UNIVERSITY OF HARTFORD ACOUSTICS
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# Acoustic & Vibratory Characterization of Footfall Noise, Phase 2

By

Robert Tanen
Jonathan Silver

with
Michelle C. Vigeant, Ph.D.
Robert D. Celmer, Ph.D.
Director, Acoustics Laboratory

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## Abstract

Prior to Phase I of this study, existing literature concerning footfalls was primarily focused on its transmission between spaces, such as a floor/ceiling's Impact Isolation Class. This study sought to measure the sound power spectra and vibratory signature produced by footfalls using both human subjects and two standard tapping machines. Within the University's reverberation room, twelve floor profiles were tested with the tapping machines, which included eleven from Phase I. In addition, three of the previously tested floors and a new floor profile were tested by human subjects. Fourteen subjects (seven male and seven female) walked on the floor surfaces while wearing three different types of footwear: leather-soled shoes with hard heels, rubber-soled shoes with rubber heels, and sneakers. Sound power spectra and vibratory signatures for each condition were measured in both narrow and 1/3 octave bands using the procedures of ISO 3741. Two tapping machines were utilized on each floor profile, one with rubber-footed drop weights and the other with cored samples of shoe soles used by the human participants. The data for each floor profile were averaged by shoe type, and 95% confidence intervals were calculated for the human subject data. This study produced the following results: A verification of repeatability from Phase I to Phase II, improved correction curves that enable modeling of tapping machine data as human data, sound power footfall data for vinyl flooring applied directly to concrete, a comparison demonstrating that a rubber-tipped tapping machine produces similar spectra to that generated by women's leather shoes, and a comparison of scaled acoustic sound power spectra and its resemblance to the corresponding vibratory signature.
[Worked supported by The Paul S. Veneklasen Research Foundation]

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## Purpose

This study investigated the sound power spectra and vibratory signatures of human and tapping machine–generated footfall noise within a room using a variety of shoes and floor surfaces. Correlations between tapper and human-generated footfall noise from Phase I were further delineated.

## Introduction

Footfall noise can be a substantial contributor to activity noise in occupied rooms, especially performance spaces and lecture halls. Empirical evidence suggests that noise from footfalls is highly dependent on floor treatments within a given indoor architectural environment. Acousticians need to be able to quantify how loud footfall noise might be within a space, for example, when an architect specifies an alternative to carpet in a given aisle-way. Harder floor surfaces have acoustic consequences that can become important as in the case of audience members leaving their seats during a performance, along with other circumstances.

In the past, published acoustic data regarding footfall noise pertained primarily to the acoustic spectrum in spaces **below** the source room, and the resultant Impact Isolation Class (IIC) rating for the floor/ceiling [1-8]. While these data are important for tenants living in multi-story, multi-family dwellings, Phase I of this study sought to quantify the sound power spectra generated **in the same space** as the footfalls themselves. The current study seeks to supplement the aforementioned sound power data collected during Phase I [9] by quantifying the concomitant vibratory signatures generated by various footfalls, gathering sound power data for an additional floor profile with humans and an additional tapper type, along with a more detailed analysis of correction factors between the tapper and human footfall data found in Phase I.

Measurements were conducted using the procedures outlined in ISO 3741, *Determination of Sound Power Levels of Noise Sources using Sound Pressure-Precision Methods for Reverberation Rooms* [10]. Room dimensions, volumes, and proposed configurations were verified for compliance with ISO 3741. Note that ISO 3741 requires testing in a diffuse field, and the University of Hartford's reverberation room has been certified as having met this requirement through independent ISO qualification. Utilizing the procedures described in ISO 3741 Annex E, the chamber qualified for diffuse field testing in all 1/3 octave bands from 100 – 10,000 Hz. The University's reverberation room is also decoupled from its surroundings via 3 Hz isolation springs which help to minimize measurement error induced by external vibration sources. Further, ISO 3741 stipulates the use of a rotating boom microphone, so a Brüel & Kjær Type 3923 boom microphone was configured to traverse a maximum circumferential path while traveling no closer than 1 meter to any surface within the reverberation room. Each test floor profile was also placed at least 1 meter from the walls.

Since the ISO 3741 comparison method requires a reference sound source (RSS) an ILG RSS, manufactured by ILG Industries, Chicago, IL, was used for this purpose, as described in [13]. The 1/3 octave sound power levels of the RSS were tested prior to the footfall measurements using a scanning sound intensity procedure to confirm the unit's compliance with published 1/3 octave band sound power levels. Calibrated sound intensity measurements were made with a Brüel & Kjær Type 3520 intensity probe attached to a Brüel & Kjær 3590 Pulse Portable Analyzer System. The intensity probe was used with two different pairs of Brüel & Kjær phase-matched microphones: Type 4183 ½" with a 12-mm spacer and Type 4235 ¼" with a 6-mm spacer. This enabled a measurement range of 100 Hz–10,000 Hz. The RSS was placed within a "shoe box" shaped control volume with five rectangular sides, delineated using thin rods and string. The control surface measured approximately 1.4 meters high by 1 meter wide by 1 meter long, with a total area of about 6.6 $m^2$. A scanning wand technique was used to average the sound intensity over each surface during a 30-second time period. The average sound intensity on each side was combined with the corresponding surface area to sound power using the relation W = IA. The total sound power spectrum was computed by summing the values from the five sides. The result of the sound intensity tests confirmed the ILG deviated less than +/- 1 dB from the published values in [13] over the frequency span 100 – 6,300 Hz, and measured 2 dB and 3 dB below [13] in the 8 kHz and 10 kHz bands, respectively. These bands were adjusted accordingly in the Pulse Sound Power software, described below.

## Phase I (2007)

*Floor Profiles*

A range of floors typically used in public venues, including those used in concert halls, were tested during the first phase of this project. The 11 floor profiles that were chosen are listed in Table 1 below. It should be noted that components of Profiles #2–11 include additions to Profile #1 (poured concrete), and that each additional profile, except profile #3, was installed on Profile #2 (wooden sub-floor). The decision to construct individual wooden sub-floors for each floor profile enabled authenticity in construction, as well as consistent contact with the underlying concrete during testing.

Table 1: List of Floor Profiles

| Floor Profile | Description |
|---|---|
| 1 | Poured Concrete, 3" thick |
| 2 | Profile 1, plus ¾" wood sub–floor |
| 3 | Profile 1, plus rubber-backed short pile nylon carpet |
| 4 | Profile 2, plus rubber-backed short pile nylon carpet |
| 5 | Profile 2, plus 42 oz, looped, woven wool carpet, 0.25" pile height |
| 6 | Profile 5, with ¼" rubber pad below carpet |
| 7 | Profile 2, plus 0.056" sheet vinyl floor covering |
| 8 | Profile 2, plus 0.070" sheet vinyl floor covering |
| 9 | Profile 2, plus 0.076" sheet vinyl floor covering |
| 10 | Profile 2, plus ¾" tongue-in-groove oak flooring |
| 11 | Profile 2, plus 12"x12" Porcelain tile w/ 3/16" grout line |

Detailed descriptions of the materials and procedure used to create each of the above listed floor profiles can be found in the Phase I report [9]. For reference, the poured concrete base (Figure 1) a schematic of the wooden sub-floor on the concrete slabs and the actual wooden sub-floor (Schematic 1 and Figure 2) are pictured below:

| **Figure 1 – Profile 1, Poured Concrete** | **Schematic 1 –Wooden Sub-Floor on Concrete Slab** | **Figure 2 – Actual Sub Floor on Concrete Slab** |
|---|---|---|
|  |  |  |

*Shoes for Human Subjects*

Three different types of shoes, in both male and female styles, were utilized to collect data with all eleven profiles. Both male and female test subjects were recruited to walk on each floor profile with sneakers, rubber-soled shoes, and leather-soled shoes. These different shoe-types were meant to correspond to relatively soft, medium, and hard footwear, respectively. Details for each shoe are shown in Table 2 below, with photographs shown in Appendix A. Variation in women's shoe sizes were due to inconsistencies in brand-to-brand sizing. Shoes were chosen to fit all of the test subjects such that they could walk safely and consistently without slipping out of the shoes.

**Table 2: Shoe Schedule**

| | Brand | Shoe Name | Size | Heel Material | Heel Width | Heel Length | Heel Thickness |
|---|---|---|---|---|---|---|---|
| **Men's** | | | | | | | |
| **Leather Sole** | Mercanti Fiorentini | | 13 | wood | 3 1/8" | 3 1/4" | nominal 1" |
| **Rubber Sole** | Nunn-Bush | | 13 | rubber | 3 1/4" | nominal 4" | 1" |
| **Sneaker** | Reebok | Classic | 13 | no heel | N/A | N/A | N/A |
| **Women's** | | | | | | | |
| **Leather Sole** | Ditto by Vanelli | | 9.5 | plastic | 2" | 2 3/4" | 7/8" |
| **Rubber Sole** | White Mountain | | 8.5 | rubber | 2 3/8" | 2 1/2" | nominal 2" |
| **Sneaker** | Reebok | Classic Princess | 9 wide | no heel | N/A | N/A | N/A |

*Shoes for Tapping Machine*

Two pairs of each shoe were purchased: one for the test subjects to wear and one additional pair for fitting to the tapping machine. The extra shoes were cored to match the 3 cm diameter of the tapping machine weights using a 1 ¼" hole saw and a drill press. Figures 3 and 4, below, show examples of the coring process. The cored shoes were then glued to grade N-42 neodymium "rare-earth" magnets, rated at 3340 gauss. The assembled cores were attached via magnetism directly to the tapping machine weights, which provided a strong, temporary bond (Figure 5, below). Visual monitoring during testing confirmed that negligible movement of the magnets relative to the hammers occurred. Further details regarding the creation of magnetically attached cored shoe samples for the tapping machine can be found in the Phase I report [9].

| **Figure 3 – Shoe Coring Machine** | **Figure 4 – Cored Shoe** | **Figure 5 – "Shoed Magnets attached to Tapping** |
|---|---|---|
|  |  |  |

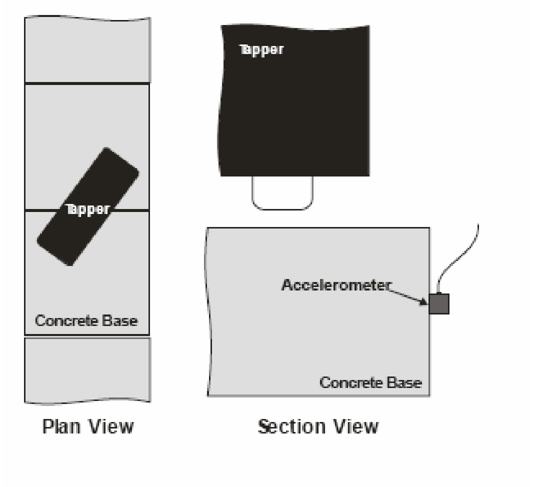
## Procedure – Phase II (2008)

*Test Subjects*

Fourteen test subjects participated in the current study, and were recruited from the University of Hartford student body, staff, and faculty. Seven male and seven female subjects, aged 19 to 50, were selected on the basis of their shoe size. Several participants (both male and female) who participated in Phase I of the study also participated in Phase II. Every participant signed consent forms and were compensated $10 each. The study was approved by the University's Human Subjects Committee on February 1, 2008; see Appendix B for documentation.

*Rubber Footed Tapping Machine*

A standard Brüel & Kjær Type 3207 tapping machine was used to simulate human footfalls (using the shoe core samples previously mentioned). The Type 3207 (Figure 6 below) tapping machine utilizes five weights of 500 grams each, impacting at 2 Hz. This resulted in an impact frequency of 10 Hz. In addition, a Brüel & Kjær Type 3204 tapping machine was also used for testing in the current study. The Type 3204 (pictured below in Figure 7) has all of the same general specifications as the Type 3207 (listed above), but the Type 3204 has a second set of weights with rubber pads attached. The rubber padded drop-weights were used to investigate potential relationships to the sound power levels measured with the 3207 tapping machine plus cored shoe samples. The tapping machines were placed at a 45-degree angle across the center of the floor profile being tested as shown in Schematic 2 below.

| **Schematic 2 – Tapping Machine/Accelerometer Placement** | **Figure 6 – Type 3207 Tapping Machine** | **Figure 7 – Type 3204 Tapping Machine** |
|---|---|---|
|  |  |  |

*New Floor Profile*

During Phase I, three vinyl floor profiles were constructed; each of a different thickness but all attached to the wooden sub-floor. A twelfth floor profile, which consisted of a medium thickness vinyl attached directly to the concrete base, was added for Phase II. After the concrete base was cleaned (to ensure proper bonding to the vinyl), an adhesive was spread evenly across the base using a notched glue trowel. As shown in Figure 8, a 100-lb roller was utilized during installation to remove trapped air bubbles and produce a continuous bond. The vinyl was then allowed to cure for more than 24 hours to ensure that a solid, even bond was made with the concrete base (see Figure 9). Due to the nature of this construction, however, the floor could not be constructed until all other tests had been performed as it rendered the concrete base unusable with the other profiles.

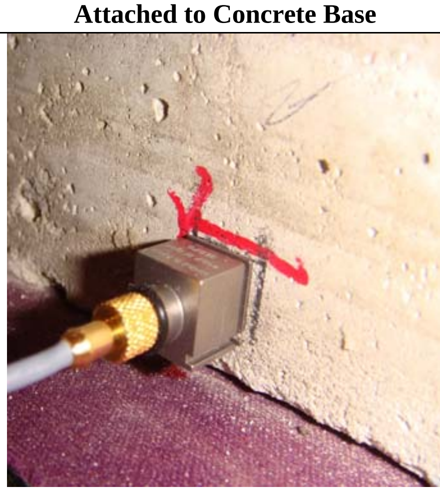
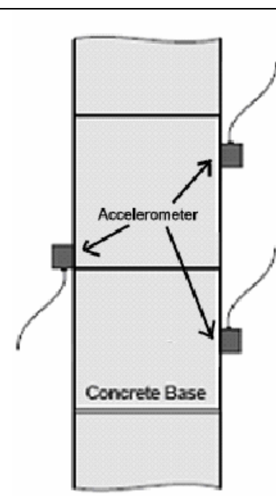
| **Figure 8 – Rolling Vinyl onto Concrete** | **Figure 9 – Vinyl on Concrete** |
| --- | --- |
|  |  |

*Tapper Tests*

The footfall measurement procedure involved human tests on floor Profiles #1, #3, and #10, as well as on new Profile #12. Both tapping machines, the Type 3207 (with all of the male and female cored shoe samples) and the Type 3204 (with rubber-tipped weights), were used to conduct tests on all 12 floor profiles. The human subjects walked on only one floor on any given day to ensure a consistent floor surface for all test subjects. This allowed contact to be maintained between the concrete walkway and the wooden sub-floor, which in turn allowed each human subject to walk on an identical floor profile. Over the course of the approximately twoweek testing period, each subject walked in each of the three pairs of shoes on each of the four floor profiles.

