Comparison and Testing of Various Noise Wall Materials

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ABSTRACT

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Noise abatement is an ever growing need in today’s world as traffic volumes increase. Noise barriers provide local resident relief from high noise levels that can be created from a high volume highway. A standard noise barrier can be constructed from multiple types of materials, such as concrete or steel. These different types each have acoustical qualities that are particular to that material. To define which materials provided the best abatement, a two-part study was conducted to compare the decibel levels for six different materials and to compare the Federal Highway Administration’s (FHWA) Traffic Noise Model (TNM) to the field results. To obtain the field results, an extensive field study was performed with recording microphones placed in specific patterns behind the wall. The model was used to replicate the field setup, and the model results were compared to the results obtained in the field. The amount of noise reduction from the field recording ranged from 11 dB to 19 dB. Based on a statistical analysis, it was found that the top material choices were the clear panel, concrete panel, hollow fiberglass panel, and steel panel. The other two, acoustic fabric and earthen berm, were significantly worse. Seventeen sites were compared to the FHWA model. The statistical analysis from the model comparisons found that of the 17 sites that 5 of them were significantly different from the model. Overall, the noise barrier materials were determined and the application of the noise model was found to be limited.
To my parents, Rick and Lucy Theberge, my sister Ashleigh Theberge, and most of all my lovely fiancée Brittany Smith. Without all their support and encouragement none of this would be possible.
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CHAPTER 1: INTRODUCTION

Noise barriers are a necessary structure on the sides of the highway to protect the local residents from the excessive road noise. There are many different materials that noise barriers can be made out of. As of 2004, the most used noise barrier material is concrete which accounts for approximately 80% of all the noise barriers in the United States [1]. Besides concrete, noise barriers can be made out of metal, plastic, wood or soil. Each of these materials has advantages and disadvantages both acoustically and aesthetically.

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 [1]. 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 various noise testing prior to any changes to examine existing condition of a highway.
The FHWA provides a model (Traffic Noise Model-TNM) for predicting highway noise levels for various noise barrier alignments and heights. The TNM provides various components that can be made custom to certain situations [2]. The major components of the model consist of vehicle volume and class, site layout and topography, and various meteorological conditions. These parameters provide the user with the ability to change and adapt the model to certain situations that they are analyzing. If this model can provide accurate representations of what a field situation would produce, it could save a considerable amount of time and money needed for field testing each wall.

This study was done to determine which of the currently used noise barrier materials performed best and whether the FHWA TNM can provide accurate and precise results. The currently used noise barriers were tested by measuring noise levels behind...
the wall, while recording vehicle volume, class, and lane position. There were seven
different materials field test all over the State of Ohio. These results were then compared
to each other to determine which material provided the best noise reduction. The field
results were also used to compare to the TNM. 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
a correct representation of the field.

This research project evaluated various noise wall materials (hollow fiberglass
walls, rubber-filled fiberglass walls, concrete walls, steel walls, clear walls and earthen
walls), performance, and durability. Though this analysis, the most effective noise wall
material for the reduction of traffic generated noise associated with freeways for a
location and situation was determined. 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.
CHAPTER 2: LITERATURE REVIEW

In 1969 the National Environmental Policy Act (23 CFR Part 772, rev. 2010) was created and adopted by the FHWA to limit traffic noise for new roadway construction or modification supported with federal funds [3]. As most state-initiated transportation projects utilize federal funds, the state agency must comply with the federal regulations [4].

2.1 Testing

2.1.1 Insertion Loss

Sound barriers are used to help reduce roadside noise by reflecting or absorbing sound caused by traffic [5]. The effectiveness of the noise barriers is quantified by determining the reduction of noise, which is called the insertion loss [6]. A before and after test is the most effective way to determine insertion loss according to the FHWA procedure for noise measurement [3]. For this test, initial testing is done with no barrier present and the additional testing is performed after the barrier is constructed. If a barrier is already in place, control sites where traffic volumes and topography are similar to the barrier test site may be chosen [7]. When no control site is available, the FHWA recommends the use of the Traffic Noise Model (TNM) as a before prediction [3]. Insertion loss can be found using data from the model and barrier site.

2.1.2 Microphone Locations

There are two different types of microphones needed for analysis, a reference microphone and multiple receiver microphones [8]. 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 down the interstate away from any obstructions and placed receivers behind the wall in residents’ backyards. [9]. 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 [10]. 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 [11]. 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).

2.2 Reflective vs. Absorptive

Several types of noise barriers and configurations are 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 [12]. 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 are:

1. More reflective surface (NRC 0.7 instead of 0.8)
2. Addition of a 6 in. reflective cap along the top of the wall
3. Addition of a 2ft reflective base along the bottom of the wall

Three barrier configurations were used to test these modifications:

1. Barrier and receivers on the same side of the roadway
2. Barrier and receivers on the opposite side of the roadway
3. Barrier and receivers on the both sides (parallel) of the roadway

The highest recorded 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 were 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 will increase the noise levels.

Herman examined the differences between the single and parallel barrier configurations and the reflective and absorptive surfaces on a full-scale site. He noted that with the current amount of noise barriers in the U.S. and with an increase expected in the future that it is imperative to find the best noise abatement configuration [13]. The
purpose of this project was to examine the attenuation theory and performance degradation phenomenon. The attenuation theory deals with the diffraction of the sound waves over the top of the barrier, which creates direct line of sight to a receiver and causes the sound to travel a longer distance to a receiver. Performance degradation deals with the effect of numerous reflections between parallel barriers.

2.2.1 Diffraction

Sound waves can take three paths as they approach a noise barrier [8]. 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 2.1.

![Figure 2.1. Three paths of sound waves [8]](image)

The diffraction of sound waves over the top of the barrier happens for both absorptive and reflective barriers [13]. Herman observed that there was no significant difference in diffraction between single barriers with a reflective or absorptive surface. Anderson et al. investigated the effect of a 6 in. reflective cap on an absorptive barrier [12]. They found a 0.6 dB increase when using the reflective cap compared to having no
cap. The FHWA Noise Barrier Design Handbook provides different types of designs that can be used for the top of the barrier [8]. The handbook notes that the T-profile top provided an average insertion loss of 2.5 dB and performed better than the other profile types. May and Osman investigated the effect of a 30 in. wide T-profile top on an existing noise barrier. The addition of the T-profile increased in the existing insertion loss. This increase ranged between 1-1.5 dB more than the original barrier.

2.2.2 Performance Degradation

The reflections from parallel barriers can cause increased noise levels at the receivers behind the noise barrier [12]. This phenomenon is known as performance degradation and is shown in Figure 2.2.

![Figure 2.2. Reflection of noise in parallel barrier situation [8]](image)

Herman proved this phenomenon by testing a pair of reflective parallel barriers and a pair of absorptive parallel barriers [13]. 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 the addition of an opposing reflective barrier to an existing reflective barrier had a degradation that varied from 0.6-2.8dB [11].

