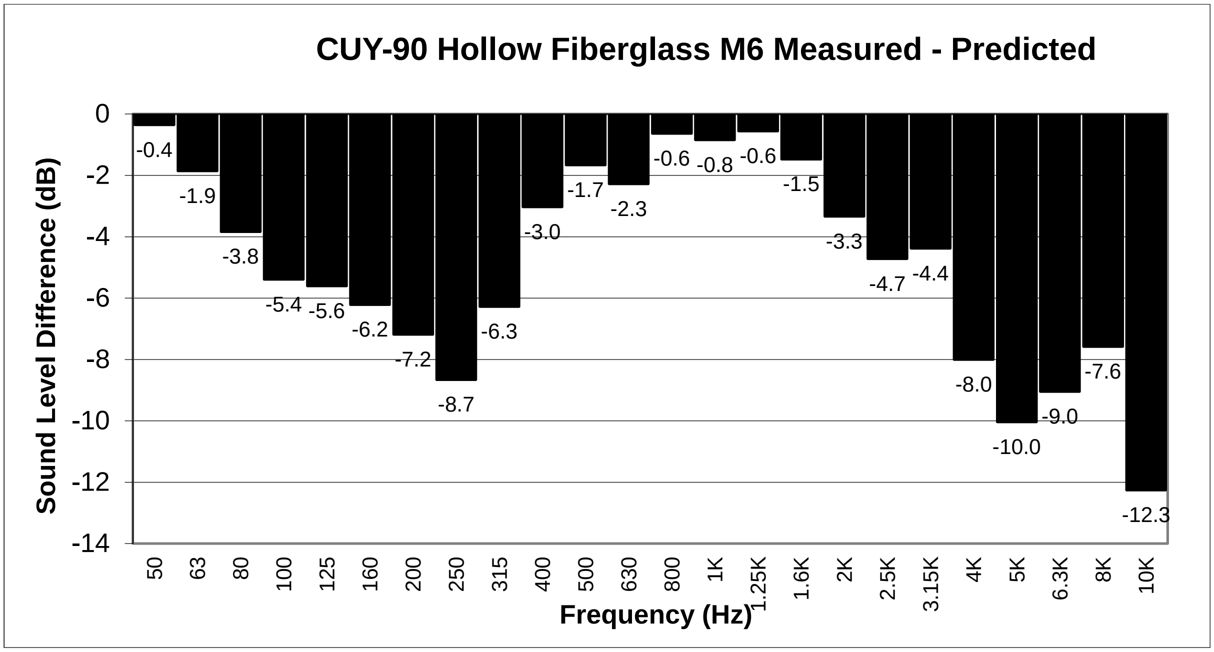
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



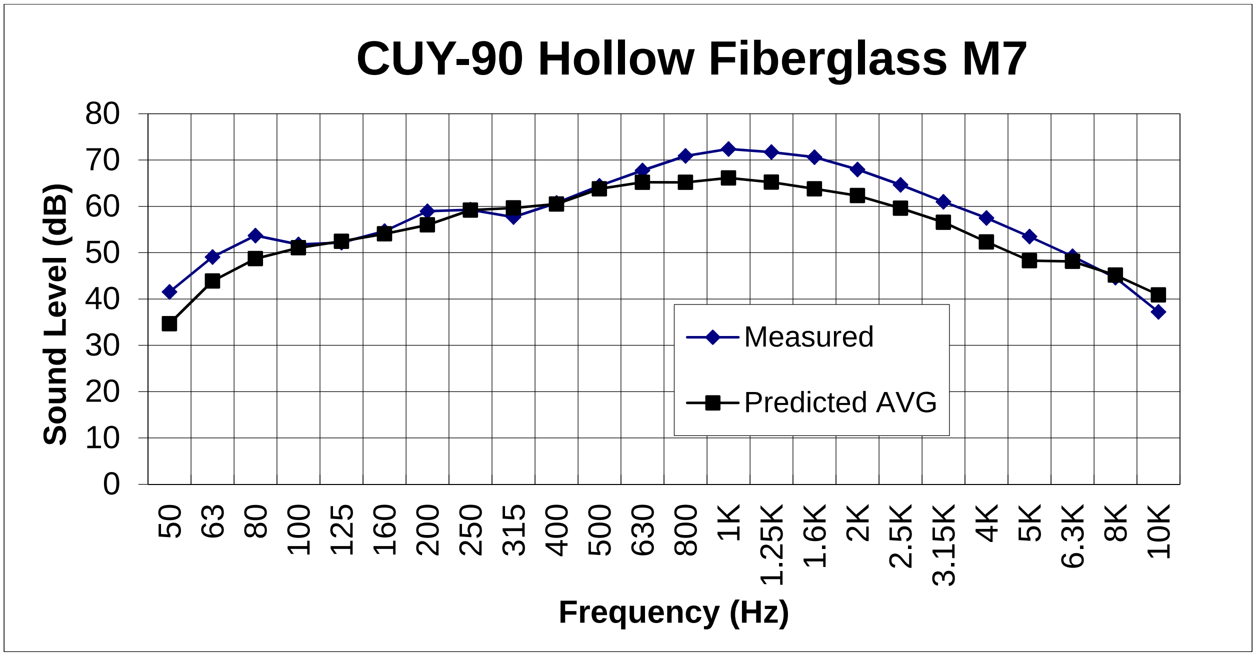


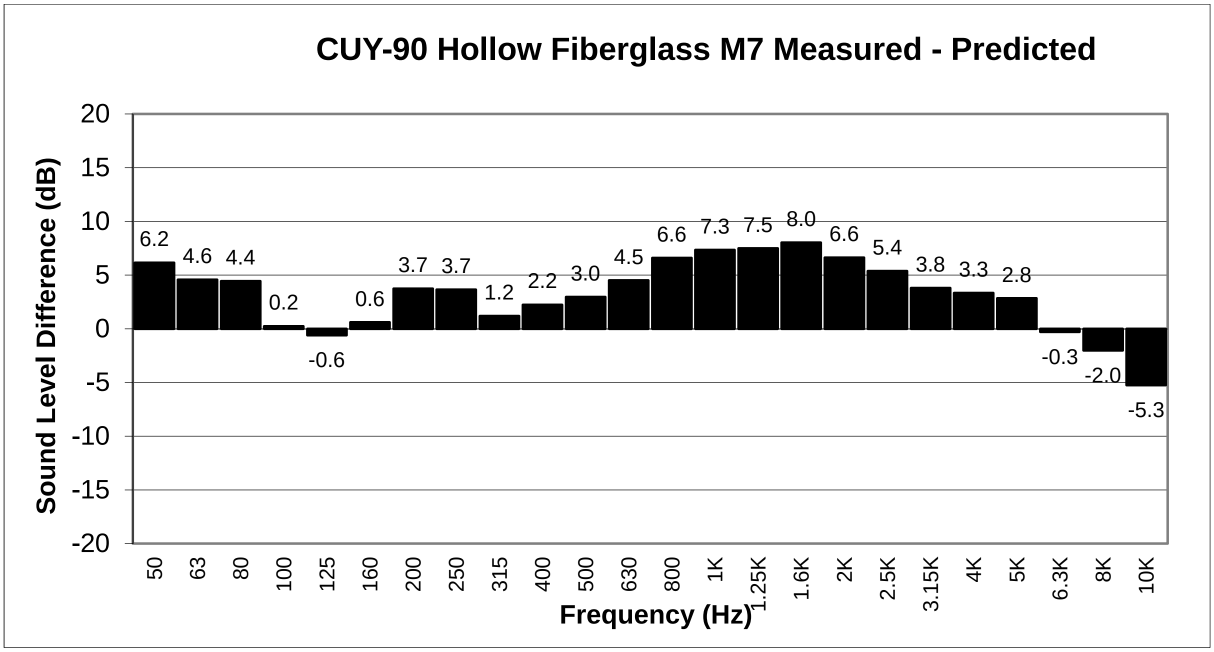
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



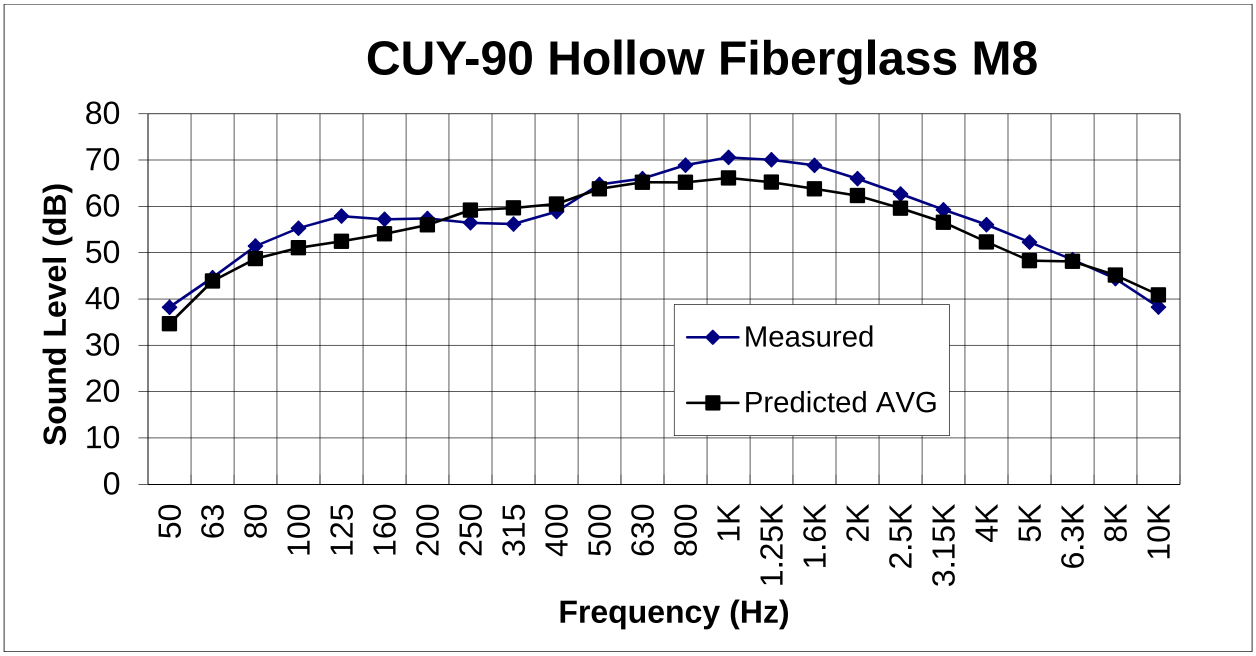


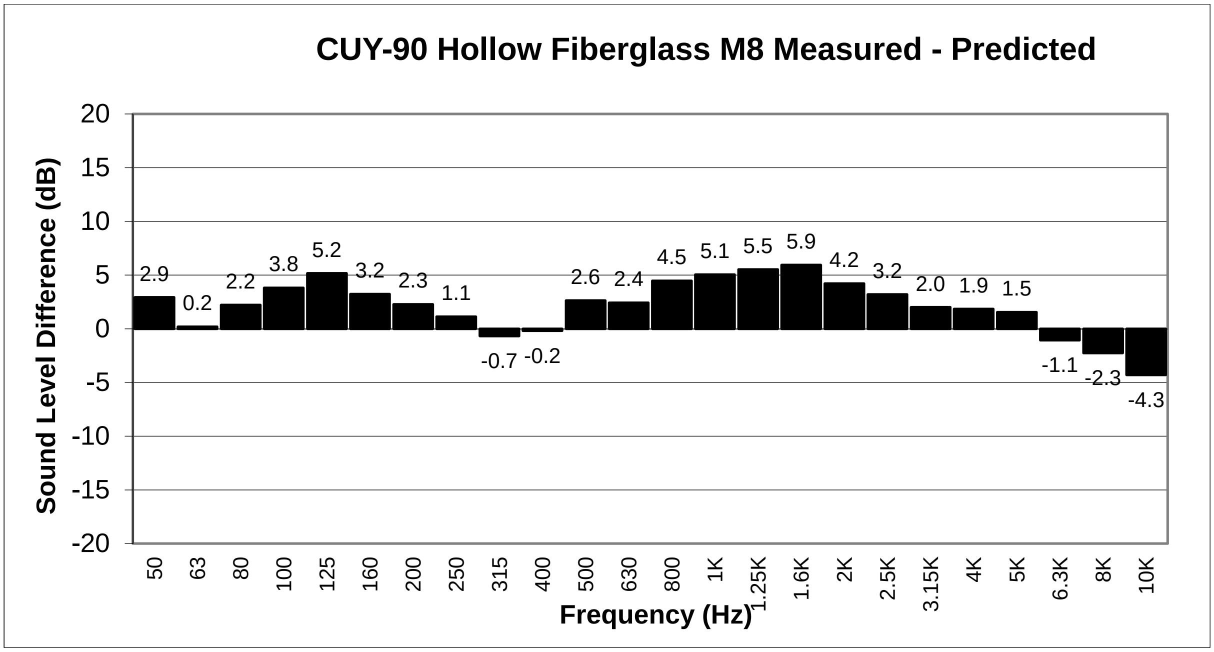
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



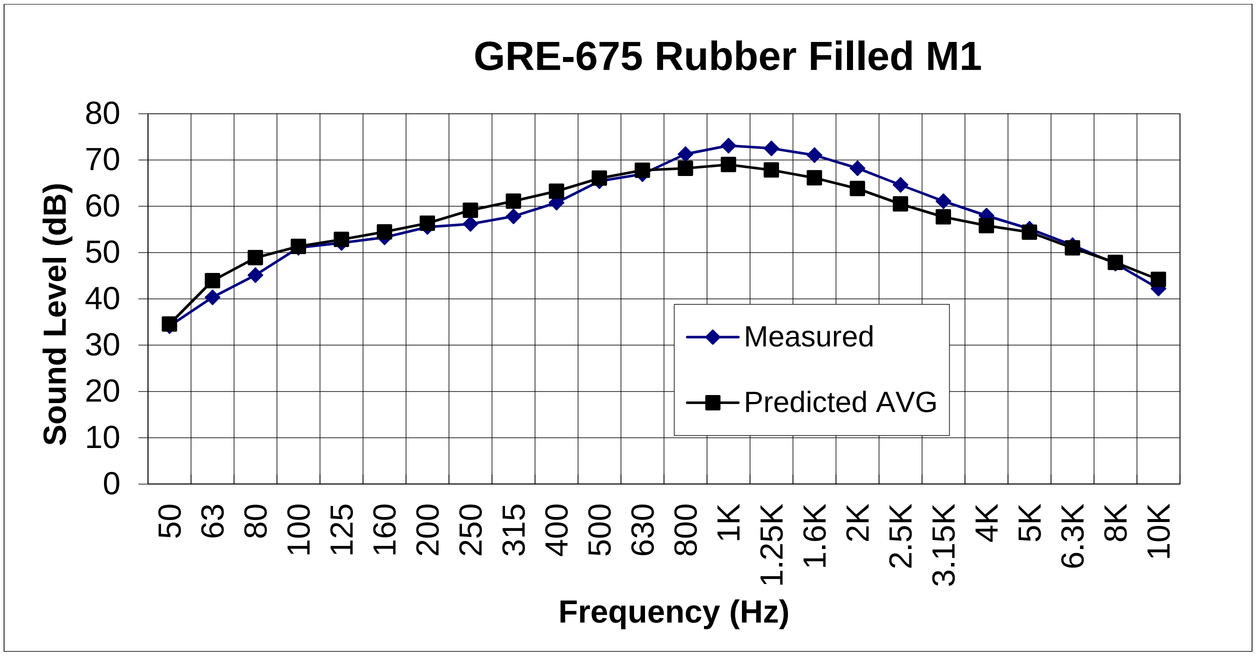


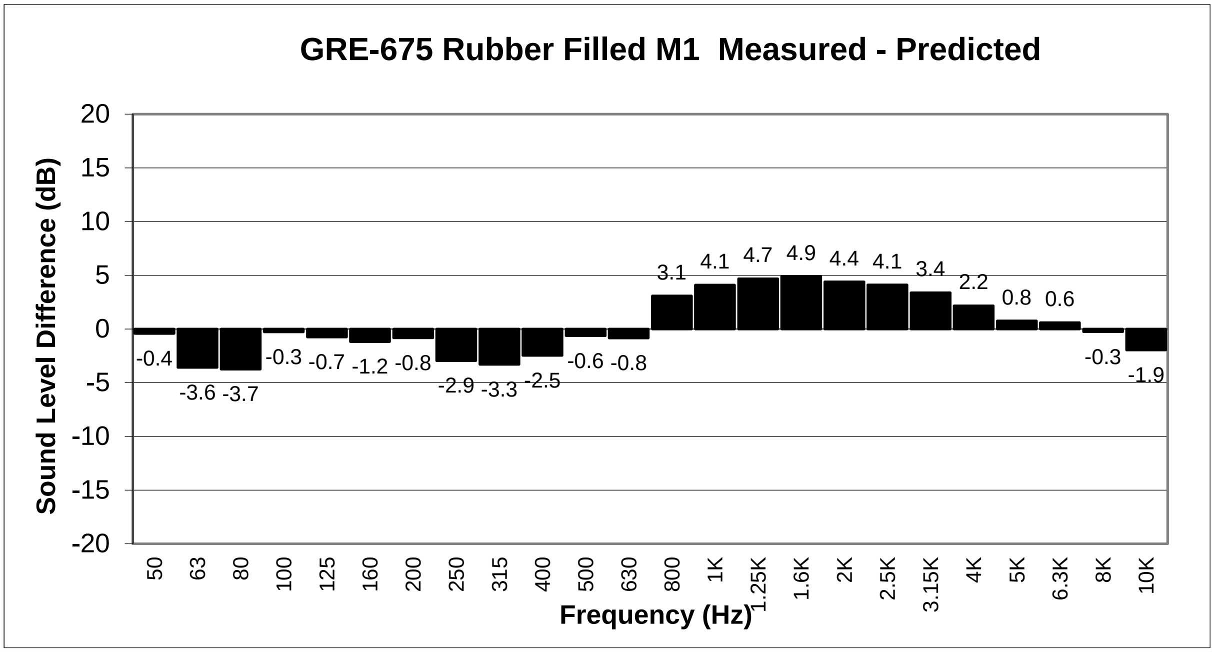
Site 10: Cuyahoga County, I-90; Hollow Fiberglass Wall



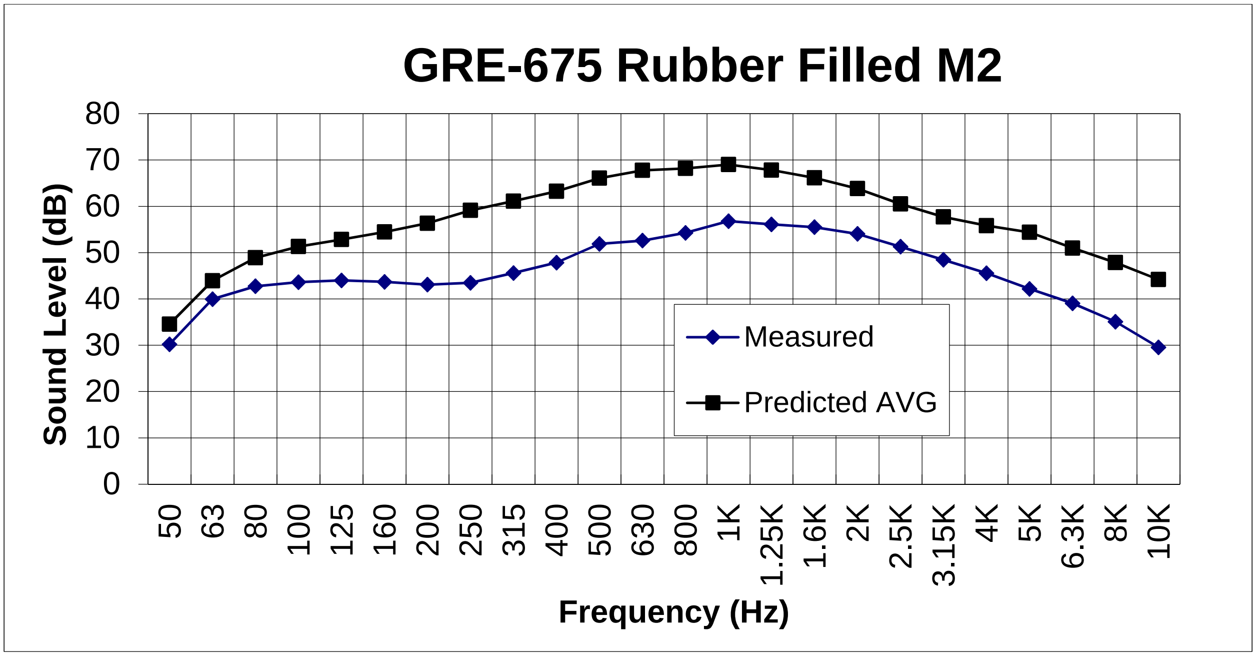


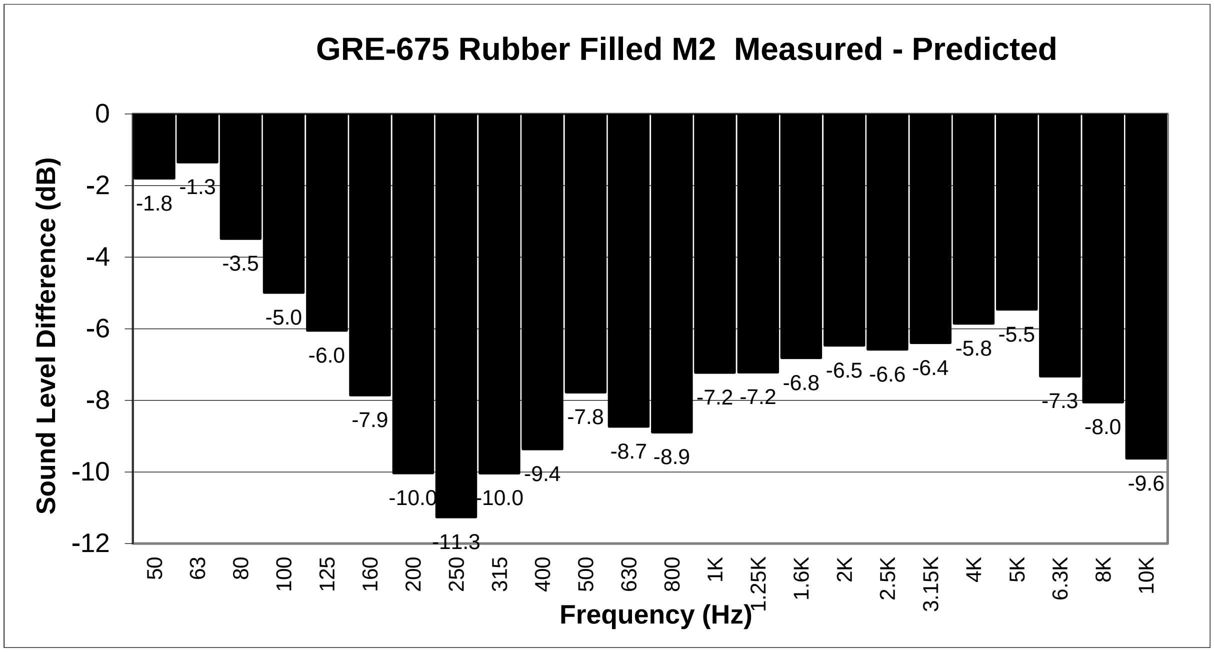
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



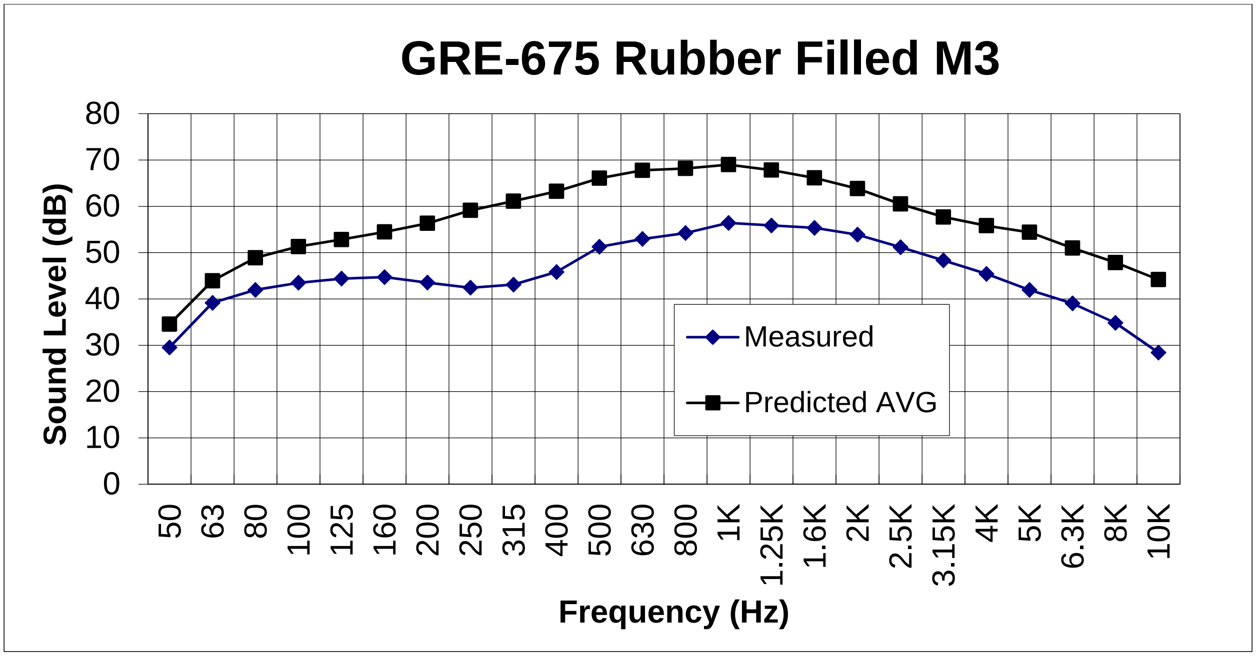


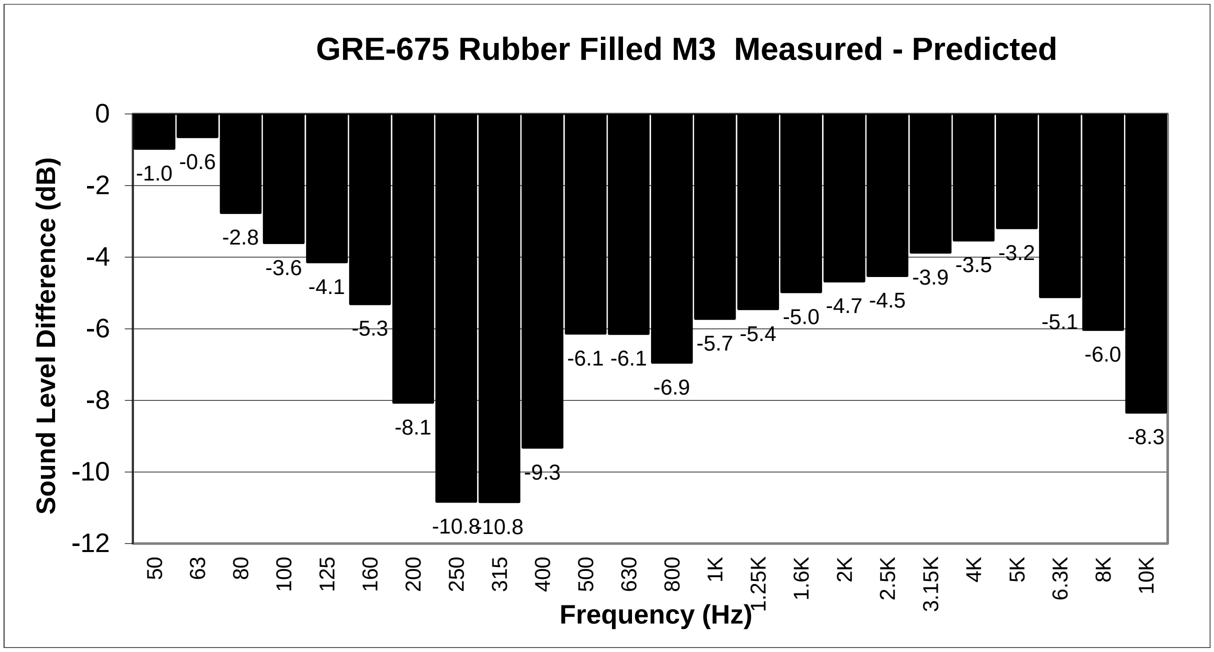
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



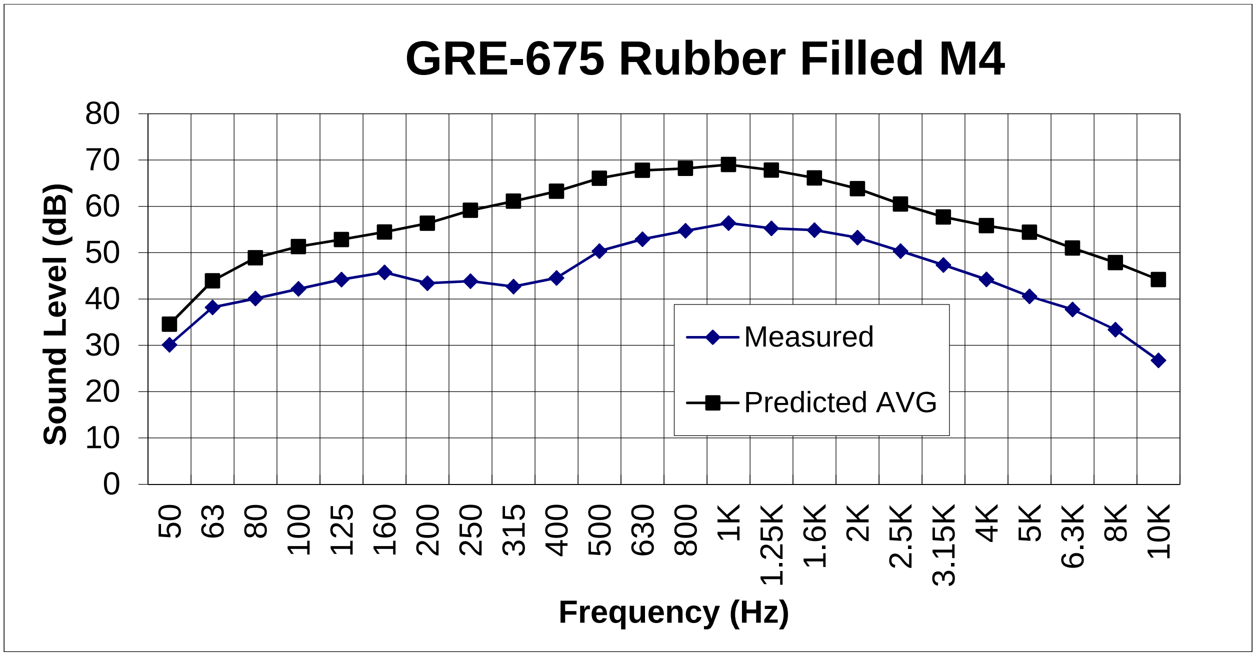


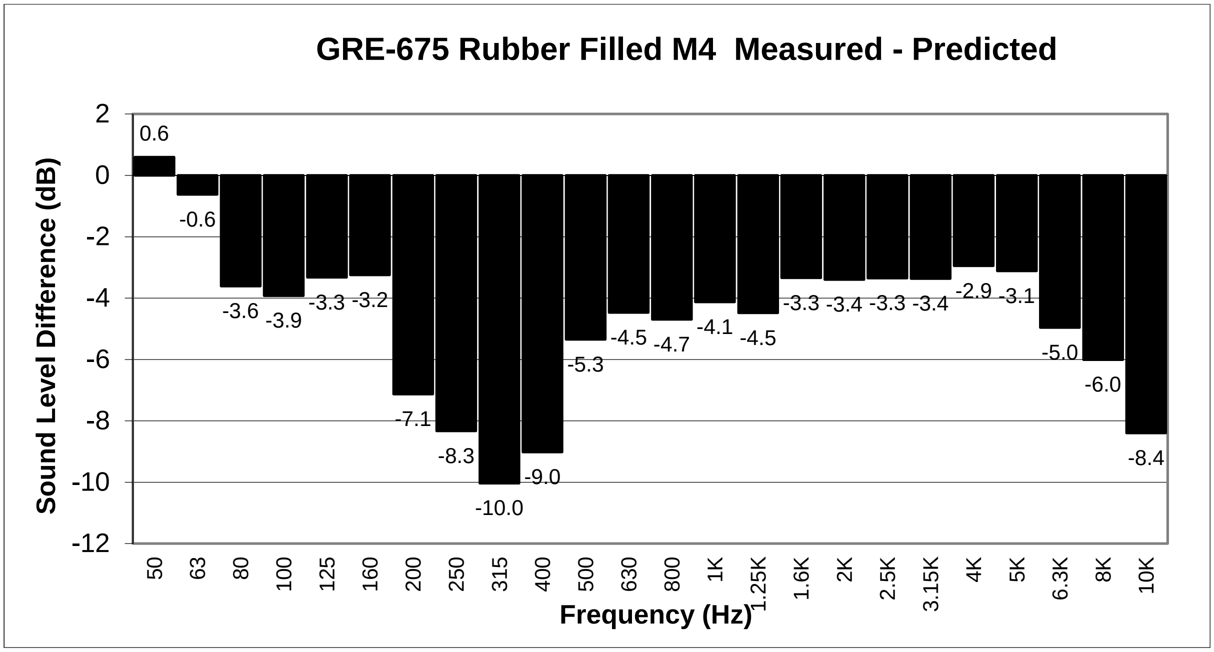
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