*Vibration Tests*

Three Brüel & Kjær Type 4507B-4 vertically reading, side-mount accelerometers were used to simultaneously measure each floor vibration, along with the aforementioned radiated sound power spectra. The Type 4507B-4 accelerometers were chosen for their sensitivity and ability to measure vertical vibration with a side mount using beeswax, as shown below in Figure 10a. The accelerometers were placed on the concrete base in three different positions (Figure 10b); two on one side positioned on the central-most concrete slabs and the third located between the first two on the opposite side. This produced a spatial average of the concrete base's vibration response while avoiding nodes. Each of the accelerometers was placed about a 0.25" above the floor in locations that were measured and marked prior to testing.

| **Figure 10a–**<br>**Side-Mount Accelerometers**<br>**Attached to Concrete Base** | **Figure 10b–**<br>**Accelerometer**<br>**Placement** |
|---|---|
|  |   |

*Sound Power Level Measurements*

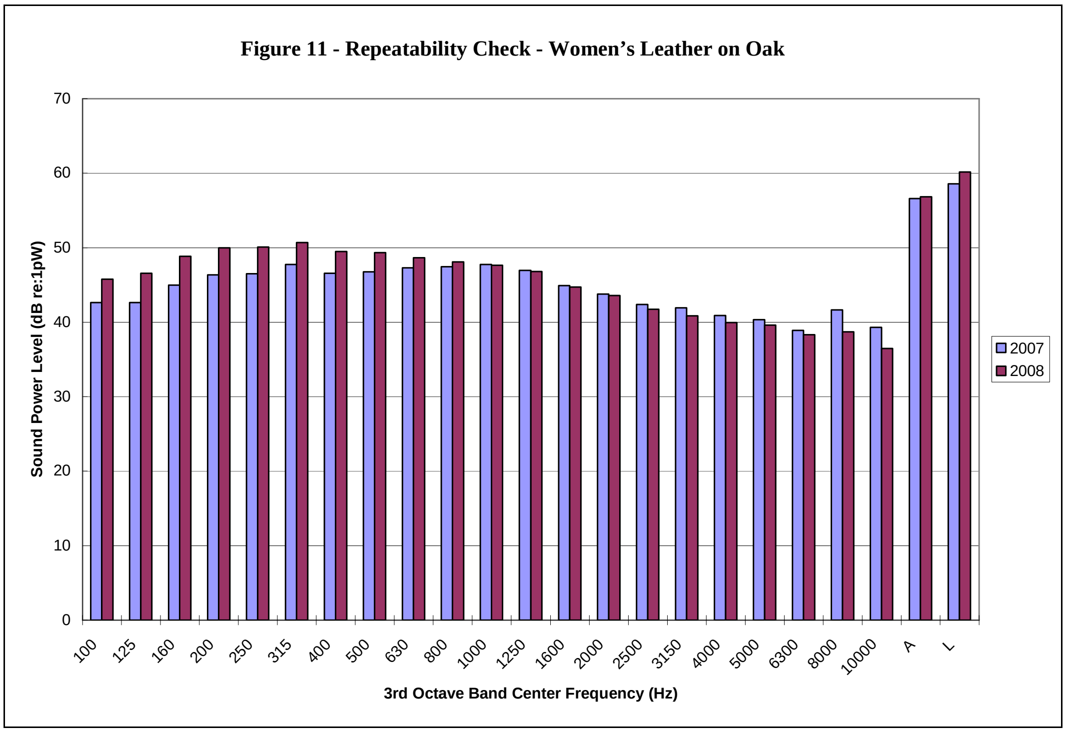
The Brüel & Kjær Type 7799 Sound Power software package was run using a Brüel & Kjær Type 3560 PULSE measurement system, version 12.5. Sound power was calculated from the pressure measurements using the RSS comparison method, all while simultaneously recording both narrow band and 1/3 octave band vibration measurements from each of the three accelerometers. The PULSE measurement system was calibrated each measurement day utilizing the following procedure: calibration of the B&K Type 4144 microphone using a B&K Type 4213 calibrator, and calibration of the B&K Type 4507B-4 accelerometers using a B&K Type 4294 calibrator. The Type 4144 microphone was placed on a rotating boom that allowed a spatial average of the sound pressure level in the room to be measured over a 32-second period, equal to one revolution of the boom. Both the background noise and the radiated sound levels of the RSS utilized the same 32-second measuring period, and were stored upon receiving acceptable levels.

After all of the measurement devices were calibrated and the proper background and reference noise levels were stored, each subject took turns walking on the given profile for a 32-second measurement period in each of the three different types of shoe. Prior to starting the measurement, the accelerometers were manually ranged after the subject walked briefly on the floor profile. The length of the floor surfaces enabled the test subjects to accomplish 4 – 5 paces before reversing directions. Practice runs were taken with the subjects, when needed, to ensure a consistent walking gait with minimized silences during reversals. For safety and quality control, a closed-circuit video monitoring system was installed to observe subjects while they walked within the reverberation room.

## Results

*Repeatability*

Human data was averaged for each floor/shoe combination. For example, for the oak floor, all seven subject data spectra for the women's rubber-soled shoe were averaged together to create one spectrum labeled "Women's Rubber on Oak". These data from Phase II was then compared with the respective averaged data from Phase I to create repeatability charts, as shown in Figure 11. With six different shoe averages per floor and three different floors re-tested in Phase II, a total of 18 repeatability charts are presented in Appendix C.

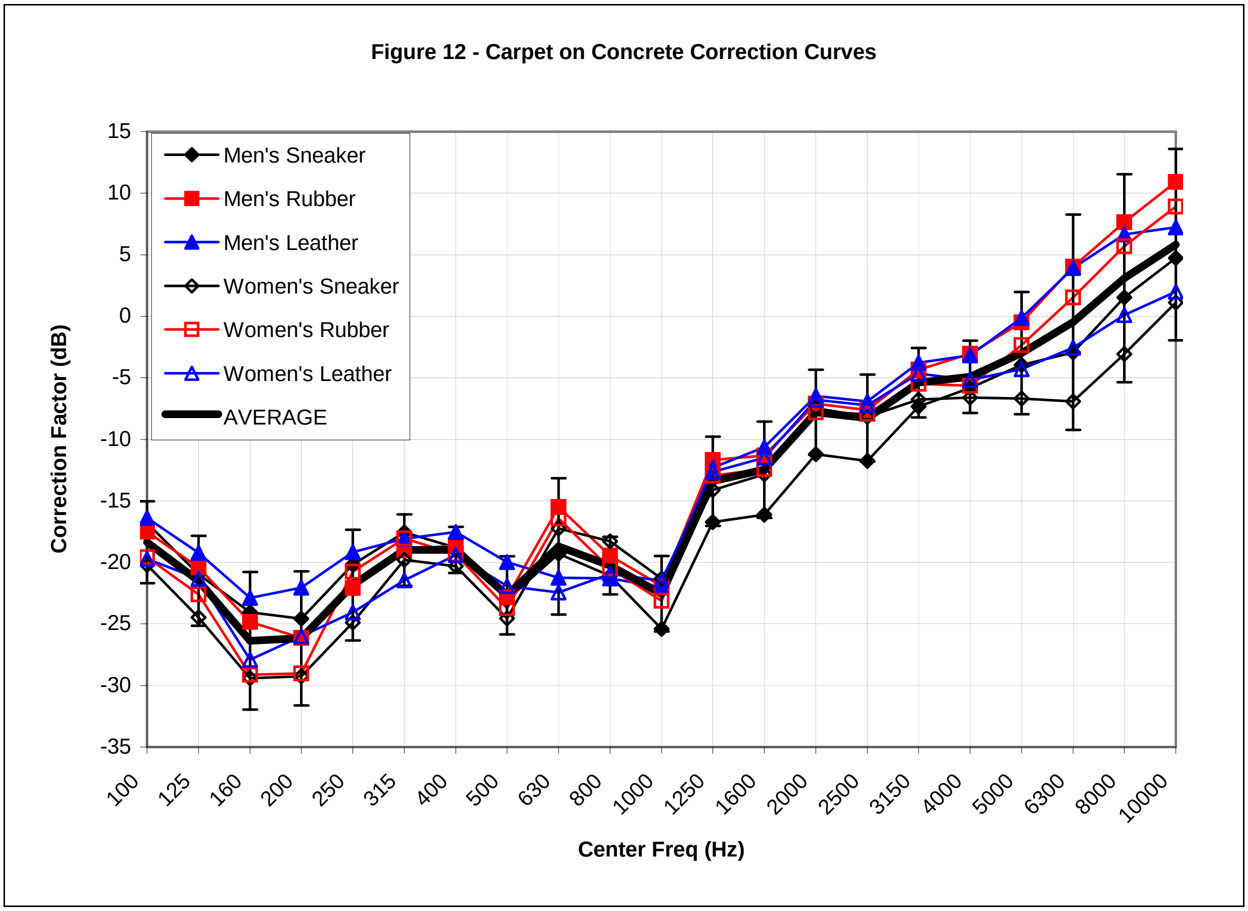



Good repeatability was found for the tapping machine from Phase I to Phase II, as the difference between the two phases on average were less than 2 dB. Additional data may be seen in Appendix C.

*Correction Curves Generated for Phase I Data*

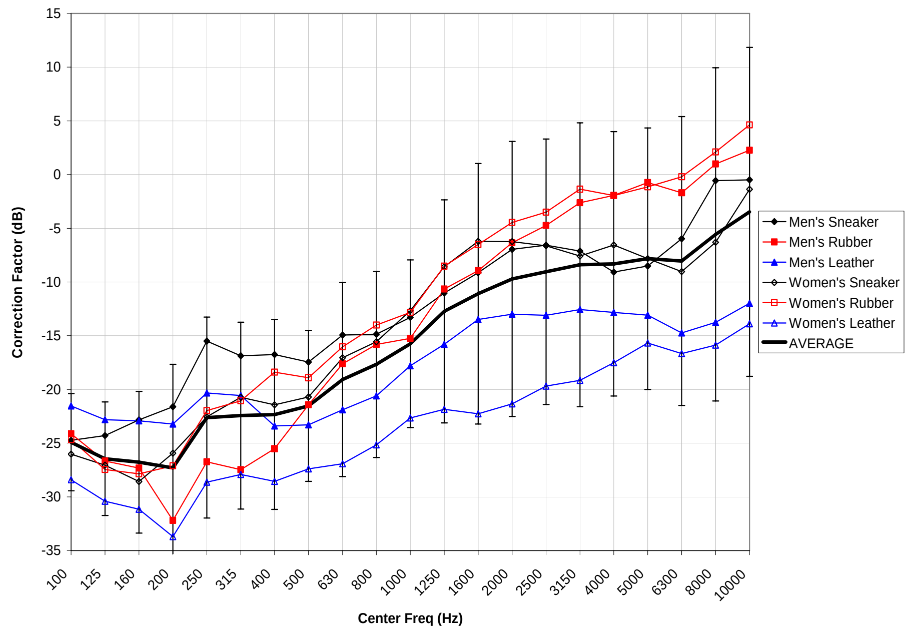
Phase II of this study called for further investigation of data trends collected from Phase I. After reviewing the interpretations made during Phase I, it was found that the linear correction factors presented were a rough approximation and applicable only to specific shoe/floor combinations. To develop a stronger correlation between the tapping machine and human sound power spectra generated, it was decided to develop correction curves rather than correction factors. The correction curves were generated by calculating the exact adjustments required for each floor/shoe combination at each 1/3 octave band. For each shoe on a given floor, the corresponding 1/3 octave correction factors were plotted concurrently which allowed trends between various shoes to be determined visually. The average of all six correction curves, with error bars, is also included to help display similarities between shoes.

For some of the floors tested it was found that one correction curve was suitable for all six shoes tested. Figure 12 shows an example of a correction curve that was independent of shoe type. The other floors found to exhibit this trend were the two wool carpet floors (Profiles #5 and #6); all three of the vinyl on sub-floor profiles (Profiles #7, #8 and #9); the carpet on sub-floor (Profile #4), save for the women's leather shoe, as shown in Table 3.



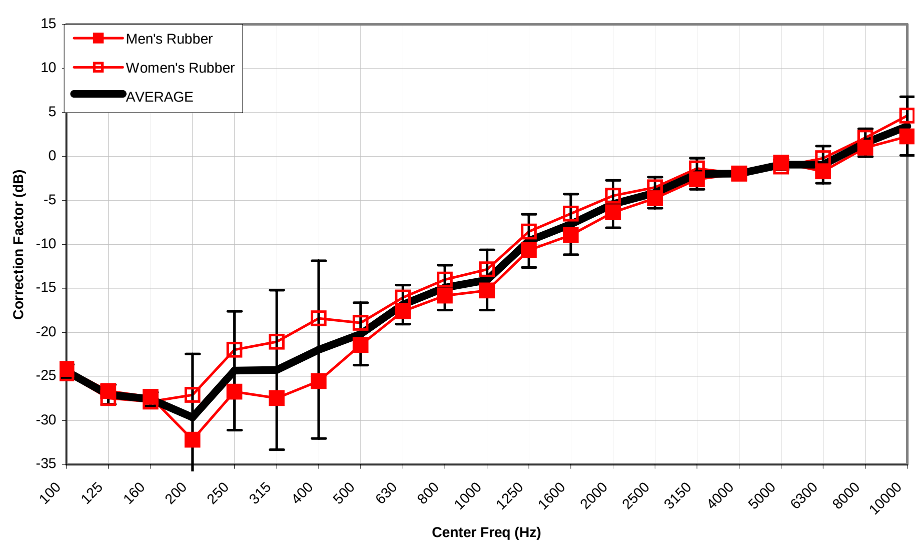

Note that for some floor types, the correction curves were not completely independent of shoe type. Figure 13a for the oak floor, Profile #10 below, demonstrates an example where strong trends were not as apparent. However, it was noted that certain shoe types did exhibit similar trends and thus sub-groups were generated to produce separate correction curves; see Figure 13b.

**Figure 13a – Oak Floor Correction Curves**



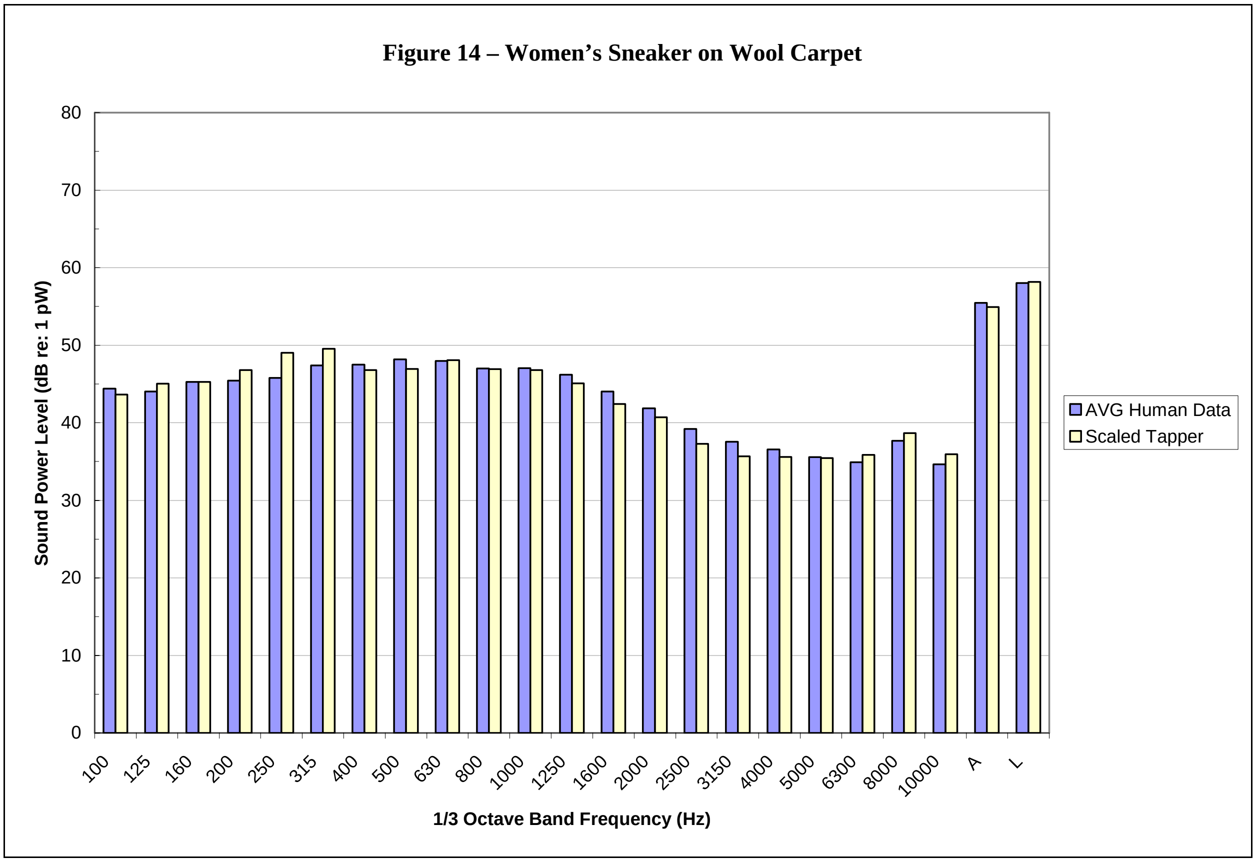

The average correction curves for a given group were then analyzed to ensure that they adequately estimated the behavior of the corresponding floor/shoe combinations. The sub-group correction curves are shown in Table 3 (next page) as well as in an application of a sub-group correction curve to a specific set of data (Figure 14).