2.3 Barrier Types

2.3.1 Clear

The clear or transparent noise barrier helps DOTs meet two objectives because they have adequate acoustic properties for sound abatement and are ascetically pleasing to residents and motorists [14]. One example of use of clear barriers is the Marquette Interchange in Milwaukee, Wisconsin. This particular noise barrier gives 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 [15]. In Baltimore City, Maryland, the transparent barriers met both of the objectives. [16]. 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 [8]. 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 a standard concrete panels so there must be significant justification for use. According to FHWA, the Sound Transmission Class (STC) of the transparent panels is 22dB [8]. In addition to the acoustics of the transparent panels, they are considered to be a reflective material [15].
2.3.2 Concrete

Concrete barriers can have either reflective or absorptive properties [17]. May and Osman performed sound testing for both reflective and absorptive concrete barriers [7]. 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 [13].

Approximately 50% of all noise barriers in the North America are made from concrete [8]. Of the materials used to make noise barriers, concrete has the highest STC value ranging from 34-40dB. Along with the transmission qualities of concrete, the face can be altered to make the wall more absorptive [7]. May and Osman used an absorptive face made of softwood shavings that were joined to the concrete face. In Herman’s full scale test, mineral rock wool was used with a perforated steel cover [13].

2.3.3 Metal

Metal barriers, are similar to concrete barriers, in that they can either be reflective or absorptive. Watts and Godfrey examined the noise transmission of an aluminum barrier with either a reflective or an absorptive face [10]. 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% confidence. At this height the absorptive face had a 13.43dB loss and the reflective face had a 12.99dB loss.
Metal barriers can be made out of steel, stainless steel or aluminum [8]. 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 18-27dB.

2.3.4 Plastic

Plastic noise barriers can be used in most circumstances [8]. They can be produced to have the same appearance and acoustic properties as any other barrier material. Roschke and Esche examined the insertion loss of a recycled plastic barrier [18]. They used the indirect before method and found that the barrier had 17.1 dB insertion loss.

Plastic barriers can be made of polyethylene, PVC, or fiberglass and have a typical STC value of 22dB [8]. Carsonite Composites, a manufacturer of fiberglass barriers, sells both filled and unfilled fiberglass barriers [19]. 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 [20]. 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.

2.3.5 Wood

In 1987, 17% of noise walls were wooden [21]. This number has decreased over the years with only 13% of barriers being made from wood in 2004 [1]. 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 [22]. 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 20dB.

Wooden barriers can either be treated wood or plywood and can be made from many different species of trees [8]. Depending on the thickness, the STC value can range from 18-24dB. A problem with wooden barriers is that they may warp [23]. If this occurs, voids are created in the panels which reduce the wall’s effectiveness. To prevent this from happening, higher grade and pressure treated lumber should be used.

2.3.6 Berm

Berms are considered to be highly absorptive because of the soil and grass covering [24]. A berm can provide a 1-3 dB increase in insertion loss when compared to a wall with a similar height and length [8]. Menge stated that berms performed well in parallel barrier situations due to their ability to act as a single barrier without the drawbacks of parallel barriers [25]. 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 [26]. 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 a berm instead of a traditional wall [24]. The berm requires
little to no maintenance and residents consider it to be more aesthetically appealing than a wall. A drawback associated with berms is the amount of land needed to construct one. Most noise sensitive areas do not have enough land to build an effective berm.

2.3.7 Acoustic Fabric Fence

Not much research has been done with the Acoustifence material, but early public opinion on the material has been positive [27] [28]. In Seattle, Washington the Acoustifence was used as a short-term solution to the excessive rail noise experienced by local residents [27]. City official Justin Garrod found that by using Acoustifence material, all FHWA noise abatement standards were meet. The city decided that the Acoustifence would be the permanent solution to the excessive rail noise. Bay City Michigan encountered a similar situation with residents complaining about noise created by idling trucks at the local Coca-Cola plant [28]. Local Bay City resident 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 [29]. The material is comprised of thick rubber matting that comes in rolls of 6 feet tall by 30 feet long and weighing approximately 180 lbs. The acoustic fabric can be attached to either a chain link fence or a wooden with 70 lb test zip ties.
2.4 Noise Source

2.4.1 Pavement Types

There are many sources of noise when a vehicle travels down a roadway, the most prominent of which is the tire/road interaction [30]. This is especially evident when a vehicle is traveling at highway speeds as shown in Figure 2.3. Along with the speed of the vehicle, the type of pavement has a substantial effect on the intensity of noise. Herman et al. investigated two different pavement materials with multiple surface treatments to determine the difference in noise levels [31]. 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 [31] [32].

![Figure 2.3. Comparison of noise levels separated by component [33]](image-url)
2.5 Life Cycle Cost

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 [34]. Along with noise abatement requirements, DOTs have structural and aesthetic requirements for noise walls [35]. The combination of these three parameters used to estimate the noise barrier service life is shown in Table 2.1. 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 [34]. Table 2.2 shows a breakdown of the primary and future cost of multiple noise barrier materials. Table 2.1 and Table 2.2 are used to make economical decision about what noise barrier material and design to use. 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 [36].
Table 2.1. Estimated noise barrier service life [34]

<table>
<thead>
<tr>
<th>Material</th>
<th>Service life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth berm</td>
<td>50+</td>
</tr>
<tr>
<td>Precast concrete, full-height panels with monolithic posts</td>
<td>50</td>
</tr>
<tr>
<td>Precast/prestressed concrete cantilever</td>
<td>50</td>
</tr>
<tr>
<td>Precast/prestressed concrete stacked panelsa</td>
<td>50</td>
</tr>
<tr>
<td>Fanwall</td>
<td>50</td>
</tr>
<tr>
<td>Carosite</td>
<td>50</td>
</tr>
<tr>
<td>Durisol</td>
<td>25</td>
</tr>
<tr>
<td>Noishield steelb</td>
<td>25</td>
</tr>
<tr>
<td>Noishield aluminum</td>
<td>25</td>
</tr>
<tr>
<td>Glue-laminated wood</td>
<td>25</td>
</tr>
<tr>
<td>Tropical hardwood and softwood post-and-panel</td>
<td>25</td>
</tr>
</tbody>
</table>

*aStacked panels (similar to the Soundcore barrier) have not been built in Illinois to date.

*bEstimated service life for Noishield steel is based on redesigned panels used successfully on projects outside Illinois.