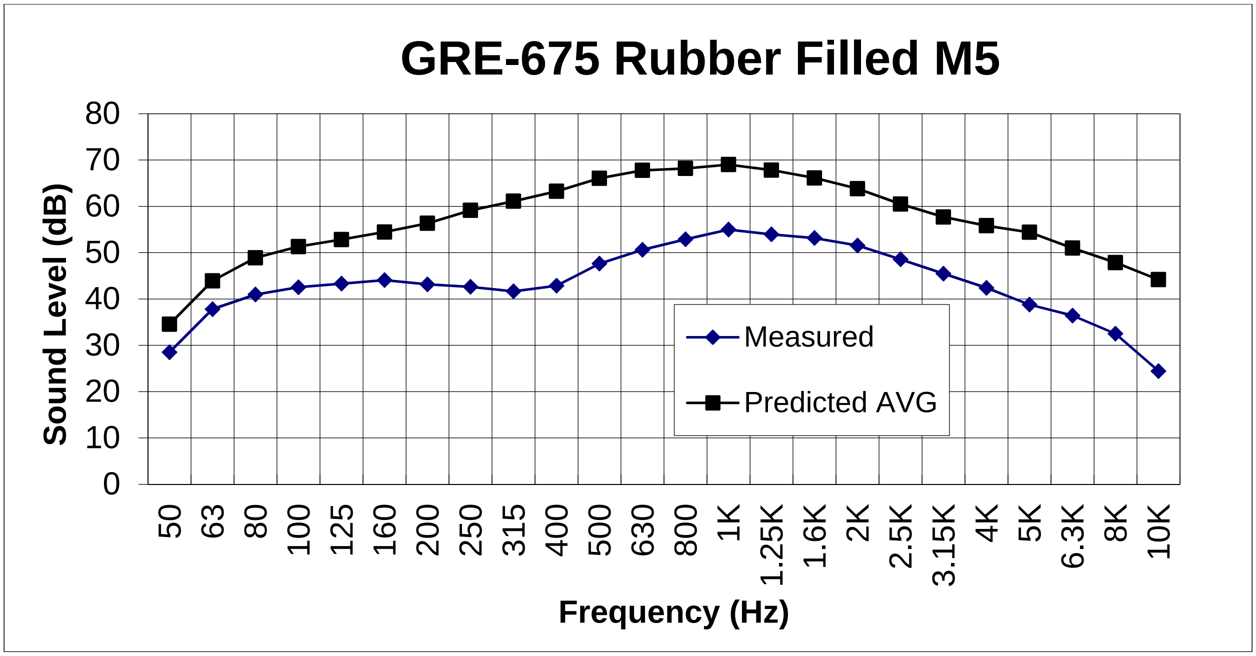


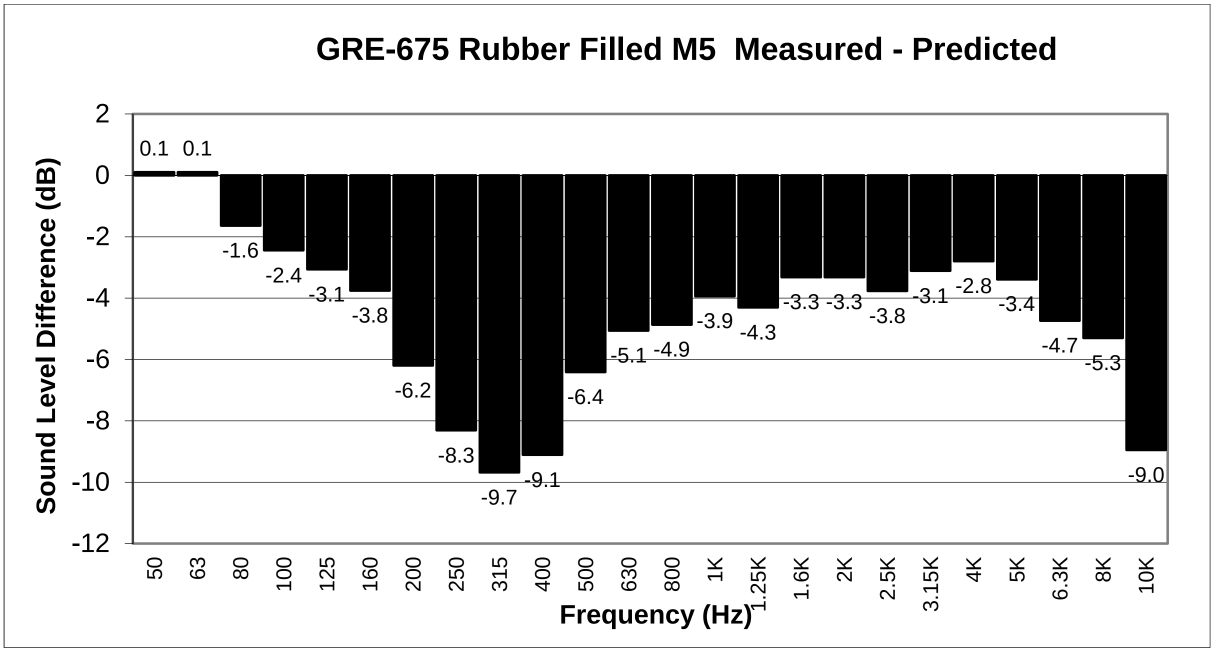
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



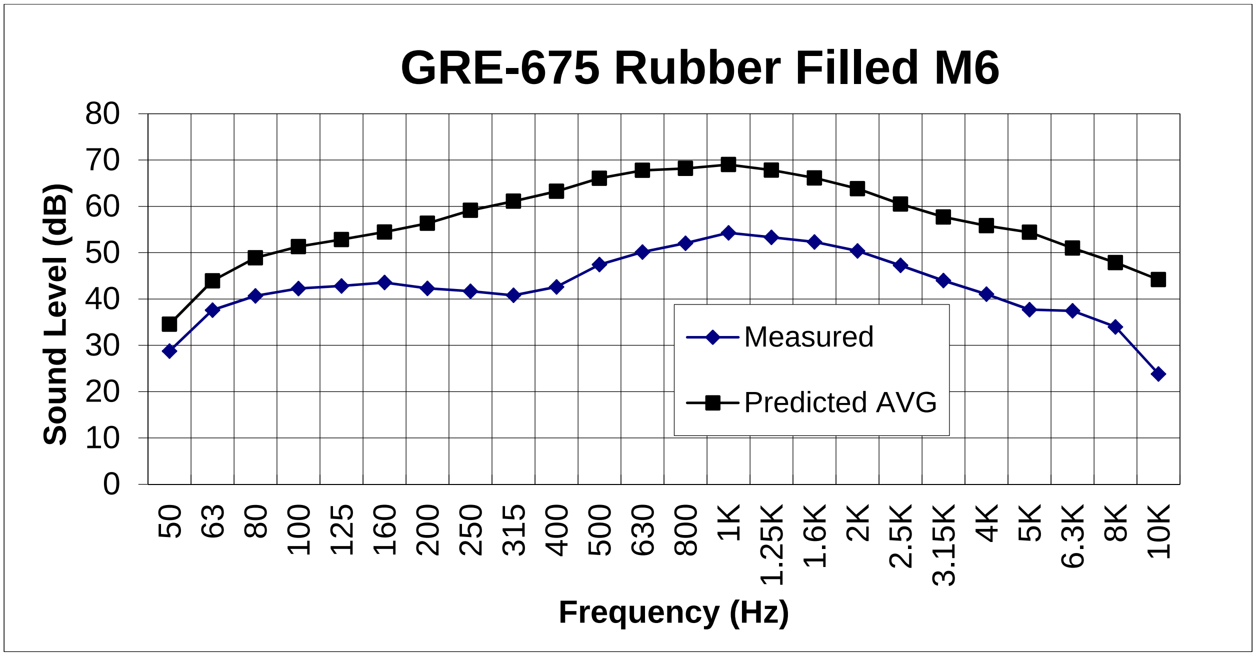


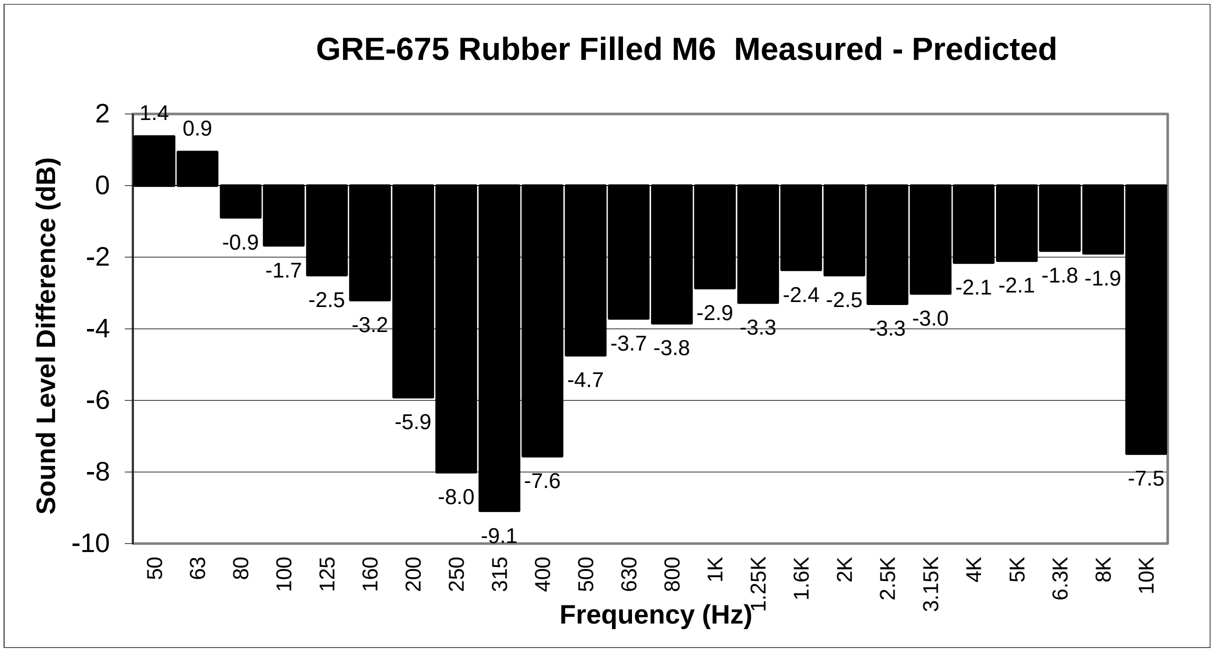
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



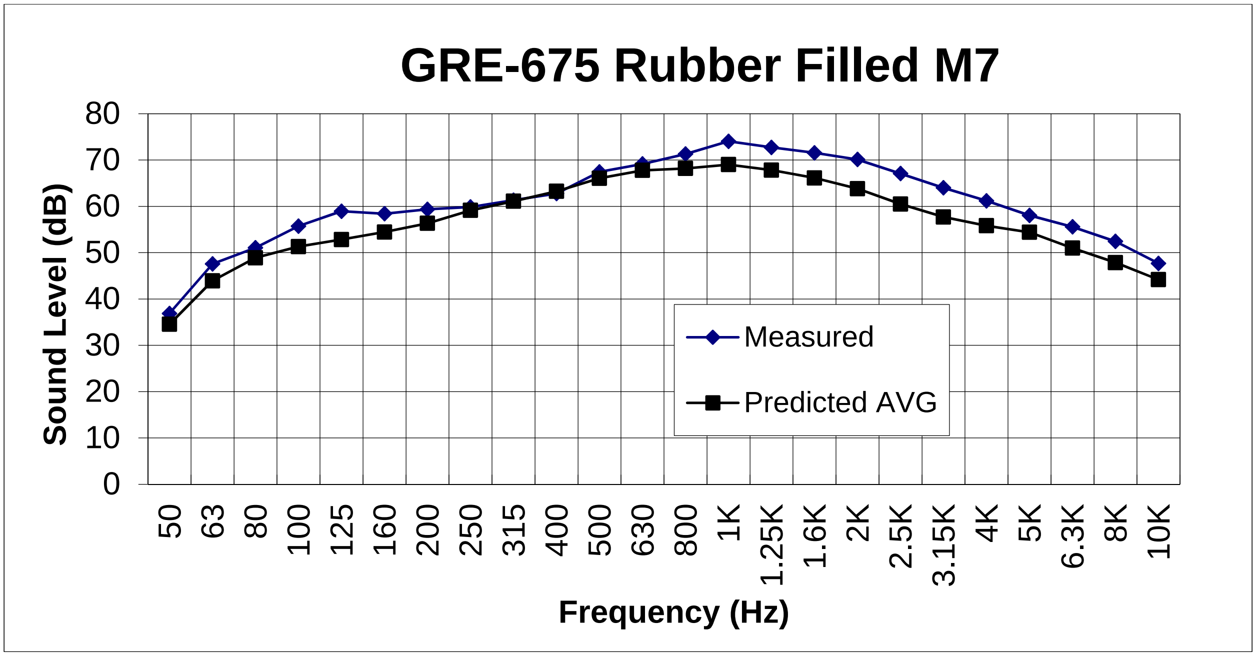


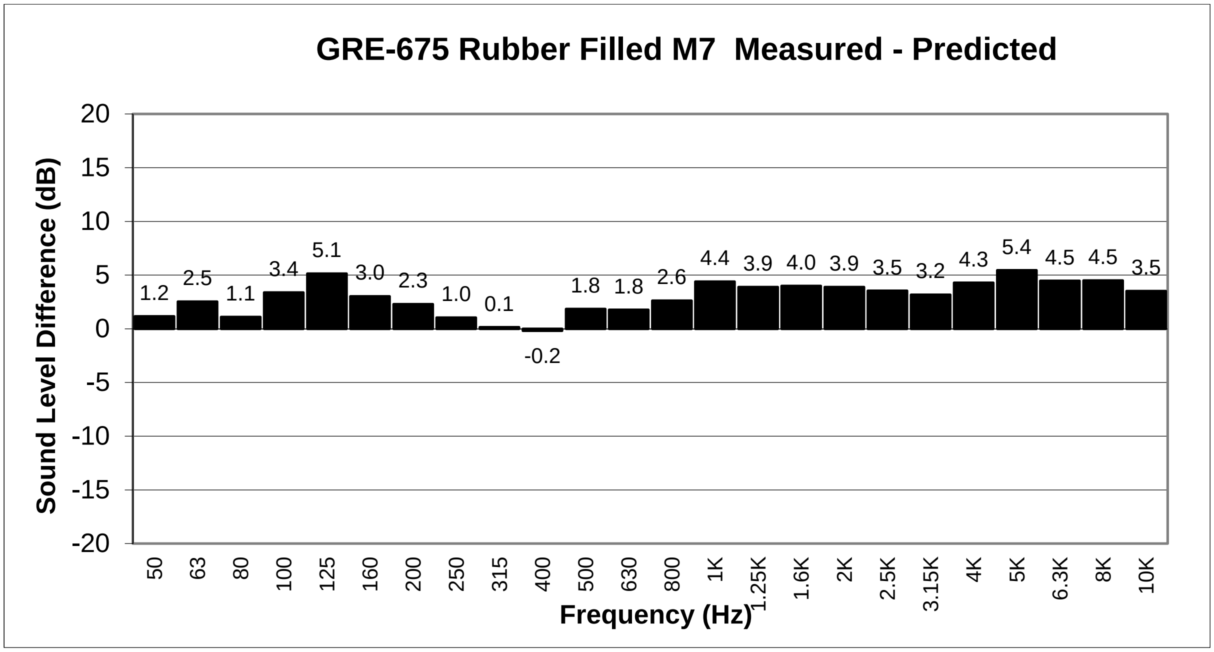
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



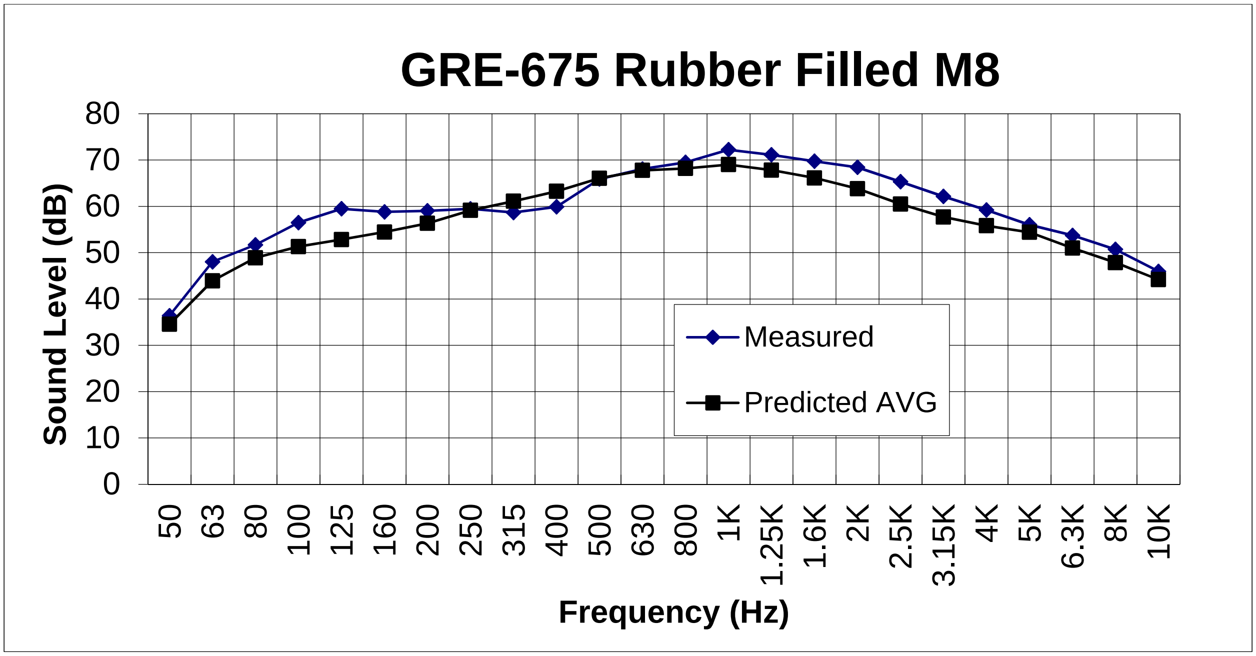


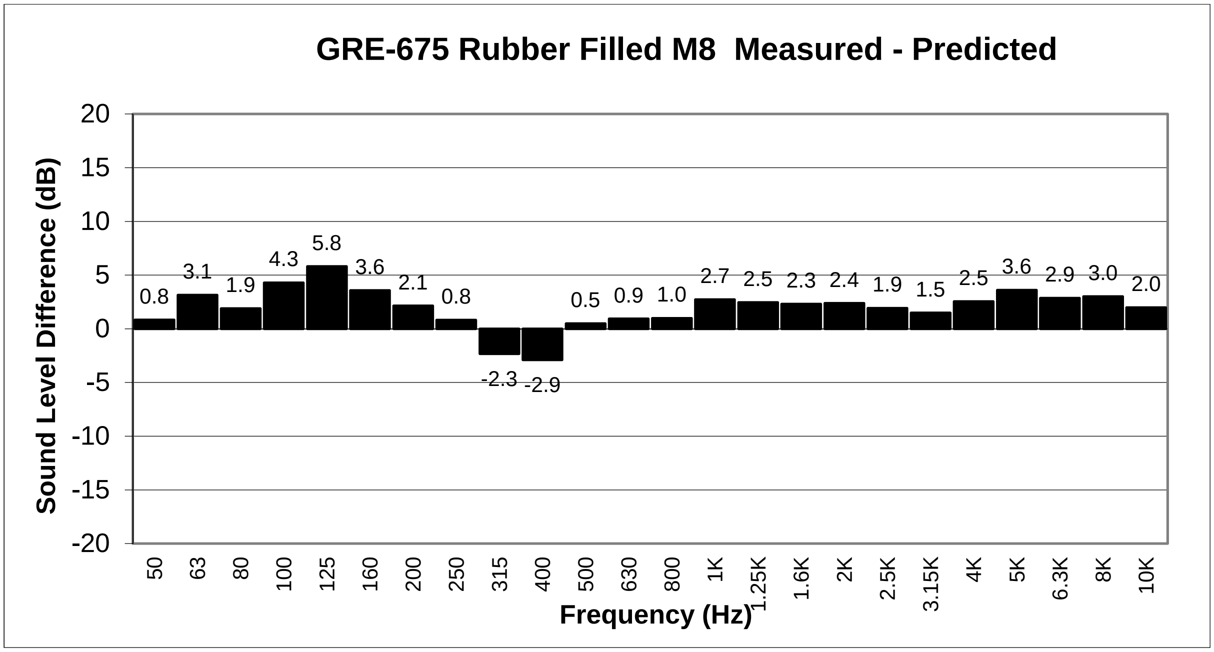
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



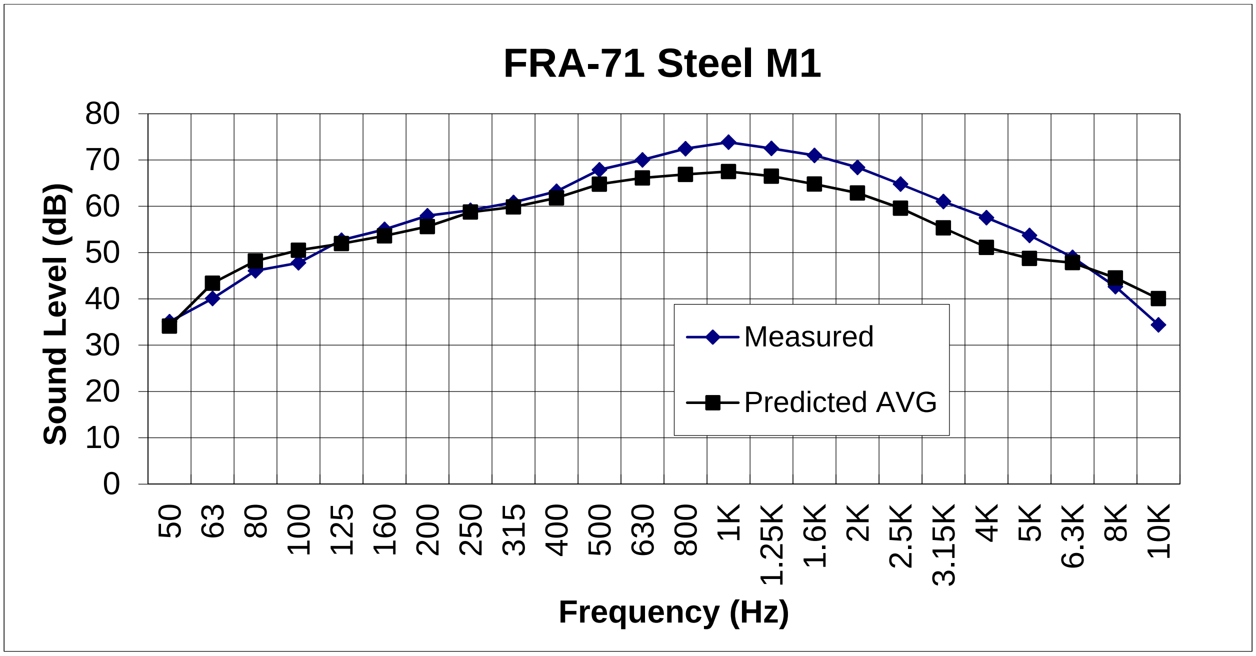


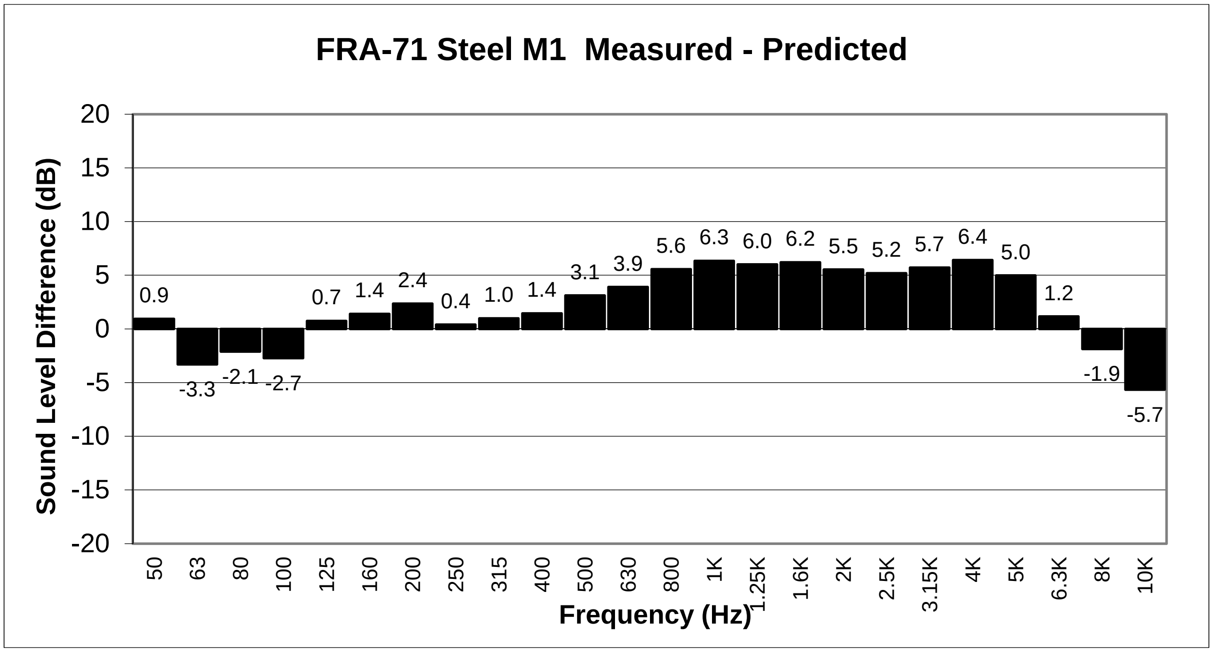
Site 11: Greene County, I-675; Rubber Filled Fiberglass Wall



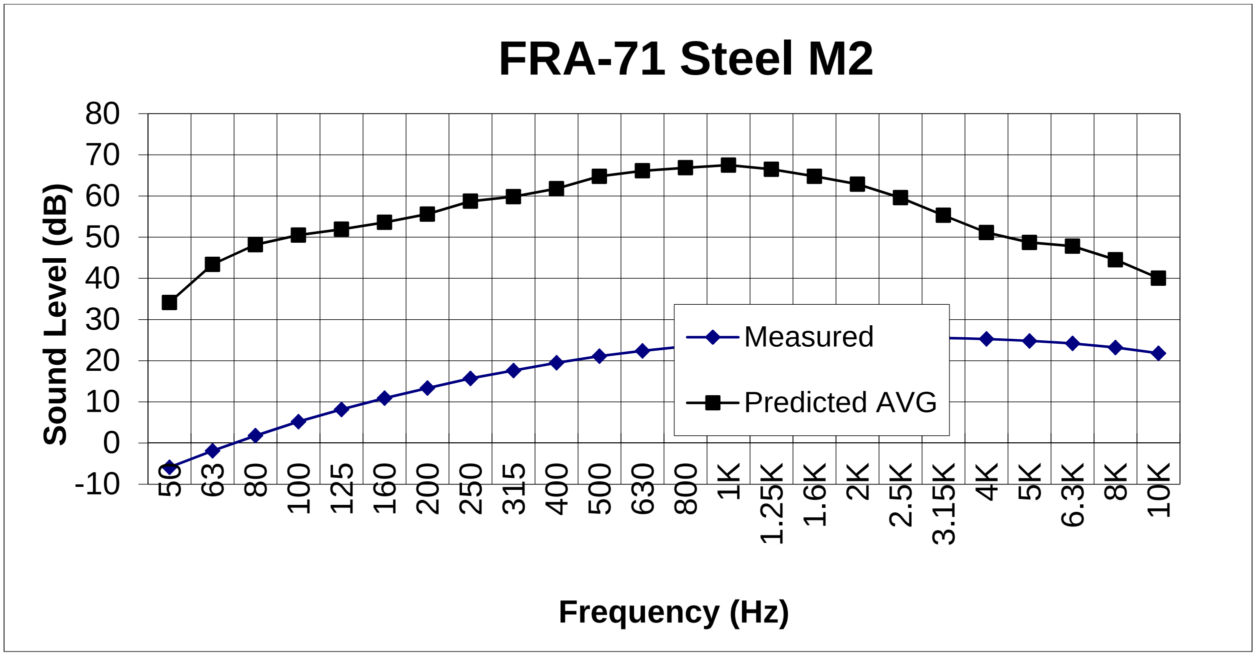


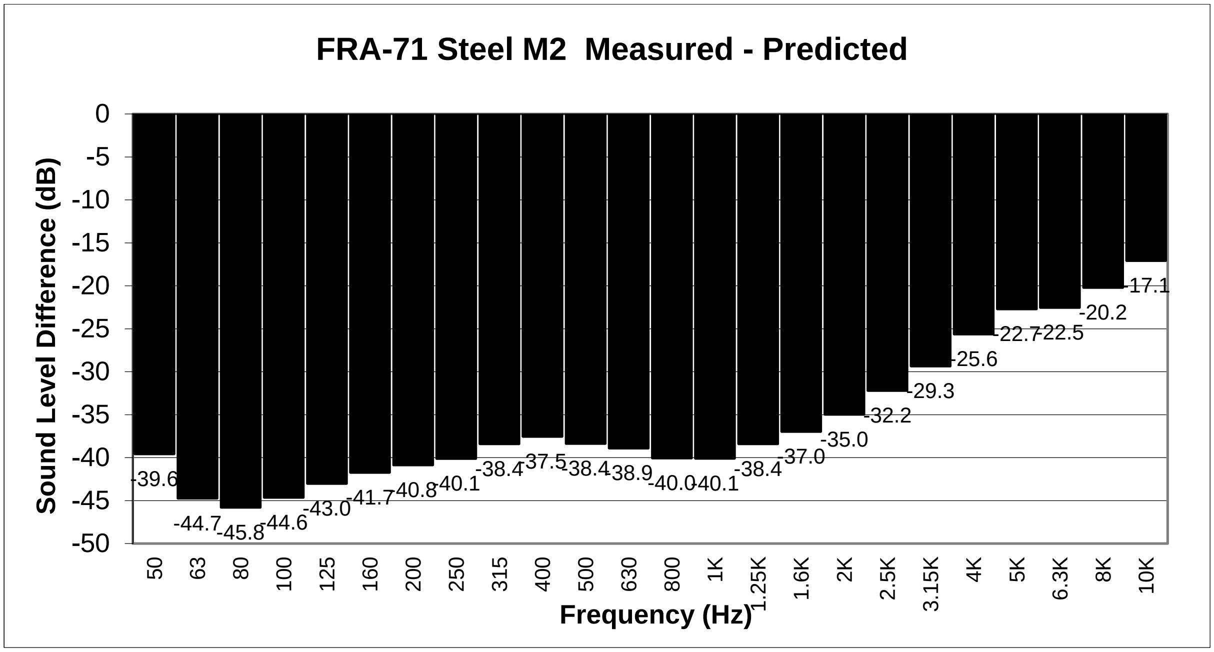
Site 12: Franklin County, I-71; Steel Wall