**Figure 13b - Oak Floor Correction Curves Grouped**



| | 1/3 Octave Band Center Frequency | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Flr** | **Applicable Shoes** | **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** |
| **#2** | **All Leather** | -22 | -25 | -23 | -23 | -24 | -23 | -24 | -25 | -23 | -23 | -22 | -21 | -21 | -21 | -21 | -21 | -20 | -22 | -21 | -18 | -16 |
| | 95% Confidence | ±5 | ±0 | ±2 | ±4 | ±4 | ±4 | ±4 | ±7 | ±3 | ±2 | ±1 | ±0 | ±1 | ±4 | ±2 | ±1 | ±1 | ±4 | ±5 | ±4 | ±5 |
| | **All Sneaker, Women's Rubber** | -23 | -22 | -22 | -20 | -17 | -14 | -15 | -15 | -13 | -11 | -10 | -6 | -5 | -6 | -8 | -10 | -10 | -8 | -5 | 0 | 4 |
| | 95% Confidence | ±3 | ±6 | ±5 | ±5 | ±6 | ±3 | ±2 | ±3 | ±3 | ±3 | ±5 | ±8 | ±8 | ±8 | ±7 | ±5 | ±3 | ±2 | ±5 | ±7 | ±4 |
| **#3** | **All Shoes** | -18 | -22 | -26 | -26 | -22 | -19 | -19 | -23 | -19 | -20 | -23 | -13 | -12 | -8 | -8 | -5 | -5 | -3 | 0 | 3 | 6 |
| | 95% Confidence | ±3 | ±4 | ±6 | ±5 | ±4 | ±3 | ±2 | ±3 | ±6 | ±2 | ±3 | ±4 | ±4 | ±3 | ±4 | ±3 | ±3 | ±5 | ±9 | ±8 | ±8 |
| **#4** | **All Shoes minus Women's Leather** | -24 | -22 | -24 | -24 | -22 | -20 | -19 | -18 | -17 | -17 | -17 | -13 | -9 | -6 | -6 | -5 | -4 | -3 | -2 | 2 | 3 |
| | 95% Confidence | ±5 | ±3 | ±4 | ±4 | ±5 | ±7 | ±9 | ±7 | ±7 | ±5 | ±4 | ±7 | ±4 | ±3 | ±2 | ±2 | ±2 | ±2 | ±4 | ±3 | ±2 |
| **#5** | **All Shoes** | -18 | -21 | -23 | -22 | -19 | -18 | -18 | -17 | -16 | -16 | -16 | -15 | -14 | -13 | -12 | -11 | -9 | -8 | -6 | -1 | 3 |
| | 95% Confidence | ±2 | ±4 | ±2 | ±3 | ±7 | ±10 | ±10 | ±7 | ±6 | ±6 | ±5 | ±5 | ±4 | ±5 | ±4 | ±4 | ±4 | ±4 | ±6 | ±6 | ±7 |
| **#6** | **All Shoes** | -14 | -19 | -25 | -24 | -19 | -14 | -12 | -16 | -13 | -13 | -13 | -6 | -5 | -2 | -2 | 0 | 0 | 1 | 4 | 8 | 10 |
| | 95% Confidence | ±1 | ±3 | ±5 | ±4 | ±5 | ±6 | ±6 | ±6 | ±7 | ±6 | ±5 | ±5 | ±5 | ±4 | ±3 | ±4 | ±3 | ±4 | ±9 | ±10 | ±9 |
| **#7,8,9** | **All Shoes** | -26 | -26 | -25 | -25 | -24 | -23 | -23 | -23 | -23 | -22 | -22 | -20 | -19 | -18 | -18 | -17 | -16 | -16 | -15 | -11 | -8 |
| | 95% Confidence | ±7 | ±6 | ±6 | ±6 | ±9 | ±9 | ±8 | ±7 | ±7 | ±7 | ±7 | ±9 | ±9 | ±10 | ±9 | ±8 | ±8 | ±9 | ±10 | ±13 | ±14 |
| **#10** | **Rubber and Sneaker Combination** | -25 | -26 | -27 | -27 | -22 | -22 | -21 | -20 | -16 | -15 | -14 | -10 | -8 | -6 | -5 | -5 | -5 | -5 | -4 | -1 | 1 |
| | 95% Confidence | ± 2 | ± 3 | ± 5 | ± 9 | ± 9 | ± 9 | ± 8 | ± 4 | ± 2 | ± 2 | ± 2 | ± 3 | ± 3 | ± 2 | ± 3 | ± 6 | ± 7 | ± 8 | ± 8 | ± 7 | ± 5 |
| **#11** | **All Rubber** | -25 | -27 | -30 | -30 | -28 | -24 | -20 | -21 | -18 | -16 | -15 | -8 | -6 | -3 | -3 | -1 | -2 | -1 | -2 | 2 | 5 |
| | 95% Confidence | ± 4 | ± 2 | ± 4 | ± 1 | ± 7 | ± 11 | ± 11 | ± 5 | ± 5 | ± 6 | ± 3 | ± 7 | ± 6 | ± 6 | ± 4 | ± 3 | ± 1 | ± 3 | ± 3 | ± 3 | ± 7 |
| **#12** | **Rubber and Sneaker Combination** | -18 | -24 | -27 | -23 | -16 | -12 | -11 | -15 | -11 | -14 | -17 | -11 | -10 | -8 | -8 | -9 | -10 | -12 | -12 | -8 | -5 |
| | 95% Confidence | ±3 | ±4 | ±6 | ±7 | ±8 | ±9 | ±7 | ±6 | ±5 | ±5 | ±4 | ±3 | ±2 | ±1 | ±2 | ±6 | ±5 | ±5 | ±8 | ±11 | ±9 |
| | **All Leather** | -19 | -22 | -24 | -22 | -20 | -18 | -15 | -15 | -28 | -26 | -16 | -26 | -17 | -15 | -12 | -14 | -17 | -19 | -17 | -16 | -14 |
| | 95% Confidence | ±10 | ±9 | ±8 | ±9 | ±13 | ±12 | ±9 | ±5 | ±4 | ±3 | ±2 | ±10 | ±10 | ±9 | ±2 | ±3 | ±3 | ±3 | ±2 | ±5 | ±10 |

**Table 3 – Correction Factors for Shoed Tapping Machine**




*Vinyl on Concrete Sound Power Results*

A new floor profile was tested in Phase II, medium vinyl applied directly to concrete, and was labeled as Profile #12. Data sets for both men and women test subjects as well as the shoed tapping machine were gathered for this floor. Examples of the men's rubber shoe on this profile are shown in Figures 15a & b; the data for the other shoes can be found in Appendix D. Figure 15a (as with those in the Appendix) depicts the average human data compared with the scaled tapping machine (Type 3207 with appropriate "shoes"). Scaling factors for this new floor profile were obtained in the same manner as was presented for the Phase I data with the exception of using data collected this year to generate the factors. Comparisons between the bare concrete and with the vinyl are also presented for reference in Figure 15b, while the remainder can be found in Appendix D.

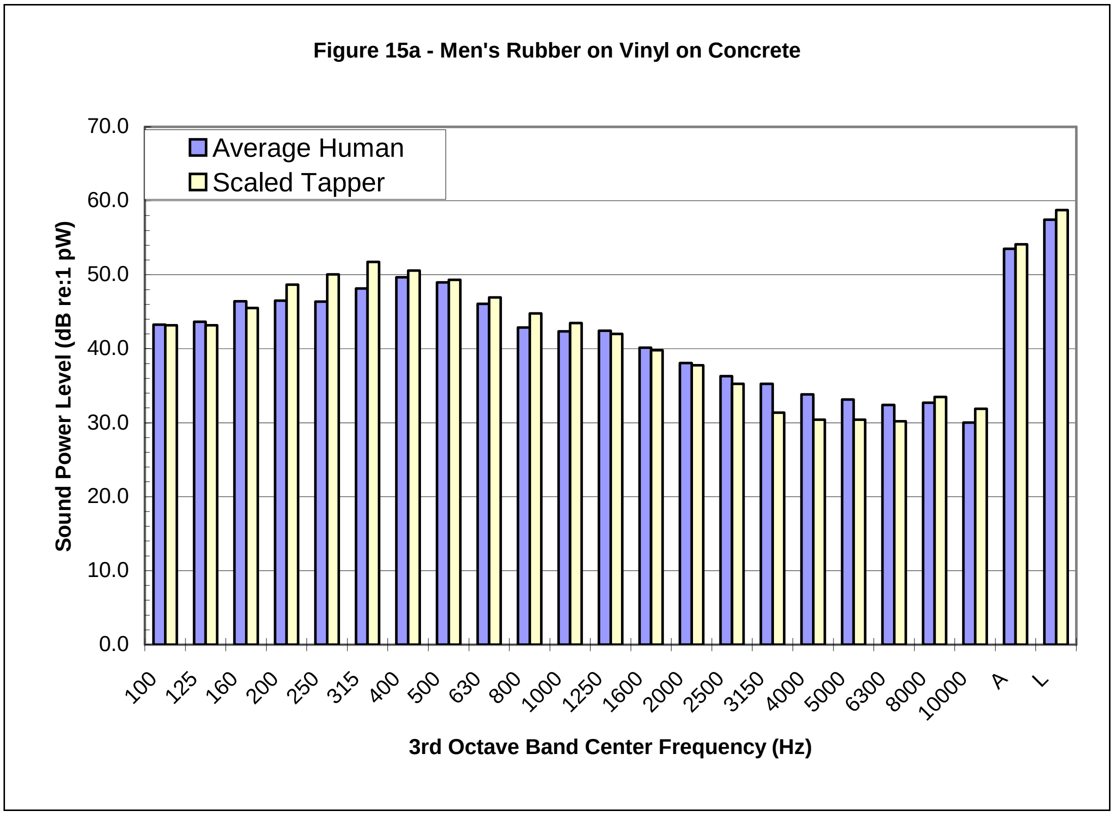


Figure 15a - Men's Rubber on Vinyl on Concrete
Average Human
Scaled Tapper
Sound Power Level (dB re:1 pW)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
A
L
3rd Octave Band Center Frequency (Hz)

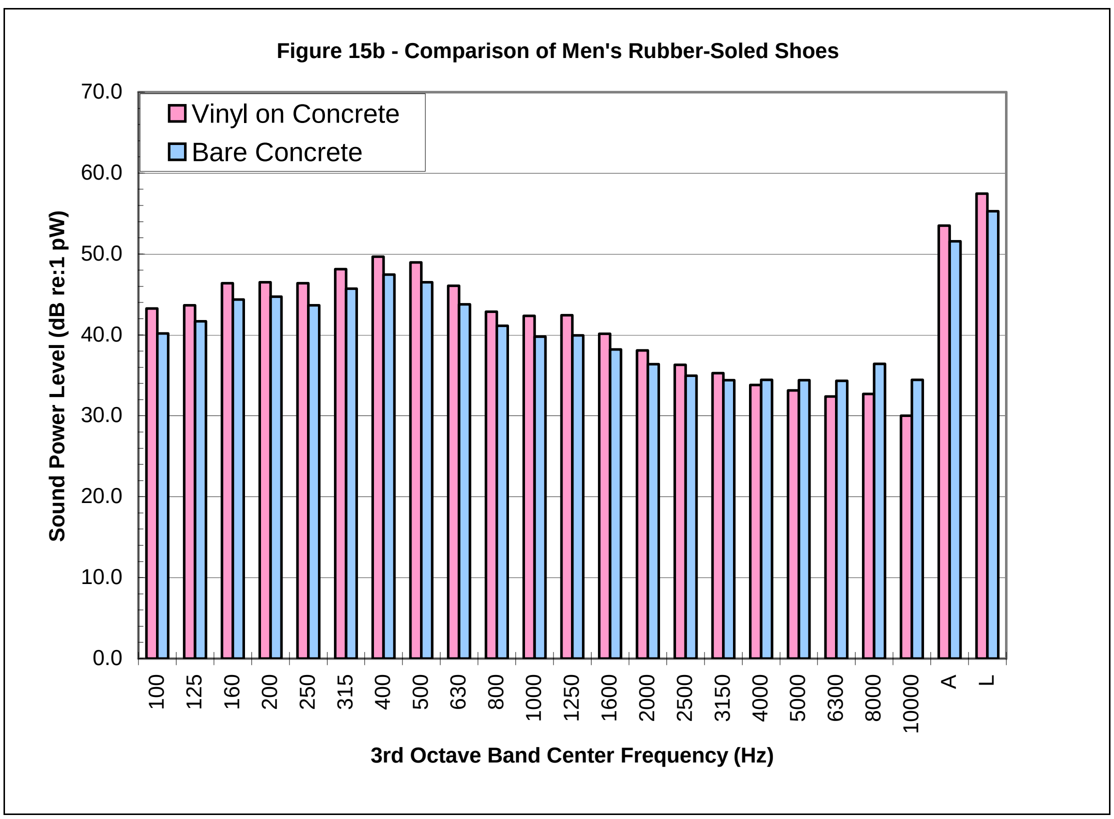


Figure 15b - Comparison of Men's Rubber-Soled Shoes
Vinyl on Concrete
Bare Concrete
Sound Power Level (dB re:1 pW)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
A
L
3rd Octave Band Center Frequency (Hz)

*Shoed Tapping Machine to Rubber Tapping Machine Correction Factors*

The Type 3204 (Rubber Footed) Tapping Machine data were compared to the data generated by each of the various shoes placed on the Type 3207 Tapping Machine. This comparison was done in an effort to find a general correction factor between the custom-shoed tapping machine tests that were conducted and those that were done with a Type 3204 Tapping Machine, a unit still in widespread use. The data were compared by computing the difference between individual-shoed tapping machine data and that from the Type 4304 rubber–tipped tapping machine data collected on the same floor; these differences were then analyzed. This allowed for six correction factors to be collected from each floor (six different shoe types: male and female – rubber, sneaker and leather). Each correction factor was then averaged with the corresponding correction factors generated by each of the 12 floor profiles. Six final rubber tapping machine–to–shoed tapping machine correction factors (one for each shoe) were then analyzed for relevance. An example of the aforementioned data is shown in Table 4 below (the remaining data can be found in Appendix E). It should be noted that the Type 3204 Tapping Machine generated excessive mechanical noise in the 400 Hz 1/3 octave band which resulted in a large correction factor for every shoe in that specific octave band.

**Table 4 - Rubber to Shoed Tapping Machine Correction Factors**

| Sound Power Levels of Tapping Machine Sounds (dB, re: 1 pico Watt) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Shoe Type** | **Center Freq. (Hz):** | **100** | **125** | **160** | **200** | **250** | **315** | **400** | **500** |
| **Men's Sneaker** | Average | -0.17 | 2.36 | 2.35 | -3.21 | -10.42 | -12.79 | -21.56 | -16.06 |
| | Standard Dev | 4.34 | 9.67 | 13.28 | 12.50 | 7.51 | 6.91 | 14.67 | 9.02 |

*Rubber Tapping Machine's Relationship with Cored Women's Leather Shoe*

Continuing to investigate relationships between the shoed tapping machine and the rubber tapping machine, several sound power spectra generated by the various "shoes" were compared with that generated by the rubber tapping machine on the same floor. The majority of the floor profiles showed a strong relationship between data generated by the women's leather shoe and the rubber tapping machine, as the correction factors were minimal (except at 400 Hz due to the tapper's noise issues), as shown in Figure 16a. The data suggest that for eight of the twelve profiles, the women's leather shoe most closely represented the sound power spectra generated by the rubber tapping machine. The four floor profiles that did not meet these criteria were the two commercial carpet arrangements (Profiles #3 and #4), the wool carpet with rubber pad (Profile #6) and the thin vinyl (Profile #7).

One example of the specific comparison between the two tapping machines is given in Figure 16b, where the cored shoe sample used on the Type 3207 tapper is the Women's Leather sole. Here, the differences in each of the $3^{rd}$ octave bands are minor, and the overall sums (both the linear and the A-weighted) are within 0.1 dB of each other.