Table 2.2. Estimated noise barrier life cycle cost [34]

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Estimated ICC [dollars/m²] (dollars/ft²)</th>
<th>Discounted future costs [dollars/m²] (dollars/ft²)</th>
<th>Estimated LCC [dollars/m²] (dollars/ft²)</th>
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</thead>
<tbody>
<tr>
<td>Earth berm</td>
<td>111 (10.33)</td>
<td>39 (3.60)</td>
<td>150 (13.93)</td>
</tr>
<tr>
<td>Precast/prestressed concrete stacked panels, steel posts</td>
<td>212 (19.67)</td>
<td>43 (4.03)</td>
<td>255 (23.70)</td>
</tr>
<tr>
<td>Precast/prestressed concrete stacked panels, concrete posts</td>
<td>262 (24.33)</td>
<td>28 (2.62)</td>
<td>290 (26.95)</td>
</tr>
<tr>
<td>Timber post-and-panel (hardwood or softwood)</td>
<td>180 (16.70)</td>
<td>122 (11.35)</td>
<td>302 (28.05)</td>
</tr>
<tr>
<td>Precast/prestressed cantilever</td>
<td>291 (27.00)</td>
<td>30 (2.80)</td>
<td>321 (29.80)</td>
</tr>
<tr>
<td>Carosite</td>
<td>273 (25.33)</td>
<td>50 (4.65)</td>
<td>323 (29.98)</td>
</tr>
<tr>
<td>Precast concrete, full-height panels, monolithic posts</td>
<td>305 (28.33)</td>
<td>28 (2.62)</td>
<td>333 (30.95)</td>
</tr>
<tr>
<td>Glue-laminated wood</td>
<td>197 (18.33)</td>
<td>145 (13.48)</td>
<td>342 (31.81)</td>
</tr>
<tr>
<td>Durisol</td>
<td>212 (19.67)</td>
<td>152 (14.14)</td>
<td>364 (33.81)</td>
</tr>
<tr>
<td>Noishield steel</td>
<td>298 (27.67)</td>
<td>131 (12.19)</td>
<td>429 (39.86)</td>
</tr>
<tr>
<td>Noishield aluminum</td>
<td>377 (35.00)</td>
<td>163 (15.15)</td>
<td>540 (50.15)</td>
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</table>
CHAPTER 3: METHODOLOGY

3.1 Instrumentation

In this study there were eight sets of recording devices used. Each set consisted of a Larson Davis sound level meter (SLM) (model 812) with a ½ inch Larson Davis preamplifier (model PRM900B) and Microphone head (2559). Each SLM was connected to a Sony Digital Audio Tape Player/Recorder (DAT) (model TCD-D8) 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). These eight pairs were mounted to an aluminum plate and then attached to a tripod. This set-up can be seen in Figure 3.1. Once the aluminum plate is placed on the tripod the microphone head should be placed at a height of five feet above the ground and at an angle of 70 degrees above horizontal [3]. From here on, the sets of SLMs and DATs will be referenced as microphones.

The un-weighted ac analog sound data collected by the SLM was saved on the DAT at 48kHz. One major advantage of the DAT usage is the ability to re-access data to the nearest second due to the clock record that is synchronous to the data.
Figure 3.1. SLM and DAT setup

The Larson Davis 2900B Real Time Analyzer (RTA) model 3200 was used to analyze the sound data recorded by the SLM and DAT. The RTA is shown in Figure 3.2. and further details on such is provided in the data reduction section of this thesis.
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 that was collected was made 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 Omegascope 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 was 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. All instrumentation used in this study can be found in Appendix A.

3.2 Calibration of Instruments

To assure proper calibration, the RTA, with its microphones preamplifier, SLM, microphone and preamplifier for microphone #1, and the acoustic calibrators were certified by the equipment suppliers.

3.3 Normalization

When using eight different microphones, there will be small variation in measured sound levels between them when recording the same noise source. The process of system normalization was done to negate this difference. 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 3.3 and Figure 3.4. 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 set and was compared to #2 through #8. Each of the seven comparisons equated to a correction factor for the remaining sets. These correction factors are used to make the values recorded Microphones #2 through #8 the same values recorded by microphone #1. These correction factors were then used to finalize the sound data for all microphones.

Figure 3.3. Front view of system normalization
3.4 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 procedures for the sound data collection and subsequent analysis can be found in the ODOT report titled “Effectiveness of Noise Barriers Installed Adjacent to Transverse Grooved Concrete Pavement” [37]

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. The microphone layout 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 #6 were at an array distance of 25 feet perpendicular to the wall (See 3.5 Site Selection for clarification) and microphone #7 and #8 were placed directly in front 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 where they could record both speed and volume separated by vehicle class and lane. Two researchers were placed behind the wall to monitor microphones #1 through #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 #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 DAT number they came out of, date, and location.

3.5 Site Selection

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 berm, 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. See Appendix B for selection criteria

3.5.1 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 3.5 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 3.6. As stated in the Field Recording section, there were six microphones placed behind the wall and two placed in front of the wall. This configuration can be seen in Figure 3.7.
Figure 3.5. Site 1 highway view of part concrete wall and part clear wall

Figure 3.6. Site 1 highway view of clear wall testing location
3.5.2 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 3.8. The microphone locations at Site 2 varied from the other sites. Due to the spacial restrictions caused by the garage behind microphone #4, microphones #5 and #6 were placed 25 feet to the south of microphones #2 and #3, respectively. The configurations of the six microphones placed behind the wall and two placed in front of the wall can be seen in Figure 3.9.
Figure 3.8. Site 2 highway view of clear wall testing location

Figure 3.9. Site 2 microphone locations
3.5.3 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 north bound wall was chosen for analysis. The wall was approximately 13 feet tall and is shown in Figure 3.10. 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. The configurations of the six microphones placed behind the wall and two placed in front of the wall can be seen in Figure 3.11.
3.5.4 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 3.12. 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. The configurations of the six microphones placed behind the wall and two placed in front of the wall can be seen in Figure 3.13.

Figure 3.12. Site 4 highway view of absorptive concrete wall testing location

Figure 3.13. Site 4 microphone locations
3.5.5 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 3.14. The locations at Site 5 for microphones #1 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. This configuration can be seen in Figure 3.15.

Figure 3.14. Site 5 highway view of absorptive concrete wall testing location

Figure 3.15. Site 5 microphone locations
3.5.6 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 3.14. The locations at Site 6 for microphones #1 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. This configuration can be seen in Figure 3.17.

Figure 3.16. Site 6 highway view of absorptive concrete wall testing location
3.5.7 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 3.18 and Figure 3.19. 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 3.20.

Figure 3.18. Site 7 highway view of earthen berm testing location

Figure 3.19. Site 7 highway view along the ditch line of the earthen berm
3.5.8 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 3.21 and Figure 3.22. 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 3.23.
Figure 3.21. Site 8 highway view of earthen berm testing location

Figure 3.22. Site 8 highway view along the ditch line of the earthen berm
3.5.9 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 south bound wall was chosen for analysis. The wall was approximately 18 feet tall and can be viewed in Figure 3.24. The locations at Site 9 for microphones #1 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. This configuration can be seen in Figure 3.25.
Figure 3.24. Site 9 highway view of hollow fiberglass wall testing location

Figure 3.25. Site 9 microphone locations
3.5.10 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 3.26. Microphones #1 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. This configuration can be seen in Figure 3.27
3.5.11 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 north bound wall was chosen for analysis. The wall was approximately 13 feet tall and can be viewed in Figure 3.28. Microphones #1 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. This configuration can be seen in Figure 3.29.
3.5.12 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 3.28 shows the location chosen for analysis as viewed from the highway. Since the wall is not visible from the highway in Figure 3.30, Figure 3.31 was provided to show the north bound wall at the testing locations. Both of these walls are approximately 17 feet tall. Microphones #1 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. This configuration can be seen in Figure 3.32.