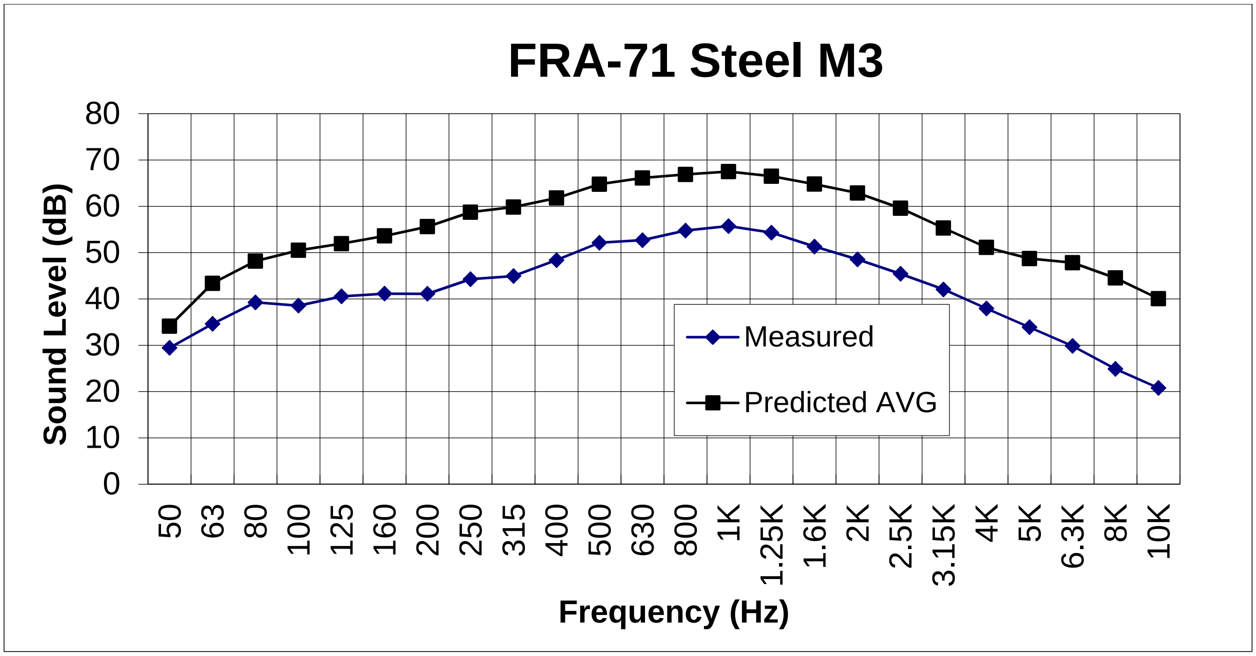


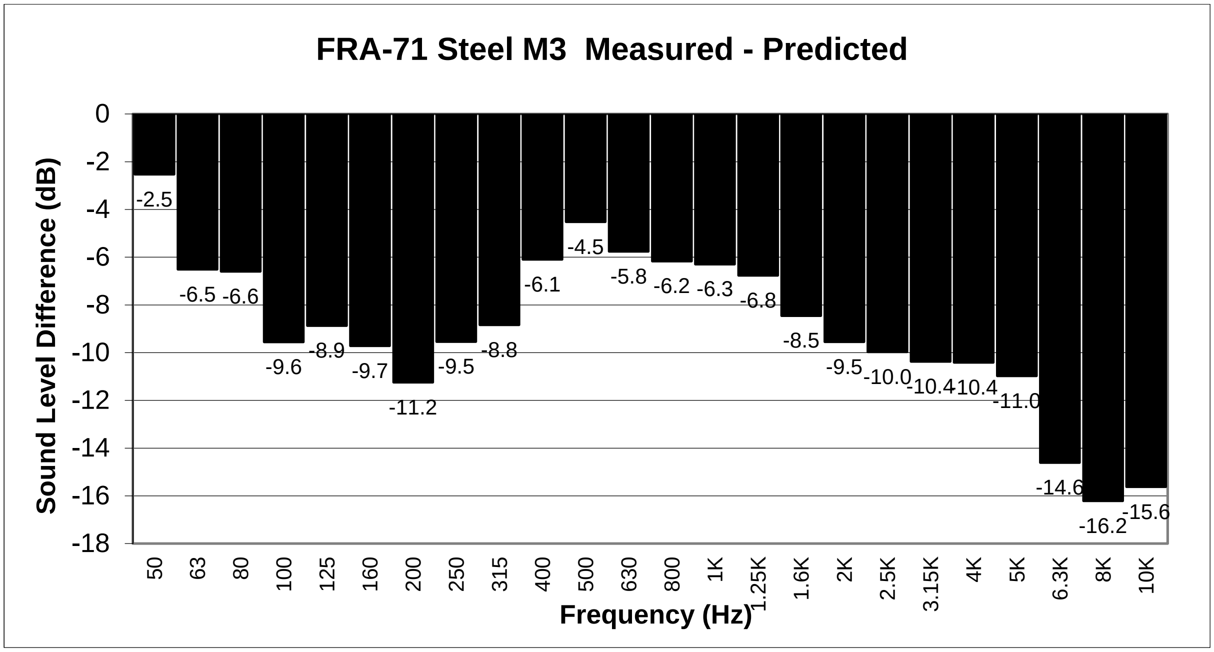
Site 12: Franklin County, I-71; Steel Wall



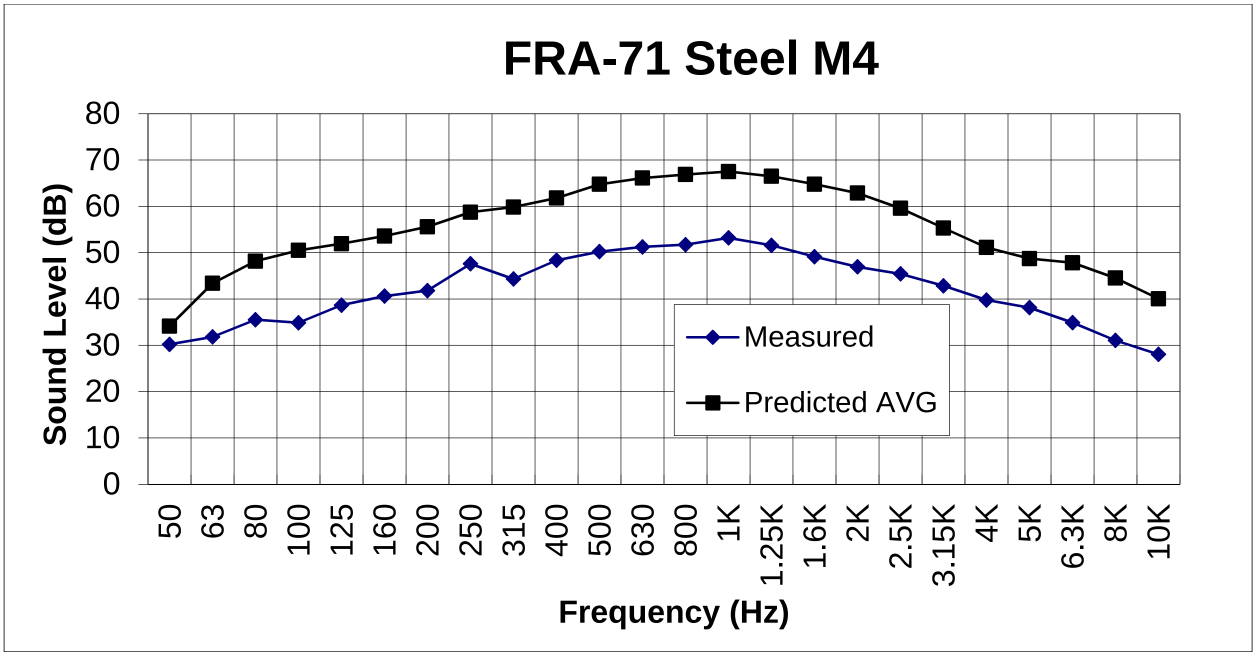


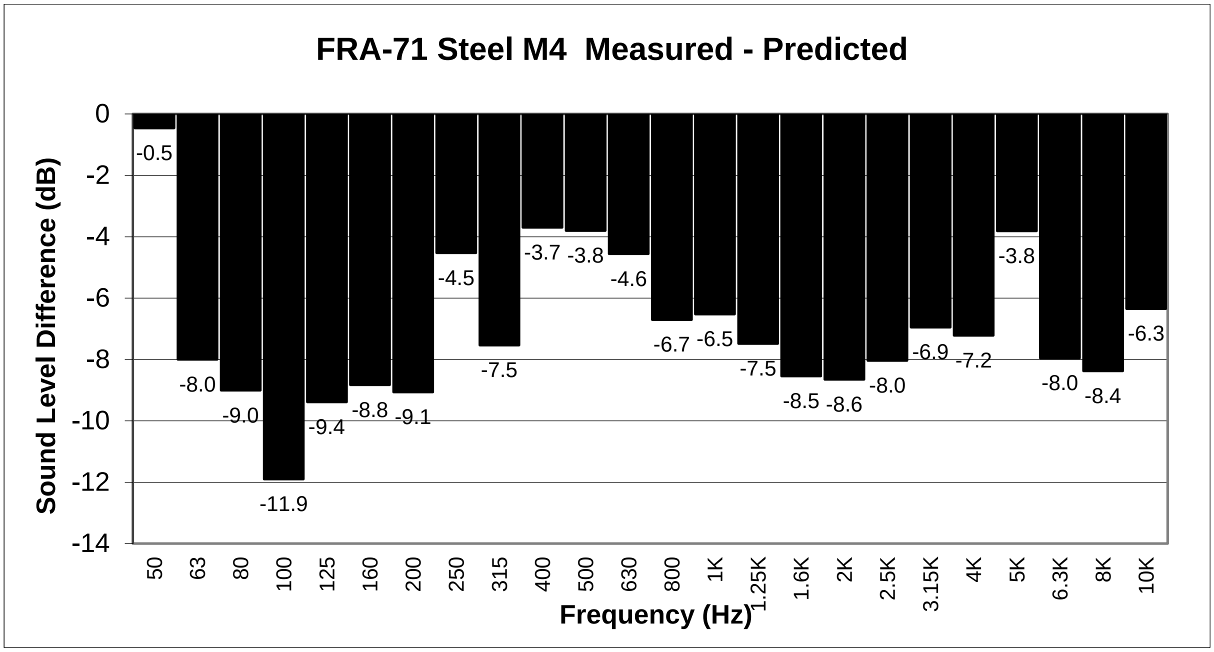
Site 12: Franklin County, I-71; Steel Wall



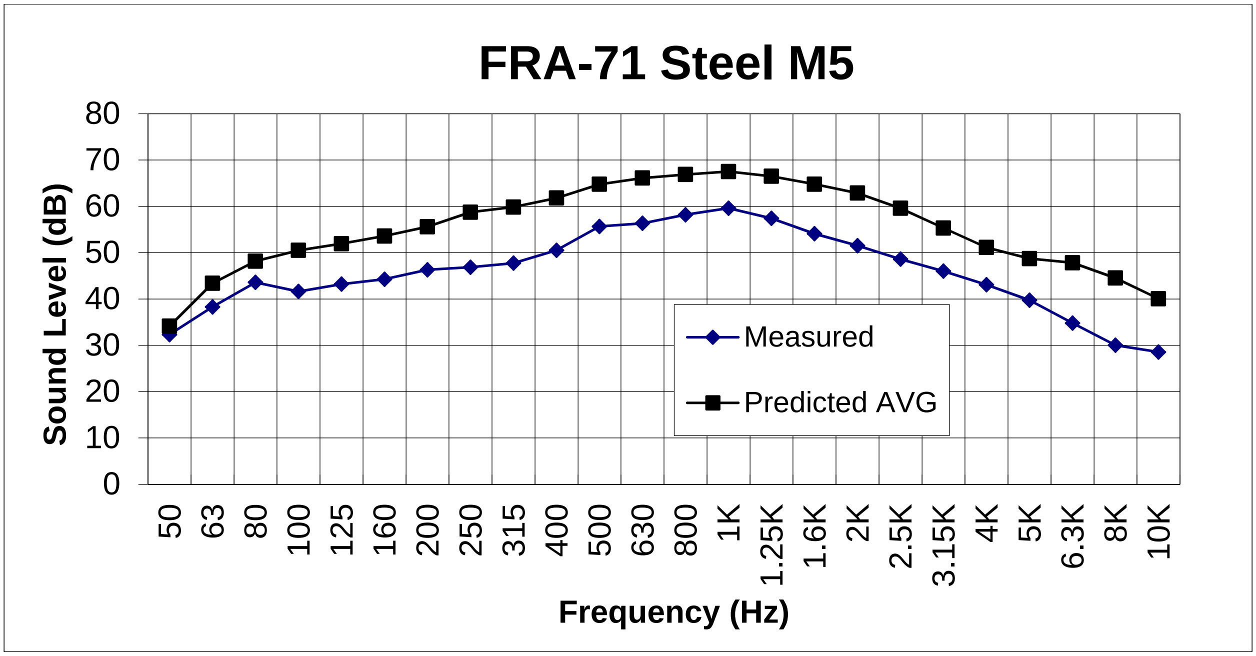


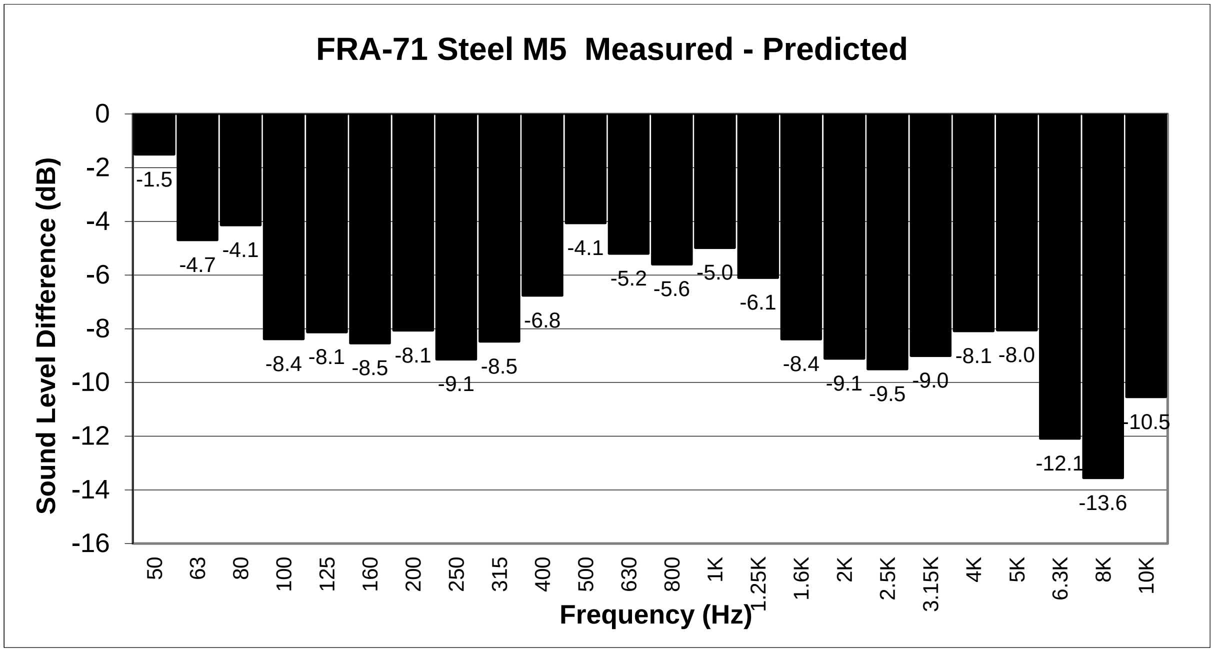
Site 12: Franklin County, I-71; Steel Wall



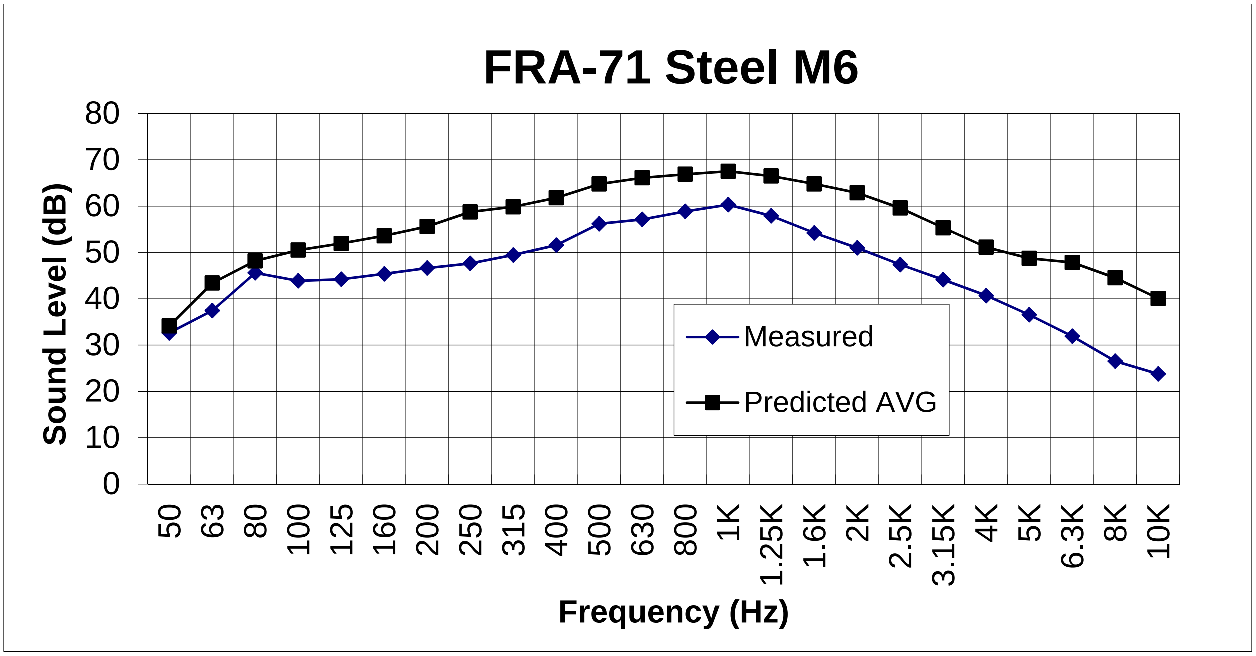


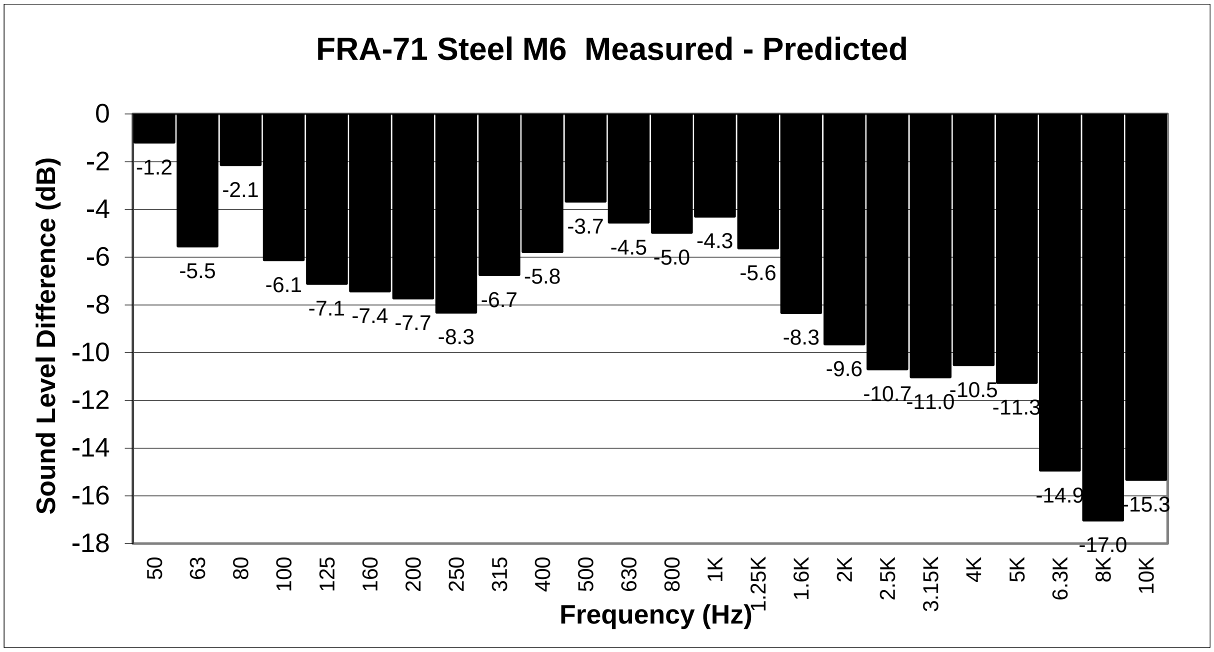
Site 12: Franklin County, I-71; Steel Wall



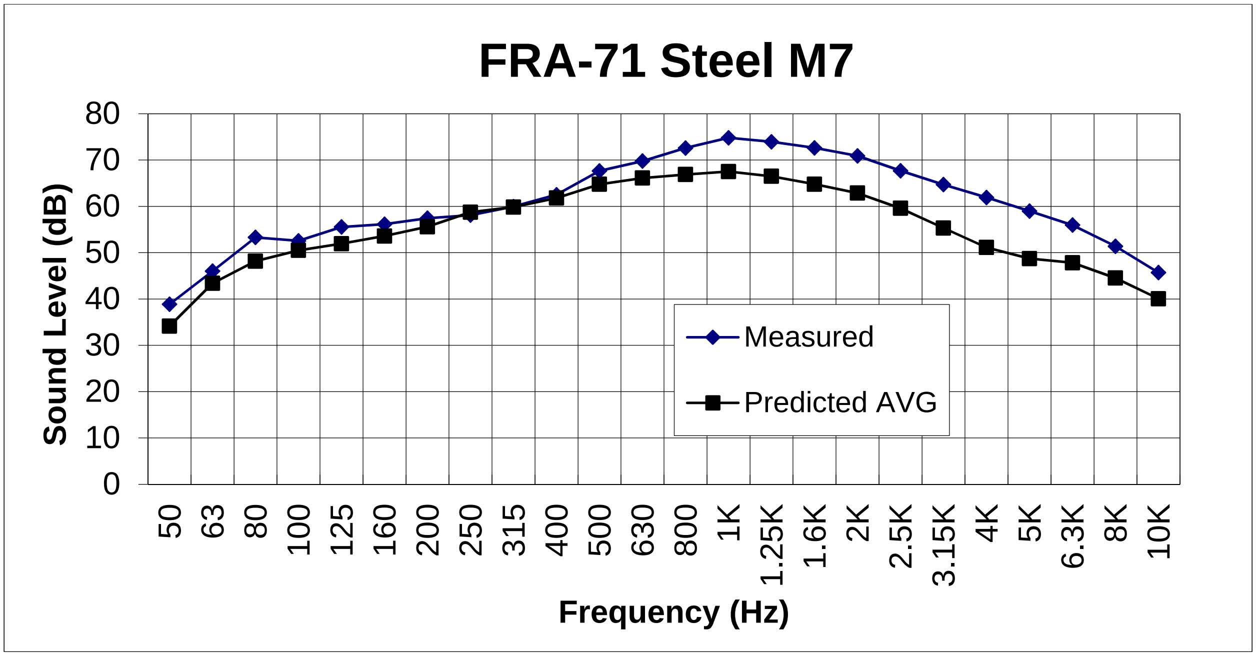


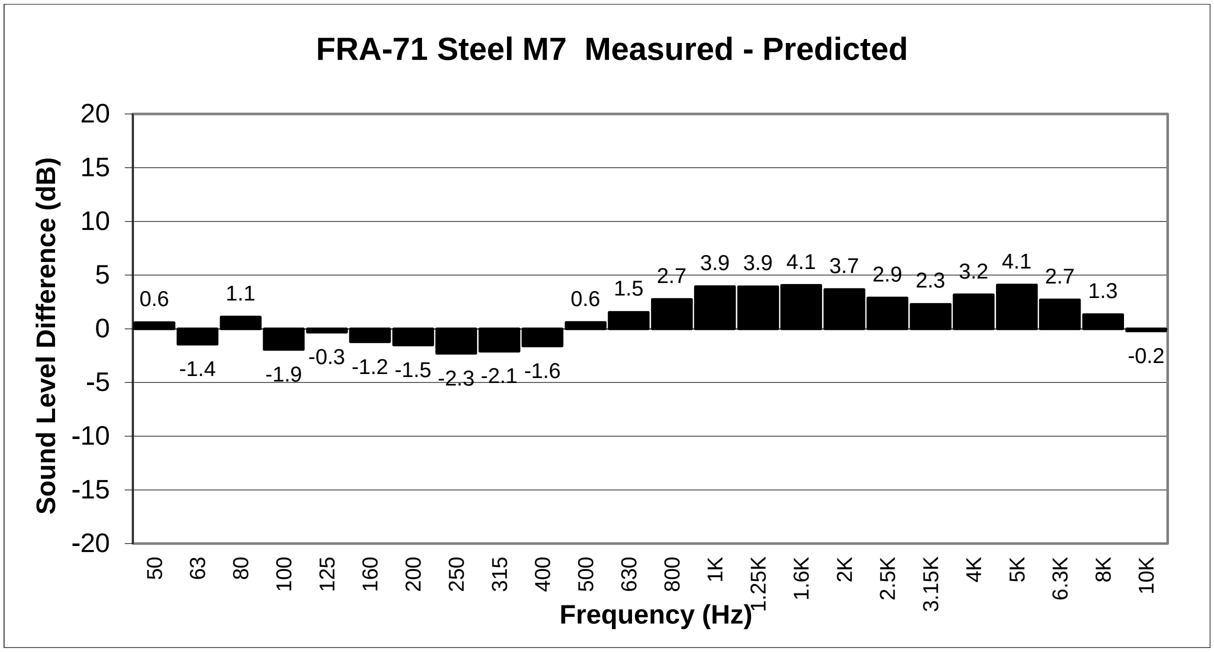
Site 12: Franklin County, I-71; Steel Wall



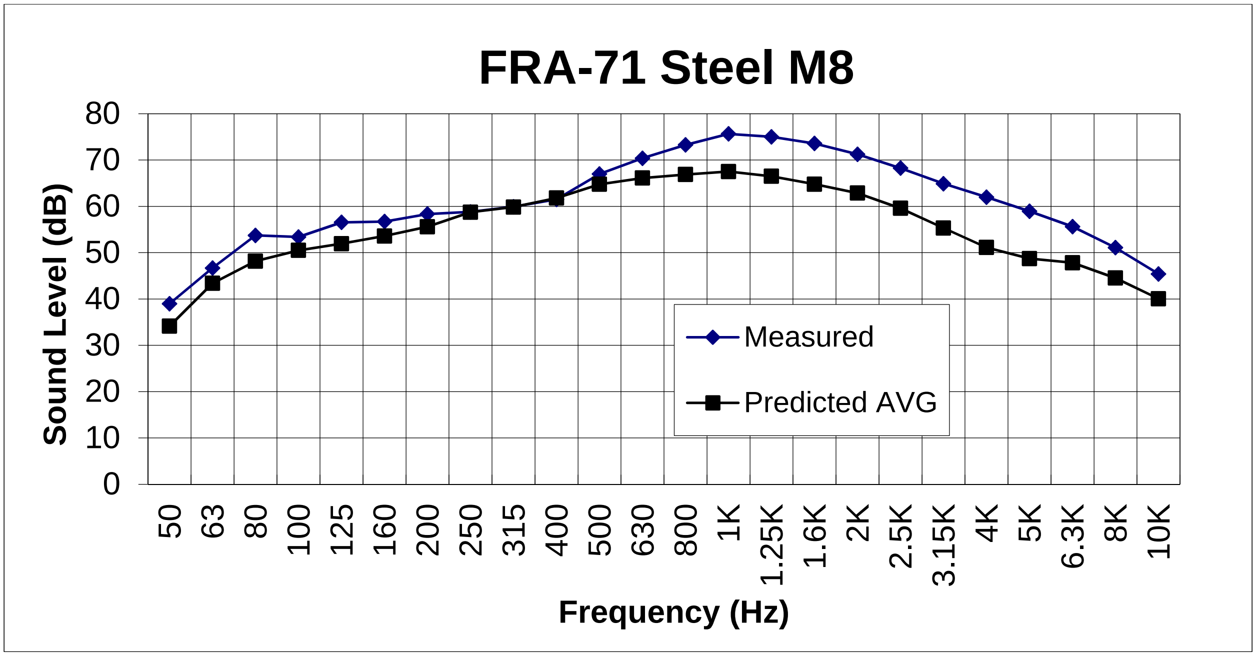


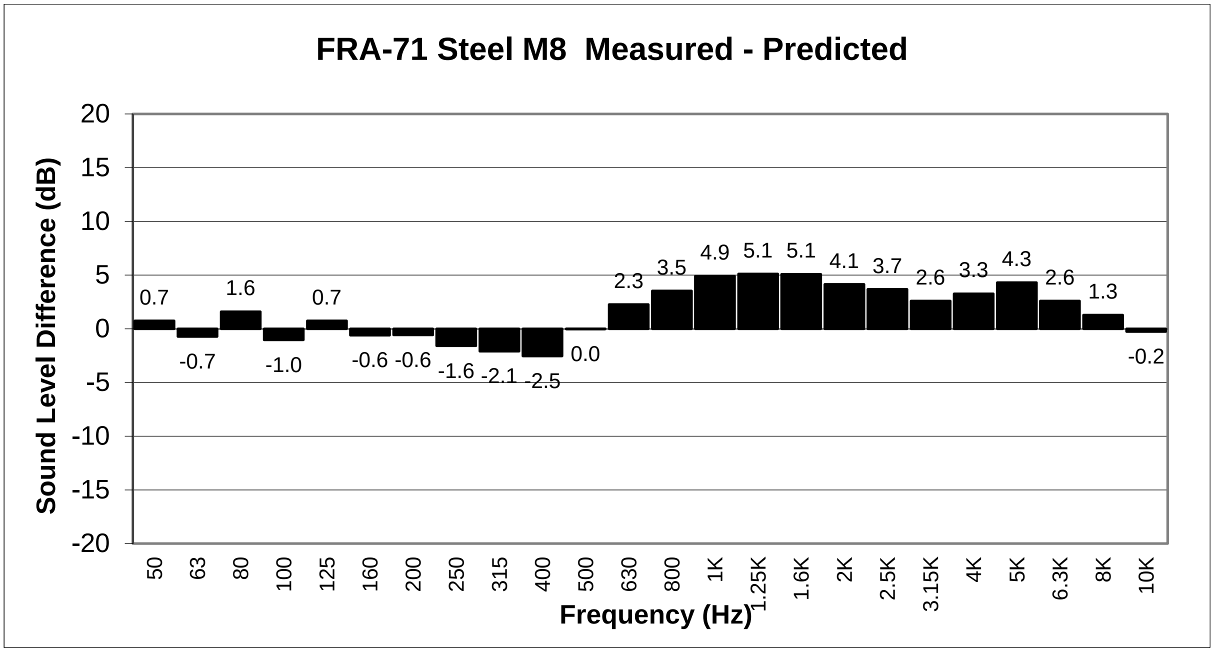
Site 12: Franklin County, I-71; Steel Wall



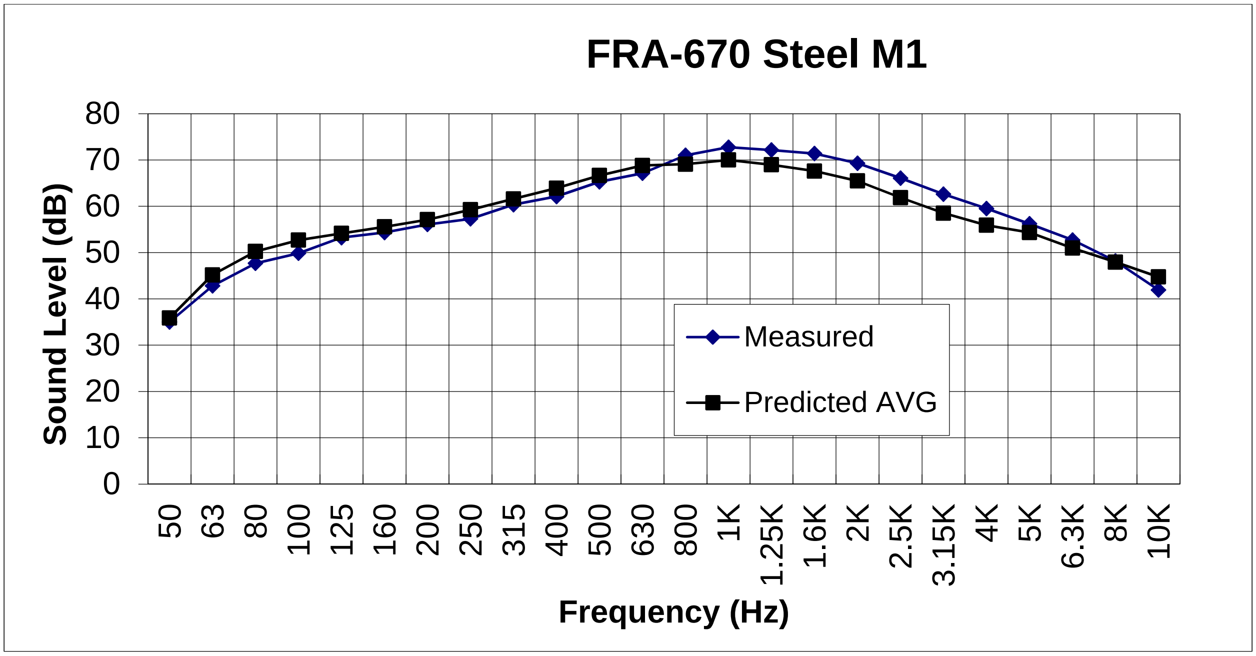


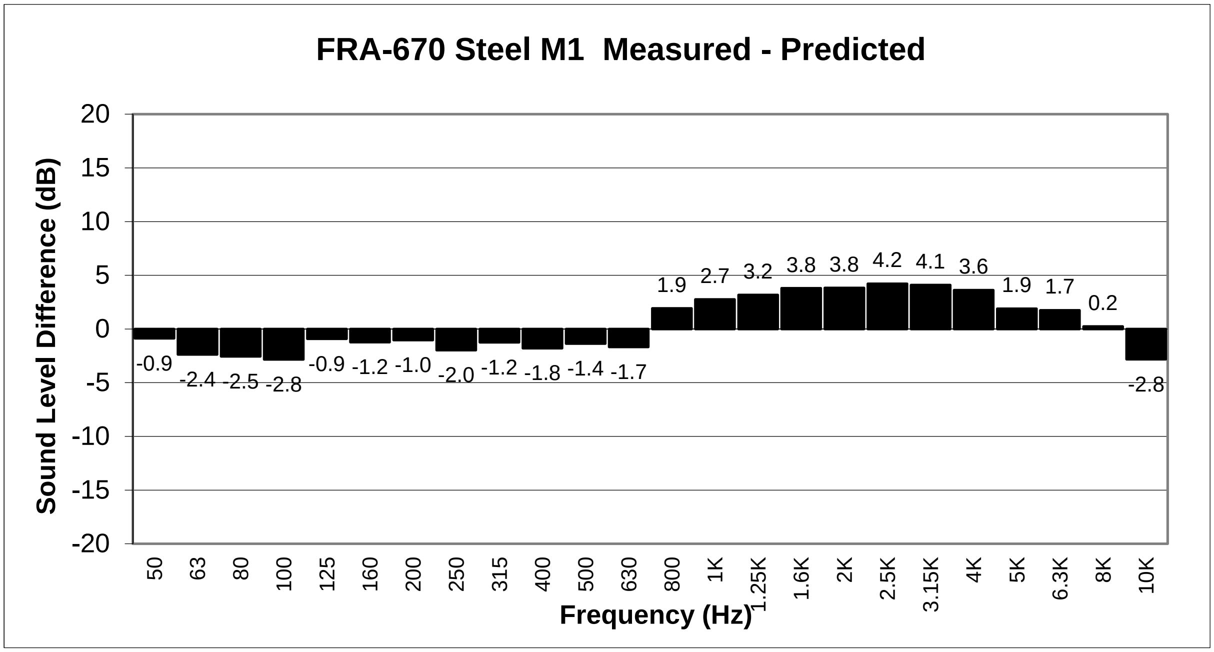
Site 12: Franklin County, I-71; Steel Wall