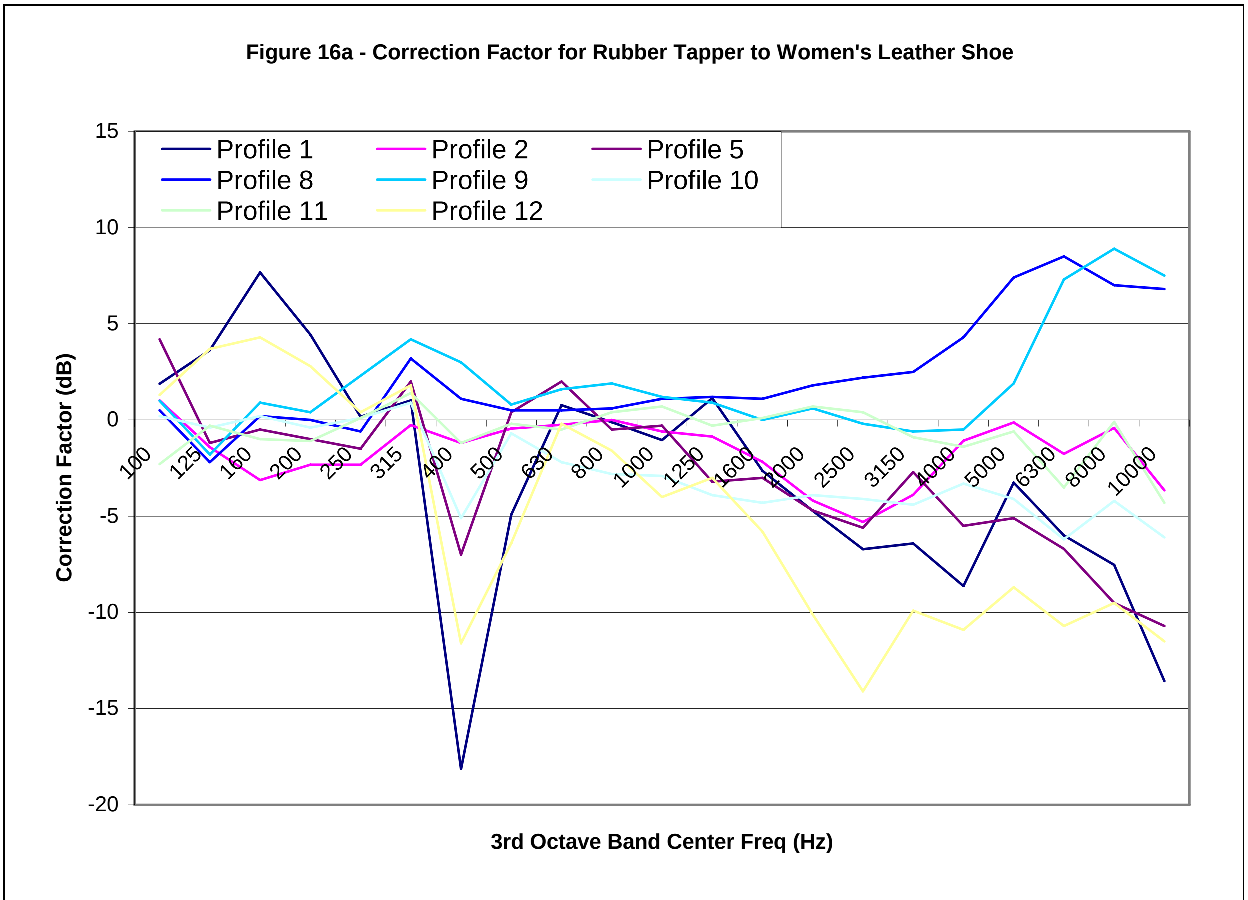


Figure 16a - Correction Factor for Rubber Tapper to Women's Leather Shoe
Profile 1
Profile 2
Profile 5
Profile 8
Profile 9
Profile 10
Profile 11
Profile 12
Correction Factor (dB)
3rd Octave Band Center Freq (Hz)
15
10
5
0
-5
-10
-15
-20
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000

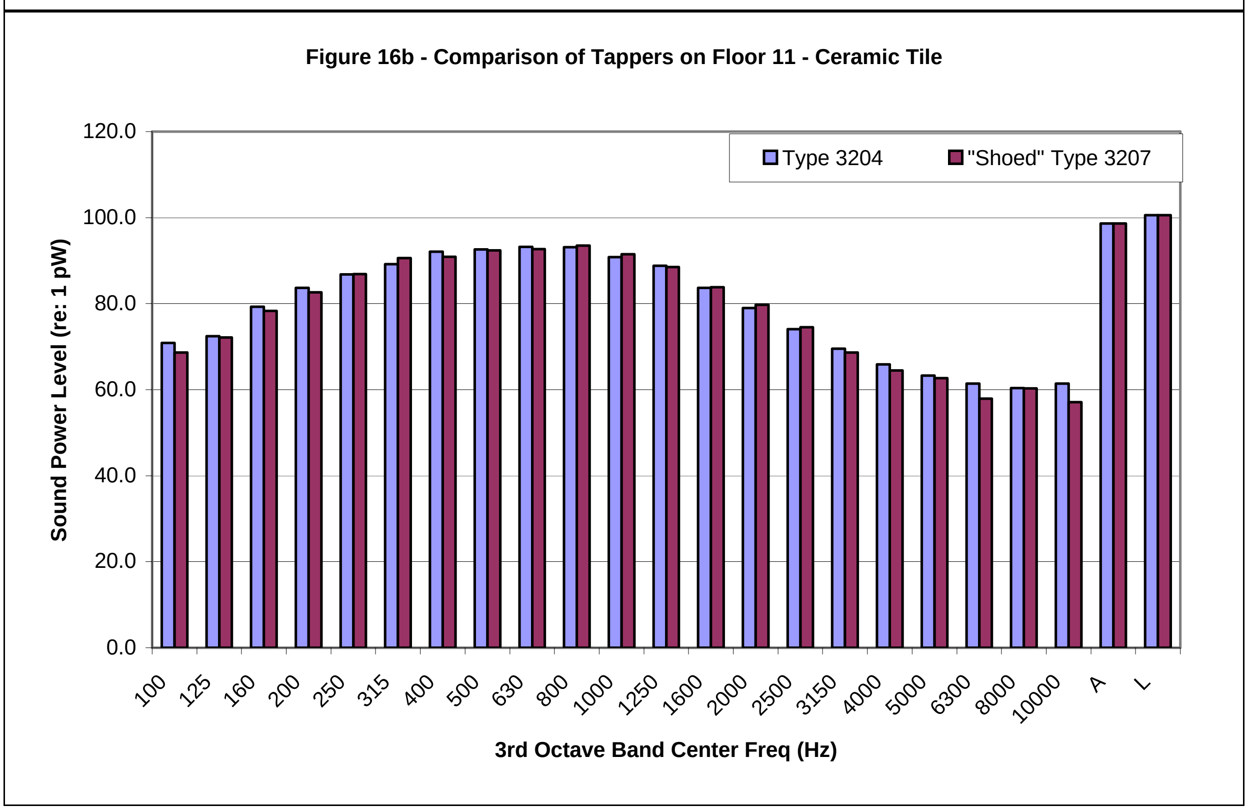


Figure 16b - Comparison of Tappers on Floor 11 - Ceramic Tile
Type 3204
"Shoed" Type 3207
Sound Power Level (re: 1 pW)
3rd Octave Band Center Freq (Hz)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
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*Vibratory Signatures*

For each individual test, the three FFT accelerometer measurements were averaged (labeled as the vibratory signature) and then compared with the concurrent FFT sound power spectra data generated. The sound power spectra and vibratory signature were then plotted on the same graph in an effort to detect overall spectral similarities. The different amplitudes were normalized relative to each other to enable qualitative spectral comparisons. The comparison yielded a consistent observation:  Floor profiles that did not involve the wooden sub-floor exhibited extremely close data trends in the low– to-mid–frequency range (Figure 17), while those that did use the wooden sub-floor did not appear to demonstrate any significant similarities (Figure 18). Additional comparisons are shown in Appendix F.

**Figure 17 – No Wooden Sub-Floor**

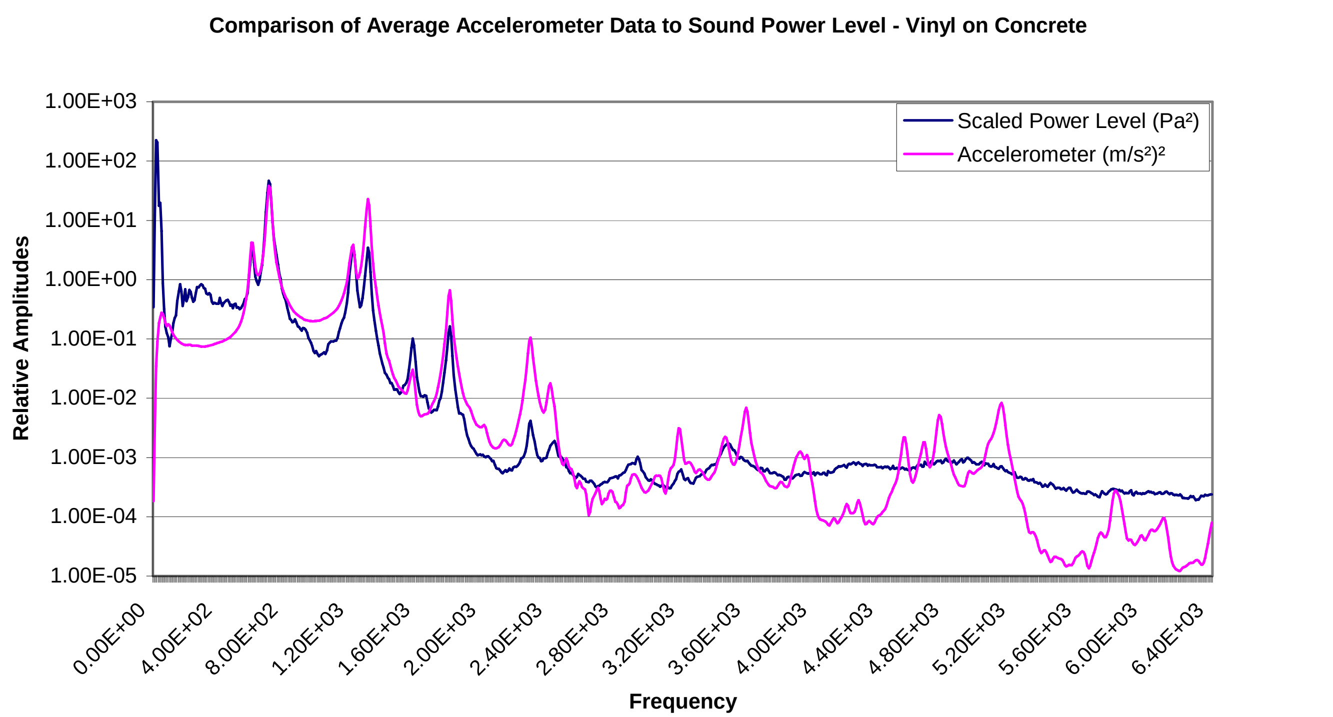
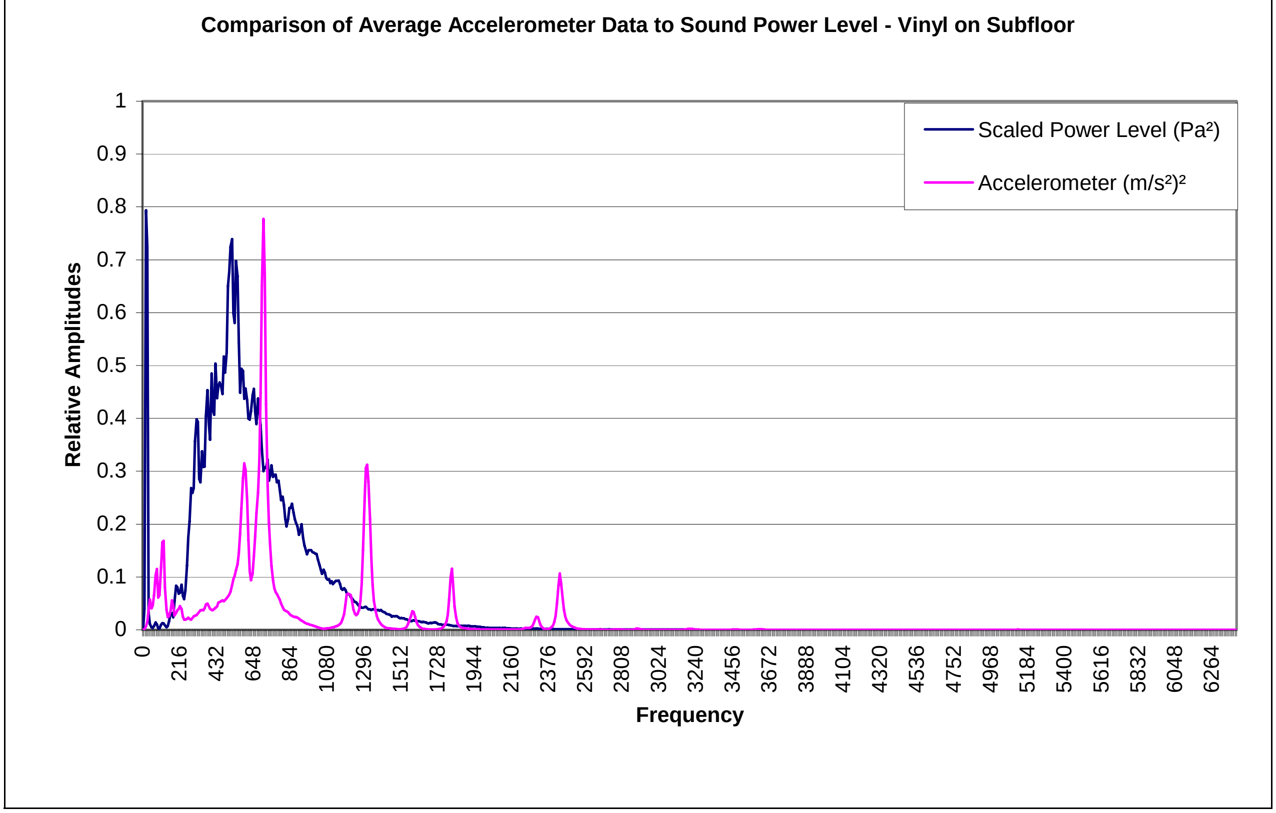


**Figure 18 – With Wooden Sub-Floor**




## Discussion and Conclusions

This study examined both the acoustic and vibratory effect of footfall noise on several different flooring types. Twelve different floor profiles were tested, using men's and women's sneakers, rubber-soled shoes, and leather-soled shoes. During Phase I the following criteria were examined: The characteristics of shoes and floors, the sound power level comparison between similar floors, and the comparability between human walking spectra and the tapping machine spectra both with and without shoes. Phase II reexamined the previous criteria in addition to the repeatability of Phase I procedure, further mining of Phase I data for improved correction curves, the investigation of a new floor profile (Vinyl on Concrete), the addition of a Rubber Footed

Type 3204 Tapping Machine and the comparability between its sound power spectra and that of a shoed tapping machine, and a comparison of a floor's vibratory signature with its corresponding acoustic spectra.

*Repeatability*

The repeatability tests were done to demonstrate a consistent use of the procedure developed in Phase I. Some floor/shoe combinations showed better repeatability than others. Regardless, the data generated in Phase II was acceptably consistent with that received during Phase I testing. Acceptable repeatability was verified by retesting particular floor profiles with returning human participants, and comparing the sound power spectra they generated from year to year. The average difference in any 1/3 octave band or overall level was ±2 dB with the largest difference being 10 dB. These differences in level can be attributed to the variability of a individual person's gait, and aging of the test floors and the shoe samples.

*Correction Curves Generated for Phase I Data*

The correction factors presented in Phase I were rough estimates of the averaged human behavior. In Phase II, the data collected during Phase I were analyzed to determine exact 1/3 octave corrections needed to produce commensurate sound power spectra to that produced by actual human subjects wearing the same shoes. These plots (i.e., Figures 12 and 13a above) were then visually inspected for trends across multiple shoes on the same floor. For some floors, like carpet on concrete (see Figure 12), all the shoes behaved approximately the same and one overall average correction could be used. On other profiles, such as oak flooring, large shoe-to-shoe deviations prevented a single average spectral correction factor from being developed (see Figure

13a). What was determined, however, was that there were similar groupings of shoes that could be averaged to produce several correction curves for a given floor (see figure 13b). Nine new corrections curves were found for different sets of floor and shoe combinations using ten of the eleven profiles from Phase I (refer to Table 4). The bare concrete floor profile yielded very tonal results and thus any shoe behaved significantly different from the others. Two more correction curves were found using the data collected in Phase II for the new vinyl–on–concrete floor profile.

The correction curves calculated in the current study offer a much more accurate representation of tapping machine data as human-generated data compared to the initial attempts in Phase I. These curves, used in conjunction with the assumption that the Type 3204 (rubber-footed) tapping machine tends to replicate the results of a women's leather shoe.

*Vinyl on Concrete Sound Power*

The new floor profile for Phase II was a Vinyl floor applied directly to the concrete. This is a very common floor installation found in commercial applications and as a result its footfall sound power levels should provide useful acoustic data. Footfall noise for vinyl on concrete (Profile #12) compared to bare concrete (Profile #1) reveals very similar sound power spectral levels. It was found that installation of a vinyl surface typically increased the radiated sound power for nearly all shoe types. The only shoe that produced less footfall sound power on a vinyl surface was the women's leather shoe. One possible reason for this increase in sound power is that the vinyl surface acts to prevent the concrete base from dissipating energy and hence the amount of airborne energy generated is increased.