Figure 3.30. Site 12 highway view of steel wall testing location
3.5.13 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 3.33. Directly behind the barrier there was a steep decline in elevation into a flat open field this can be seen in Figure 3.34. 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 3.35.

Figure 3.33. Site 13 highway view of steel wall testing location

Figure 3.34. Site 13 behind steel wall
3.5.14 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 3.36. Microphones #1 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. This configuration can be seen in Figure 3.37.
Figure 3.36. Site 14 highway view of wooden wall testing location

Figure 3.37. Site 14 microphone locations
3.5.15 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 that the fabric is attached to. The roadside view of this structure can be viewed in Figure 3.38. Microphones #1 and #2 were placed directly behind the fence at a height of 11 feet and 3 feet, respectively. 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. This configuration can be seen in Figure 3.39.

Figure 3.38. Site 15 highway view of acoustic fabric fence testing location
3.5.16 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 that the fabric was attached to and can be viewed in Figure 3.40. Microphones #1 and #2 were placed directly behind the fence at a height of 11 feet and 3 feet, respectively. 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. This configuration can be seen in Figure 3.41.
3.5.17 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 that the fabric was attached to and can be viewed in Figure 3.42. Microphones #1 and #2 were placed directly behind the fence at a height of 9 feet and 3 feet, respectively. 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. This configuration can be seen in Figure 3.43.

Figure 3.42. Site 17 highway view of acoustic fabric fence testing location
3.6 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 3.44 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 Larson Davis program “RTAUtil32” was used to convert this output into a Excel text file. The un-weighted 1/3 octave band results were then copied into a corrections spreadsheet which applied the correction factors from the system normalization. Results were then A-weighted and organized by site and microphone location.

Figure 3.44. Data Reduction Setup
3.7 FHWA Traffic Noise Model (TNM 2.5)

When a direct before and after analysis is not possible, the FHWA Traffic Noise Model is used to predict the noise levels without the noise wall. 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 can accurately predict the decibel levels that will be observed and the amount of insertion loss the wall will provide. Figure 3.45 and Figure 3.46 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 3.47. 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 3.45. Site 9 TNM plan view

Figure 3.46. Site 9 TNM profile view
**Figure 3.47. Site 9 TNM Results**

<table>
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<tr>
<th>Name</th>
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</table>
CHAPTER 4: STATISTICAL METHODOLOGY

A statistical analysis was done to determine which noise barrier materials provided a significantly higher noise reduction compared to other materials. Also the TNM data was compared to the field data to verify that there is no significant difference 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 One-way ANOVA 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.

4.1 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 $Z_{skew} = \frac{skewness}{standard\ error\ of\ skewness}$
Equation 4.1 If this $Z_{skew}$ is less than 1.96 then the data is not significantly skewed and is therefore normal.

$$Z_{skew} = \frac{skewness}{standard\ error\ of\ skewness}$$ \hspace{1cm} \text{Equation 4.1.}

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) [38]. 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:

$$t = \frac{\bar{D} - \mu_d}{s_D/\sqrt{N}}$$ \hspace{1cm} \text{Equation 4.2.}

$\bar{D}$ - Mean difference between samples
$\mu_d$ - Difference between population means~ $\mu_d=0$ due to no difference in population

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

After Equation 4.2 is run the checked if any test came back significant. For this analysis, at 95% confidence and 4 degrees of freedom, the significant value is 2.776 (from the t-distribution table) [38]. 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.

4.2 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 noise 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 [38]:

\[
SS_T = \sum_{k=1}^{K} \sum_{i=1}^{n_k} X_{ik}^2 - \frac{T^2}{N} \tag{Equation 4.3}
\]

Where:

\[
SS_T = \text{Total sum of squares}
\]

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

K = Number of groups

n = Number of observations

T = sum of scores summed across all observations and groups

N = total number of scores

\[
SS_B = \sum_{k=1}^{K} \frac{T_k^2}{n_k} - \frac{T^2}{N} \tag{Equation 4.4}
\]
Where:

SSB = Sum of squares between-groups

Tk = sum of observations for kth group

\[ SS_B = \sum_{k=1}^{K} \sum_{i=1}^{n_k} X_{ik}^2 - \sum_{k=1}^{K} \frac{T_k^2}{n_k} \]  

Equation 4.5

Where:

SSW = Sum of squares within-groups

\[ MS_B = \frac{SS_B}{K - 1} \]  

Equation 4.6

\[ MS_W = \frac{SS_W}{N - K} \]  

Equation 4.7

\[ F_{calc} = \frac{MS_B}{MS_W} \]  

Equation 4.8

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.

In order to determine if there were significant differences in the data, statistical tests at a level of confidence of 95 percent were performed. It should be noted that a significant difference merely indicates that the probability of the difference is due to the data itself and not by chance. It should also be noted that sample size plays a significant role in the results of such analysis. Small sample sizes tend to not find significance when one exist and vice versa for large sample sizes.

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.

4.3 Effect Size

Running the paired t-test or an ANOVA is not enough to fully analyze the data set [38]. The effect size is a practical way of deciding whether a manipulation has a legitimate effect. A significant result from a t-test does not necessarily indicate that the manipulation had a large, practical effect. The formula to calculate the effect size for the t-test is as follows:
\[ r = \sqrt{\frac{t^2}{t^2 + d_f}} \]  

Equation 4.9.

\[ r^2 = \frac{SS_M}{SS_T} \]  

Equation 4.10.

\( r \) – Effect size  
\( t \) – T-Statistic  
\( d_f \) - Degrees of freedom  

\( r^2 \) – Effect size  
\( SS_M \) - Between-group sum of squares  
\( SS_T \) - Total sum of squares  

0.1 – Small Effect  
0.3 – Medium Effect  
0.5 – Large Effect
CHAPTER 5: RESULTS

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. The objective of comparing the field data to the model data was to verify that the model returns similar data to that obtained in real-world conditions. 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. A model was developed using TNM 2.5 for each field site that was analyzed. Many field observations were recorded to make the model as accurate as possible. Topography, atmospheric data, volume and vehicle class, and noise wall characteristics were all collected and entered into the model. 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.

5.1 Traffic Data Analysis

As the TNM requires traffic volume, classification, and speed data for accurate results, this data was collected simultaneous as the sound data. To limit personnel, only the speed data was collected in the field via a laser speed recording device, while the count and classification data was obtained in the laboratory via recorded video in the field. The speed, count, and classification data was subdivided by travel lane for input into the TNM model. The data is provided in Table 5.1 where the outside lane corresponds to right most lane.
Table 5.1. Traffic count and speed data collected

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<td>Volume (vph)</td>
<td>Speed (mph)</td>
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5.2 Comparison of Measured (Field) and Predicted (TNM) Noise Levels

The results from the field sound data and subsequent analysis produced two TMN data outputs for each microphone: Equivalent continuous noise levels, A-frequency weighted, in 1/3 octave frequency bands (50 Hz – 10 kHz), and two broadband noise levels.