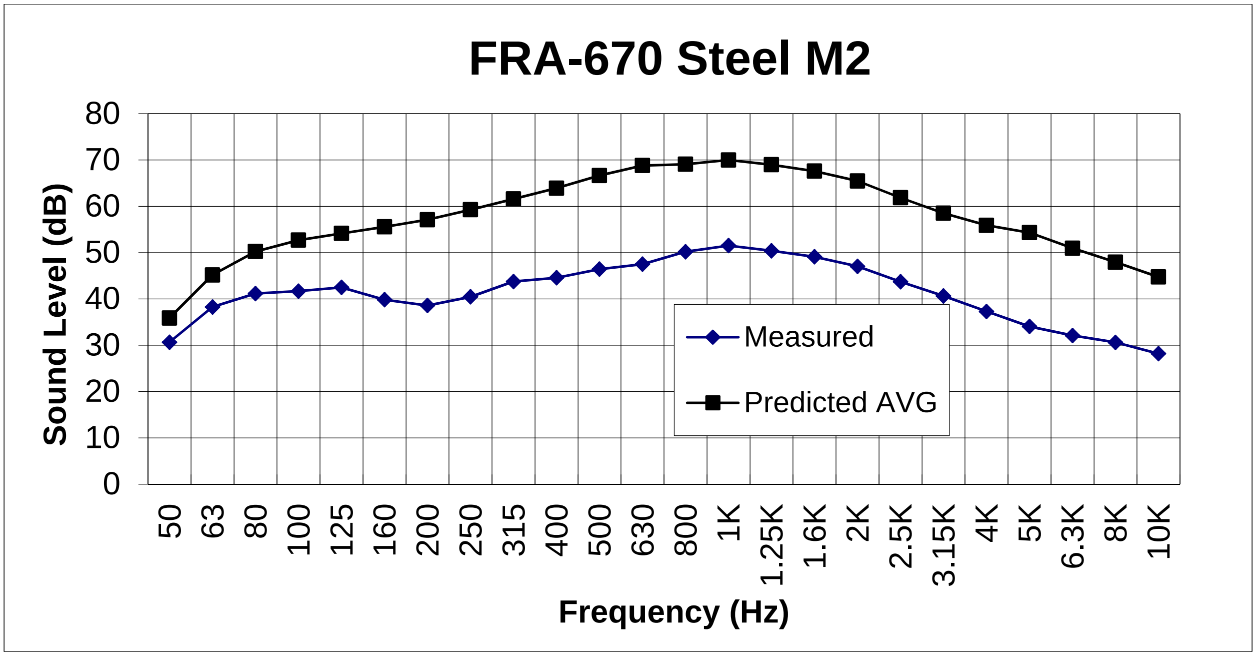


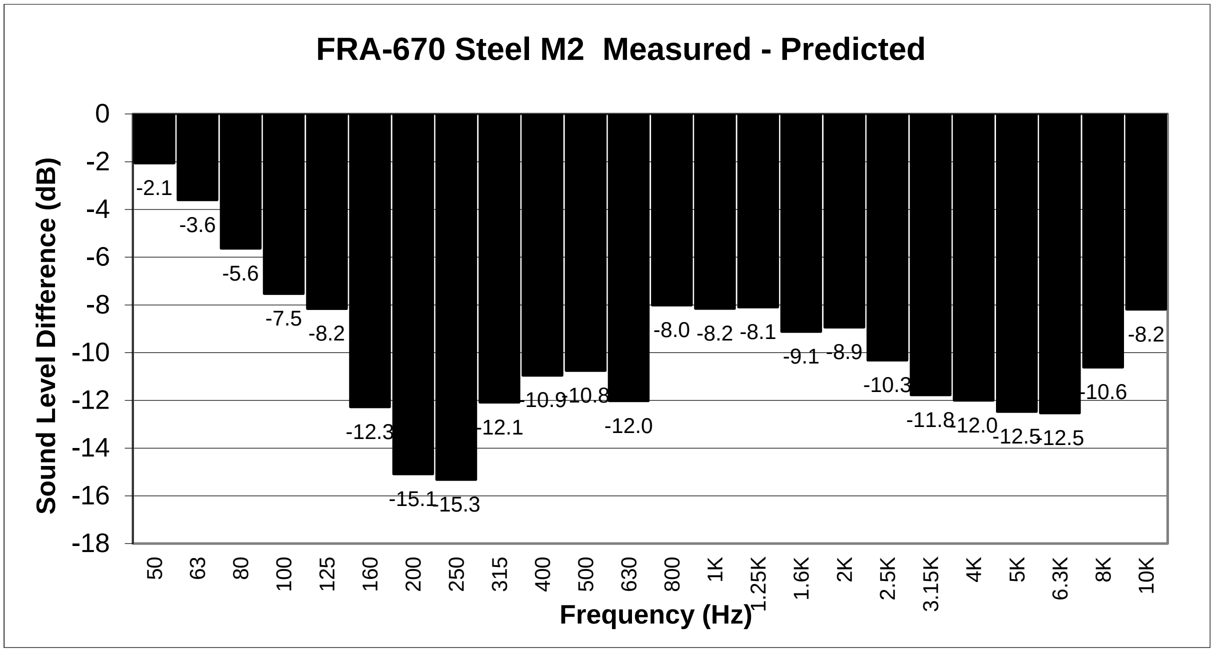
Site 13: Franklin County, I-670; Steel Wall



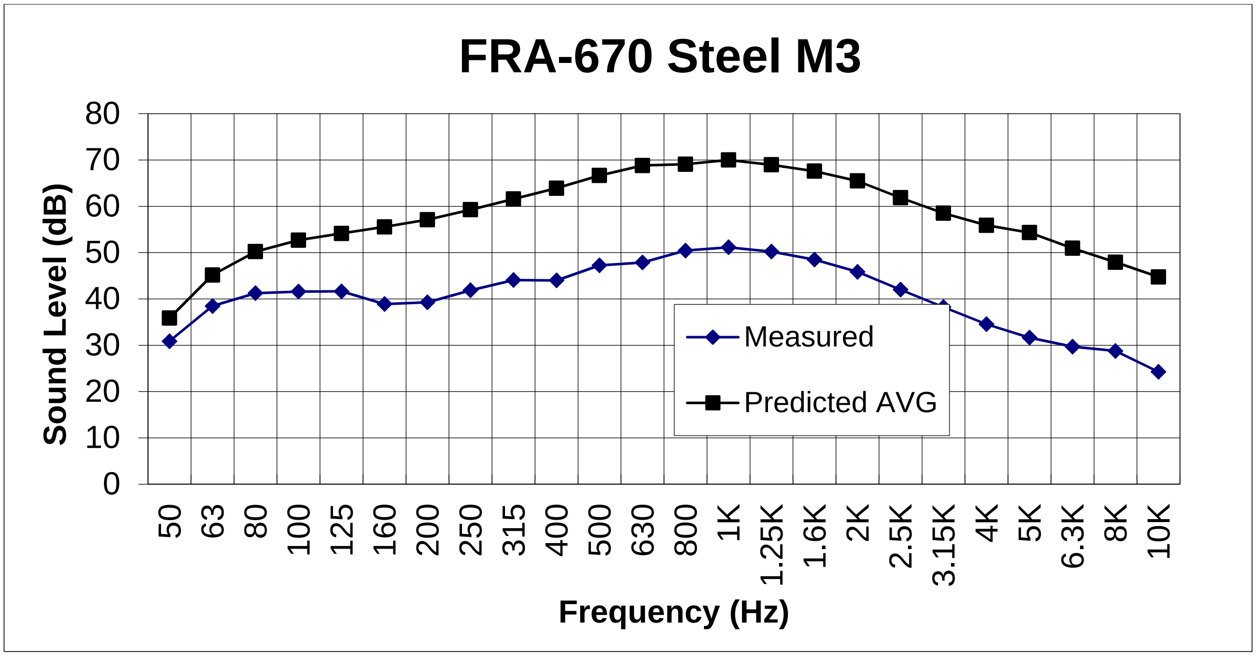


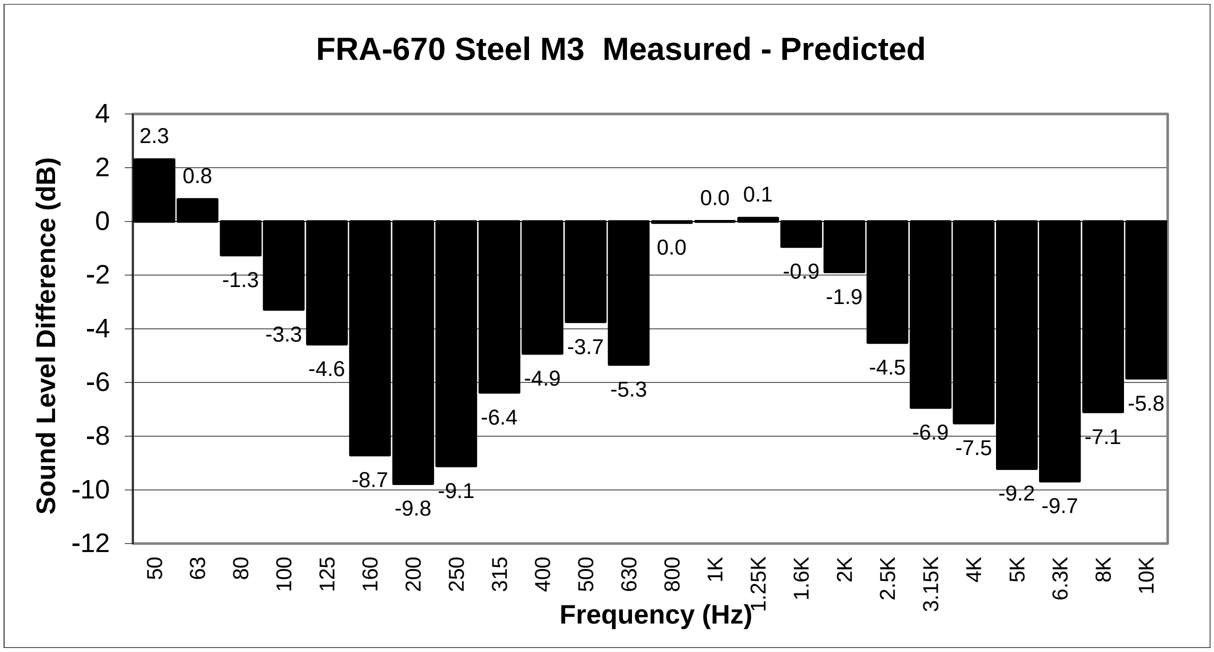
Site 13: Franklin County, I-670; Steel Wall



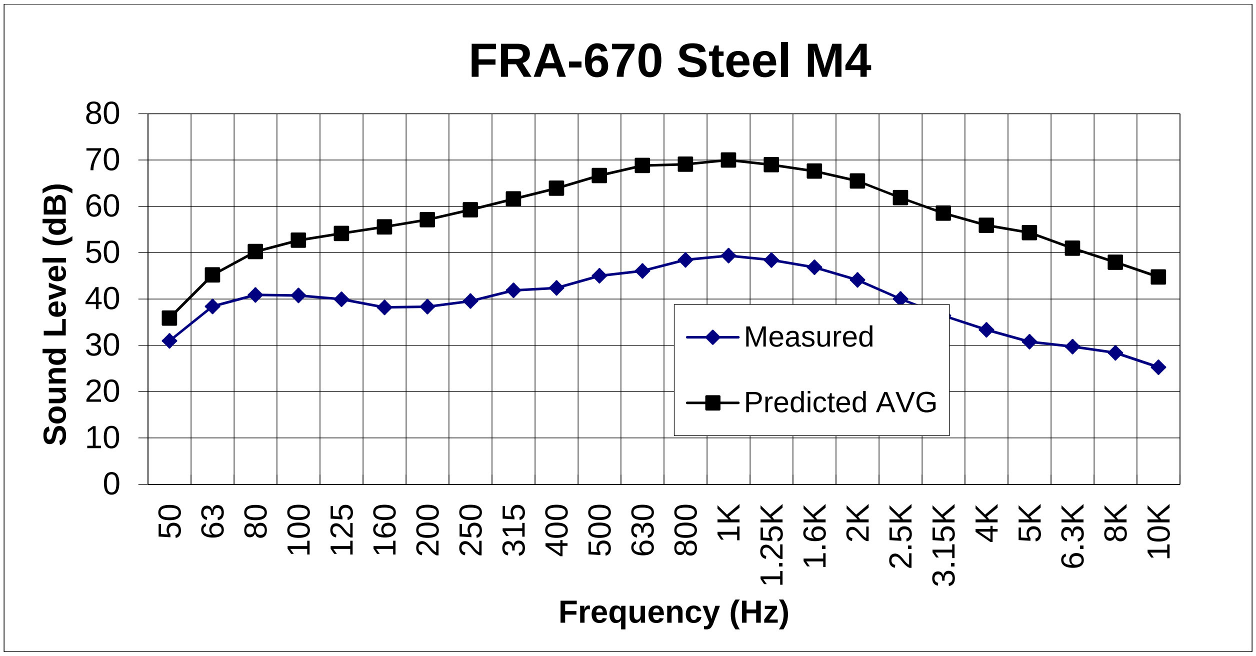


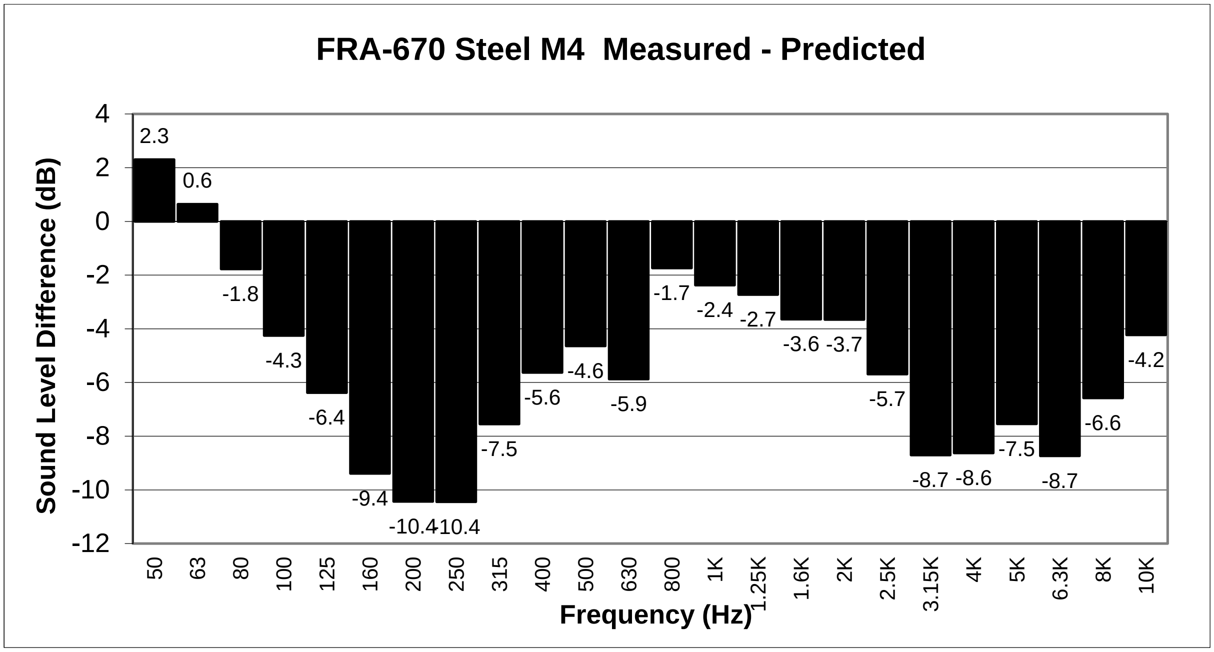
Site 13: Franklin County, I-670; Steel Wall



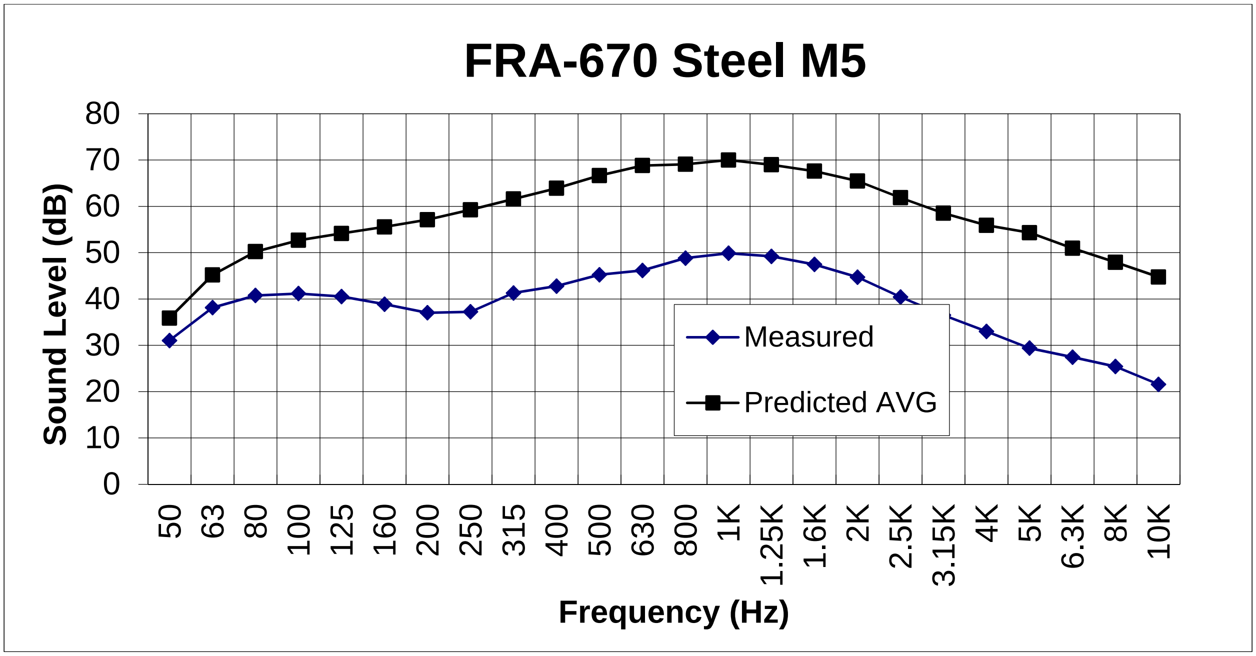


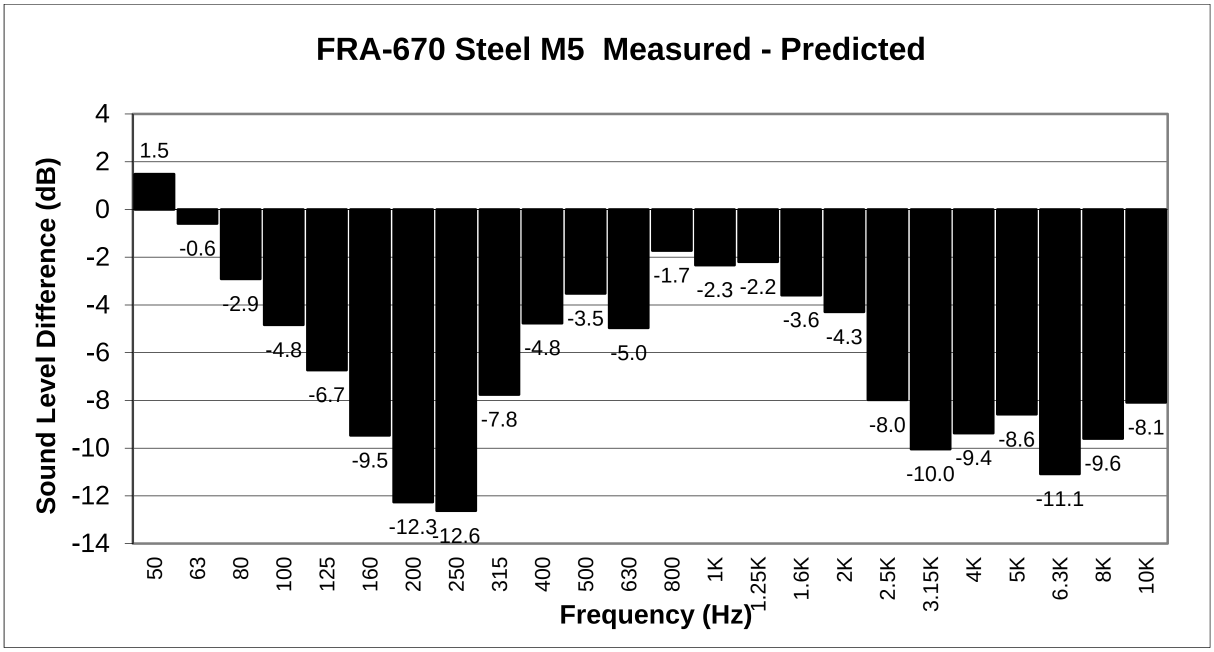
Site 13: Franklin County, I-670; Steel Wall



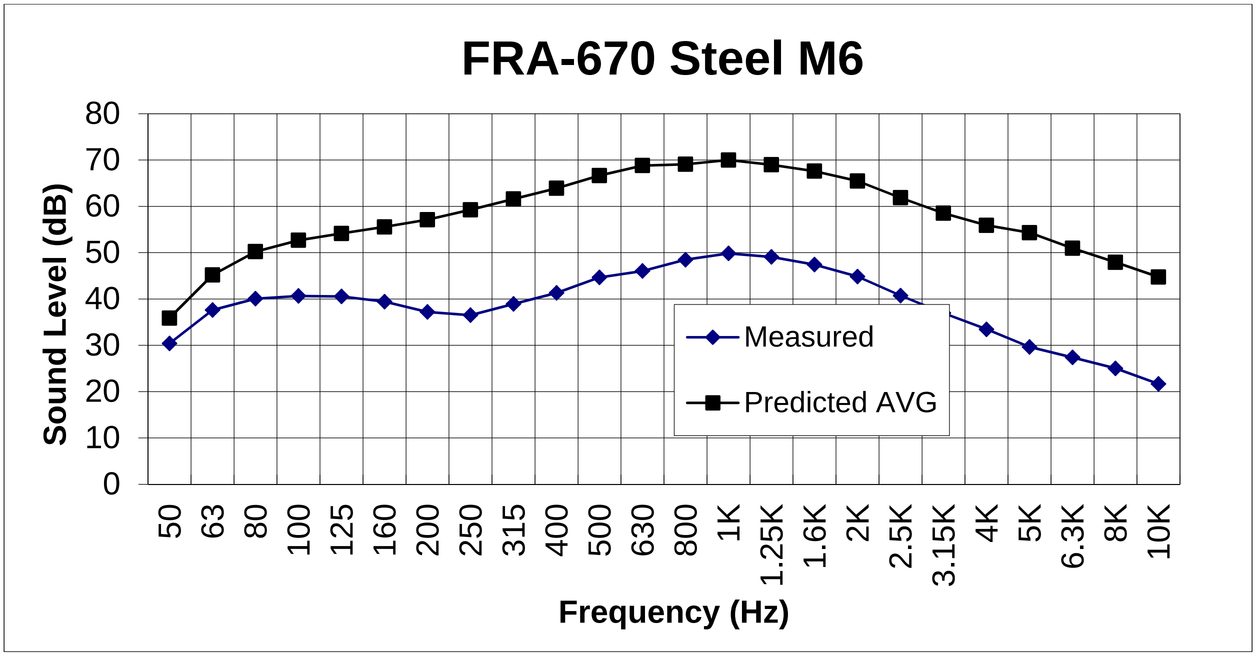


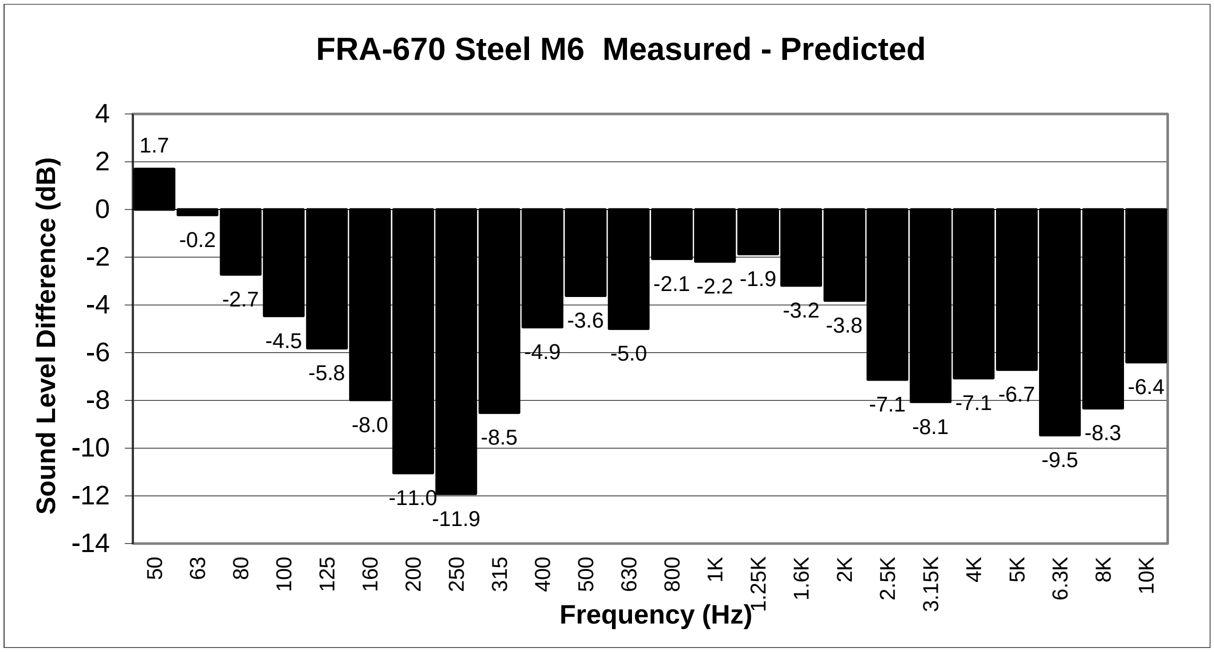
Site 13: Franklin County, I-670; Steel Wall



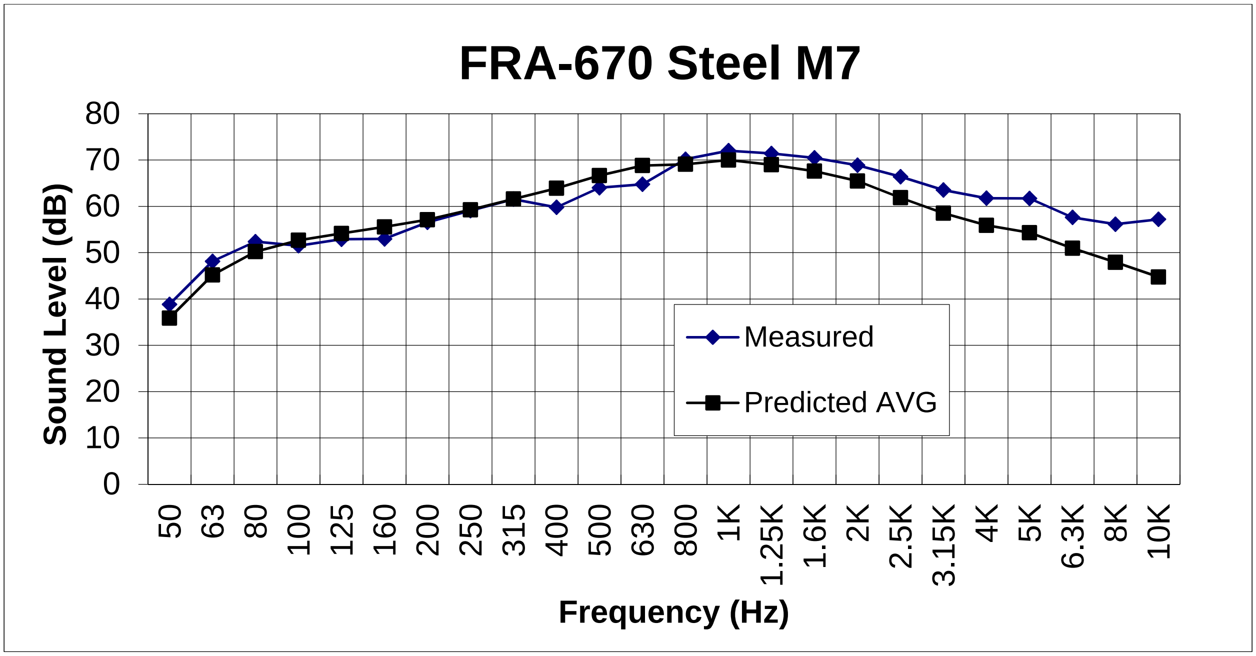


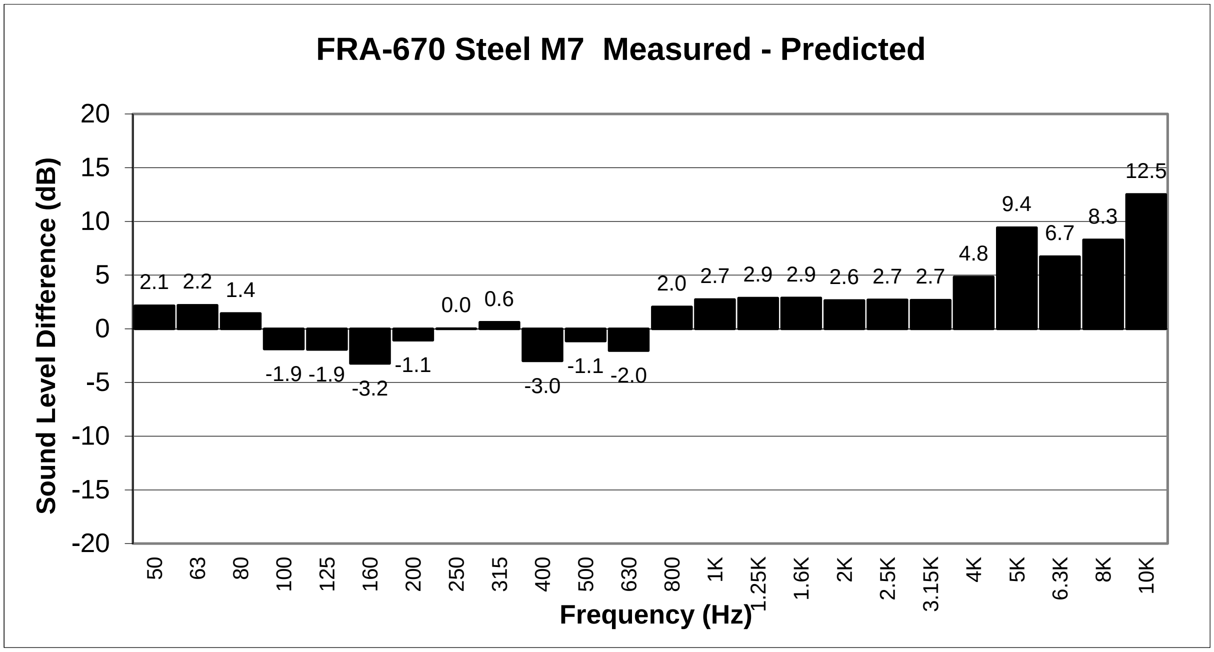
Site 13: Franklin County, I-670; Steel Wall