*Shoed Tapping Machine to Rubber Tapping Machine Correction Factors*

Investigation into the application of correction factors for the rubber tapping machine's ability to emulate a shoed tapping machine revealed that such a set of correction factors could not be produced. The differences in sound power spectra generated by the rubber tapping machine and a specific shoed tapping machine varied greatly from floor to floor. The only shoe that displayed any consistency with the rubber tapping machine was the women's leather. This relationship is further discussed in the following section.

*Rubber Tapping Machine's Relationship with Women's Leather Shoe*

The initial analysis and visual inspection of the data generated by the rubber tapping machine revealed strong similarities to that generated by the women's leather shoe; this resulted in a deeper investigation of these similarities. It was found that minute corrections (roughly 3–5 dB per 1/3 octave band) were required to make the rubber tapping machine replicate the results found for the cored women's leather shoe (on the Type 3207 Tapping Machine).

It can be concluded that tests performed with the rubber tapping machine were equivalent to the tests performed using the Type 3207 with women's leather shoes for most floors[1]. Such a relationship allows the utilization of a Type 3204 Tapping Machine to collect data and then use the corrections presented herein for comparative analysis.

*Vibratory Signatures*

Three accelerometers were utilized in the current study to acquire the vibratory signatures that correspond to the acoustic spectra quantified. After analyzing these vibratory signatures with

[1] The floor profiles which did not produce results similar to the women's leather shoe were the thin vinyl, both of the commercially available carpet setups, and the wool carpet with rubber pad underneath, all on the wood sub–floor.

their acoustic sound power level counterparts, it was found that the sound power from any profile that was based on concrete slab could be scaled to show common trends with the vibratory spectra. This relationship was most strongly displayed in the low– to mid–frequency range and tended to diverge at relatively higher frequencies. Floors utilizing the wood sub–floor did not possess these similarities as the accelerometers were placed solely on the concrete slab.

The vibratory signatures that did display some similarities to their corresponding sound power spectra were those attached directly onto the concrete–based floor profiles. This finding is most likely due to the fact that the accelerometers were attached to the concrete base and not onto each of the individual wooden sub-floors. By contrast, the floor profiles involving the wooden sub-floor had poor correlation between the vibratory and airborne signals.

The floor profiles displaying a relationship between the vibratory signature and the sound power spectra generated did so in the low– to mid–frequency range. The higher frequencies continued to demonstrate significant peaks in the vibratory signature while they were more broadband in the sound power spectra. The energy possessed by the higher frequency waves was most likely dissipated within the wooden sub–floors, resulting in less radiation of high frequency acoustical energy.

*Conclusion*

In summary, a core set of human footfall data (vibratory and sound power) has been quantified for a variety of floor and shoe types. Correction curves that model human footfall data using shoed tapping machines were established. These sound power spectra can be used to generate reverberant sound pressure level spectra for various applications. During Phases I and II a total of 12 floors and three types of shoes were investigated, chosen to offer a cross-section of typical applications. Future studies could include a further expansion of the floor construction database used for this study using other floor materials that were not covered. Also, placing the accelerometers on the wood sub–floor in addition to the concrete base could reveal additional relationships between the vibratory and acoustic spectra generated.

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Brion Koning – Cavanaugh Tocci Associates, Inc.

Ray Miller – University of Hartford

Dean Louis Manzione – University of Hartford

Professor Michelle Vigeant – University of Hartford

Professor Robert Celmer – University of Hartford

Our Test Subjects

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# Appendix A:

# Shoe Descriptions

## Appendix A: Shoe Descriptions

**Men's Leather Sole**

**• Mercanti Fiorentini**

**• Size 13**

**• Heel: 3 1/8" x 3 1/4"**

**Nominal 1" thick**

**Men's Rubber Sole**

**• Nunn Bush**

**• Size 13**

**• Heel: 3 ¼" x 4"**

**1" thick**

**Men's Sneaker**

**• Reebok Classic**

**• Size 13**

Women's Leather Sole

• Ditto by Vanelli

• Size 9.5

• Heel: 2" x 2 3/4"

7/8" thick

Women's Rubber Sole

• White Mountain

• Size 8.5

• Heel: 2 1/2" x 2 3/8"

Nominal 1 3/4" thick

Women's Sneaker

• Reebok Classic Princess

• Size 9 Wide

# Appendix B:

# Human Subjects Committee Approval Letter

UNIVERSITY OF HARTFORD

Human Subjects Committee

February 1, 2008

Robert Celmer
Department of Mechanical Engineering
University of Hartford
West Hartford, CTR 06117

Dear Professor Celmer:

Upon review by the Human Subjects Committee, your proposal, *Footfall noise characterization: Phase 2*, has been approved for one year according to exempt review guidelines established by federal regulation 45 CFR 46.110(b). Keep in mind that it is your responsibility to notify and seek approval from this Committee of any modifications to your project, and that it is your responsibility to report to this Committee, any adverse events that occur related to this evaluation.

This institution has an Assurance of Compliance on file with the Office of Human Research Protections (Federalwide Assurance FWA00003578).

Congratulations and good luck.

Sincerely,

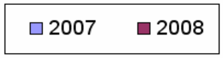
Monica J. Hardesty

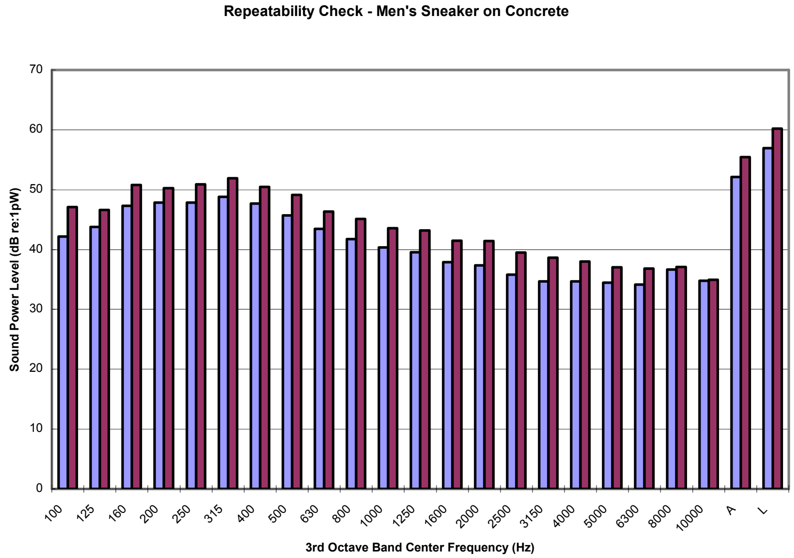
Monica J. Hardesty, PhD
Chair, Human Subjects Committee

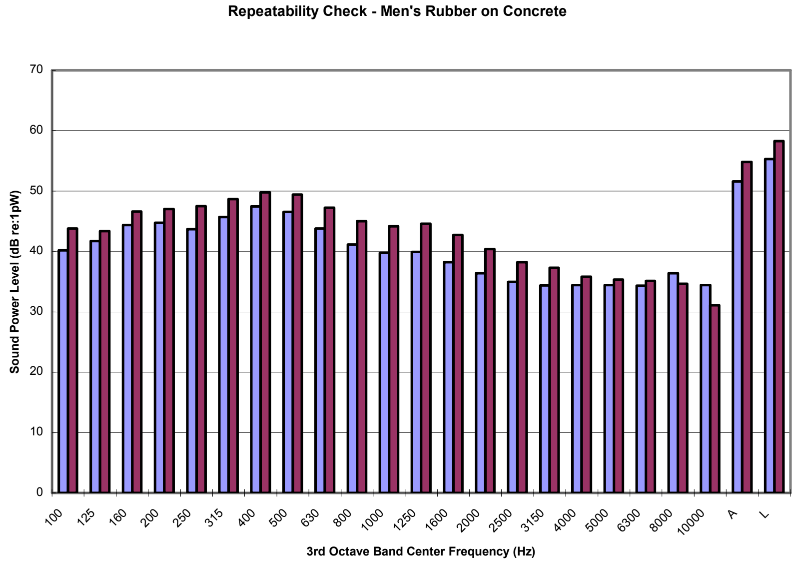
# Appendix C:

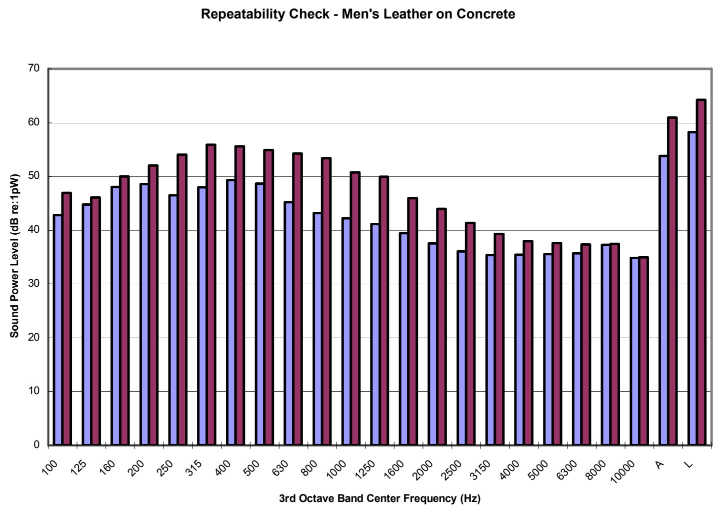
# Repeatability Study

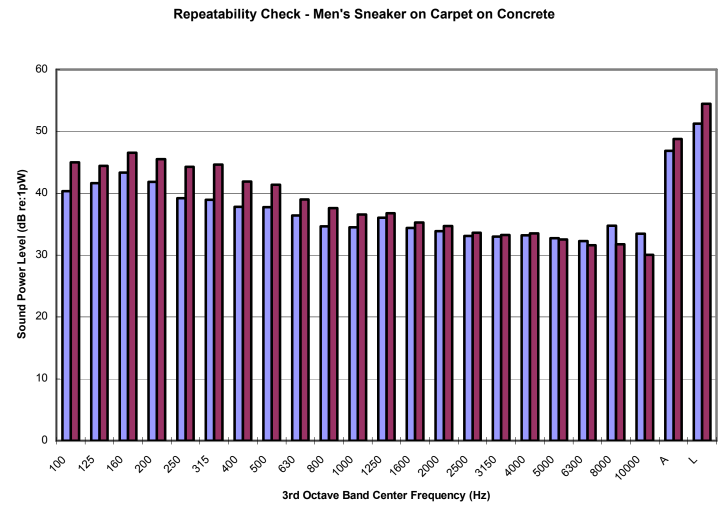
# Appendix C: Repeatability Study

Legend for all Repeatability Figures: 


Repeatability Check - Men's Leather on Concrete
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)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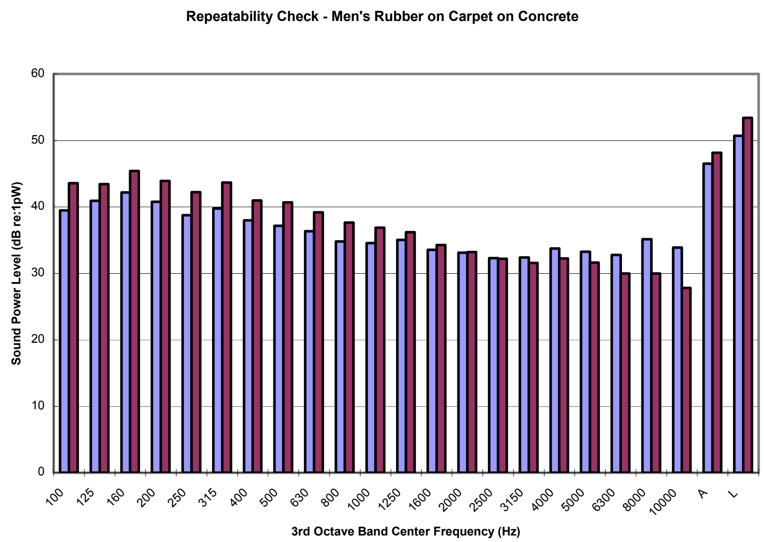
3rd Octave Band Center Frequency (Hz)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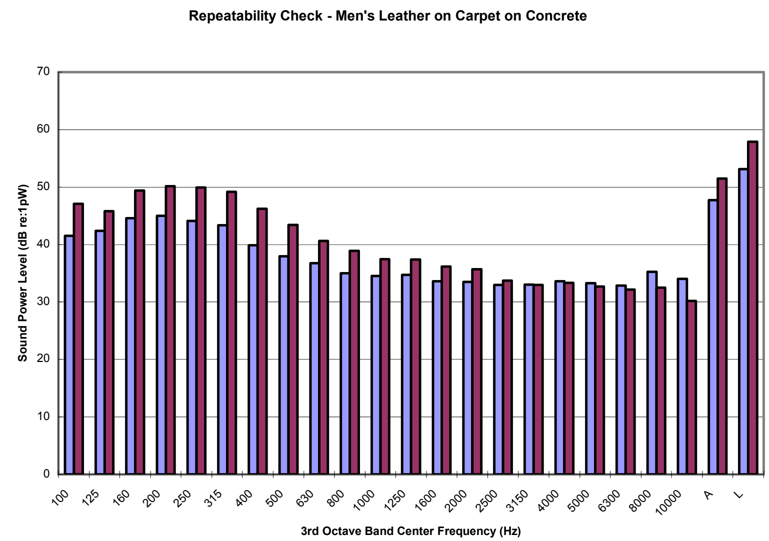
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)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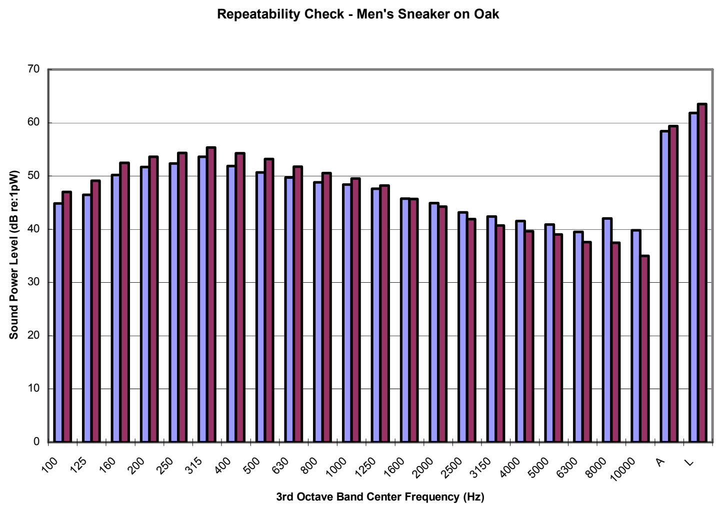
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)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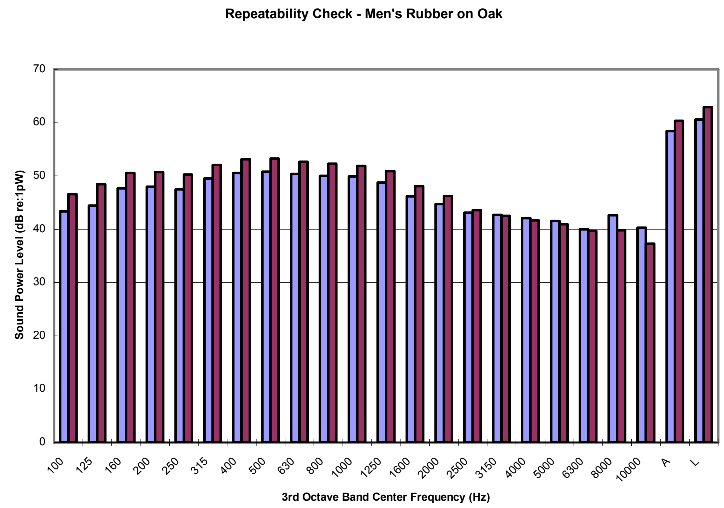
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)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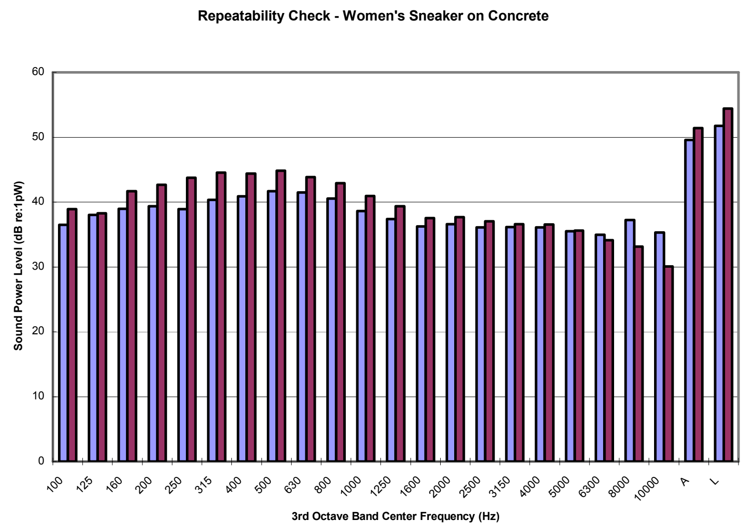
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)