The results and corresponding discussion related to the comparison of TNM model data to field data for both A-Frequency weighted and broadband levels are provided in the following sections

5.2.1 Broadband Noise Levels

Table 5.2. summarizes the field data and TNM data by site by microphone. The third column depicts the difference between the two data elements. If the TNM data is over-predicting noise levels, the error value is negative and any under-prediction is shown as positive.

Table 5.2. Measured (Field) and Predicted (TNM) Broadband Levels

<table>
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<tr>
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<th>Predicted (TNM) Level (dB)</th>
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**Site 6**

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### 5.2.2 One-third Octave Band Frequency Levels

The A-weighted one-third octave band sound levels were compared between the field data (Measured) and the predicted data (TNM) and plotted by microphone by site. The results for one study location, FRA-71 by Lighthouse Church (Clear Wall) are given in Figure 5.1 and Figure 5.2, as an example. The A-weighted one-third octave band sound levels is utilized to understand the frequency-dependent relationship to the 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 5.1. Measured and predicted one-third octave sound levels for FRA-71 by Lighthouse Church

Figure 5.2. indicates differences between the field and TNM data by octave levels. The values greater than 0 are considered an under-prediction of the model as compared to the field data and any value less than 0 is an over-prediction. For this particular site and microphone, it can be seen that the greatest over-prediction is 7.4 dB at 10,000 frequency level. In Addition the greatest under-prediction is 5.5 dB in general this figure represents most other sites. Figure 5.1 Error! Reference source not found. and Figure 5.2, are provided in Appendix A.
5.2.3 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 were compared to the results from the field portion. As before in the field comparison, the noise reductions were used to compare the model to the field. The paired t-test was used to compare each site to its corresponding model and the results can be found in Table 5.3.

Figure 5.2. Measured and predicted one-third octave sound levels for FRA-71 by Lighthouse Church
### Table 5.3. Comparison of Measured and Predicted Noise Levels

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<th>Paired Difference</th>
<th>Degrees of Freedom</th>
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<td>-3.07</td>
<td>2.23</td>
<td>0.91</td>
</tr>
</tbody>
</table>

*Significant Difference

Of the 17 comparisons, five sites were found to have significantly 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, overall the TNM model cannot consistently accurately represent the wall material nor the quality of the material, in terms of degradation.
5.3 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. The objective of comparing the field data to the model data was to verify that the model returns similar data to that obtained in real-world conditions. 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. A model was developed using TNM 2.5 for each field site that was analyzed. Many field observations were recorded to make the model as accurate as possible. Topography, atmospheric data, volume and vehicle class, and noise wall characteristics were all collected and entered into the model. 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.

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. To make the sites comparable to one another, the data from each site was normalized by taking the decibel reading at microphone #1 and subtracting the decibel reading at microphones #2. 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.

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 comparison. In addition, the one rubber-filled fiberglass and two hollow fiberglass walls were combined and labeled as fiberglass. Table 5.4 summarizes the descriptive data for the various wall materials by material type.

Table 5.4. Descriptive Data for Noise Wall Material

<table>
<thead>
<tr>
<th>Wall Material Type</th>
<th>Sample Size</th>
<th>Field Mean Noise Reduction (dB)</th>
<th>Standard Deviation (dB)</th>
<th>Average Wall Height (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>2</td>
<td>16.19</td>
<td>1.24</td>
<td>15.5</td>
</tr>
<tr>
<td>Concrete</td>
<td>4</td>
<td>16.00</td>
<td>3.43</td>
<td>15.0</td>
</tr>
<tr>
<td>Earthen</td>
<td>2</td>
<td>13.28</td>
<td>2.67</td>
<td>8.0</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>3</td>
<td>16.73</td>
<td>2.12</td>
<td>14.7</td>
</tr>
<tr>
<td>Steel</td>
<td>2</td>
<td>19.27</td>
<td>2.04</td>
<td>14.5</td>
</tr>
<tr>
<td>Acoustic Fabric Fence</td>
<td>3</td>
<td>8.89</td>
<td>1.22</td>
<td>9.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16</strong></td>
<td><strong>14.90</strong></td>
<td><strong>3.92</strong></td>
<td><strong>12.9</strong></td>
</tr>
</tbody>
</table>

The ANOVA indicated significant differences between materials and the Gabriel post hoc test indicated that the clear wall material, fiberglass wall material, and steel 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.

In regards to other material types, there were degradation concerns with all but two of the concrete walls. The remaining sites experienced soil eroding from the base of
the wall and the physical structure of the wall deteriorating. The worst case was the wooden wall which was heavily warped with large gaps in the middle of the wall.
CHAPTER 6: CONCLUSION

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.

6.1 TNM 2.5

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 can skew the results and not correctly represent the noise levels produced at the site. Therefore, overall the TNM model cannot accurately represent the wall material nor the quality of the material, in terms of degradation. Thus, the model can be useful only in simple cases of projection noise not affected by a noise wall.
6.2 Noise Barrier Materials

The goal for this portion of the study was to identify the noise barrier material that produced the best 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 60 minutes. Once the recording sessions were finished, the tapes are replayed through the Larson Davis RTA and a spreadsheet is developed. The sheets are organized by microphone number with a minute by minute decibel reading for each A-weighted octave band. These decibel readings were the 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 worse noise reduction than all of the other materials. There was no statistical difference between the remaining materials. In regards to other material types, there were degradation concerns with all but two of the concrete walls. The remaining sites
experienced soil eroding from the base of the wall and the physical structure of the wall deteriorating. The worst case was the wooden wall which was heavily warped with large gaps in the middle of the wall. Based upon the lack of degradation at the concrete noise wall sites and the similar noise reduction potential, it is recommended that ODOT continue to utilize concrete materials for noise abatement and minimize the use of other materials, unless a maintenance plan and constructability plan can be developed to minimize degradation of those wall materials.

6.2.1 Acoustic Fabric

The Acoustic Fabric did not perform nearly as well as the traditional noise walls. The Acoustic Fabric produced a noise reduction 8.89 dB while the traditional noise walls had noise reductions of 16-19 dB. From these results the Acoustic Fabric cannot perform as well as a traditional wall but can be used to provide temporary relief while a permanent solution is found. The durability of the Acoustic Fabric should also be examined more in-depth. With the fabric being attached to just a chain link fence, wind loads and dead loads from the fabric should be examined to verify whether the chain link fence can withstand these factors.

6.3 Recommendations for Future Research

Based on the results found in this study, there are multiple directions to consider for future research. The number one recommendation would be to increase the sample size and collect more data. Using only 17 sites with eight microphone sets did not equate to a large enough sample size to provide strong data. For this type of study, a controlled environment would be more useful than a field study. In a controlled environment, the
researcher could control every factor so that the only difference between the noise barriers will be the material. In the case of this study, traffic volumes and terrain differed at every site.