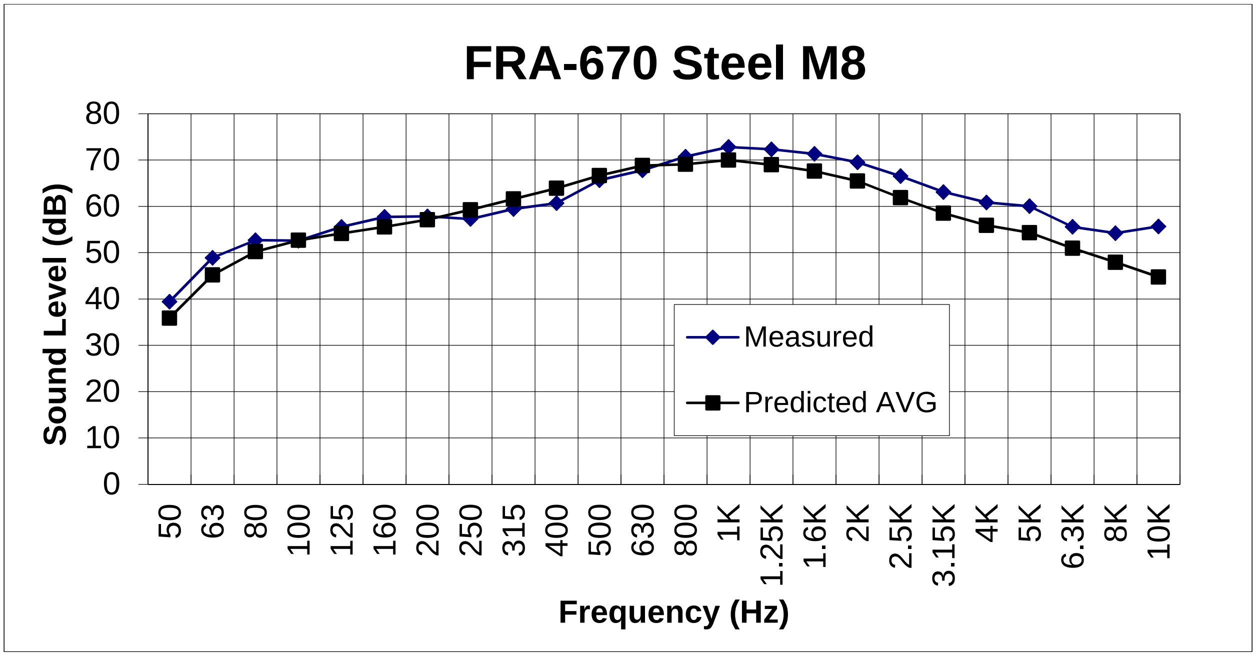


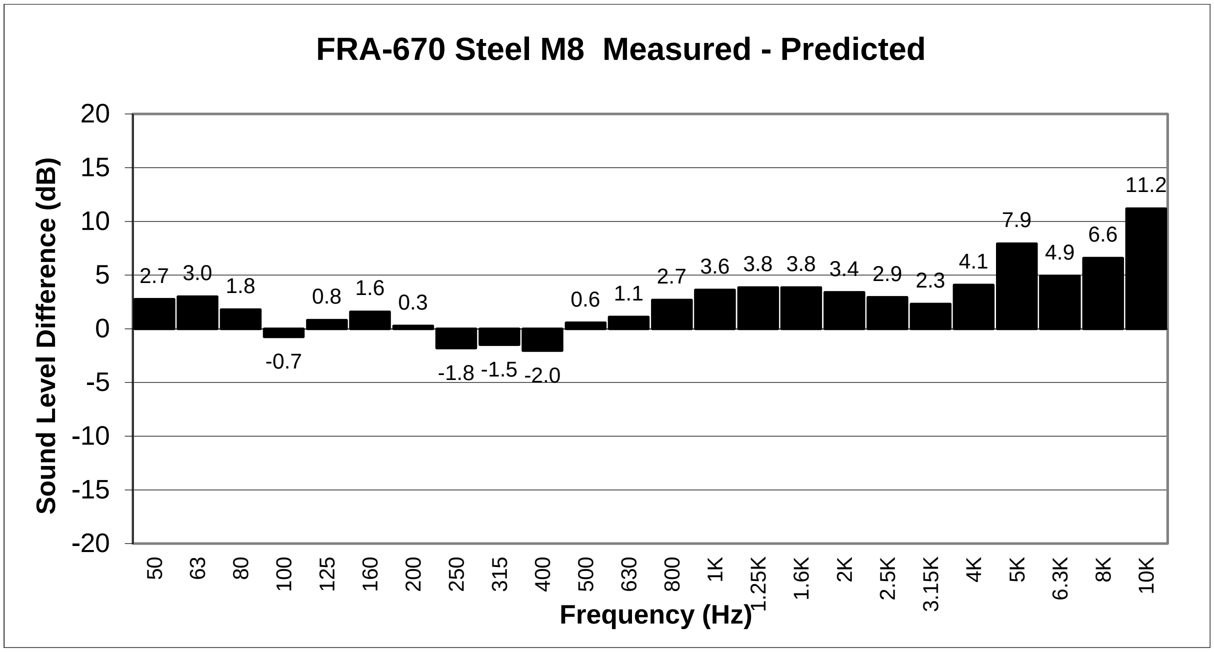
Site 13: Franklin County, I-670; Steel Wall



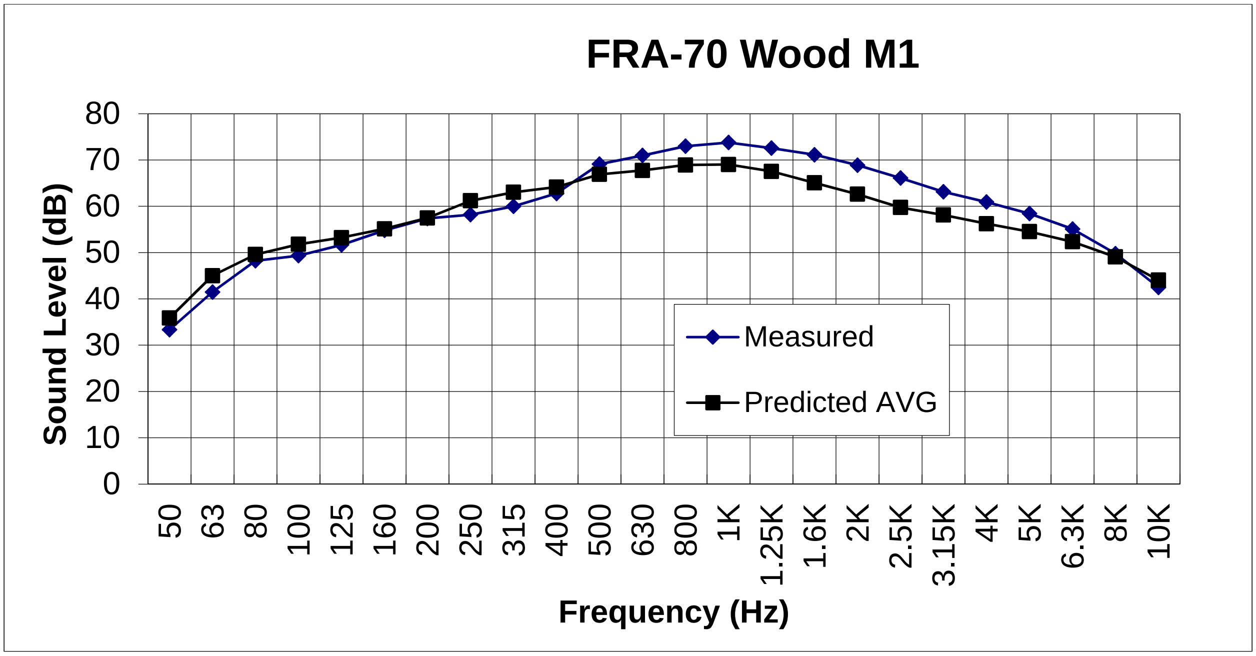


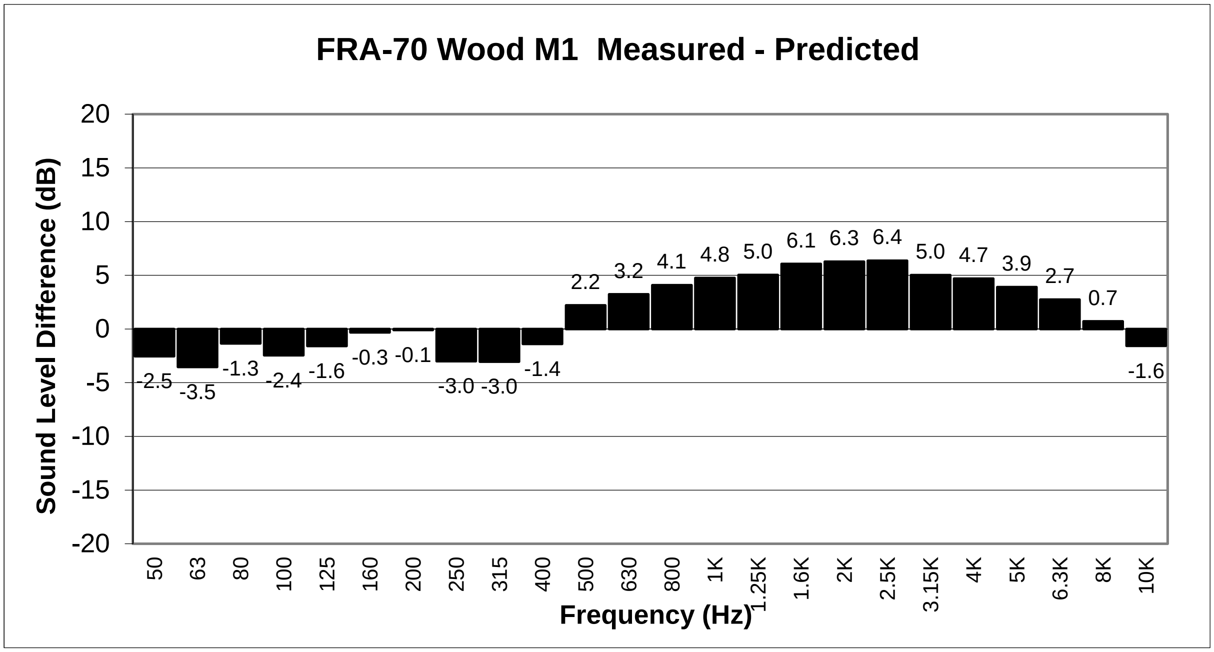
Site 13: Franklin County, I-670; Steel Wall



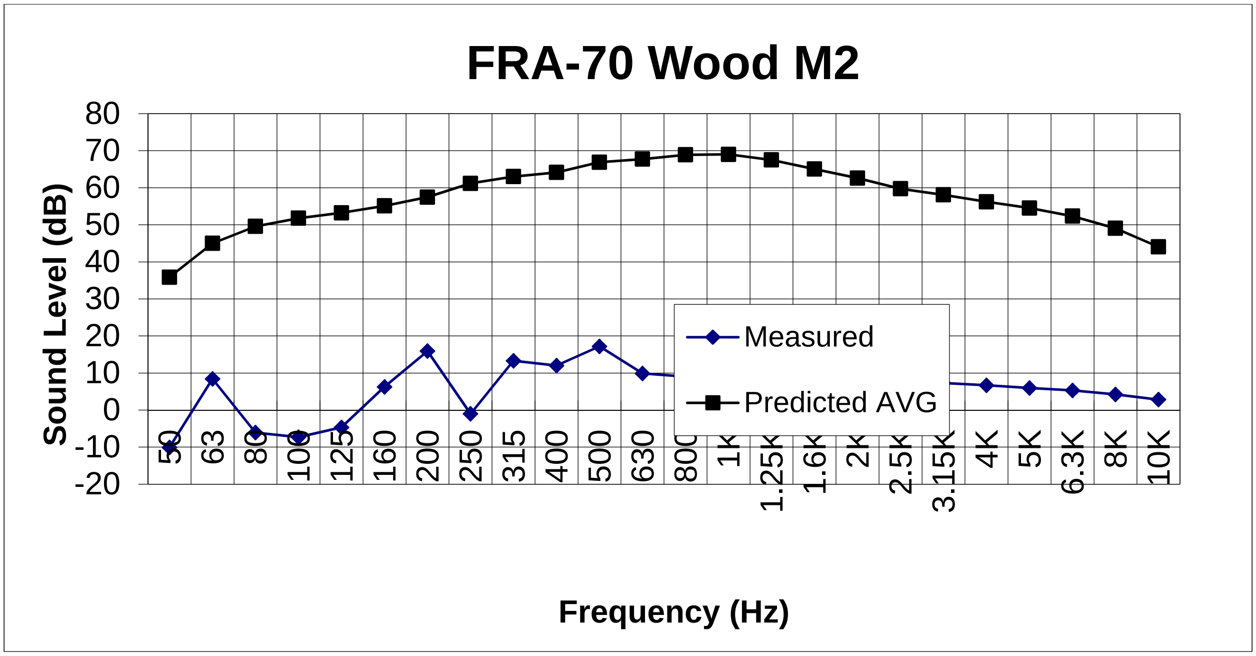


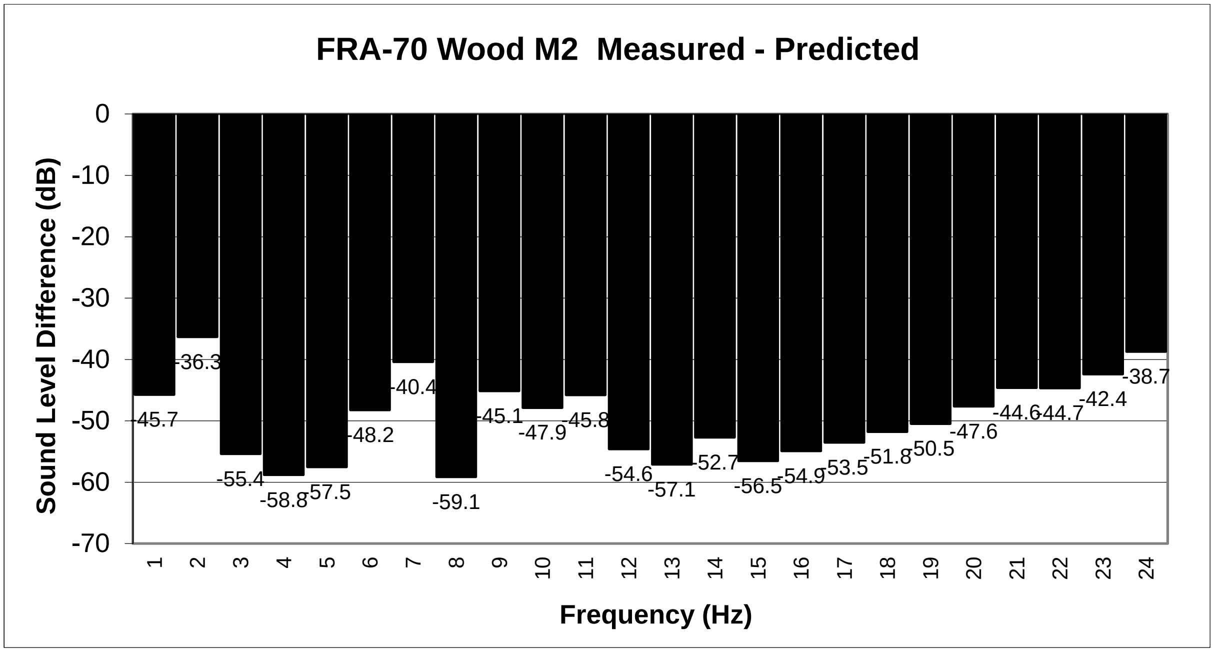
Site 14: Franklin County, I-70; Wood Wall



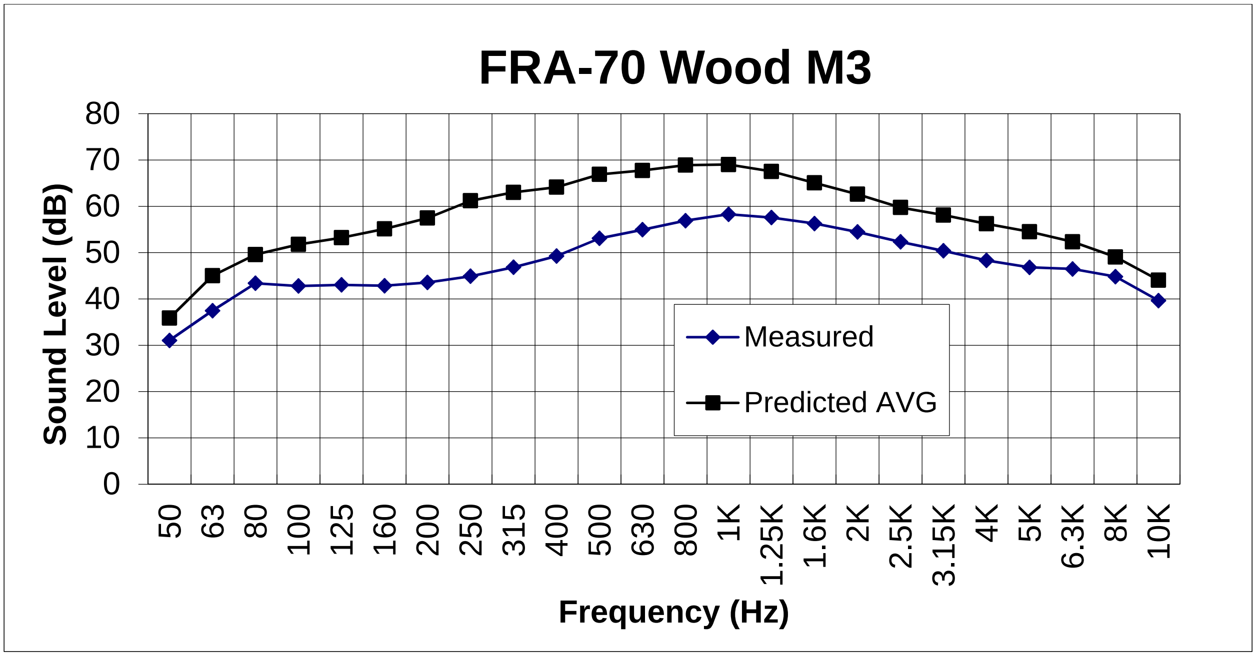


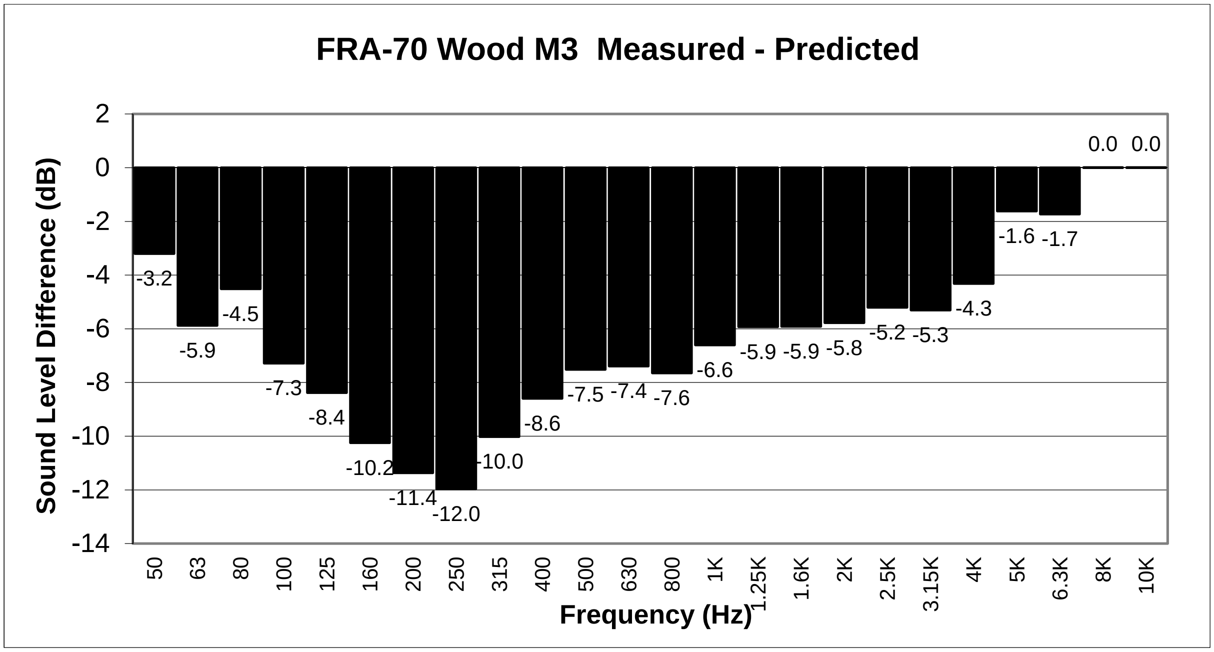
Site 14: Franklin County, I-70; Wood Wall



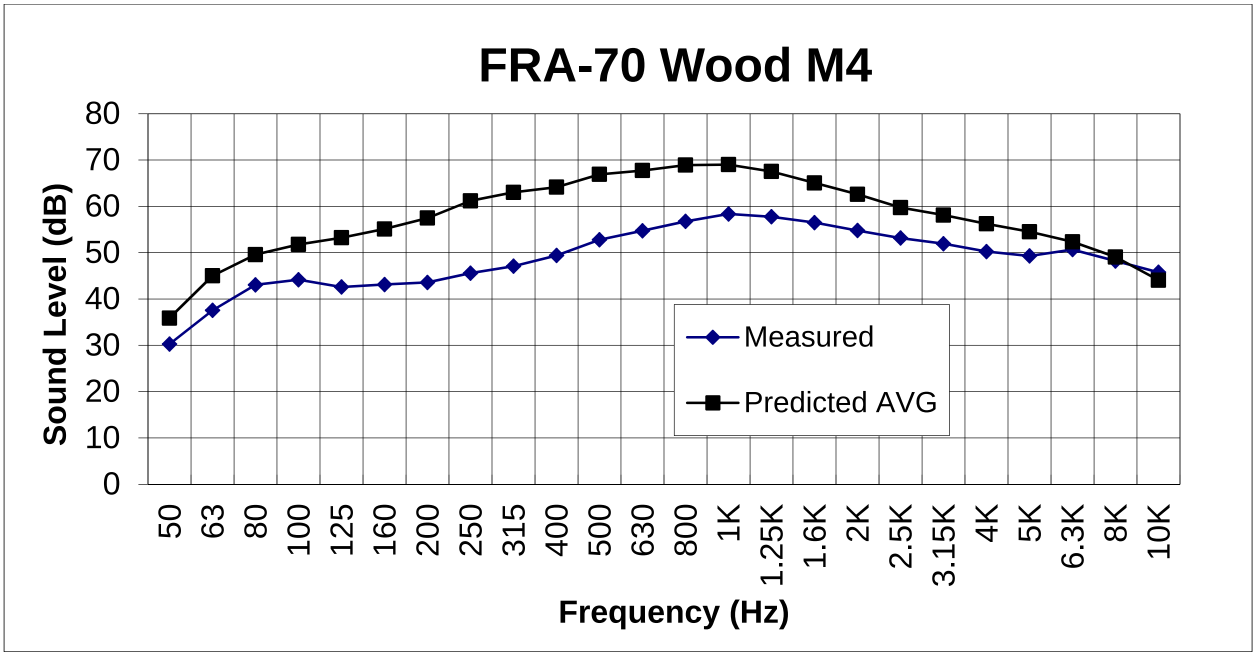


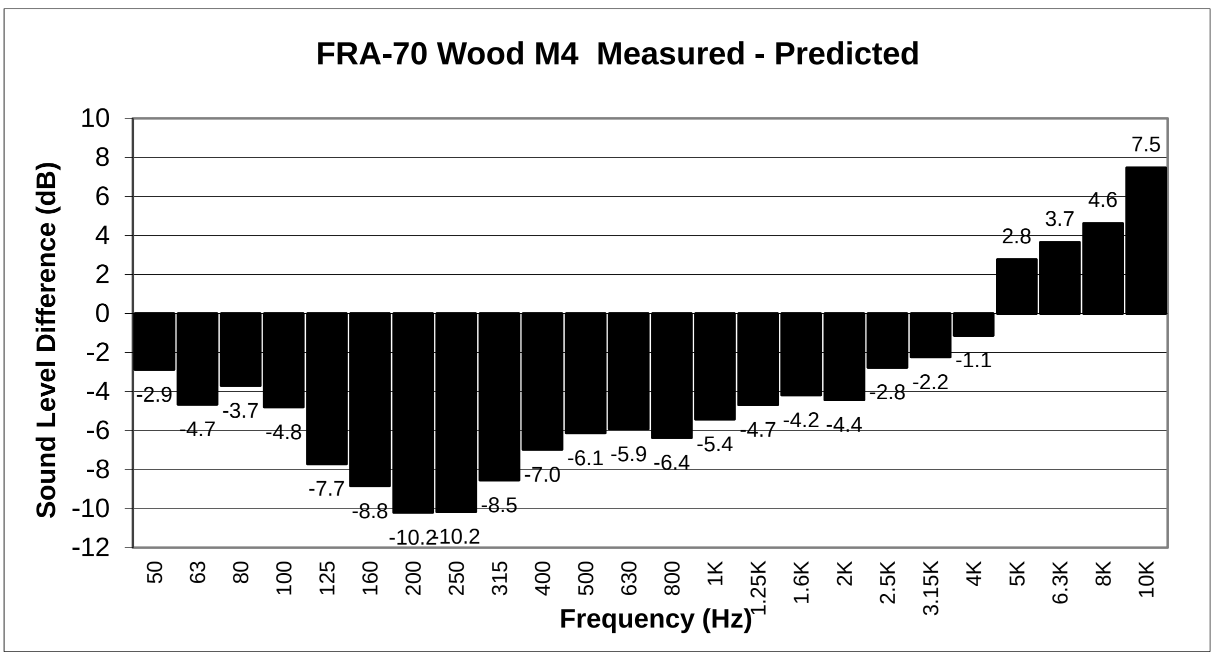
Site 14: Franklin County, I-70; Wood Wall



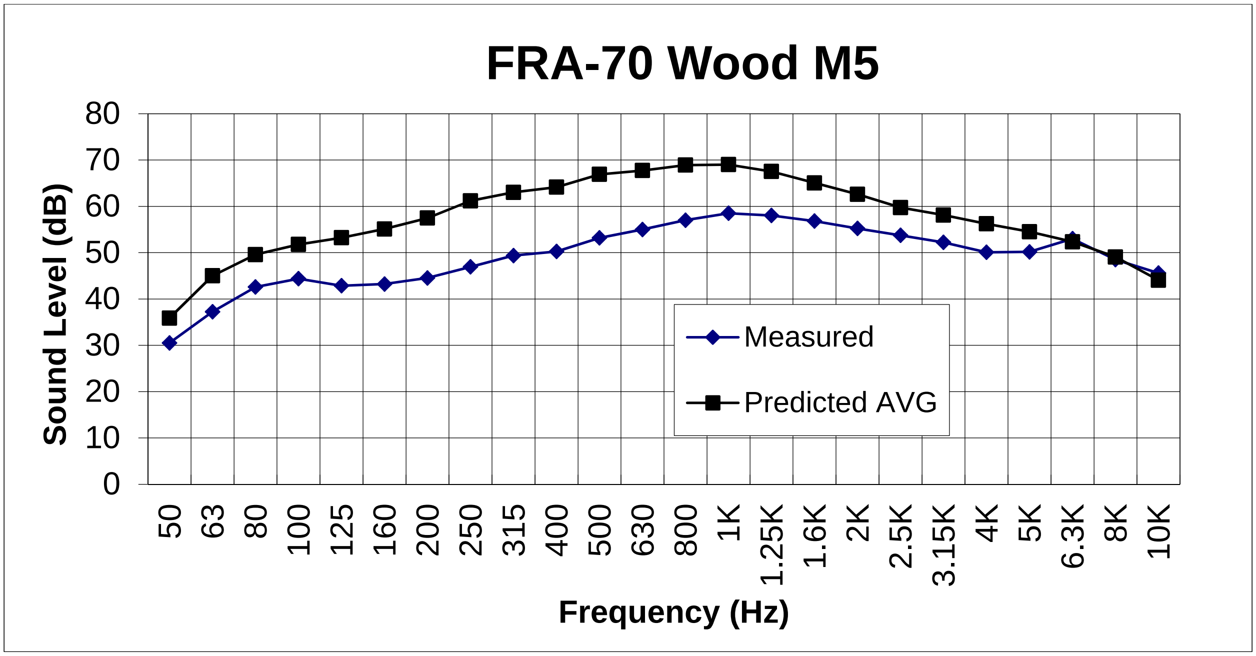


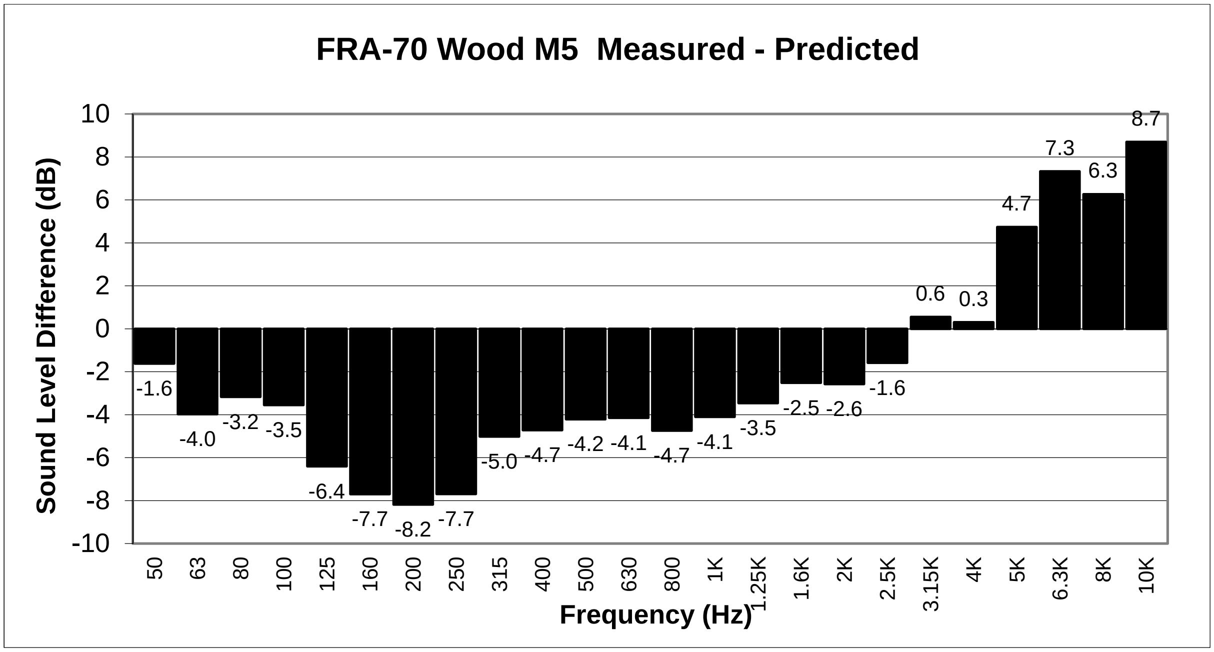
Site 14: Franklin County, I-70; Wood Wall



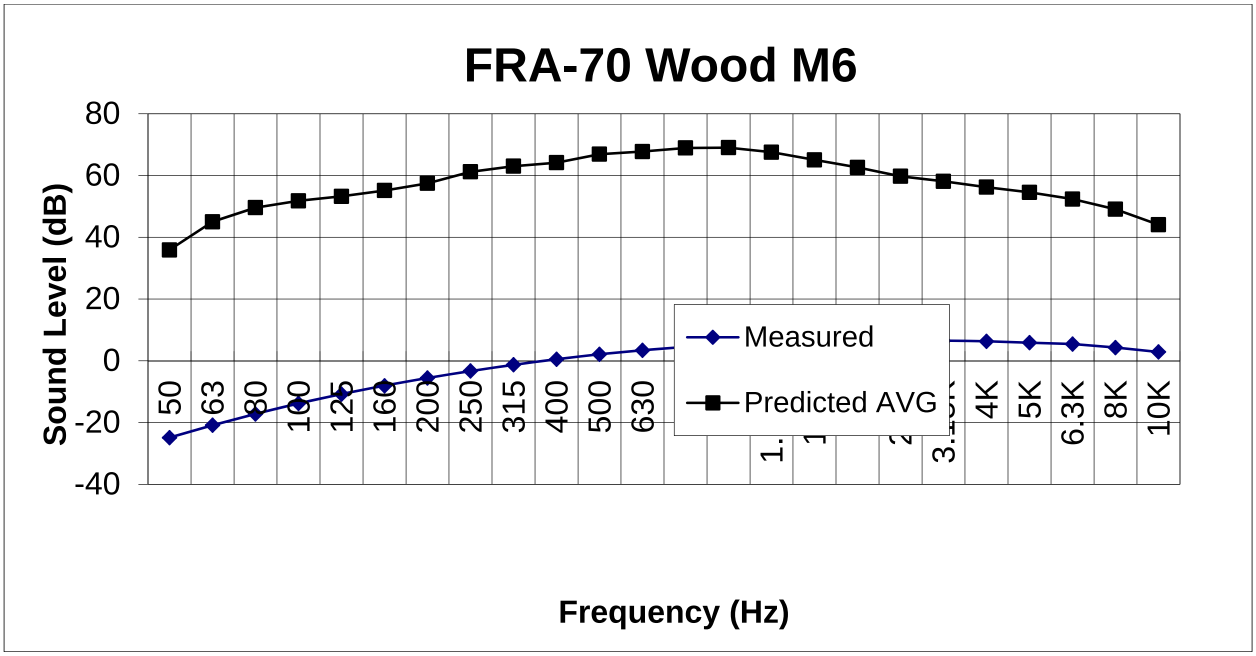


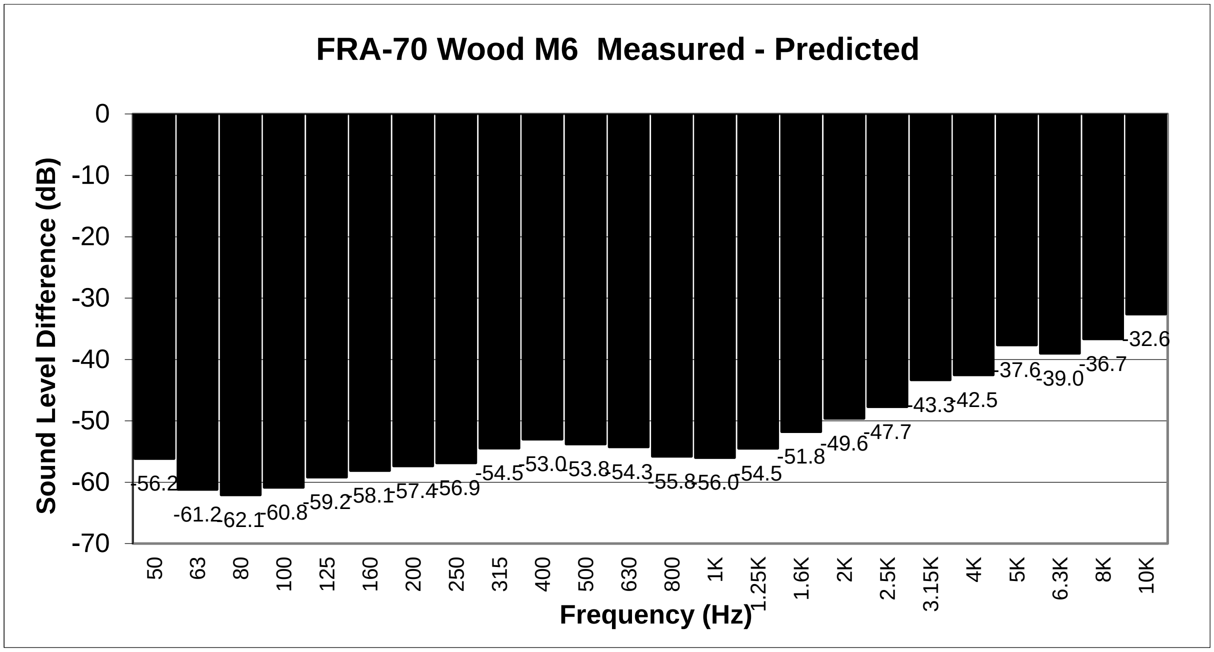
Site 14: Franklin County, I-70; Wood Wall