Repeatability Check - Men's Leather on Oak
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)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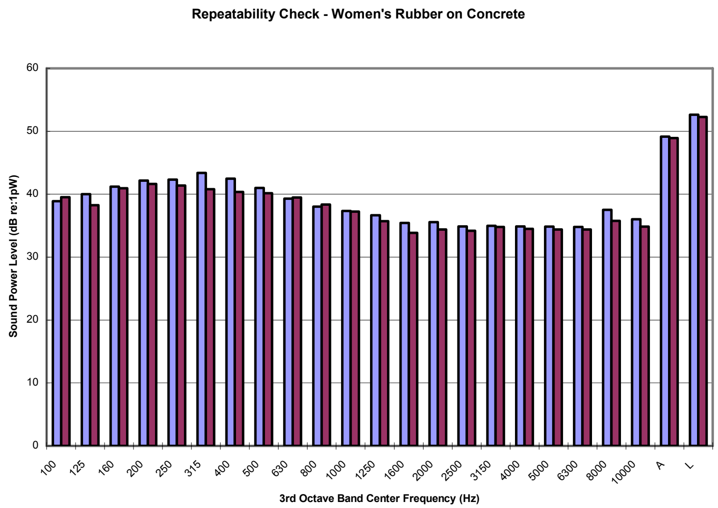
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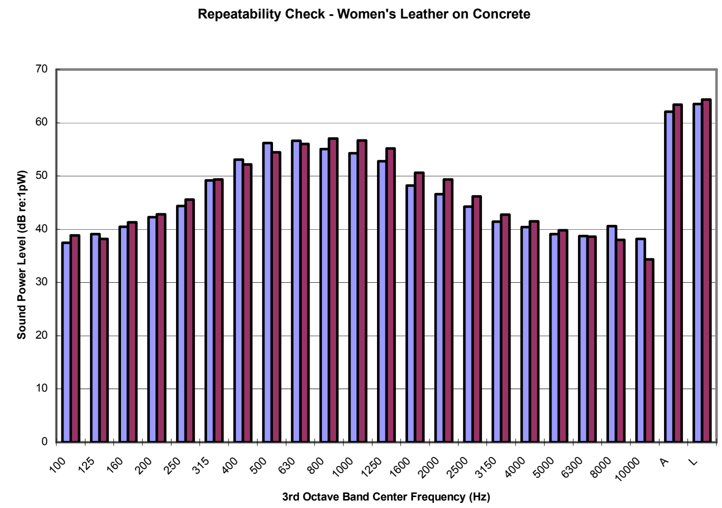
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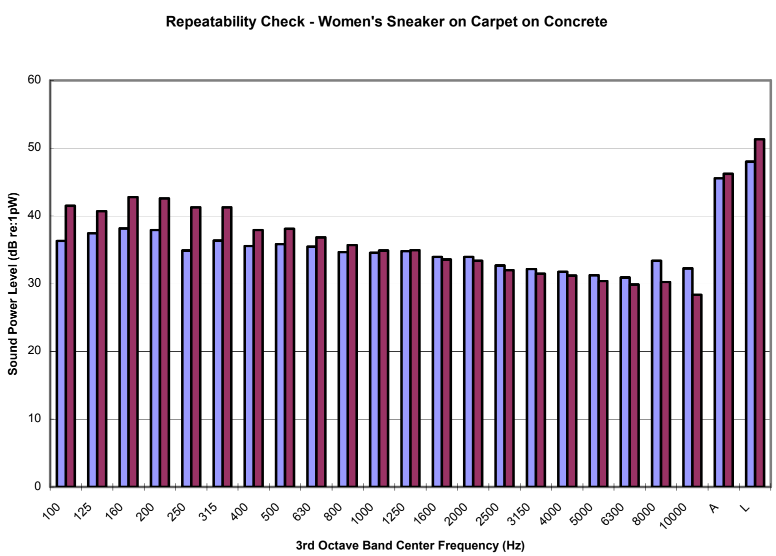
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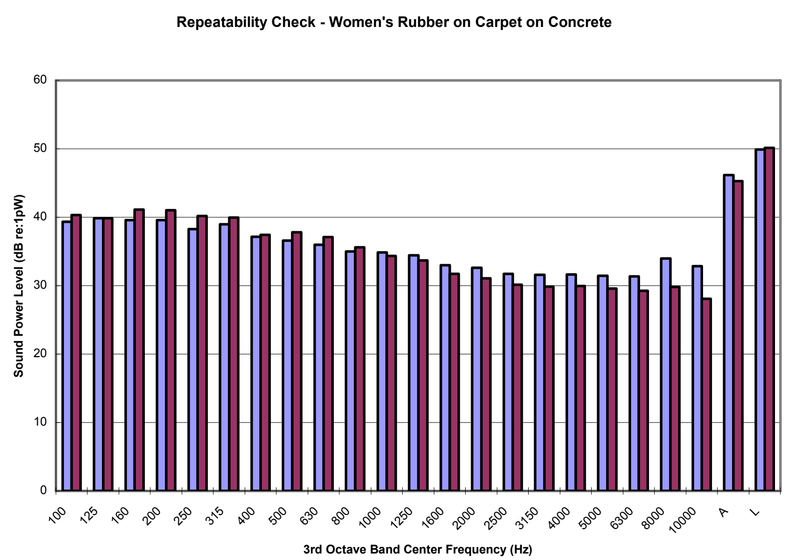
Repeatability Check - Women's Rubber on Carpet on Concrete
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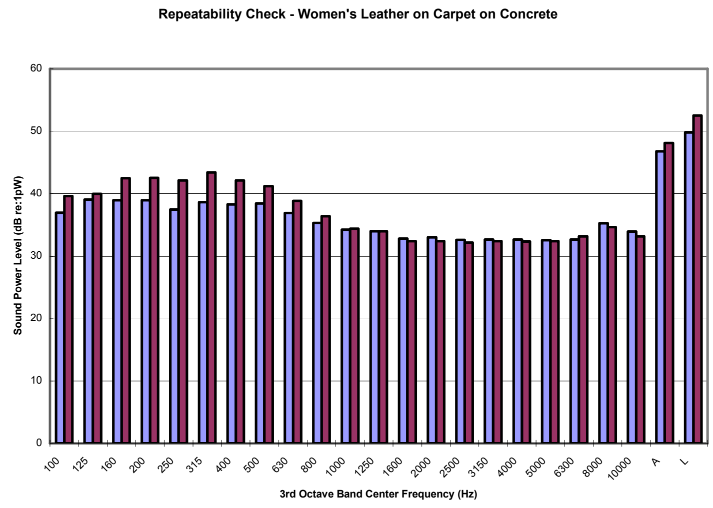
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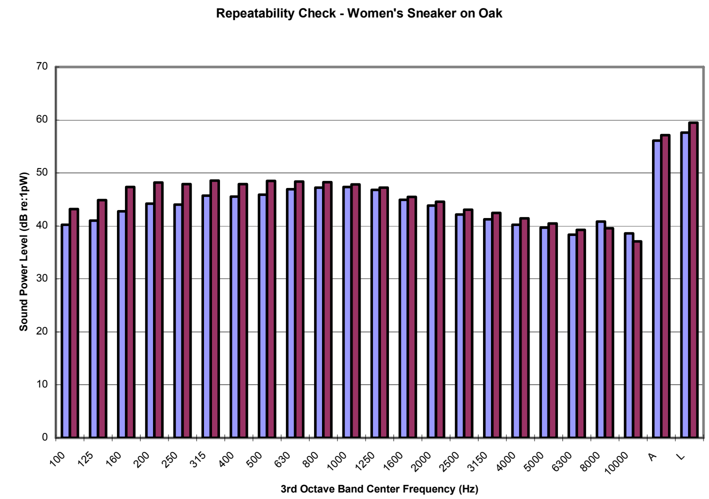
Repeatability Check - Women's Sneaker on Oak
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)
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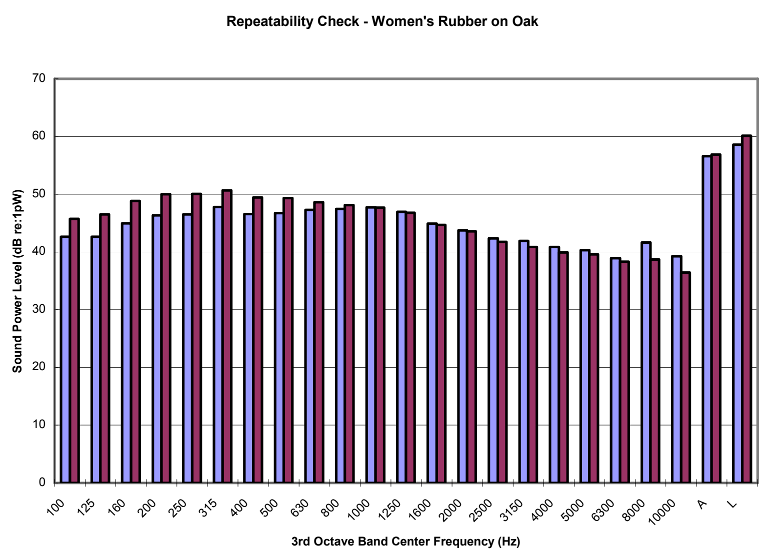
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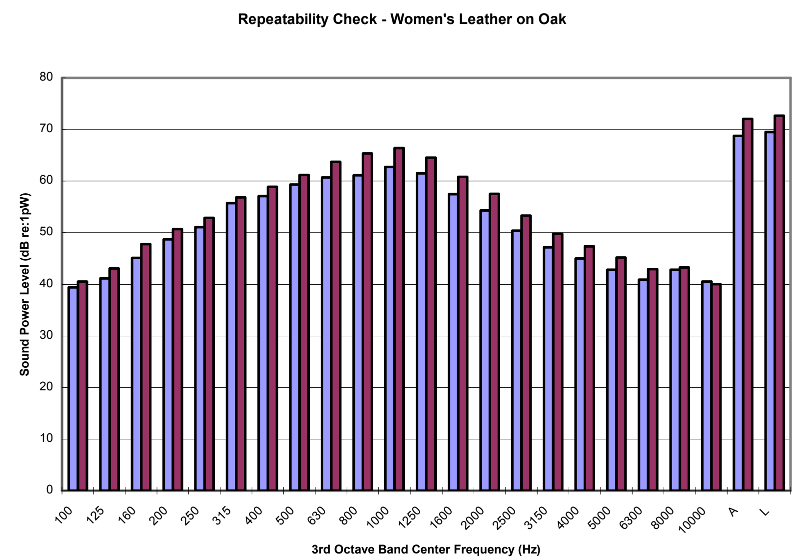
Repeatability Check - Women's Leather on Oak
Sound Power Level (dB re:1pW)
3rd Octave Band Center Frequency (Hz)
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# Difference in Tapper Data from 2007 to 2008

**University of Hartford Acoustics Laboratory**
Spring 2008 Footfall Noise Characterization
Sponsor: Paul S. Veneklasen Research Foundation