With respect to highway noise there are two items to help control the noise level, the noise barrier and the source. This study examined the noise barrier in a field setting and in all cases the pavement was asphalt. Examination of quieter pavement would be useful because the tire pavement interaction is the number one source of high noise levels on a highway. Also, conducting an investigation on how the noise levels are affected as the pavement ages (and determining the significance of pavement of age) would be beneficial. To provide proper noise abatement, it may be appropriate to reduce the noise at the source rather than try and remediate it with a wall. Each of the materials that were examined has a specific construction and maintenance cost associated with them. Since the materials tested performed similarly in noise reduction, a more extensive research should be performed analyzing the life cycle cost of noise barriers discussing the associated cost as well as any environmental considerations.
REFERENCES


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APPENDIX A– ONE-THIRD OCTAVE BAND COMPARISON

Site 1 – FRA-71 Clear (Church)
FRA-71 Clear M3

Sound Level (dB)

Frequency (Hz)

Measured

Predicted

AVG

FRA-71 Clear M3  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
FRA-71 Clear M4

Sound Level (dB) vs Frequency (Hz)

- Measured
- Predicted
- AVG

FRA-71 Clear M4  Measured - Predicted

Sound Level Difference (dB) vs Frequency (Hz)
FRA-71 Clear M5

**Sound Level (dB)** vs **Frequency (Hz)**

- Measured
- Predicted
- AVG

**Sound Level Difference (dB)**

- Measured - Predicted

---

**FRA-71 Clear M5 Measured - Predicted**

- Frequency (Hz): 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1K, 1.25K, 1.6K, 2K, 2.5K, 3.15K, 4K, 5K, 6.3K, 8K, 10K


---
FRA-71 Clear M7

Sound Level (dB)

Frequency (Hz)

FRA-71 Clear M7  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 2 – FRA-71 Clear

FRA-71 Clear M1

FRA-71 Clear M1  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
FRA-71 Clear M2

Sound Level (dB)

Frequency (Hz)

FRA-71 Clear M2  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
FRA-71 Clear M3

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

FRA-71 Clear M3  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
FRA-71 Clear M5

Sound Level (dB)

Frequency (Hz)

Measured

Predicted

AVG

Sound Level Difference (dB)

Frequency (Hz)
FRA-71 Clear M6

Sound Level (dB) vs Frequency (Hz)

Measured
Predicted
AVG

FRA-71 Clear M6  Measured - Predicted

Sound Level Difference (dB) vs Frequency (Hz)

-16 -14 -12 -10 -8 -6 -4 -2 0

50 63 80 100 125 160 200 250 315 400 500 630 800 1000

1K 1.25K 1.6K 2K 2.5K 3K 4K 5K 6.3K 8K 10K

-0.8 -6.1 -7.7 -10.3 -11.5 -12.5 -12.8 -13.5 -12.4 -12.3 -6.7
FRA-71 Clear M7

Sound Level (dB)

Frequency (Hz)

-20 -15 -10 -5 0 5 10 15 20

-1.4 -0.2 0.1 1.6 1.8 2.3 2.6 2.6 1.6 1.6 1.6 0.7 0.7 0.1 0.5 1.1 1.5 1.6 1.8 4.3 8.5 9.1 14.7

FRA-71 Clear M7  Measured - Predicted
Site 3 – GRE-675 Concrete

**GRE675 Concrete M1**

![Graph showing measured and predicted sound levels](image1)

**GRE675 Concrete M1 Measured - Predicted**

![Bar chart showing sound level differences](image2)
GRE675 Concrete M3

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

GRE675 Concrete M3  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
GRE675 Concrete M4

Sound Level (dB) vs Frequency (Hz)

Sound Level Difference (dB) vs Frequency (Hz)

Comparison of Measured vs Predicted Sound Levels for GRE675 Concrete M4
**GRE675 Concrete M5**

**Sound Level (dB)**

- 50
- 63
- 80
- 100
- 125
- 160
- 200
- 250
- 315
- 400
- 500
- 630
- 800
- 1K
- 1.25K
- 1.6K
- 2K
- 2.5K
- 3K
- 3.15K
- 4K
- 5K
- 6.3K
- 8K
- 10K

**Frequency (Hz)**

- 50
- 6380
- 100
- 125
- 160
- 200
- 250
- 315
- 400
- 500
- 630
- 800
- 1K
- 1.25K
- 1.6K
- 2K
- 2.5K
- 3K
- 3.15K
- 4K
- 5K
- 6.3K
- 8K
- 10K

**Sound Level Difference (dB)**

- 0.6
- 3.8
- 4.2
- 5.9
- 9.1
- 12.6
- 14.1
- 14.1
- 10.0
- 9.8
- 8.5
- 8.2
- 8.6
- 9.4
- 9.9
- 9.7
- 9.2
- 9.9
- 9.7
- 9.6

**GRE675 Concrete M5  Measured - Predicted**

- 50
- 63
- 80
- 100
- 125
- 160
- 200
- 250
- 315
- 400
- 500
- 630
- 800
- 1K
- 1.25K
- 1.6K
- 2K
- 2.5K
- 3K
- 3.15K
- 4K
- 5K
- 6.3K
- 8K
- 10K
Site 4 – MOT-75 Concrete

MOT-75 Concrete M1

Sound Level (dB)

Frequency (Hz)

MOT-75 Concrete M1 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
MOT-75 Concrete M2

Sound Level (dB)

Frequency (Hz)

MOT-75 Concrete M2 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
MOT-75 Concrete M4

Measured
Predicted
AVG

Sound Level Difference (dB)
Frequency (Hz)

MOT-75 Concrete M4  Measured - Predicted

Sound Level (dB)
Frequency (Hz)
MOT-75 Concrete M6

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

Sound Level Difference (dB)

Frequency (Hz)
MOT-75 Concrete M7

Sound Level (dB)

Frequency (Hz)

Measured

Predicted

AVG

MOT-75 Concrete M7  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)

-20  -15  -10  -5  0  5  10  15  20

50  63  80  100  125  160  200  250  315  400  500  630  800  1K  1.25K  1.6K  2K  2.5K  3.15K  4K  5K  6.3K  8K  10K
Site 5 – STA-77 Concrete

### STA-77 Concrete M1

#### Measured vs Predicted

- **Measured**
- **Predicted**
- **AVG**

#### Sound Level Difference (dB)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Sound Level Difference (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>-2.3</td>
</tr>
<tr>
<td>63</td>
<td>0.2</td>
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<tr>
<td>80</td>
<td>0.7</td>
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<td>100</td>
<td>0.5</td>
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<td>125</td>
<td>0.1</td>
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<tr>
<td>160</td>
<td>1.4</td>
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<td>200</td>
<td>0.9</td>
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<tr>
<td>250</td>
<td>1.6</td>
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<tr>
<td>315</td>
<td>2.7</td>
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<td>400</td>
<td>4.1</td>
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<td>500</td>
<td>4.9</td>
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<td>630</td>
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<td>800</td>
<td>5.4</td>
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<tr>
<td>1K</td>
<td>4.9</td>
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<td>4.9</td>
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<td>6.3K</td>
<td>1.4</td>
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<tr>
<td>8K</td>
<td>0.9</td>
</tr>
<tr>
<td>10K</td>
<td>1.6</td>
</tr>
</tbody>
</table>