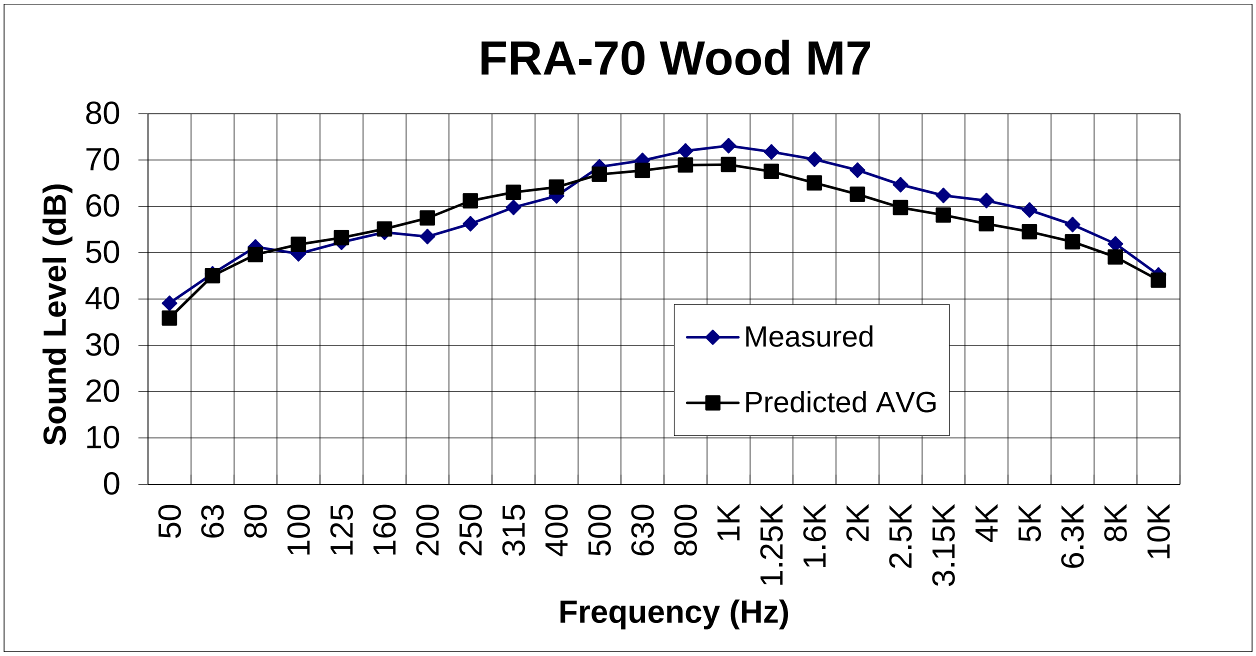


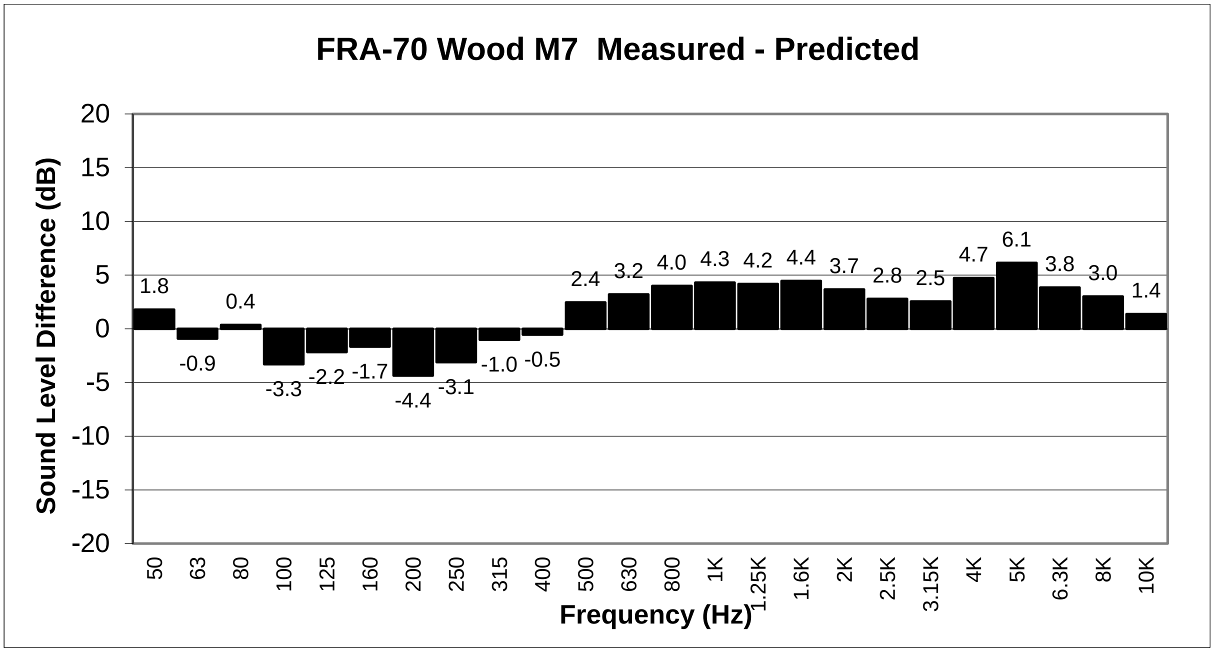
Site 14: Franklin County, I-70; Wood Wall



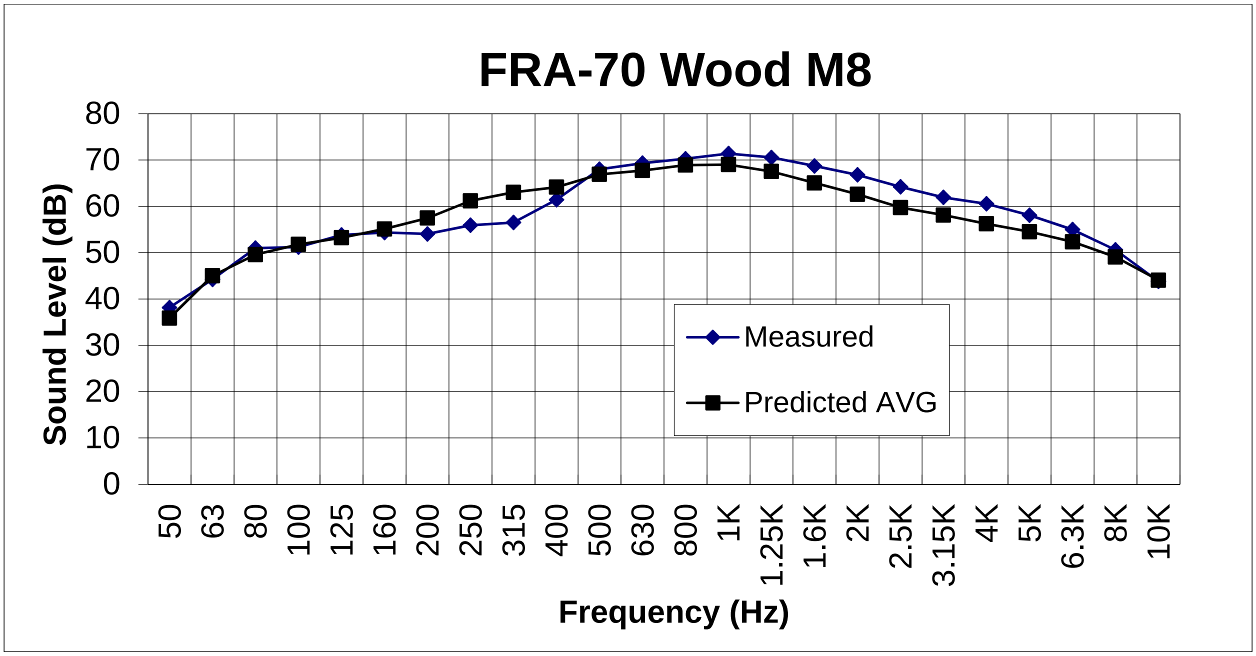


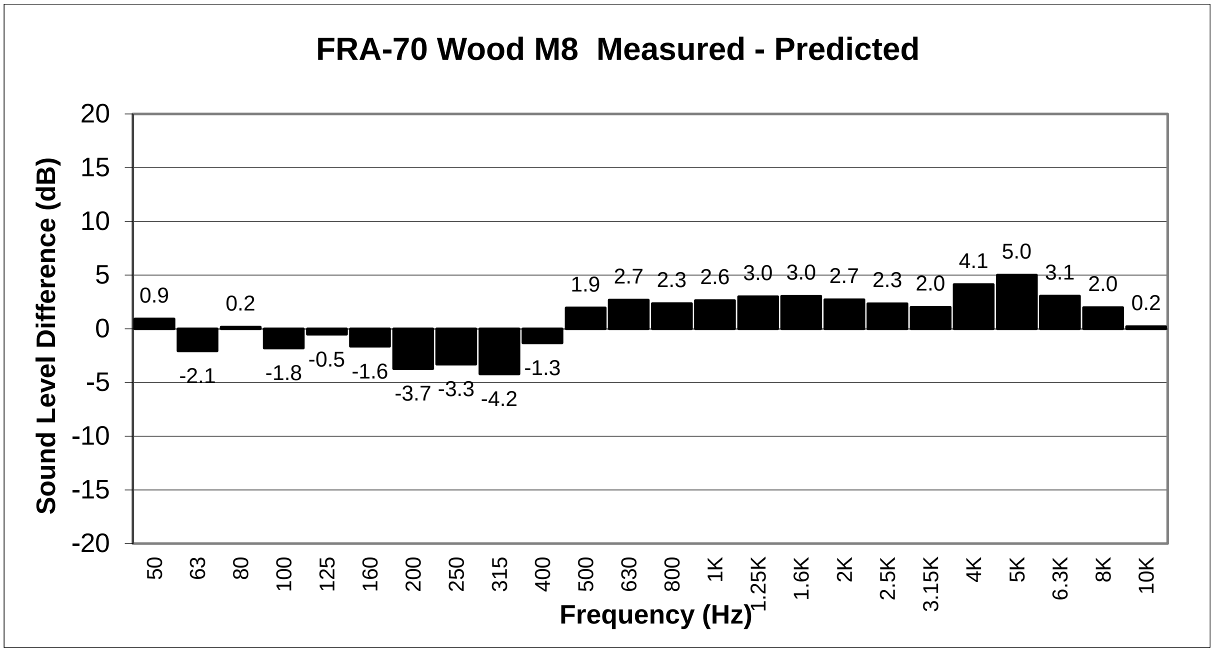
Site 14: Franklin County, I-70; Wood Wall



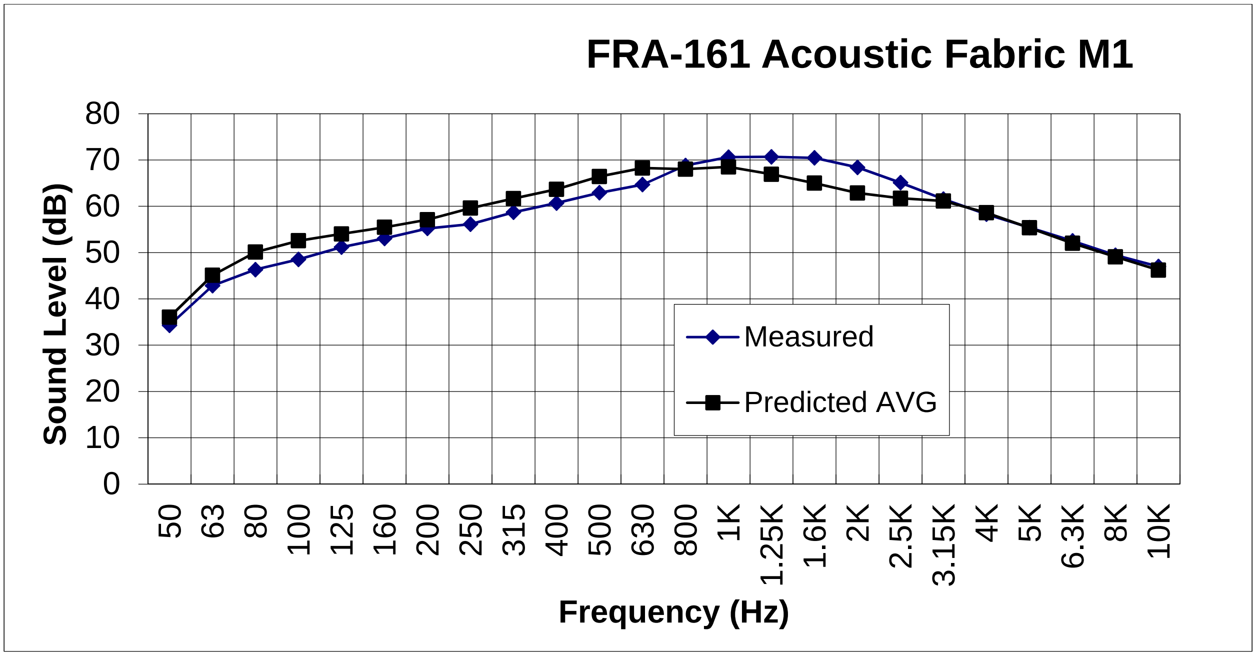


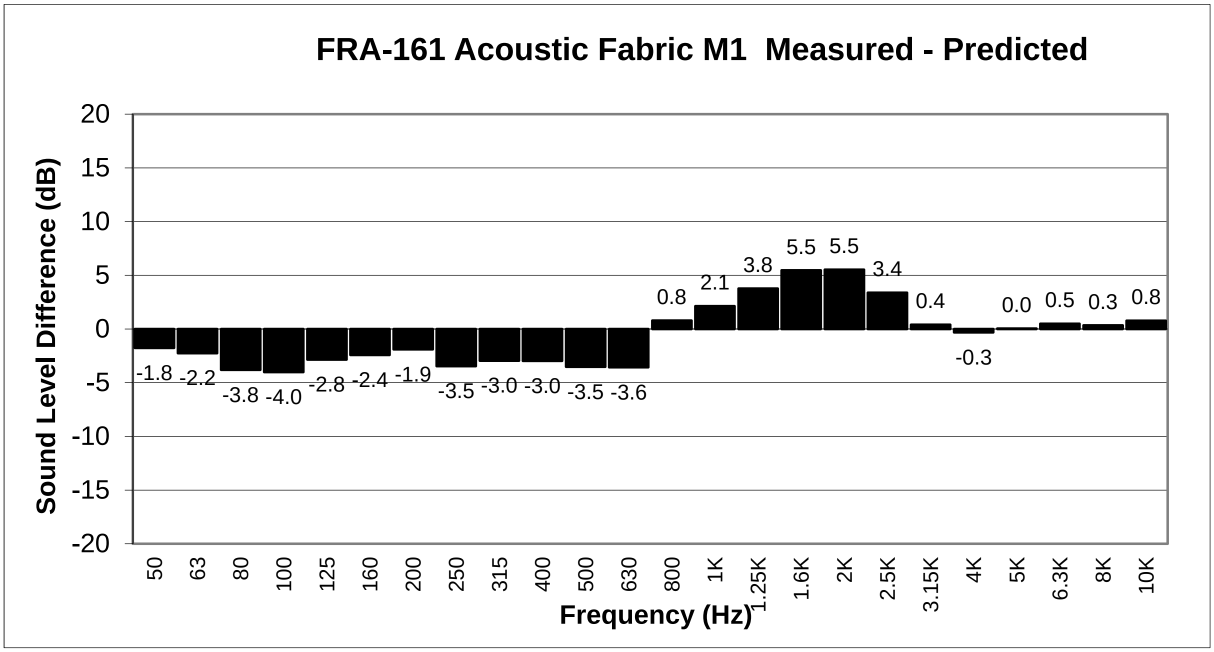
Site 14: Franklin County, I-70; Wood Wall



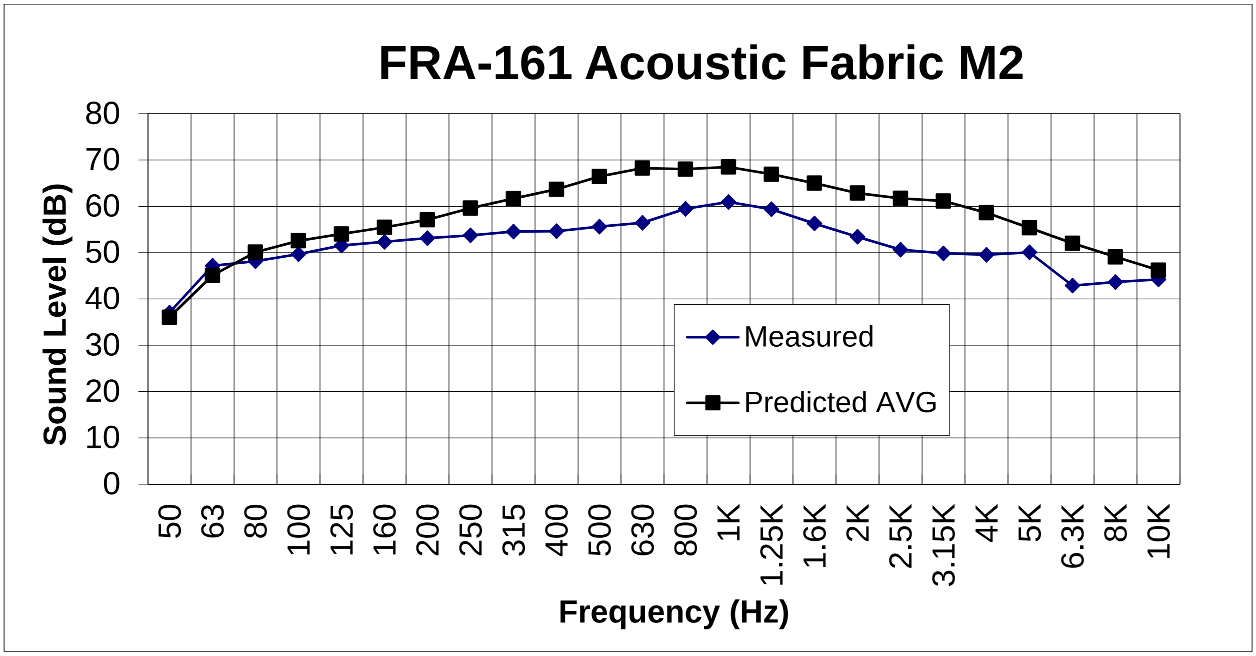


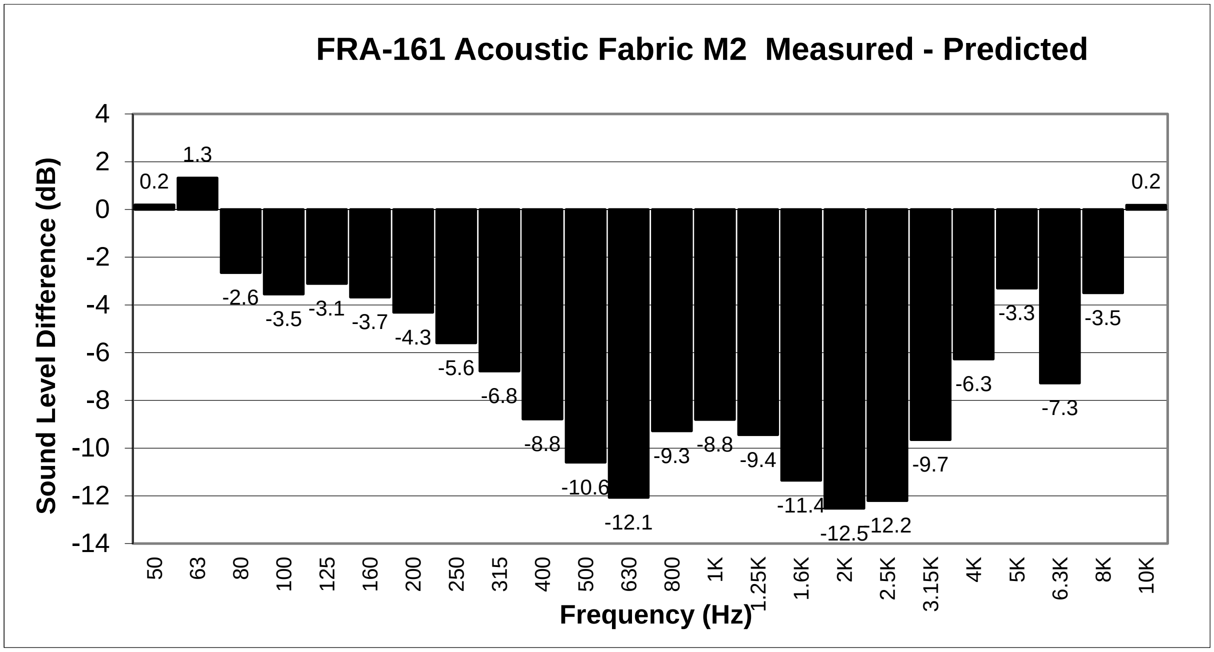
Site 15: Franklin County, SR-161; Acoustic Fabric Fence



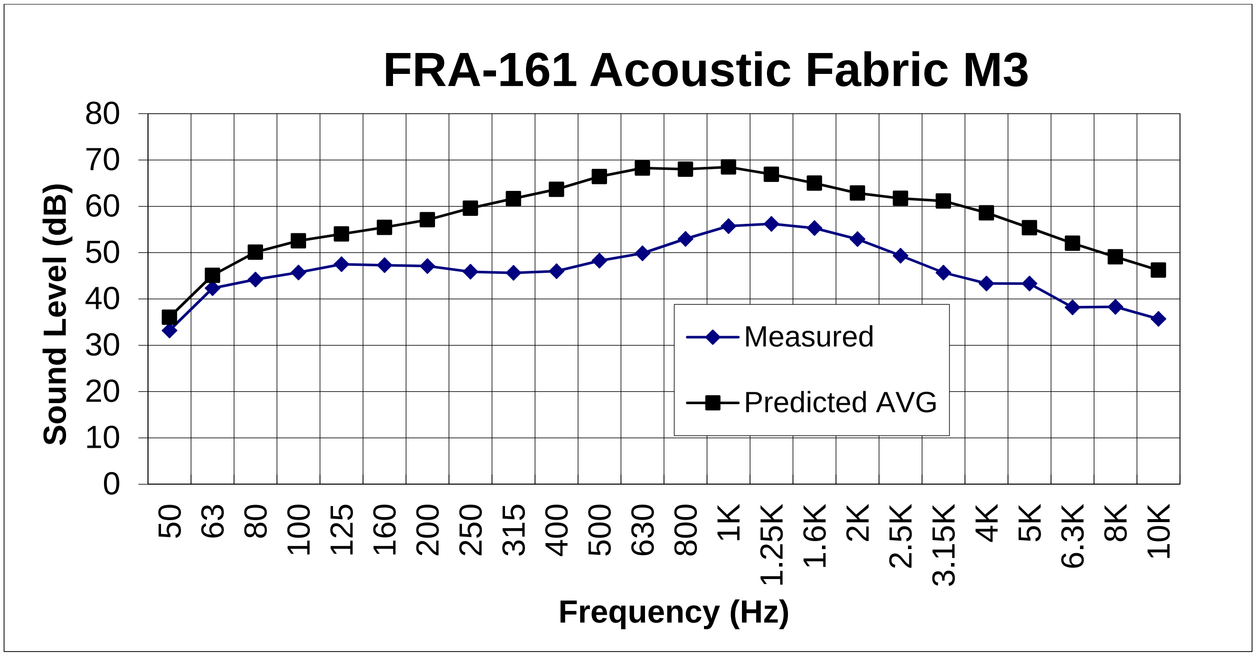


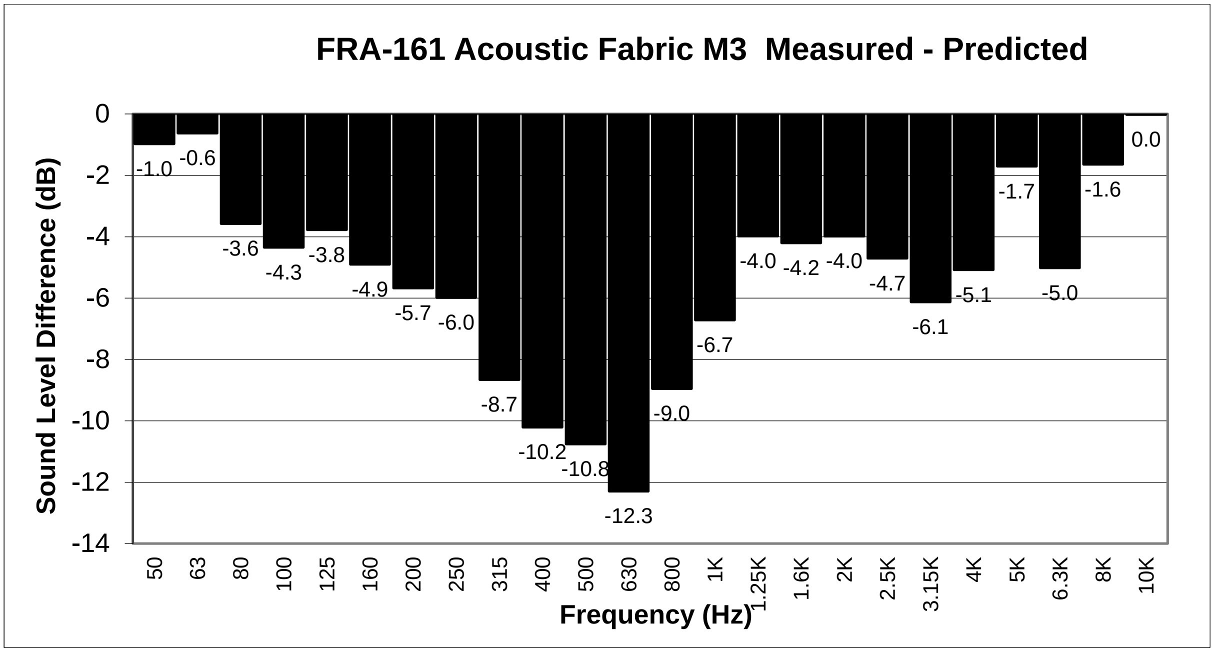
Site 15: Franklin County, SR-161; Acoustic Fabric Fence



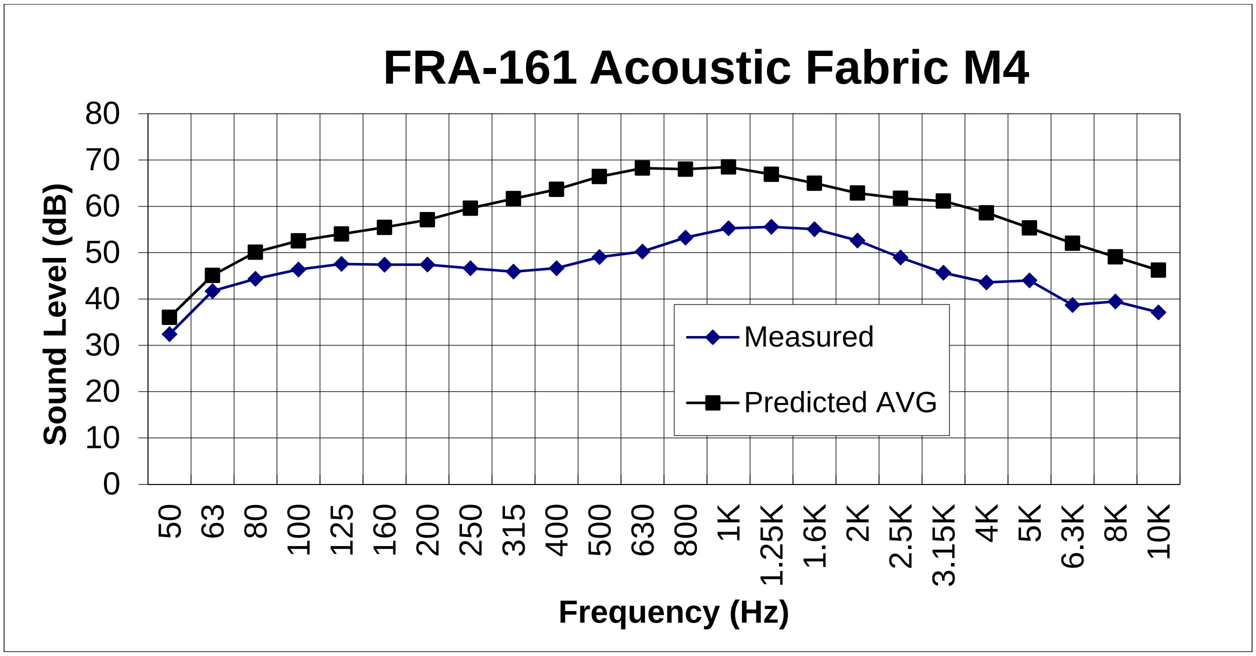


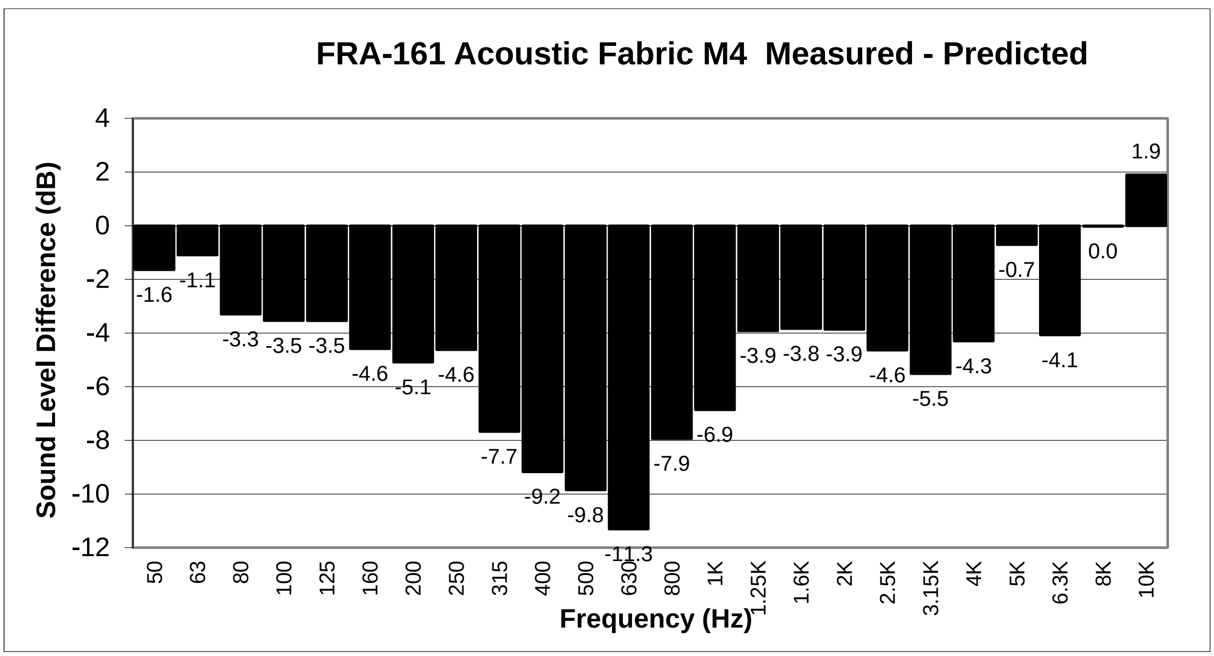
Site 15: Franklin County, SR-161; Acoustic Fabric Fence