## Sound Power Levels of Tapper Sounds (dB, re: 1 picoWatt)

| Floor Profile | Floor Profile | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) Concrete | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
| | Men's Sneaker | 0.28 | 0.81 | 3.36 | 0.01 | -0.06 | -1.50 | 0.30 | -0.68 | 0.02 | -0.95 | 0.10 | 0.46 | 0.13 | -0.40 | 0.27 | 1.26 | 1.24 | 4.31 | 2.16 | 0.93 | 2.18 | 0.42 | 1.57 |
| | Men's Rubber | 0.19 | 0.12 | -0.46 | -6.80 | -2.19 | -0.22 | -2.00 | -3.58 | 2.68 | 0.51 | -0.58 | 2.36 | 1.54 | 0.70 | 0.14 | -0.98 | -1.75 | -1.00 | -1.60 | -0.28 | -0.08 | -2.02 | -2.55 |
| | Men's Leather | 1.18 | 0.06 | 0.42 | -0.01 | 1.30 | 2.06 | 0.64 | 1.16 | -1.58 | -0.55 | 1.17 | -0.12 | 0.56 | 5.52 | 1.19 | -1.49 | -2.60 | -1.99 | -0.06 | -0.22 | -0.23 | -0.81 | -0.66 |
| | Women's Sneaker | 8.97 | 7.69 | 6.74 | 2.73 | 6.24 | 10.86 | 10.74 | 7.47 | 10.49 | 7.32 | 4.41 | 6.52 | 3.38 | 4.11 | 4.84 | 7.59 | 5.26 | 4.54 | 3.51 | 3.45 | 3.64 | 6.59 | 6.53 |
| | Women's Rubber | 0.54 | 1.83 | 3.28 | 0.46 | -1.60 | -2.68 | -0.51 | -1.51 | 0.12 | -0.63 | -0.79 | 0.62 | 2.28 | 1.37 | -0.16 | -3.11 | -2.93 | -6.44 | -8.65 | -7.00 | -5.20 | -0.01 | 1.39 |
| | Women's Leather | 3.50 | -0.55 | 0.66 | -1.15 | 0.17 | 1.31 | 0.93 | 1.75 | 0.53 | 0.96 | 2.82 | 2.63 | 1.90 | 6.35 | 4.65 | 3.72 | 3.44 | 6.93 | 4.87 | 1.79 | 3.97 | 1.54 | 1.28 |
| | Rubber Tapper | 2.12 | -2.55 | -6.59 | -8.36 | -0.03 | -0.44 | 17.45 | 3.30 | -4.42 | -2.44 | -5.62 | -10.35 | -10.78 | -13.12 | -21.69 | -24.88 | -22.11 | -22.01 | -20.23 | -17.39 | -7.32 | -8.20 | -5.57 |
| (2) Sub-floor | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
| | Men's Sneaker | 3.01 | 2.52 | 1.24 | -0.47 | 0.90 | 2.74 | 3.10 | 2.54 | 4.44 | 4.57 | 6.12 | 7.77 | 6.30 | 4.91 | 2.00 | -1.14 | -2.52 | -1.52 | -2.15 | -3.12 | -2.71 | 3.39 | 2.30 |
| | Men's Rubber | 2.48 | 0.89 | -0.19 | 1.62 | 1.61 | 2.50 | 1.71 | 2.77 | 5.76 | 6.42 | 4.43 | 7.08 | 9.03 | 10.36 | 8.43 | 3.34 | -0.87 | -7.67 | -11.80 | -13.15 | -17.50 | 3.71 | 2.31 |
| | Men's Leather | -1.41 | 1.78 | 0.57 | 1.34 | -0.43 | 1.85 | 1.39 | 0.42 | 3.52 | 2.68 | 1.76 | 1.92 | 0.19 | 0.72 | -0.76 | -0.32 | 2.47 | 5.58 | 4.64 | 1.87 | 0.85 | 1.75 | 1.47 |
| | Women's Sneaker | 1.56 | 3.29 | 4.94 | 0.41 | 1.50 | 1.25 | 1.65 | 0.92 | 1.62 | 0.91 | 3.00 | 5.20 | 4.26 | 3.11 | 1.09 | -0.74 | -1.25 | -4.79 | -5.57 | -4.32 | -4.85 | 1.66 | 2.31 |
| | Women's Rubber | -0.07 | 0.21 | 1.00 | 0.51 | -0.76 | 1.95 | 1.51 | 1.48 | 2.66 | 4.81 | 4.22 | 5.31 | 6.44 | 5.47 | 1.91 | 0.59 | -0.74 | -2.43 | -1.53 | 0.16 | 1.67 | 2.28 | 0.99 |
| | Women's Leather | -1.44 | -5.03 | -1.49 | 0.78 | 0.28 | 1.49 | -0.05 | 0.15 | 2.25 | 2.16 | 1.37 | 1.40 | -1.20 | -4.31 | -6.27 | -6.92 | -4.45 | -6.97 | -8.65 | -6.24 | -4.58 | 1.22 | 1.05 |
| | Rubber Tapper | 0.69 | 3.53 | 4.13 | 4.32 | 2.76 | -1.16 | -1.31 | -0.70 | -0.17 | -1.07 | -2.40 | -3.68 | -5.76 | -8.05 | -10.38 | -11.80 | -10.56 | -10.44 | -8.00 | -5.13 | 0.41 | -2.03 | -1.36 |
| (3) Carpet/Concrete | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
| | Men's Sneaker | 2.62 | 3.11 | 4.94 | -1.41 | -0.44 | -2.06 | -1.96 | -3.42 | -3.59 | -0.58 | -1.43 | 2.63 | 0.62 | 2.86 | 1.11 | 5.72 | 4.92 | 1.51 | -1.72 | 0.26 | 1.56 | -0.08 | 2.20 |
| | Men's Rubber | 4.27 | 4.66 | 4.06 | -2.25 | -0.61 | -2.52 | -2.63 | -3.09 | -1.35 | -1.47 | -1.11 | -0.17 | 0.03 | -0.19 | -1.61 | -1.36 | -1.57 | -0.78 | -1.88 | -1.40 | 0.83 | -0.63 | 1.70 |
| | Men's Leather | -0.64 | -0.71 | 1.20 | -3.00 | -0.53 | -0.03 | 0.40 | -0.97 | -0.55 | -1.29 | -1.84 | 0.43 | 0.46 | 1.12 | -0.07 | 0.48 | -0.52 | 0.64 | -1.06 | -1.90 | -2.11 | -0.74 | -0.41 |
| | Women's Sneaker | 3.68 | 4.26 | 4.07 | -0.47 | -0.62 | -1.72 | -1.84 | -3.81 | -0.88 | 3.56 | 4.51 | 5.70 | 3.31 | 4.86 | 3.34 | 5.61 | 3.53 | -0.93 | -6.04 | -7.28 | -6.35 | 1.84 | 2.30 |
| | Women's Rubber | -0.64 | 2.74 | 2.70 | -3.59 | 0.50 | 3.41 | 5.49 | 2.70 | 5.48 | 4.35 | 2.45 | 8.83 | 6.87 | 9.41 | 8.67 | 10.57 | 8.09 | 9.56 | 9.77 | 8.08 | 8.36 | 3.08 | 1.51 |
| | Women's Leather | 0.02 | -4.16 | -5.85 | -3.79 | -0.76 | -0.56 | -2.93 | -6.55 | -1.82 | -2.67 | -3.80 | -0.79 | -1.06 | 0.21 | -1.24 | -2.42 | -3.57 | -3.28 | -9.21 | -9.96 | -8.66 | -2.90 | -3.36 |
| | Rubber Tapper | 1.28 | -6.17 | -8.30 | -6.12 | -0.46 | 4.04 | 23.57 | 11.65 | -1.82 | 8.90 | 9.11 | 22.64 | 22.65 | 26.89 | 24.84 | 22.86 | 25.78 | 24.84 | 27.96 | 27.35 | 31.57 | 12.22 | 10.31 |
| (4) Carpet/Sub-floor | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
| | Men's Sneaker | 5.99 | 4.32 | 3.09 | 1.08 | 0.66 | 4.52 | 7.86 | 6.99 | 7.51 | 5.52 | 3.47 | 1.83 | 4.15 | 4.18 | 2.66 | 1.92 | 1.93 | 2.46 | 2.18 | 1.31 | 1.56 | 5.27 | 4.04 |
| | Men's Rubber | 0.81 | 2.70 | 0.34 | 1.34 | 2.14 | 4.39 | 4.11 | 4.58 | 3.43 | 3.62 | 1.60 | 0.48 | 3.83 | 4.21 | 2.74 | 1.84 | 1.51 | 1.92 | 1.35 | 2.38 | 3.79 | 3.25 | 2.39 |
| | Men's Leather | 2.93 | 4.74 | 0.80 | 2.88 | 2.19 | 1.38 | 2.97 | 1.98 | -1.70 | -4.89 | -4.73 | -4.29 | -0.31 | 2.65 | 2.11 | 3.25 | 1.37 | 0.17 | -2.99 | -3.16 | -2.53 | 1.58 | 2.18 |
| | Women's Sneaker | 6.36 | 7.10 | 5.16 | 0.38 | 0.23 | 3.53 | 6.84 | 5.75 | 8.00 | 7.05 | 4.44 | 4.89 | 4.63 | 3.80 | 2.16 | 1.18 | 1.79 | 1.36 | -0.65 | -0.56 | 1.08 | 5.10 | 4.78 |
| | Women's Rubber | -0.60 | 0.10 | 1.58 | 1.66 | 3.23 | 4.49 | 5.88 | 3.99 | 3.57 | 1.98 | 0.15 | 1.86 | 4.56 | 5.06 | 3.98 | 3.42 | 3.56 | 3.20 | 1.97 | 2.83 | 5.18 | 3.23 | 2.10 |
| | Women's Leather | 3.81 | 0.26 | -0.44 | -1.26 | -1.88 | -1.69 | -2.07 | -4.33 | -8.24 | -11.23 | -11.66 | -12.92 | -10.44 | -6.79 | -4.15 | -3.62 | -4.72 | -3.78 | -7.56 | -7.49 | -5.56 | -3.66 | -1.80 |
| | Rubber Tapper | 6.93 | 0.61 | -0.06 | -0.33 | -0.24 | -4.87 | 5.20 | -4.45 | -7.62 | -0.26 | -0.47 | 5.64 | 9.01 | 16.69 | 19.62 | 20.38 | 22.77 | 21.80 | 26.11 | 25.39 | 30.59 | 0.25 | 0.41 |
| (5) Wool | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
| | Men's Sneaker | 3.30 | 4.58 | 7.30 | 0.34 | 0.07 | 1.09 | 2.61 | 2.34 | 1.37 | 1.88 | 1.35 | 1.35 | 0.63 | 0.97 | 1.91 | 2.88 | 2.72 | 4.37 | 4.72 | 4.75 | 1.19 | 1.87 | 3.89 |
| | Men's Rubber | 8.94 | 4.40 | 2.38 | 0.99 | 3.19 | 1.14 | 2.99 | 3.39 | 0.97 | 0.29 | 0.29 | 0.96 | 1.59 | 2.69 | 4.38 | 3.71 | 0.92 | -2.32 | -6.44 | -7.83 | -7.79 | 1.70 | 2.73 |
| | Men's Leather | 4.68 | 6.26 | 2.33 | 3.87 | 6.02 | 2.98 | 6.27 | 8.38 | 5.60 | 3.57 | 5.48 | 5.40 | 5.50 | 4.36 | 2.93 | 2.42 | 1.00 | 1.02 | 1.52 | -0.52 | -2.41 | 5.55 | 5.06 |
| | Women's Sneaker | 4.28 | 0.90 | 3.84 | -1.25 | -0.72 | -3.12 | -4.11 | -2.21 | -3.36 | -2.85 | -0.87 | 0.21 | 0.70 | 3.19 | 4.51 | 6.44 | 8.03 | 7.92 | 8.23 | 5.51 | 1.97 | -0.49 | 0.81 |
| | Women's Rubber | 5.74 | 3.07 | 5.21 | -2.84 | -0.16 | -2.37 | -3.83 | -1.38 | -2.18 | -2.20 | -1.13 | -0.11 | -1.23 | 0.16 | 2.31 | 2.69 | 4.66 | 5.17 | 6.37 | 6.54 | 5.26 | -0.90 | 1.36 |
| | Women's Leather | 8.22 | 4.72 | 4.64 | 3.07 | 4.81 | 2.60 | 5.52 | 5.51 | 3.75 | 3.68 | 2.76 | 3.26 | 3.96 | 4.77 | 6.04 | 6.73 | 7.03 | 8.10 | 7.52 | 7.91 | 14.65 | 4.20 | 4.33 |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rubber Tapper | -1.02 | 4.35 | 2.74 | 3.08 | 3.28 | -3.98 | 4.62 | -5.70 | -8.23 | -2.21 | -4.14 | 1.95 | 1.68 | 4.12 | 5.04 | 1.70 | 3.02 | 2.81 | 4.39 | 9.32 | 20.57 | -0.97 | 0.12 |
| **(6) Wool/Pad** | **Center Freq. (Hz):** | **100** | **125** | **160** | **200** | **250** | **315** | **400** | **500** | **630** | **800** | **1000** | **1250** | **1600** | **2000** | **2500** | **3150** | **4000** | **5000** | **6300** | **8000** | **10000** | **A** | **L** |
| | Men's Sneaker | 2.47 | 3.04 | 7.19 | 1.27 | -1.13 | -2.43 | -1.87 | -1.89 | -6.80 | -4.60 | -0.66 | 0.53 | -0.91 | -0.82 | -0.99 | -0.88 | -1.18 | -2.07 | -7.46 | -7.79 | -3.77 | -0.27 | 3.65 |
| | Men's Rubber | 6.05 | 2.74 | 3.66 | -1.13 | -2.70 | -2.18 | -0.20 | -1.42 | -8.23 | -6.38 | -0.84 | 0.11 | -1.17 | 1.33 | 1.87 | 7.58 | 6.74 | 7.00 | 13.08 | 16.96 | 20.22 | -1.53 | 1.35 |
| | Men's Leather | -1.38 | -0.89 | 0.77 | -2.95 | -3.44 | -2.47 | -1.91 | -3.36 | -5.45 | -4.77 | -2.14 | -0.21 | -0.33 | -1.40 | -1.14 | -1.78 | -2.33 | -0.35 | -0.22 | -0.45 | 0.74 | -2.37 | -1.03 |
| | Women's Sneaker | 1.86 | 3.56 | 5.47 | -0.10 | -2.86 | -1.12 | 0.21 | 0.91 | -4.61 | 0.10 | 2.88 | 1.63 | 0.79 | 0.68 | -0.41 | -1.16 | -0.93 | -1.97 | -7.51 | -8.47 | -7.62 | 1.18 | 3.10 |
| | Women's Rubber | 9.11 | 6.49 | 11.00 | 7.35 | 10.57 | 10.67 | 16.28 | 17.25 | 14.24 | 20.66 | 24.78 | 28.48 | 26.09 | 27.46 | 26.14 | 25.22 | 24.80 | 23.25 | 21.26 | 19.44 | 19.30 | 19.73 | 14.41 |
| | Women's Leather | 2.44 | -8.61 | -7.57 | -7.35 | -5.71 | -4.41 | -4.96 | -7.14 | -8.14 | -5.81 | -3.19 | -2.28 | -2.38 | -1.34 | -2.34 | -2.28 | -4.60 | -2.90 | -2.35 | 0.52 | 6.69 | -5.70 | -6.25 |
| | Rubber Tapper | 1.70 | -7.08 | -5.64 | -7.83 | 0.43 | 10.28 | 31.96 | 12.73 | 8.07 | 16.03 | 10.67 | 23.36 | 22.05 | 26.97 | 26.86 | 23.88 | 26.77 | 25.01 | 31.12 | 32.26 | 39.85 | 20.49 | 17.54 |
| **(7) Thin Vinyl** | **Center Freq. (Hz):** | **100** | **125** | **160** | **200** | **250** | **315** | **400** | **500** | **630** | **800** | **1000** | **1250** | **1600** | **2000** | **2500** | **3150** | **4000** | **5000** | **6300** | **8000** | **10000** | **A** | **L** |
| | Men's Sneaker | -3.23 | -0.65 | 2.28 | 2.76 | 2.29 | 3.99 | 4.21 | 2.83 | 3.68 | 5.25 | 3.17 | 0.70 | 1.84 | -1.02 | -1.97 | -0.14 | 2.13 | 3.59 | 2.66 | 2.01 | 0.20 | 3.43 | 2.85 |
| | Men's Rubber | -0.32 | 0.09 | 1.30 | -2.38 | -3.48 | -1.89 | -1.74 | -1.56 | 0.80 | 2.58 | 1.57 | 0.10 | 0.93 | 0.17 | -1.35 | -2.37 | -0.51 | 1.43 | -1.80 | -1.15 | 0.13 | -0.36 | -1.03 |
| | Men's Leather | -4.01 | -3.16 | 0.90 | 1.05 | -1.26 | 0.63 | 1.47 | 0.88 | 3.19 | 4.97 | 5.23 | 7.67 | 8.38 | 8.86 | 8.11 | 2.88 | 2.32 | 2.22 | 4.17 | 1.89 | -0.26 | 2.69 | 1.84 |
| | Women's Sneaker | 0.64 | 3.58 | 4.70 | 1.10 | 0.77 | -0.63 | -0.19 | 0.39 | 1.09 | 1.29 | 1.36 | -0.12 | -0.42 | -1.55 | 0.82 | 2.62 | 4.63 | 4.30 | 2.68 | 3.54 | 11.19 | 0.79 | 1.39 |
| | Women's Rubber | -0.79 | -0.33 | 3.72 | 5.08 | 8.00 | 9.83 | 8.10 | 4.40 | 1.87 | 3.37 | 3.59 | 1.39 | 1.08 | -1.28 | -3.45 | -3.98 | -3.70 | -4.62 | -4.49 | -5.38 | -4.05 | 4.53 | 5.18 |
| | Women's Leather | -1.76 | -5.01 | 1.31 | -0.66 | -0.94 | 0.88 | 0.62 | -0.35 | 1.06 | 1.99 | 1.93 | 2.47 | 2.45 | 2.10 | 2.62 | 3.95 | 3.06 | 3.56 | 1.53 | -0.36 | -0.29 | 1.09 | 0.77 |
| | Rubber Tapper | 3.81 | -0.62 | 1.12 | 2.81 | 0.59 | -3.06 | 0.12 | -2.88 | -1.47 | -1.45 | -2.68 | -4.06 | -4.47 | -6.32 | -7.91 | -8.81 | -8.36 | -7.88 | -6.61 | -5.48 | -1.09 | -2.43 | -2.10 |
| **(8) Medium Vinyl** | **Center Freq. (Hz):** | **100** | **125** | **160** | **200** | **250** | **315** | **400** | **500** | **630** | **800** | **1000** | **1250** | **1600** | **2000** | **2500** | **3150** | **4000** | **5000** | **6300** | **8000** | **10000** | **A** | **L** |
| | Men's Sneaker | -3.74 | -3.38 | 1.81 | 0.63 | -0.62 | -0.96 | -0.49 | -0.01 | -0.64 | -4.10 | -6.88 | -8.78 | -8.84 | -9.86 | -10.21 | -6.69 | -2.71 | -2.45 | -4.21 | -3.73 | -3.84 | -3.09 | -1.47 |
| | Men's Rubber | -2.42 | -3.94 | -0.32 | -0.64 | -4.15 | -3.71 | -2.27 | -0.71 | -4.33 | -5.04 | -6.36 | -7.84 | -8.20 | -9.26 | -9.65 | -8.26 | -4.58 | -5.25 | -4.82 | -5.95 | -4.18 | -3.65 | -2.74 |
| | Men's Leather | -2.80 | -2.91 | 0.86 | 0.48 | 0.43 | 1.40 | 0.49 | 2.46 | 2.25 | 2.28 | 2.59 | 1.13 | 1.28 | 1.11 | -0.18 | 0.86 | 1.45 | 0.51 | 1.58 | 4.74 | 3.34 | 1.89 | 1.57 |
| | Women's Sneaker | -2.70 | -0.48 | 3.21 | 1.49 | -0.37 | 0.74 | -0.80 | 1.56 | 2.06 | 0.76 | 2.42 | 0.68 | -0.13 | 1.02 | 2.11 | 4.03 | 3.25 | -0.69 | 2.06 | 2.29 | 0.17 | 1.19 | 0.96 |
| | Women's Rubber | -1.21 | -0.61 | 3.52 | 3.11 | 8.07 | 11.33 | 8.86 | 5.71 | 3.60 | 3.19 | 1.22 | 0.38 | 1.35 | 1.82 | 0.91 | 1.84 | -0.04 | 0.28 | 3.29 | 5.36 | 5.81 | 5.13 | 5.33 |
| | Women's Leather | -2.22 | -3.19 | -0.72 | 0.65 | -1.30 | -0.56 | 0.41 | 2.94 | 1.72 | 1.58 | 2.80 | 3.35 | 3.33 | 4.42 | 4.10 | 4.40 | 3.94 | 6.46 | 6.51 | 3.71 | 0.32 | 2.07 | 1.56 |
| | Rubber Tapper | -2.79 | -1.51 | -0.71 | 0.29 | -0.74 | -4.49 | -2.59 | -0.55 | -3.21 | -4.63 | -6.22 | -7.12 | -9.20 | -10.48 | -12.72 | -13.29 | -13.91 | -13.61 | -12.98 | -10.94 | -10.89 | -4.93 | -3.91 |
| **(9) Thick Vinyl** | **Center Freq. (Hz):** | **100** | **125** | **160** | **200** | **250** | **315** | **400** | **500** | **630** | **800** | **1000** | **1250** | **1600** | **2000** | **2500** | **3150** | **4000** | **5000** | **6300** | **8000** | **10000** | **A** | **L** |
| | Men's Sneaker | -1.94 | 3.74 | 2.98 | 2.02 | 4.12 | 5.25 | 6.52 | 5.74 | 6.39 | 6.38 | 4.98 | 5.63 | 6.89 | 4.47 | 2.25 | 1.21 | 2.14 | 2.50 | 1.71 | 1.75 | 1.24 | 5.62 | 4.29 |
| | Men's Rubber | -5.67 | -0.50 | -0.05 | -0.82 | -1.53 | -2.54 | -0.96 | 3.62 | 6.55 | 7.31 | 6.98 | 7.42 | 8.59 | 8.17 | 5.04 | 4.09 | 4.52 | 2.48 | 2.87 | 2.78 | 3.61 | 2.78 | 0.06 |
| | Men's Leather | -0.35 | 3.37 | 2.02 | 0.66 | 2.58 | 2.32 | 3.23 | 1.44 | 1.50 | 2.67 | 3.98 | 3.99 | 6.72 | 7.45 | 6.80 | 7.88 | 8.32 | 6.69 | 5.76 | 5.58 | 3.88 | 2.45 | 2.23 |
| | Women's Sneaker | -6.19 | -0.06 | 3.79 | 1.87 | 3.94 | 2.24 | 2.52 | 1.99 | 1.72 | 1.79 | 1.15 | 0.61 | 2.05 | 1.11 | 2.01 | 1.68 | 1.94 | -0.99 | -0.05 | -0.69 | -0.11 | 1.86 | 1.03 |
| | Women's Rubber | -5.72 | 1.41 | 2.30 | 3.24 | 8.84 | 10.74 | 11.68 | 8.16 | 8.78 | 8.50 | 8.95 | 8.70 | 10.33 | 10.62 | 8.15 | 5.86 | 3.88 | 1.13 | -1.09 | -2.27 | -1.38 | 8.68 | 6.06 |
| | Women's Leather | -4.27 | -0.71 | 2.00 | 1.15 | 2.86 | 0.93 | 1.37 | 2.11 | 3.28 | 3.50 | 3.45 | 4.11 | 3.54 | 4.50 | 5.33 | 6.67 | 6.32 | 4.78 | 5.79 | 6.24 | 5.39 | 3.12 | 2.62 |
| | Rubber Tapper | -0.10 | 3.99 | 2.18 | 0.67 | 0.81 | -1.85 | -1.50 | -2.16 | -2.50 | -2.40 | -3.88 | -4.79 | -5.36 | -7.07 | -8.41 | -8.64 | -8.56 | -9.04 | -10.23 | -9.49 | -11.43 | -3.46 | -2.87 |
| **(10) Oak Flooring** | **Center Freq. (Hz):** | **100** | **125** | **160** | **200** | **250** | **315** | **400** | **500** | **630** | **800** | **1000** | **1250** | **1600** | **2000** | **2500** | **3150** | **4000** | **5000** | **6300** | **8000** | **10000** | **A** | **L** |
| | Men's Sneaker | -1.51 | 2.02 | 3.70 | 1.21 | 1.07 | 1.32 | 3.30 | 3.58 | 4.49 | 3.55 | 3.61 | 3.38 | 3.40 | 4.63 | 4.97 | 3.59 | -0.02 | 0.13 | 2.14 | 1.78 | 0.62 | 3.09 | 2.33 |
| | Men's Rubber | 1.71 | 0.10 | 2.44 | -1.29 | 1.97 | -0.98 | -1.59 | 1.31 | 4.24 | 4.81 | 3.20 | 7.01 | 7.67 | 9.65 | 10.44 | 9.71 | 7.29 | 6.13 | 6.04 | 3.17 | 2.80 | 1.43 | 0.39 |
| | Men's Leather | -2.65 | 0.48 | 2.94 | 1.59 | 2.39 | 1.51 | -1.42 | -0.98 | 0.51 | 2.50 | 4.22 | 5.58 | 6.79 | 6.35 | 6.12 | 6.27 | 4.44 | 2.44 | 1.15 | -0.87 | -1.49 | 1.48 | 0.91 |
| | Women's Sneaker | -0.55 | 1.74 | 3.46 | 1.32 | 0.23 | 0.35 | 1.53 | 1.47 | -0.08 | 3.42 | 6.81 | 6.24 | 8.05 | 5.92 | 5.09 | 0.74 | 2.11 | 0.20 | 0.75 | 1.27 | 2.03 | 2.85 | 2.05 |
| | Women's Rubber | -1.52 | 1.43 | 3.46 | 2.01 | 1.72 | 0.07 | 2.63 | 3.42 | 4.46 | 5.14 | 3.62 | 7.41 | 7.68 | 7.59 | 7.30 | 7.13 | 4.28 | 4.92 | 4.87 | 2.19 | 3.84 | 3.47 | 2.36 |
| | Women's Leather | 1.97 | -1.66 | 0.54 | -3.31 | 1.87 | 0.06 | -1.85 | -1.72 | -2.81 | -1.82 | -1.62 | -2.49 | -2.14 | 0.42 | 3.94 | 4.96 | 6.13 | 5.10 | 1.86 | 0.50 | 1.15 | -1.69 | -1.54 |
| | Rubber Tapper | 2.99 | 0.07 | 0.91 | -2.63 | 1.62 | -0.74 | 2.14 | -3.05 | -3.41 | -4.47 | -6.13 | -7.41 | -8.51 | -8.77 | -7.92 | -8.61 | -10.66 | -14.16 | -12.26 | -11.74 | -9.42 | -5.97 | -4.59 |
| **(11) Ceramic Tile** | **Center Freq. (Hz):** | **100** | **125** | **160** | **200** | **250** | **315** | **400** | **500** | **630** | **800** | **1000** | **1250** | **1600** | **2000** | **2500** | **3150** | **4000** | **5000** | **6300** | **8000** | **10000** | **A** | **L** |
| | Men's Sneaker | 4.16 | 4.52 | 2.78 | 1.86 | 4.02 | 3.84 | 2.39 | 1.55 | 1.20 | 1.42 | 1.46 | 2.19 | 0.81 | 1.06 | 0.32 | 1.90 | 3.50 | 3.33 | 1.90 | -0.76 | 0.12 | 2.05 | 2.74 |
| | Men's Rubber | 0.37 | 1.50 | 1.54 | 3.03 | 5.23 | 4.81 | 2.72 | 1.25 | 1.38 | 2.47 | 1.98 | 3.92 | 4.10 | 5.57 | 3.58 | 3.92 | 3.34 | 2.51 | 4.44 | -1.00 | 1.16 | 3.28 | 3.46 |
| | Men's Leather | 1.23 | 1.68 | 0.71 | 2.17 | 4.24 | 4.32 | 1.99 | 1.07 | 0.73 | 1.59 | 1.41 | 2.01 | 2.11 | 4.16 | 6.16 | 3.62 | 1.31 | 1.56 | 1.84 | 3.14 | 2.57 | 1.49 | 1.83 |
| | Women's Sneaker | 5.58 | 4.83 | 3.93 | 1.48 | 1.89 | 3.00 | 0.75 | 1.36 | -0.93 | -1.63 | -0.79 | -0.09 | -0.36 | 0.71 | 1.06 | 1.84 | 1.21 | -3.39 | -4.62 | -1.76 | -2.25 | 0.48 | 2.72 |
| | Women's Rubber | 5.05 | 5.45 | 0.66 | 0.30 | 0.53 | 1.07 | 2.71 | 3.13 | 2.31 | 2.32 | 1.41 | 4.70 | 3.10 | 3.85 | 1.74 | 3.57 | 3.10 | 4.18 | 3.80 | 0.55 | -0.49 | 1.65 | 1.45 |
| | Women's Leather | -0.37 | 0.21 | 0.37 | 1.06 | 2.81 | 3.05 | 0.79 | -0.99 | -1.17 | -1.00 | -0.80 | -1.03 | -0.76 | 0.38 | 1.32 | -1.24 | -2.68 | -0.53 | -1.76 | 1.16 | 2.15 | -0.81 | -0.38 |
| | Rubber Tapper | 2.18 | 3.06 | 2.22 | 3.58 | 3.41 | 2.12 | 1.12 | -2.39 | -4.04 | -6.31 | -10.16 | -11.91 | -14.02 | -16.13 | -17.65 | -19.88 | -21.55 | -22.25 | -20.97 | -20.01 | -13.96 | -8.81 | -6.92 |