#### Frequency (Hz)

- 50
- 63
- 80
- 100
- 125
- 160
- 200
- 250
- 315
- 400
- 500
- 630
- 800
- 1K
- 1.25K
- 1.6K
- 2K
- 2.5K
- 3.15K
- 4K
- 5K
- 6.3K
- 8K
- 10K
STA-77 Concrete M2

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

Sound Level Difference (dB)

Frequency (Hz)
STA-77 Concrete M4

Sound Level (dB)
Frequency (Hz)

-2.5 -6.5 -6.4 -7.7 -8.2 -11.4 -12.6 -13.4 -14.7
50 63 80 100 125 160 200 250 315 400 500 630 800 1K 1.25K 1.6K 2K 2.5K 3K 4K 5K 6.3K 8K 10K

Sound Level Difference (dB)
Frequency (Hz)
STA-77 Concrete M5

Sound Level (dB)
Frequency (Hz)

-1.1 -6.4 -9.4 -12.4
-5.5 -9.9 -9.1
-5.1 -9.1

Measured
Predicted
AVG

STA-77 Concrete M5  Measured - Predicted

Sound Level Difference (dB)
Frequency (Hz)
STA-77 Concrete M7

Sound Level (dB)

Frequency (Hz)

STA-77 Concrete M7  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 6 – WAR-75 Concrete

### WAR-75 Concrete M1

![Graph showing sound level vs. frequency for WAR-75 Concrete M1. The graph compares measured and predicted values. The x-axis represents frequency in Hz, and the y-axis represents sound level in dB. The graph shows a plot of measured and predicted values with a comparison column showing the difference between the two.]
Site 7 – CUY-480 Earthen Berm

CUY-480 Earthen Berm M1

CUY-480 Earthen Berm M1 Measured - Predicted
CUY-480 Earthen Berm M7

Sound Level (dB)

Frequency (Hz)

Measured

Predicted

AVG

CUY-480 Earthen Berm M7  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 8 – MIA-75 Earthen Berm

MIA-75 Earthen Berm M1

Sound Level (dB)

Frequency (Hz)

MIA-75 Earthen Berm M1  Measured - Predicted

Sound Level Difference (dB)
MIA-75 Earthen Berm M2

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

Sound Level Difference (dB)

Frequency (Hz)
MIA-75 Earthen Berm M3

Sound Level (dB)

Frequency (Hz)

MIA-75 Earthen Berm M3  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
MIA-75 Earthen Berm M5

Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)

Sound Level (dB)
MIA-75 Earthen Berm M7

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

MIA-75 Earthen Berm M7  Measured - Predicted

Sound Level Difference (dB)
MIA-75 Earthen Berm M8

Frequency (Hz)

Sound Level (dB)

Measured

Predicted

AVG

MIA-75 Earthen Berm M8  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 9 – CUY-71 Hollow Fiberglass

**CUY-71 Hollow Fiberglass M1**

![Graph showing sound level versus frequency for CUY-71 Hollow Fiberglass M1. The graph includes data points for measured and predicted values, with a focus on frequency (Hz) on the x-axis and sound level (dB) on the y-axis.]

**CUY-71 Hollow Fiberglass M1 Measured - Predicted**

![Graph showing the difference between measured and predicted sound levels for CUY-71 Hollow Fiberglass M1. The graph includes frequency (Hz) on the x-axis and sound level difference (dB) on the y-axis.]

- Measured
- Predicted
- AVG

Sound Level Difference (dB) vs Frequency (Hz) for CUY-71 Hollow Fiberglass M1.
CUY-71 Hollow Fiberglass M2

Sound Level (dB)

Frequency (Hz)

Measured

Predicted

AVG

CUY-71 Hollow Fiberglass M2  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
CUY-71 Hollow Fiberglass M3

Sound Level (dB)

Frequency (Hz)

-2.0 -4.7 -6.8 -10.5 -10.3 -11.1 -12.7 -12.6 -13.3 -13.4 -13.1 -12.9 -13.7 -13.4 -15.3

Sound Level Difference (dB)

Frequency (Hz)
CUY-71 Hollow Fiberglass M4

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

CUY-71 Hollow Fiberglass M4  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
CUY-71 Hollow Fiberglass M6

CUY-71 Hollow Fiberglass M6  Measured - Predicted
Site 10 – CUY-90 Hollow Fiberglass

CUY-90 Hollow Fiberglass M1

Sound Level (dB) vs Frequency (Hz)

CUY-90 Hollow Fiberglass M1 Measured - Predicted

Sound Level Difference (dB) vs Frequency (Hz)
CUY-90 Hollow Fiberglass M2

Sound Level (dB)

Frequency (Hz)

CUY-90 Hollow Fiberglass M2 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
CUY-90 Hollow Fiberglass M3

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

CUY-90 Hollow Fiberglass M3 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
CUY-90 Hollow Fiberglass M7

Sound Level (dB)

Frequency (Hz)

CUY-90 Hollow Fiberglass M7 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 11 – GRE-675 Rubber Filled

GRE-675 Rubber Filled M1

![Graph showing sound level and frequency for GRE-675 Rubber Filled M1.

- measured vs. predicted
- AVG difference]

GRE-675 Rubber Filled M1 Measured - Predicted

![Graph showing sound level difference and frequency for GRE-675 Rubber Filled M1.

- measured vs. predicted
- AVG difference]
Site 12 – FRA-71 Steel

FRA-71 Steel M1

FRA-71 Steel M1 Measured - Predicted
FRA-71 Steel M2

Sound Level (dB)

Frequency (Hz)

FRA-71 Steel M2 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
FRA-71 Steel M4

Sound Level (dB) vs Frequency (Hz)

- Measured
- Predicted
- AVG

FRA-71 Steel M4 Measured - Predicted

Sound Level Difference (dB) vs Frequency (Hz)

- Measured - Predicted
FRA-71 Steel M7

Sound Level (dB)

Frequency (Hz)

FRA-71 Steel M7 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 13 – FRA-670 Steel

**FRA-670 Steel M1**

Sound Level (dB) vs Frequency (Hz)

- **Measured**
- **Predicted AVG**

**FRA-670 Steel M1 Measured - Predicted**

Sound Level Difference (dB) vs Frequency (Hz)

- Measured vs Predicted for different frequency bands.
sound level (dB)

frequency (Hz)

FRA-670 Steel M2

Measured - Predicted

Sound Level Difference (dB)
FRA-670 Steel M4

Sound Level (dB)
Frequency (Hz)

Measured
Predicted
AVG

FRA-670 Steel M4 Measured - Predicted

Sound Level Difference (dB)
Frequency (Hz)
FRA-670 Steel M5

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

Sound Level Difference (dB)

Frequency (Hz)
FRA-670 Steel M6

Sound Level (dB)

Frequency (Hz)

FRA-670 Steel M6 Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 14 – FRA-70 Wood

FRA-70 Wood M1

FRA-70 Wood M1 Measured - Predicted
FRA-70 Wood M5

Measured vs Predicted

Sound Level (dB)

Frequency (Hz)

FRA-70 Wood M5  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
FRA-70 Wood M6

Sound Level (dB)

Frequency (Hz)

FRA-70 Wood M6  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
FRA-70 Wood M7

Sound Level (dB)

Frequency (Hz)

FRA-70 Wood M7 Measured - Predicted

Frequency (Hz)
FRA-70 Wood M8

Sound Level (dB)

Frequency (Hz)

Measured

Predicted

AVG

FRA-70 Wood M8  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 15 – FRA-161 Acoustic Fabric

**FRA-161 Acoustic Fabric M1**

![Graph showing sound level in dB vs frequency (Hz) for FRA-161 Acoustic Fabric M1. The graph compares measured and predicted values.]