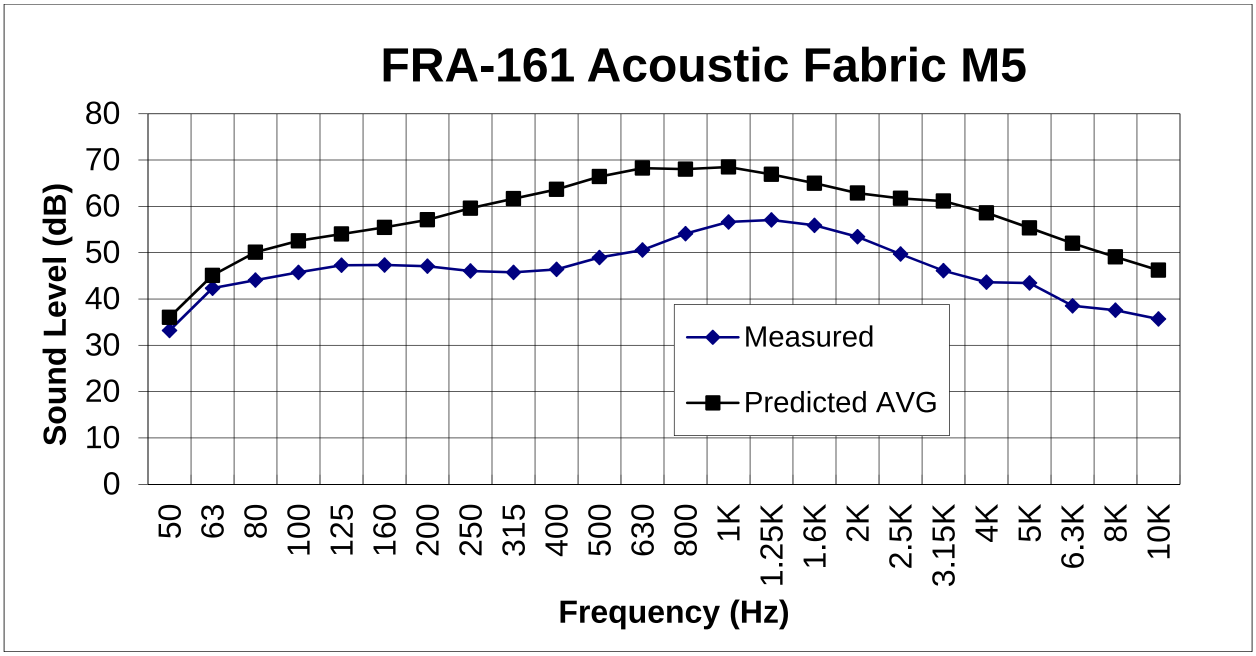


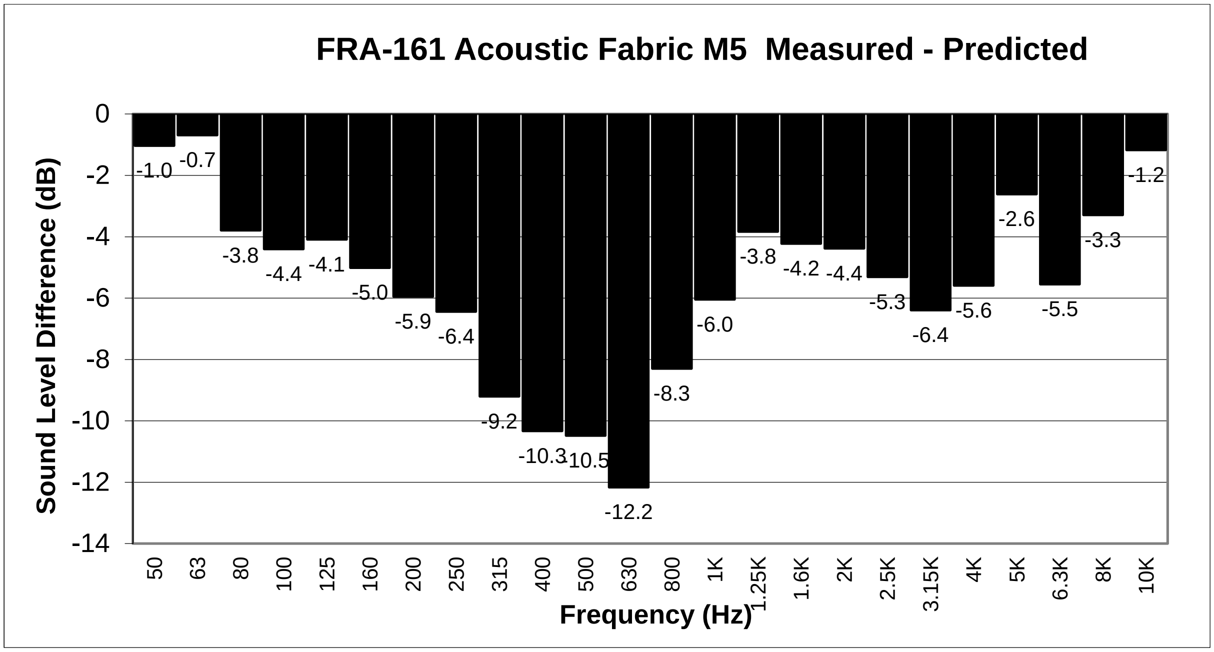
Site 15: Franklin County, SR-161; Acoustic Fabric Fence



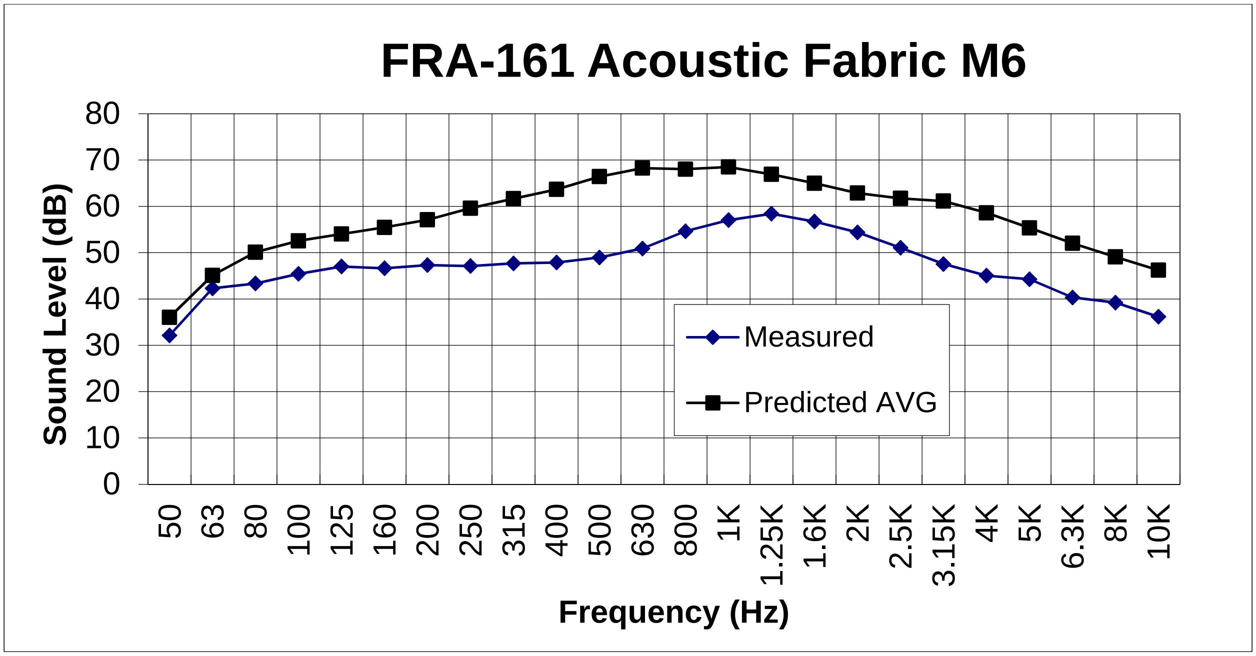


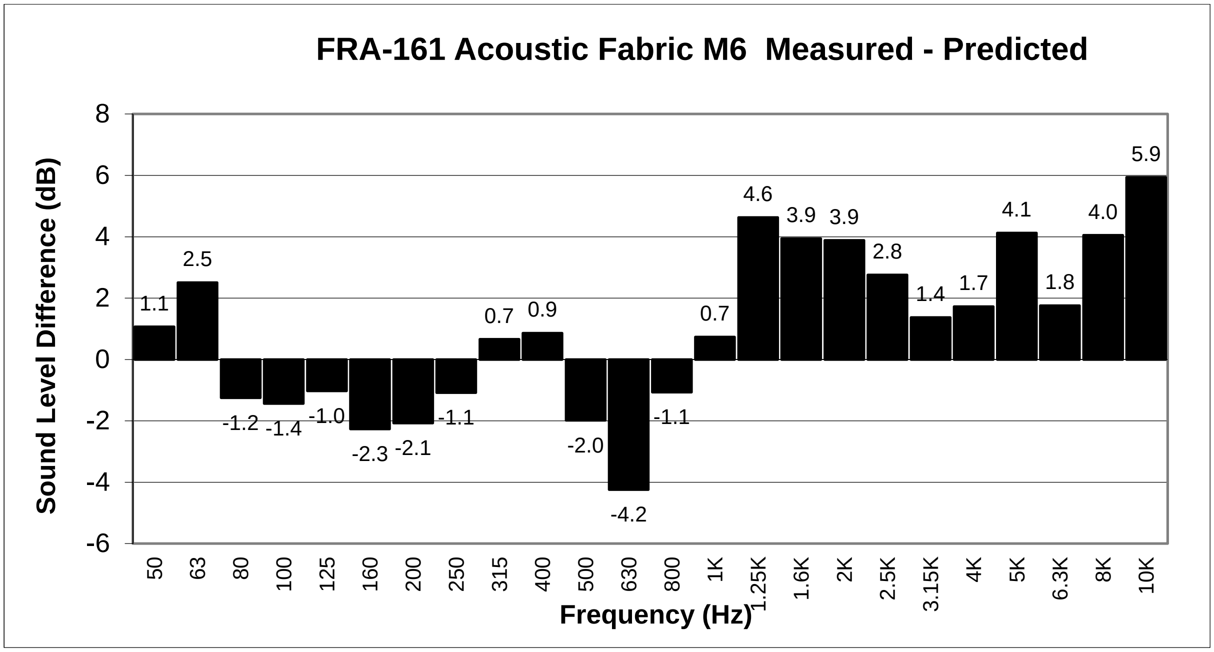
Site 15: Franklin County, SR-161; Acoustic Fabric Fence



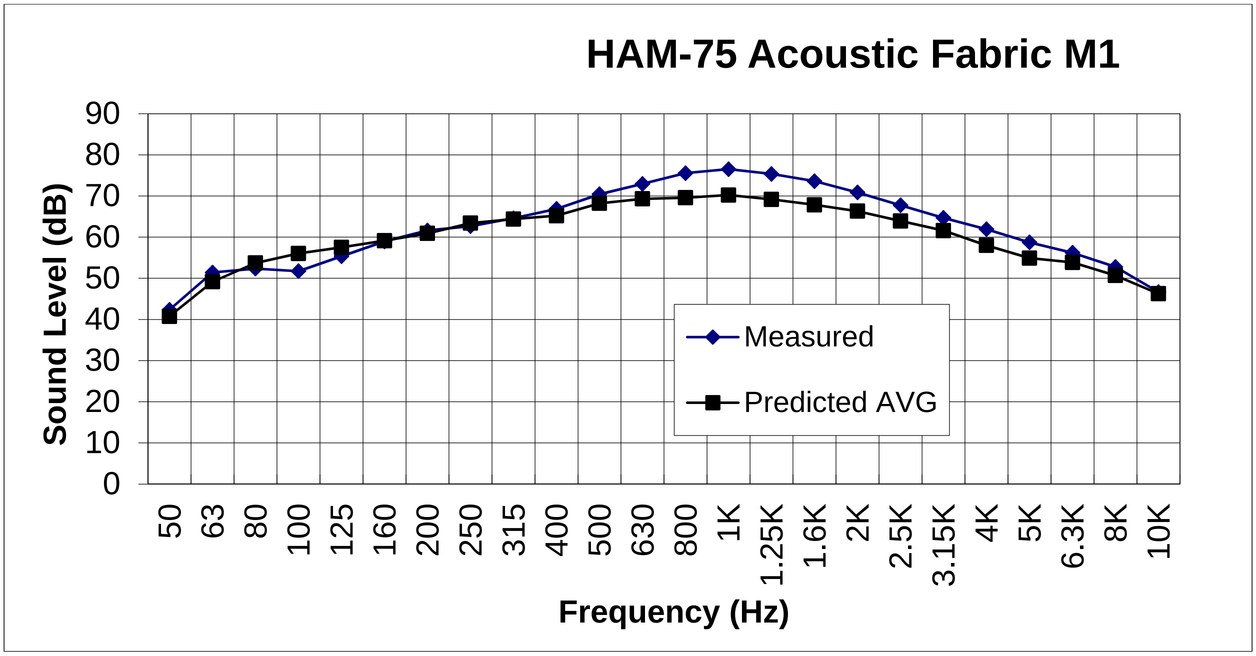


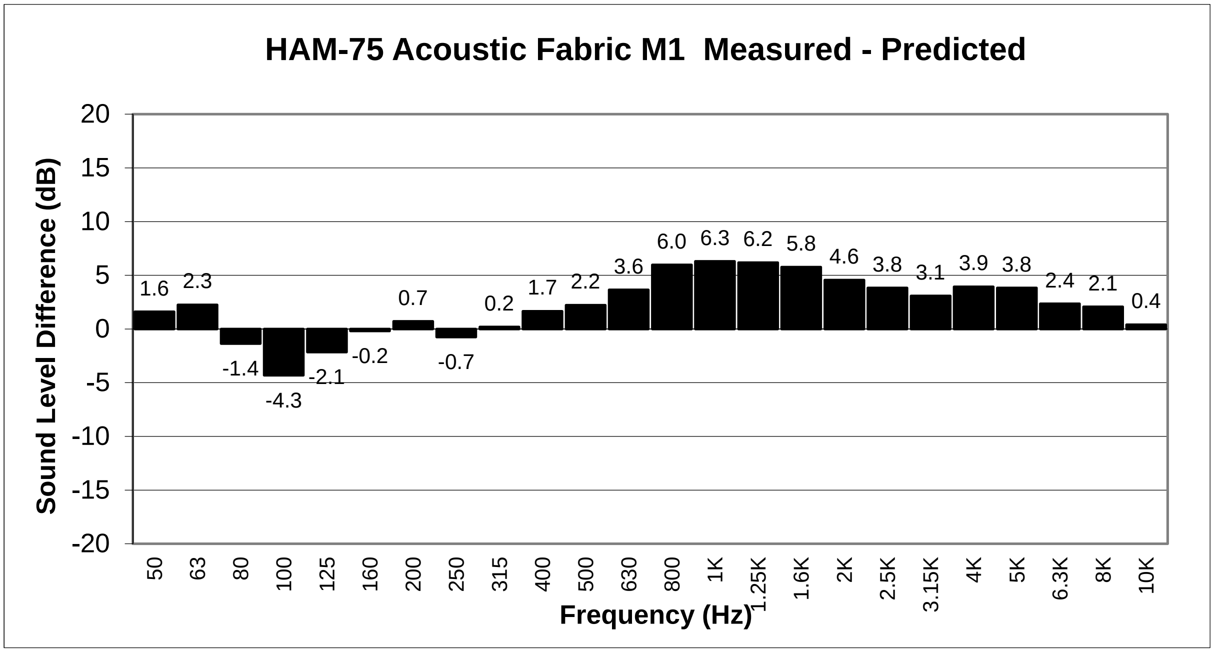
Site 15: Franklin County, SR-161; Acoustic Fabric Fence



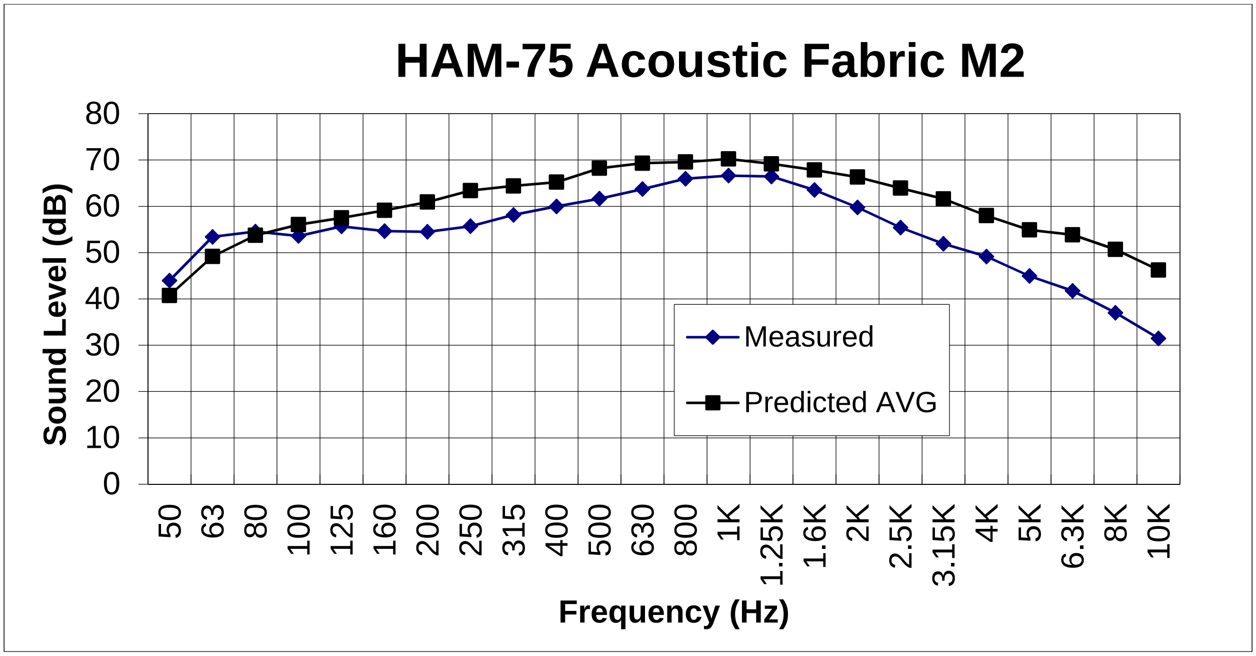


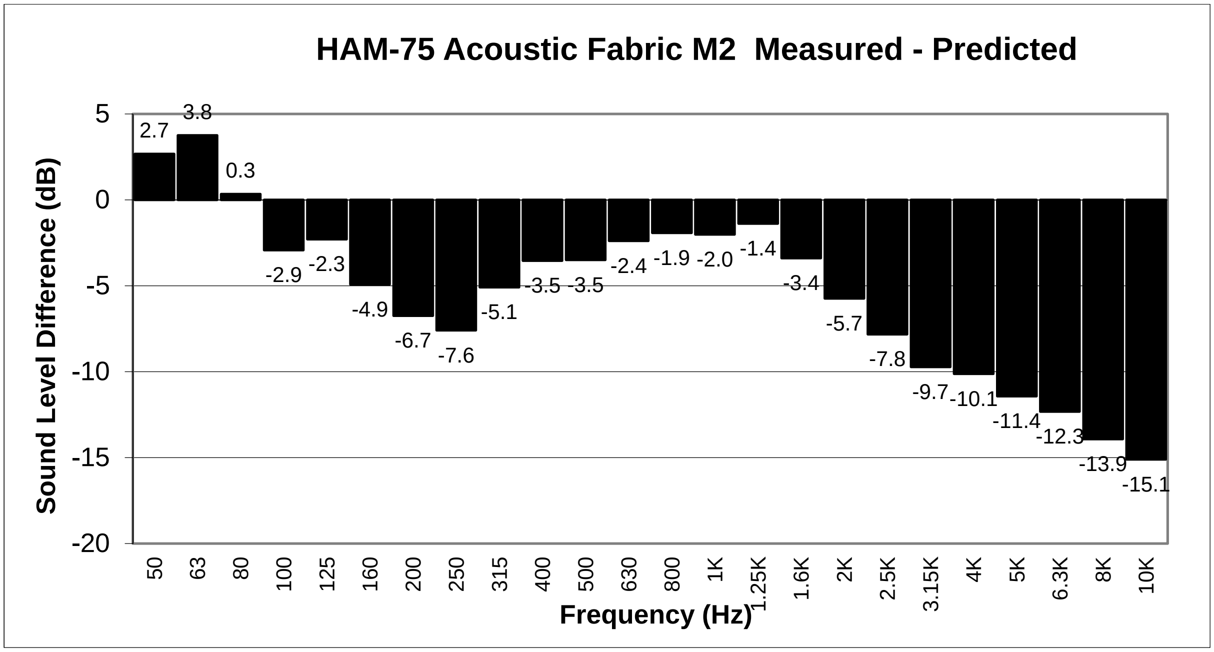
Site 16: Hamilton County, I-75; Acoustic Fabric Fence



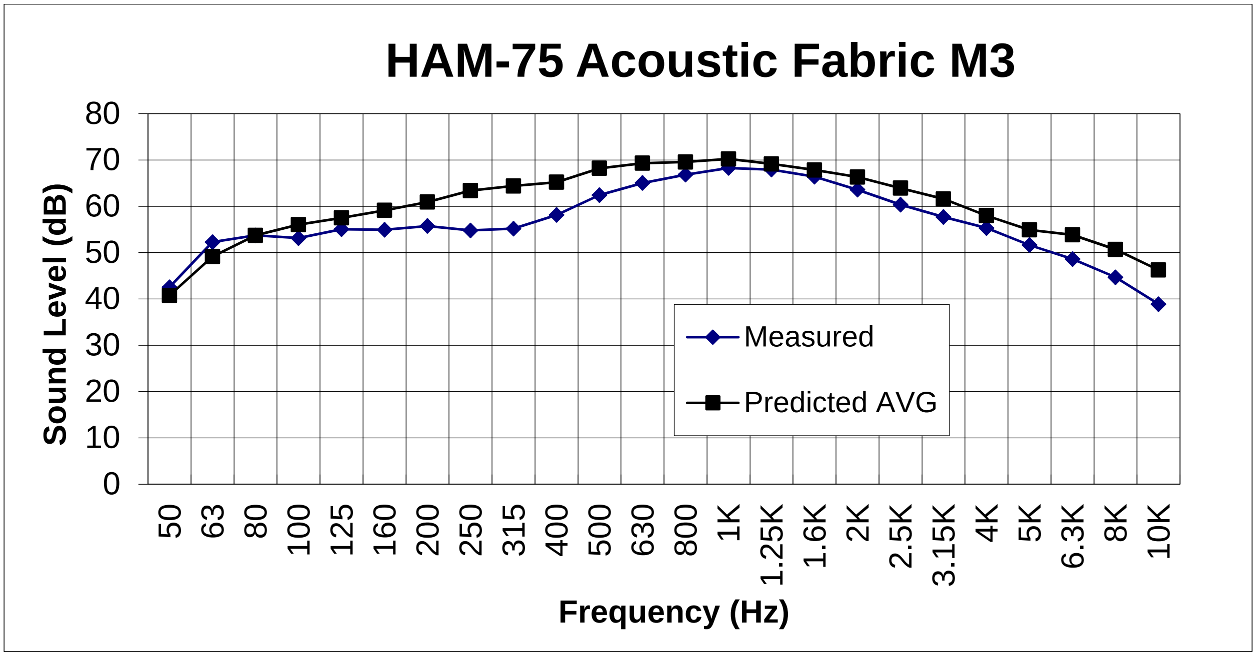


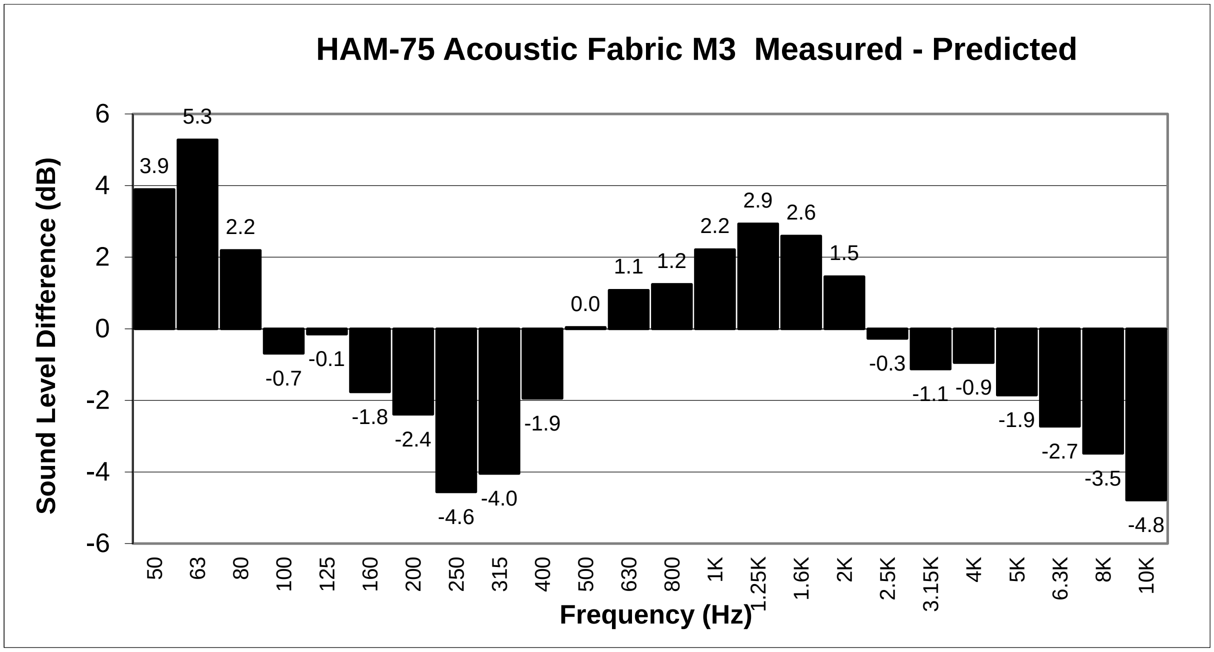
Site 16: Hamilton County, I-75; Acoustic Fabric Fence



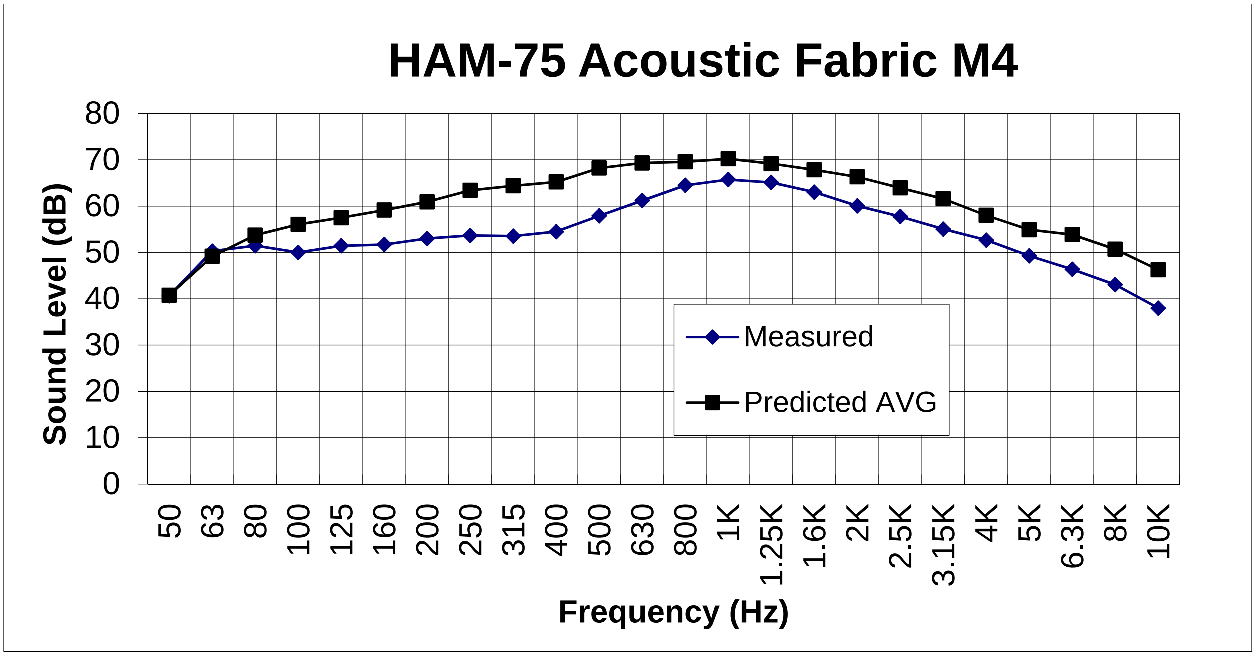


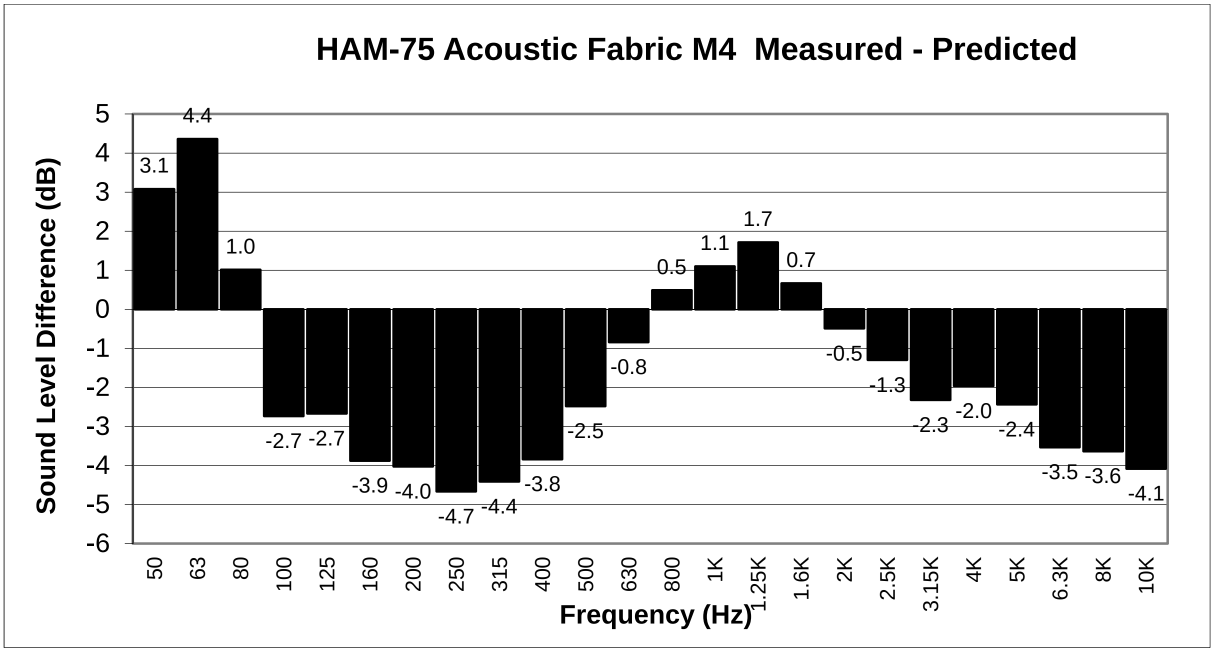
Site 16: Hamilton County, I-75; Acoustic Fabric Fence



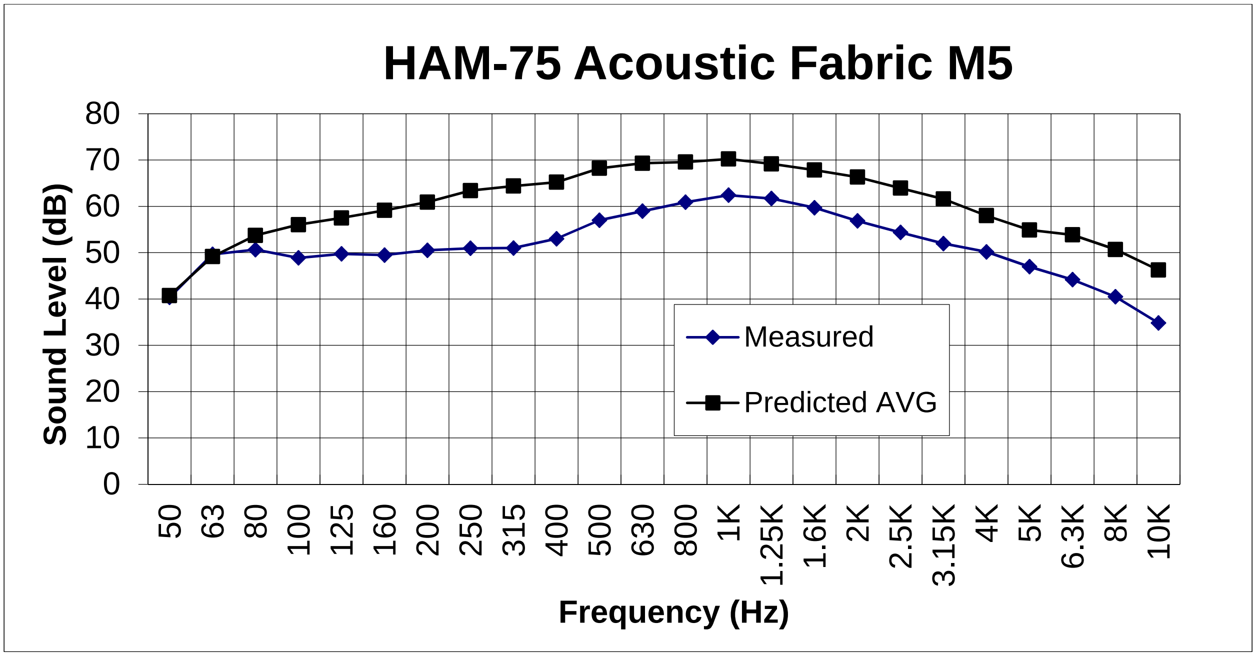


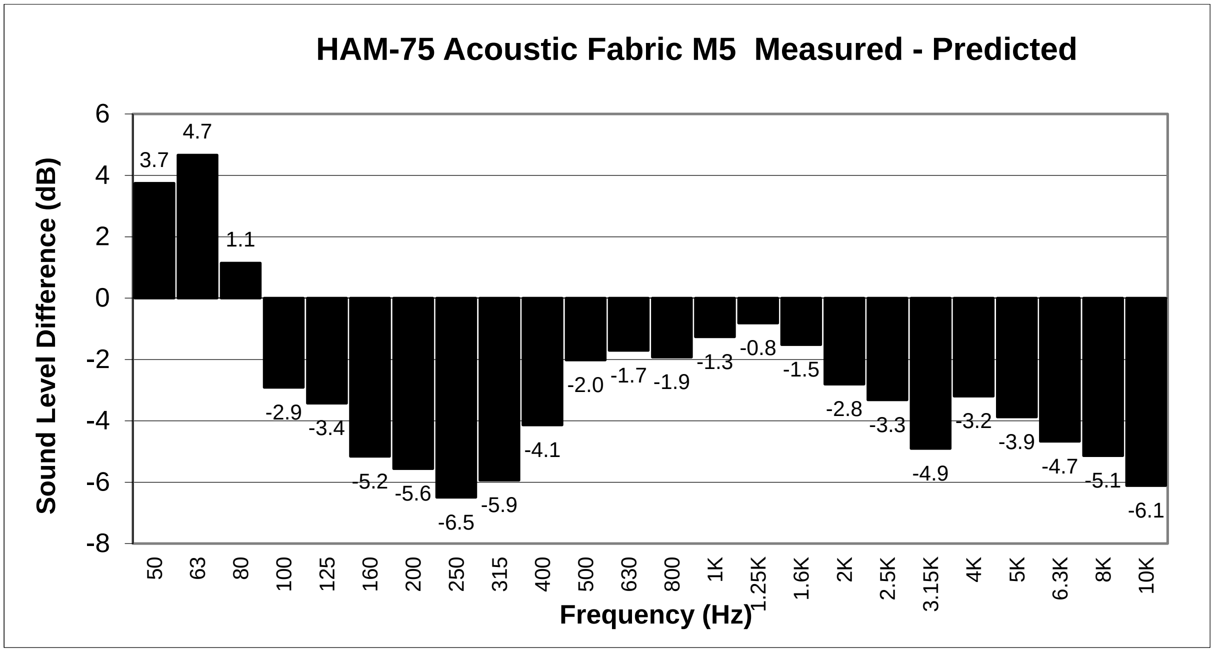
Site 16: Hamilton County, I-75; Acoustic Fabric Fence