**FRA-161 Acoustic Fabric M1 Measured - Predicted**

![Graph showing sound level difference in dB vs frequency (Hz) for FRA-161 Acoustic Fabric M1. The graph displays the difference between measured and predicted values.]

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measured</th>
<th>Predicted</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>-1.8</td>
<td>-2.2</td>
<td>-2.2</td>
</tr>
<tr>
<td>63</td>
<td>-3.8</td>
<td>-4.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>80</td>
<td>-2.8</td>
<td>-2.4</td>
<td>-2.4</td>
</tr>
<tr>
<td>100</td>
<td>-3.5</td>
<td>-4.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>125</td>
<td>-3.0</td>
<td>-3.5</td>
<td>-3.5</td>
</tr>
<tr>
<td>160</td>
<td>-3.5</td>
<td>-3.8</td>
<td>-3.8</td>
</tr>
<tr>
<td>200</td>
<td>-3.5</td>
<td>-3.0</td>
<td>-3.0</td>
</tr>
<tr>
<td>250</td>
<td>-2.1</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>315</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>400</td>
<td>-0.3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Sound Level Difference (dB)

-20, -15, -10, -5, 0, 5, 10, 15, 20
FRA-161 Acoustic Fabric M2

Sound Level (dB)

Frequency (Hz)

- Measured
- Predicted

AVG

Sound Level Difference (dB)

Frequency (Hz)
FRA-161 Acoustic Fabric M3

Sound Level (dB) vs. Frequency (Hz)

- Measured
- Predicted
- AVG

FRA-161 Acoustic Fabric M3  Measured - Predicted

Sound Level Difference (dB) vs. Frequency (Hz)

-1.0 -0.6 -3.6 -4.3 -4.9 -8.7 -10.2 -10.8 -12.3 -14
FRA-161 Acoustic Fabric M6

Sound Level (dB) vs. Frequency (Hz)

- Measured
- Predicted
- AVG

FRA-161 Acoustic Fabric M6  Measured - Predicted

Sound Level Difference (dB) vs. Frequency (Hz)
Site 16 – HAM-75 Acoustic Fabric

HAM-75 Acoustic Fabric M1

HAM-75 Acoustic Fabric M1  Measured - Predicted
HAM-75 Acoustic Fabric M3

Sound Level (dB)

Frequency (Hz)

Measured
Predicted
AVG

HAM-75 Acoustic Fabric M3  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
HAM-75 Acoustic Fabric M5

Sound Level (dB)

Frequency (Hz)

HAM-75 Acoustic Fabric M5  Measured - Predicted

Sound Level Difference (dB)

Frequency (Hz)
Site 17 – HAM-126 Acoustic Fabric

HAM-126 Acoustic Fabric M1

Sound Level (dB)
Frequency (Hz)

HAM-126 Acoustic Fabric M1  Measured - Predicted

Sound Level Difference (dB)
Frequency (Hz)
HAM-126 Acoustic Fabric M2

Sound Level (dB)

Frequency (Hz)

-1.5 -1.9 -2.5
-6.3 -6.2 -5.8
-7.3 -7.2
-8.4
-9.8
-12

50 63 80 100 125 160 200 250 315 400 500 630 800 1K 1.25K 1.6K 2K 2.5K 3.15K 4K 5K 6.3K 8K 10K

Sound Level Difference (dB)

Frequency (Hz)

50 63 80 100 125 160 200 250 315 400 500 630 800 1K 1.25K 1.6K 2K 2.5K 3.15K 4K 5K 6.3K 8K 10K

-1.5 -1.9 -2.5
-6.3 -6.2 -5.8
-7.3 -7.2
-8.4
-9.8
-12

HAM-126 Acoustic Fabric M2 Measured - Predicted

1.8
0.5
6.6
-0.2
-2.5
-1.3 -1.0
-2.4
-3.3
-4.1
-5.0
-5.1 -5.8
-7.3 -7.2
-8.4
-9.8
HAM-126 Acoustic Fabric M3

Sound Level (dB)

Frequency (Hz)

-1.4 -0.9 -2.1 -5.8 -5.6 -9.0 -11.2 -11.7 -10.2 -8.1 -6.9 -6.6 -5.6 -4.6 -3.5 -2.5 -2.6 -1.4 -0.9 0.9 5.1 -2 -4 -6 -8 -10 -12 -14

Sound Level Difference (dB)

Frequency (Hz)

-1.4 -0.9 -2.1 -5.8 -5.6 -9.0 -11.2 -11.7 -10.2 -8.1 -6.9 -6.6 -5.6 -4.6 -3.5 -2.5 -2.6 -1.4 -0.9 0.9 5.1 -2 -4 -6 -8 -10 -12 -14
HAM-126 Acoustic Fabric M4

Sound Level (dB) vs Frequency (Hz)

- Measured
- Predicted
- AVG

HAM-126 Acoustic Fabric M4  Measured - Predicted

Sound Level Difference (dB) vs Frequency (Hz)

-1.3 -1.0 -2.2 -5.3 -4.8 -6.1 -6.6 -8.1 -8.7 -8.7 -6.8 -7.0 -5.2 -5.2 -4.1 -3.8 -2.4 -1.5 -1.3 -1.0 -1.1 1.1 5.8 -2.4 -4.4 -6.6 -8.7 -10
HAM-126 Acoustic Fabric M5

Measured vs Predicted

Sound Level Difference (dB)

Frequency (Hz)

-0.8 -0.5
-1.9
-4.8
-4.2
-5.3 -5.4
-6.5 -6.3
-5.4
-3.8
-4.9
-3.7
-4.2
-3.6 -2.6
-1.3 -1.1 -1.1 -0.7
-4.5
HAM-126 Acoustic Fabric M6

**Sound Level (dB)**

- Measured
- Predicted
- AVG

**Frequency (Hz)**

- 50
- 63
- 80
- 100
- 125
- 160
- 200
- 250
- 315
- 400
- 500
- 630
- 800
- 1K
- 1.25K
- 1.6K
- 2K
- 2.5K
- 3.15K
- 4K
- 5K
- 6.3K
- 8K
- 10K

**Sound Level Difference (dB)**

- Measured - Predicted

**Frequency (Hz)**

- 50
- 63
- 80
- 100
- 125
- 160
- 200
- 250
- 315
- 400
- 500
- 630
- 800
- 1K
- 1.25K
- 1.6K
- 2K
- 2.5K
- 3.15K
- 4K
- 5K
- 6.3K
- 8K
- 10K

**Sound Level Difference (dB)**

- Measured - Predicted