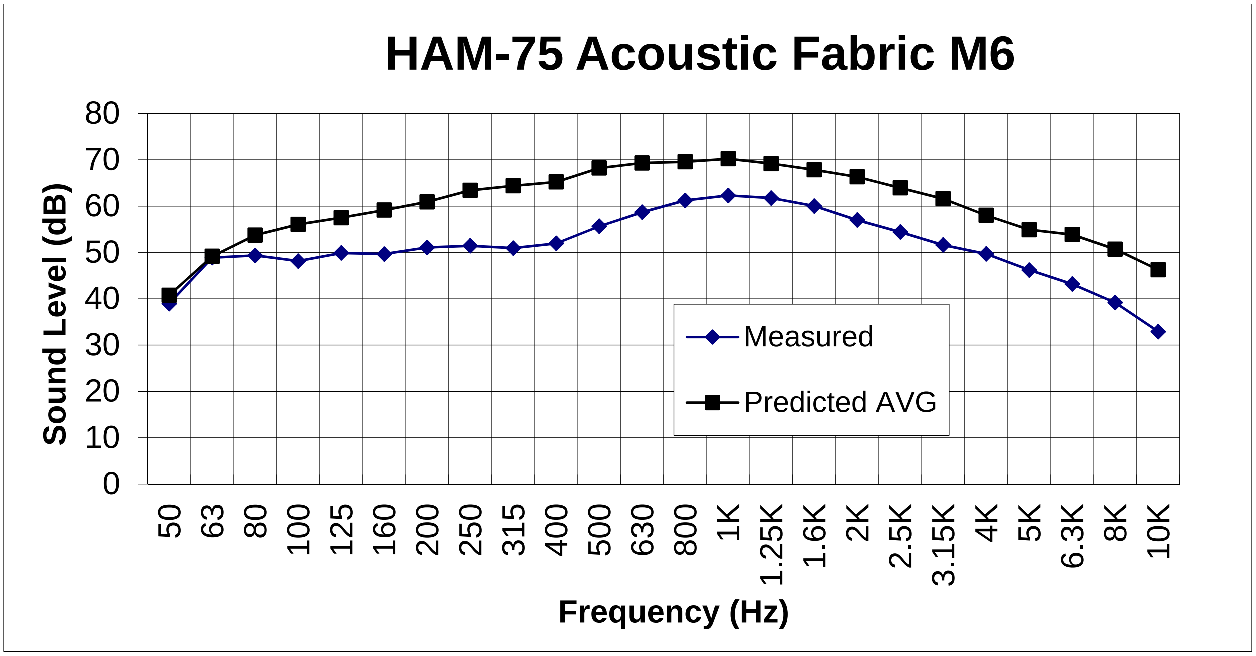


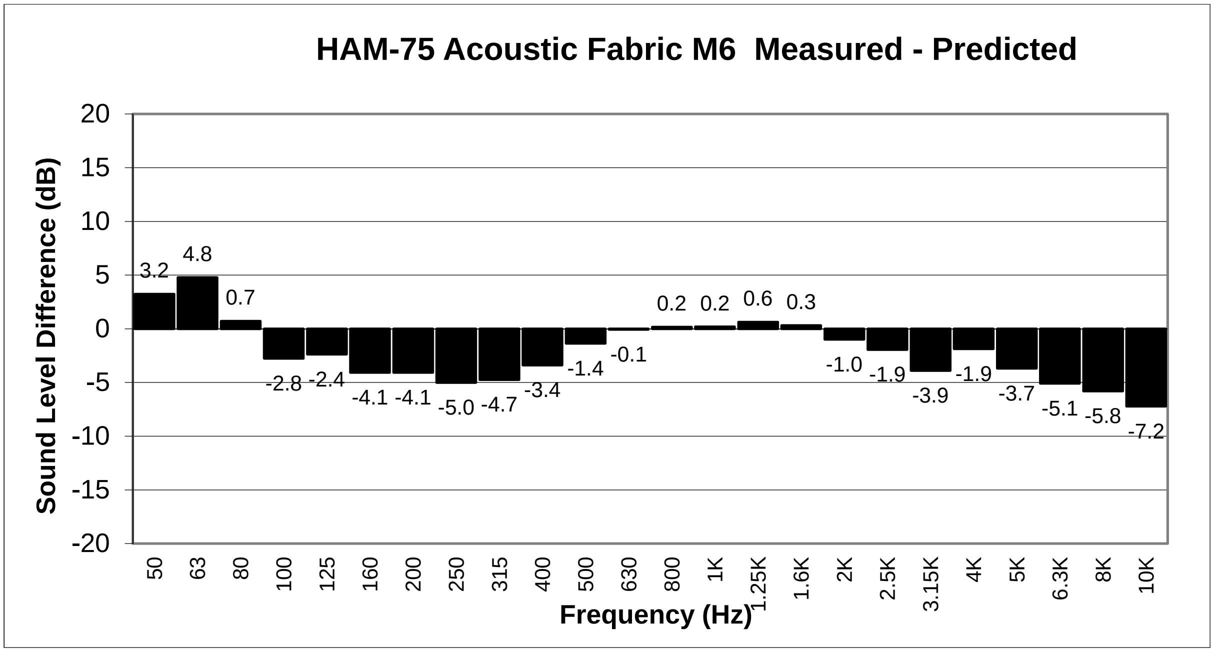
Site 16: Hamilton County, I-75; Acoustic Fabric Fence



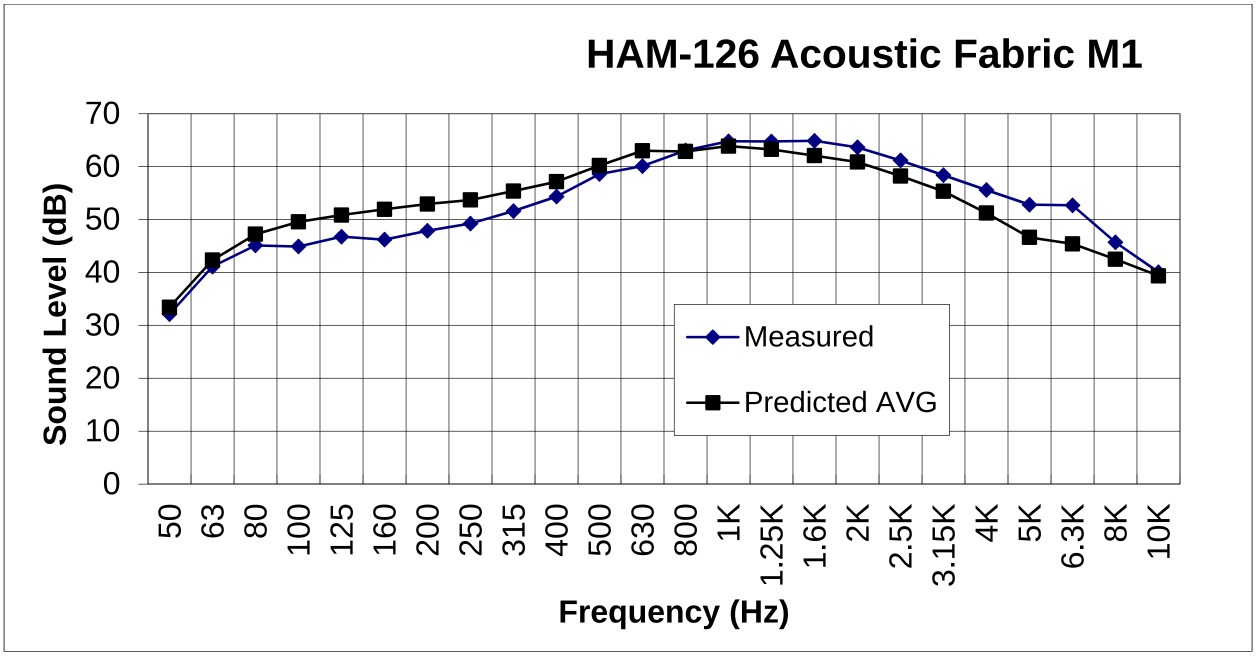


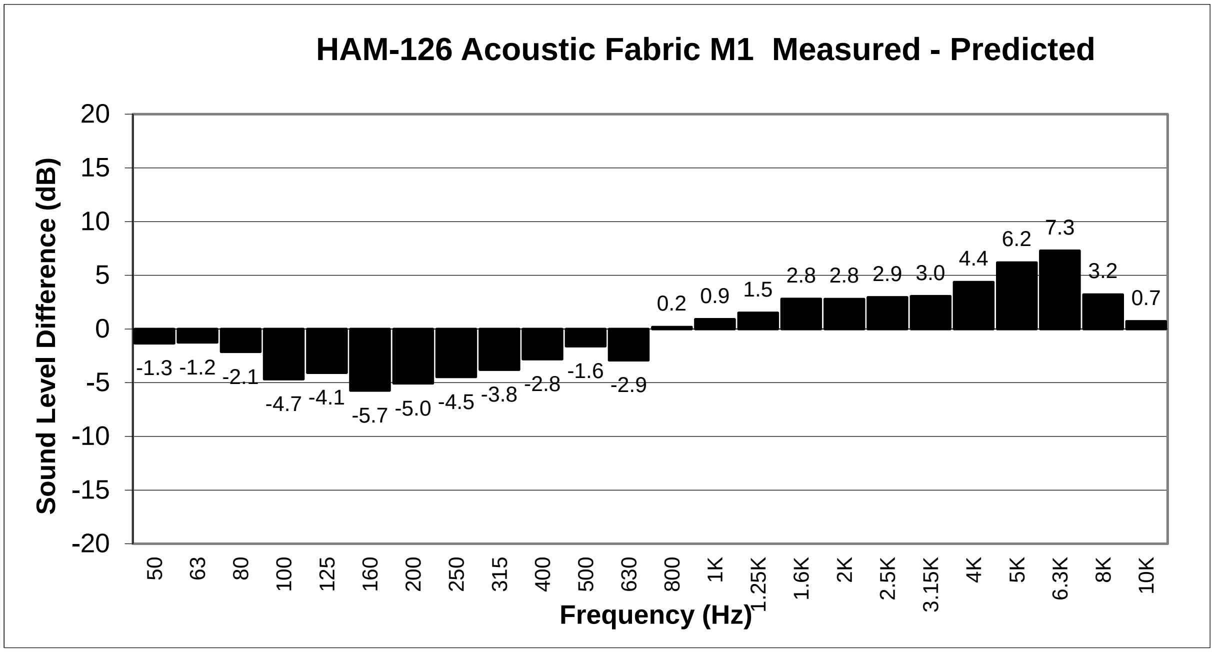
Site 16: Hamilton County, I-75; Acoustic Fabric Fence



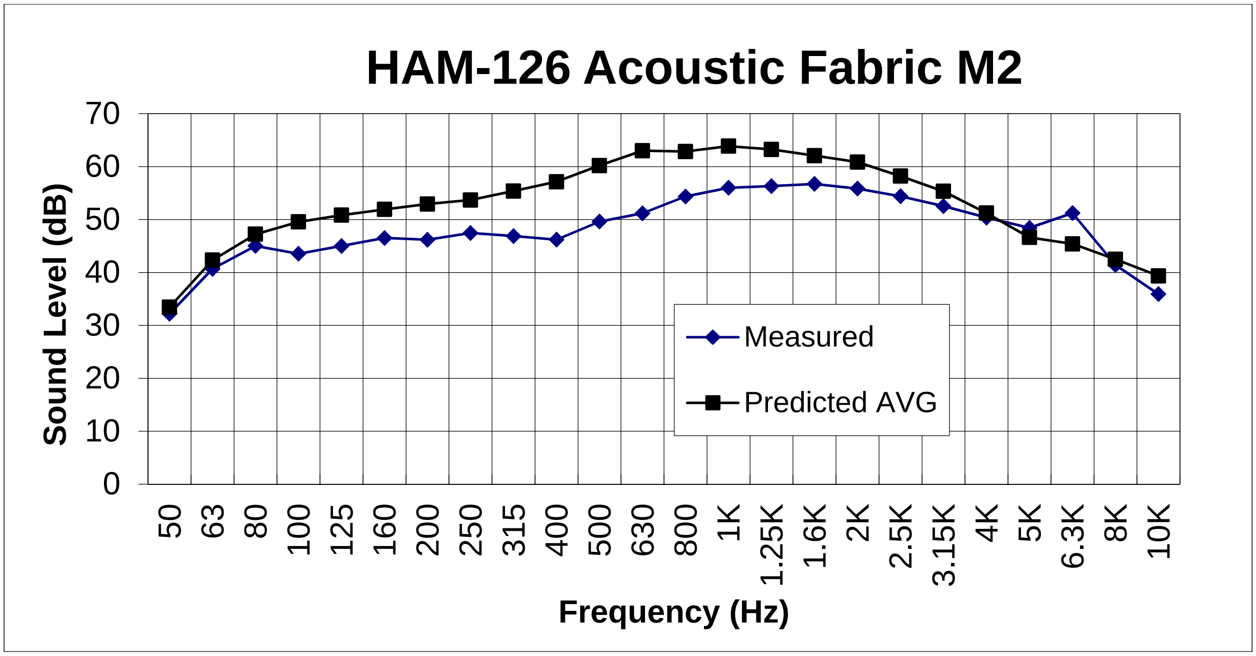


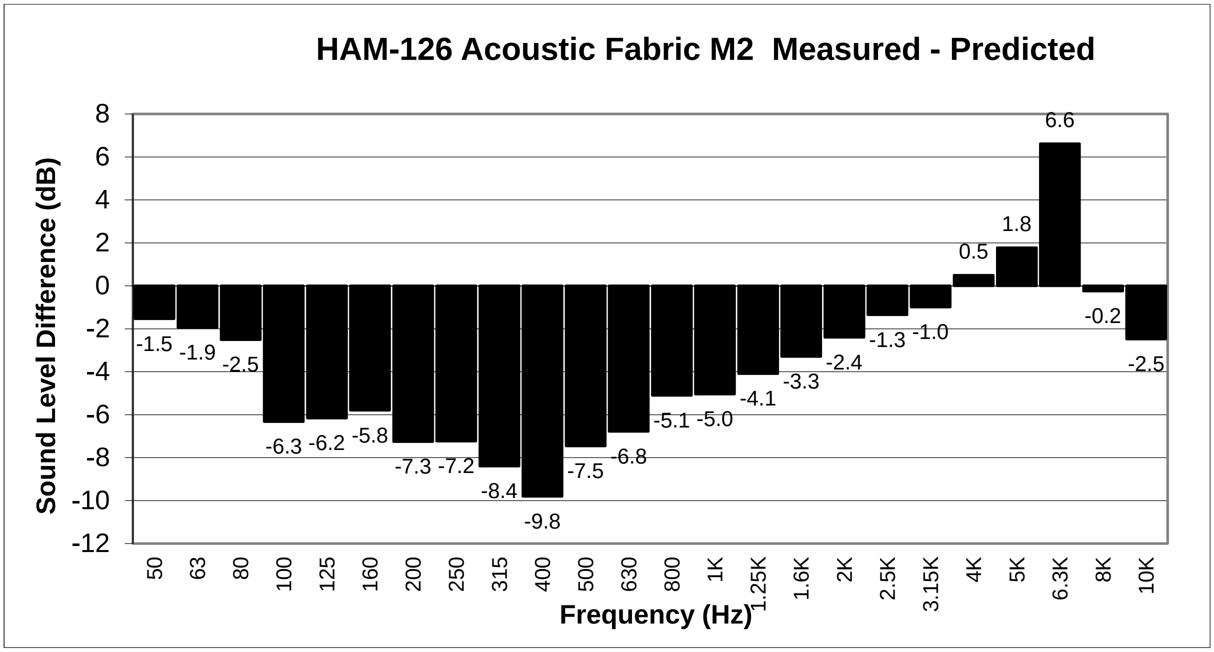
Site 17: Hamilton County, SR-126; Acoustic Fabric Fence



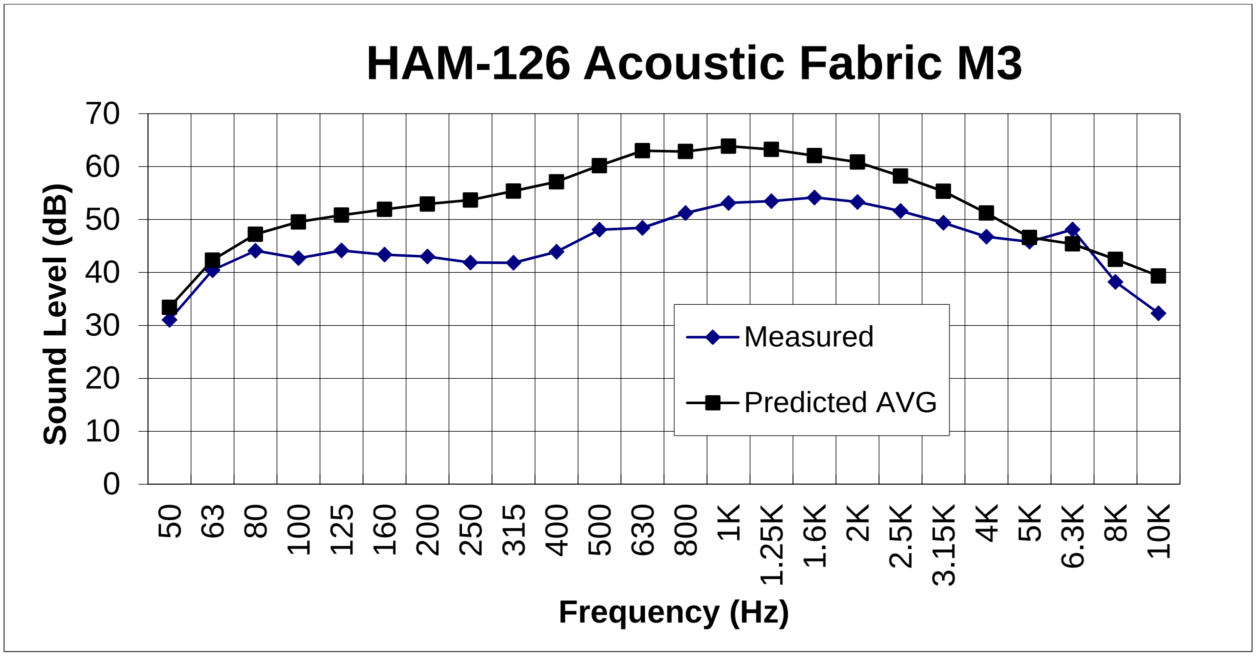


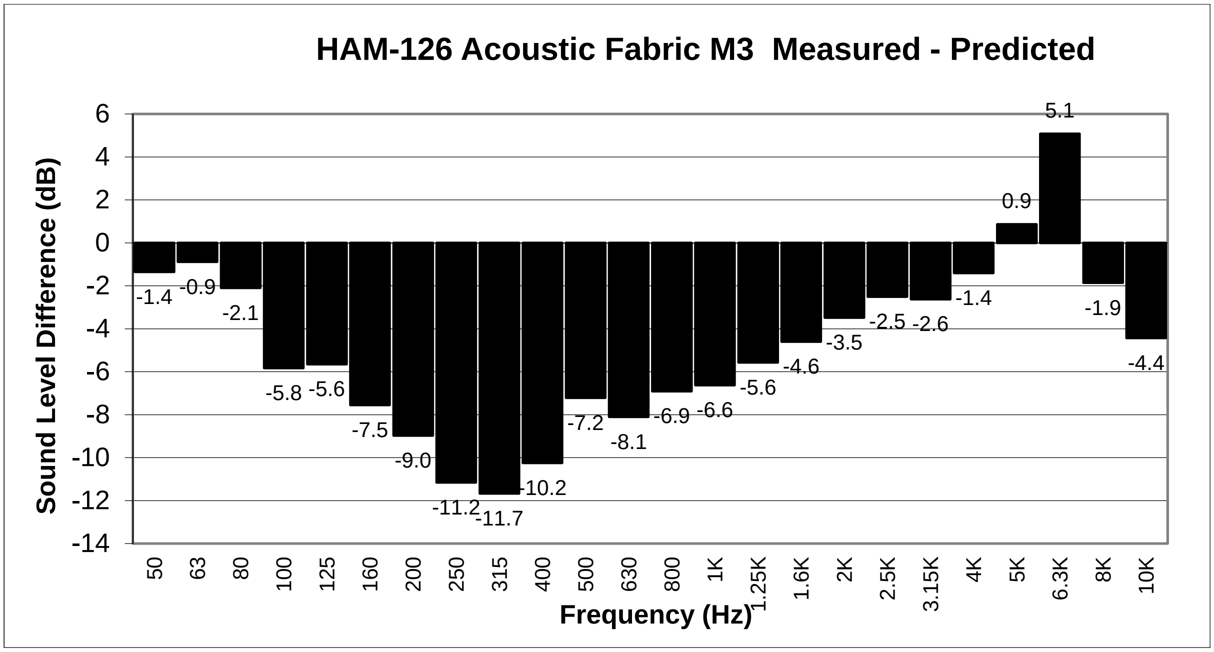
Site 17: Hamilton County, SR-126; Acoustic Fabric Fence



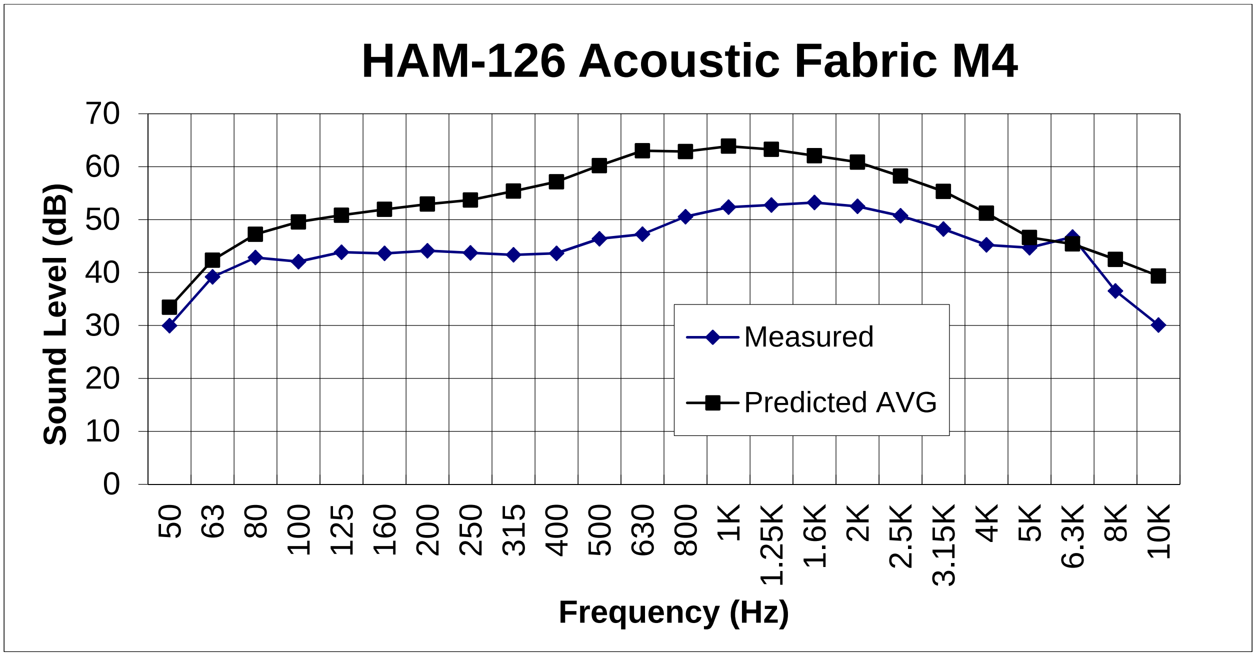


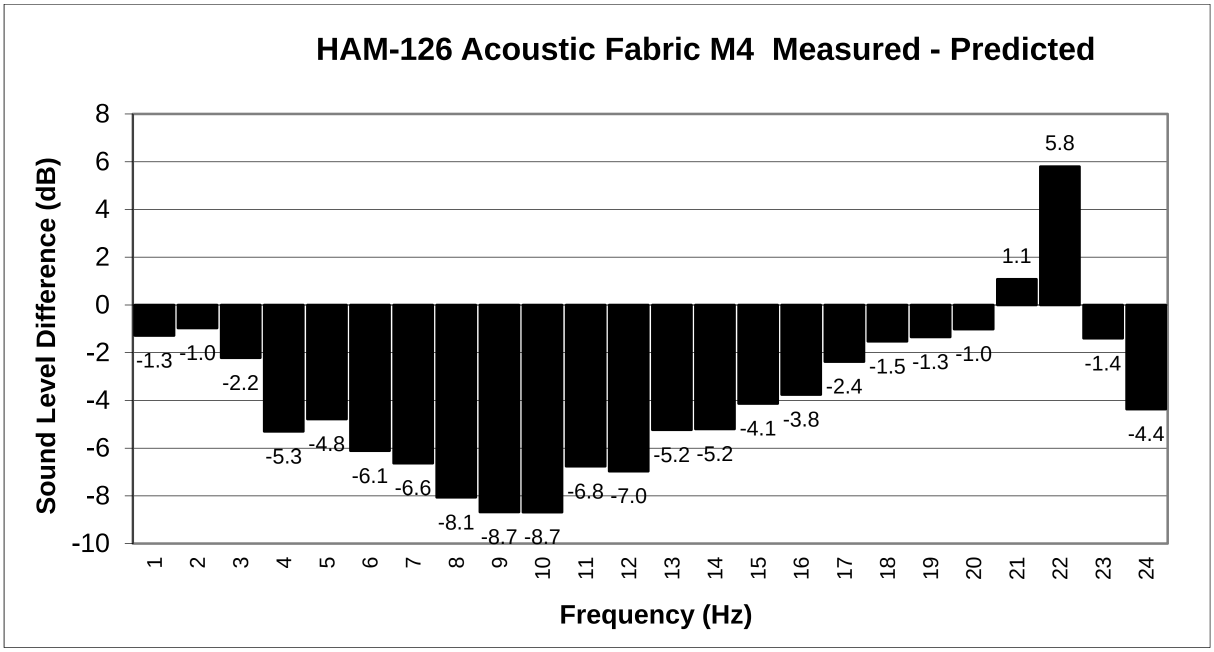
Site 17: Hamilton County, SR-126; Acoustic Fabric Fence



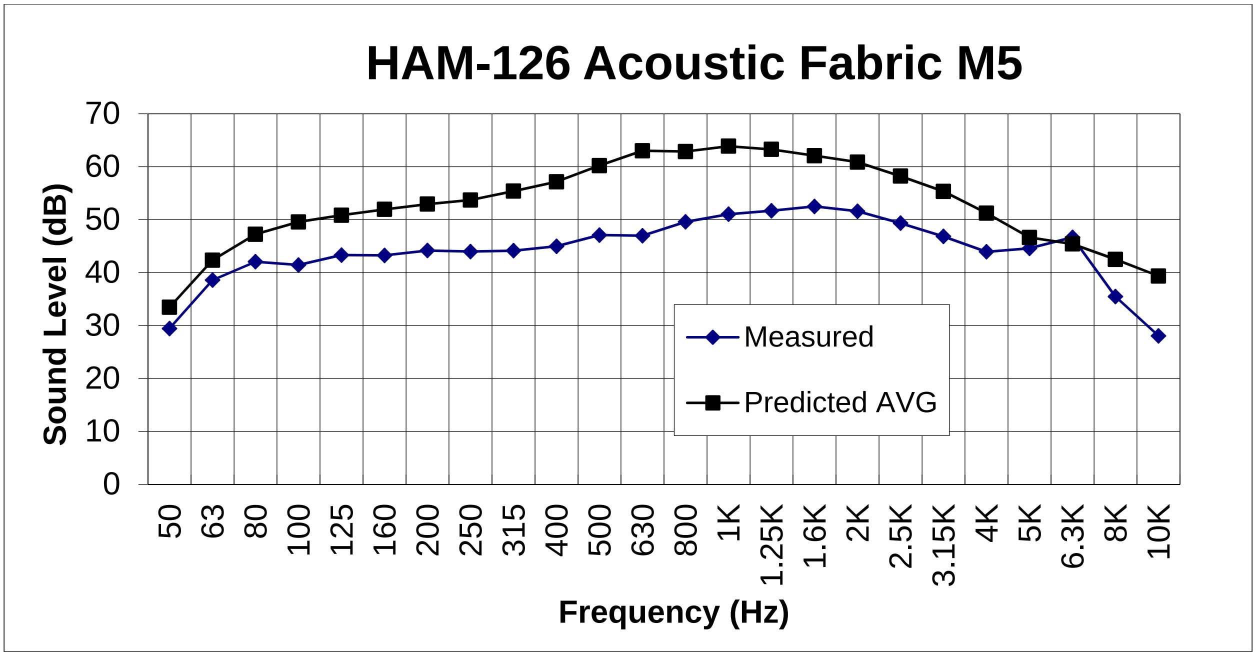


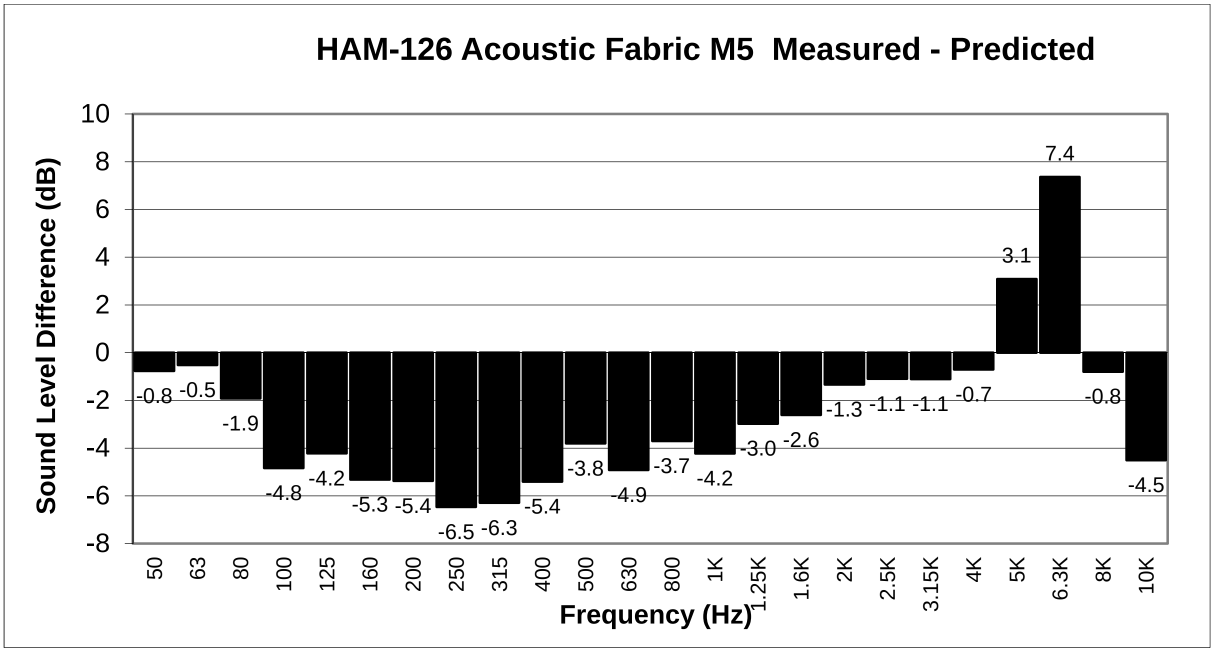
Site 17: Hamilton County, SR-126; Acoustic Fabric Fence





Site 17: Hamilton County, SR-126; Acoustic Fabric Fence





Site 17: Hamilton County, SR-126; Acoustic Fabric Fence