# Appendix D:
# Additional Data for
# Floor Profile 12

# Appendix D: Additional Data for Floor Profile 12 – Vinyl on Concrete

**Averaged Human Data**

| (12) Vinyl/Concrete | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Men's Sneaker** | **44.3** | **44.9** | **48.3** | **49.4** | **49.6** | **49.7** | **49.1** | **47.2** | **44.9** | **42.8** | **41.3** | **40.7** | **38.3** | **37.7** | **35.7** | **34.8** | **34.4** | **33.9** | **33.8** | **34.6** | **33.2** | **53.2** | **58.3** |
| | 95% Confidence | 5.6 | 5.0 | 5.8 | 6.0 | 7.2 | 6.9 | 6.5 | 6.9 | 7.1 | 7.5 | 9.8 | 9.7 | 9.0 | 8.0 | 6.2 | 5.7 | 5.3 | 5.5 | 7.0 | 9.9 | 14.1 | 6.9 | 6.1 |
| | **Men's Rubber** | **43.3** | **43.7** | **46.4** | **46.5** | **46.4** | **48.1** | **49.7** | **49.0** | **46.1** | **42.9** | **42.4** | **42.4** | **40.2** | **38.1** | **36.3** | **35.3** | **33.8** | **33.1** | **32.4** | **32.7** | **30.0** | **53.5** | **57.5** |
| | 95% Confidence | 5.9 | 5.2 | 5.3 | 5.7 | 5.6 | 5.2 | 3.6 | 3.5 | 4.5 | 6.0 | 6.6 | 7.2 | 7.9 | 7.5 | 7.1 | 5.8 | 4.9 | 4.4 | 4.5 | 4.7 | 4.1 | 4.9 | 4.5 |
| | **Men's Leather** | **46.2** | **46.1** | **49.9** | **52.2** | **54.3** | **56.0** | **56.0** | **54.8** | **52.7** | **51.0** | **48.1** | **47.1** | **43.0** | **41.0** | **38.5** | **37.0** | **35.2** | **33.9** | **33.8** | **34.3** | **32.1** | **59.7** | **63.7** |
| | 95% Confidence | 5.1 | 4.7 | 5.4 | 6.6 | 7.4 | 8.4 | 8.6 | 7.1 | 4.3 | 4.7 | 5.6 | 9.3 | 11.8 | 12.3 | 11.3 | 9.9 | 6.3 | 4.3 | 4.6 | 4.4 | 3.8 | 5.6 | 6.2 |
| | **Women's Sneaker** | **40.3** | **40.2** | **42.5** | **43.0** | **43.5** | **44.4** | **45.0** | **45.8** | **44.9** | **43.4** | **41.2** | **39.6** | **37.4** | **37.3** | **36.6** | **35.7** | **35.1** | **34.3** | **33.5** | **33.2** | **31.1** | **51.6** | **54.8** |
| | 95% Confidence | 4.1 | 4.4 | 6.0 | 7.7 | 10.2 | 11.5 | 11.7 | 10.0 | 9.1 | 9.7 | 11.7 | 12.4 | 12.5 | 12.2 | 12.8 | 11.4 | 11.5 | 10.6 | 9.9 | 7.9 | 9.9 | 10.7 | 9.8 |
| | **Women's Rubber** | **42.7** | **41.7** | **43.5** | **44.3** | **44.4** | **44.1** | **43.3** | **43.1** | **41.7** | **40.0** | **39.0** | **37.8** | **35.7** | **35.8** | **34.0** | **34.3** | **34.3** | **34.2** | **33.1** | **33.0** | **31.0** | **49.7** | **54.1** |
| | 95% Confidence | 4.8 | 5.1 | 7.6 | 6.1 | 4.9 | 5.5 | 6.4 | 7.1 | 5.9 | 6.7 | 7.0 | 6.6 | 6.9 | 8.6 | 8.1 | 8.9 | 9.2 | 10.4 | 8.1 | 6.0 | 8.4 | 6.6 | 5.5 |
| | **Women's Leather** | **38.6** | **39.2** | **42.3** | **43.7** | **45.6** | **49.2** | **51.8** | **53.7** | **54.0** | **53.3** | **50.9** | **47.6** | **42.3** | **40.5** | **38.2** | **36.2** | **35.3** | **34.0** | **33.5** | **34.0** | **31.7** | **59.1** | **61.2** |
| | 95% Confidence | 3.0 | 3.0 | 3.4 | 3.8 | 4.1 | 4.3 | 3.9 | 2.7 | 3.7 | 4.7 | 5.2 | 5.8 | 5.3 | 4.5 | 4.9 | 5.9 | 5.8 | 4.9 | 4.5 | 4.3 | 4.2 | 3.7 | 3.2 |

**Raw Tapper Data**

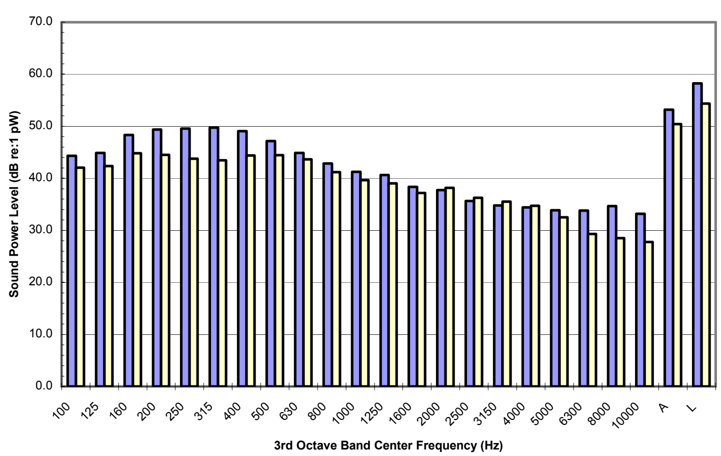
| (12) Vinyl/Cement | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Men's Sneaker | 60.1 | 65.9 | 71.8 | 67.0 | 59.9 | 55.8 | 55.2 | 59.1 | 54.5 | 55.4 | 57.1 | 50.2 | 47.7 | 45.9 | 44.3 | 44.6 | 45.1 | 44.7 | 41.1 | 36.8 | 32.9 | 65.2 | 74.6 |
| | Men's Rubber | 61.2 | 66.7 | 72.5 | 71.2 | 66.2 | 64.1 | 61.4 | 64.0 | 57.8 | 59.0 | 60.9 | 53.2 | 50.3 | 45.5 | 43.3 | 40.4 | 40.8 | 42.6 | 42.0 | 41.8 | 37.0 | 68.8 | 77.0 |
| | Men's Leather | 61.3 | 64.8 | 71.1 | 70.9 | 69.6 | 69.9 | 68.1 | 68.4 | 79.2 | 75.5 | 63.0 | 69.9 | 57.0 | 53.4 | 49.6 | 50.1 | 50.7 | 51.6 | 50.6 | 48.0 | 42.6 | 80.4 | 82.9 |
| | Women's Sneaker | 60.1 | 66.2 | 71.9 | 67.0 | 59.9 | 56.0 | 55.3 | 58.6 | 53.1 | 55.1 | 57.2 | 50.7 | 47.7 | 44.6 | 44.1 | 48.4 | 47.3 | 49.6 | 50.2 | 49.0 | 41.1 | 65.5 | 74.7 |
| | Women's Rubber | 61.3 | 65.7 | 72.4 | 68.0 | 62.5 | 59.9 | 58.5 | 62.0 | 55.6 | 56.5 | 58.4 | 51.1 | 47.8 | 43.8 | 43.0 | 42.9 | 45.9 | 47.3 | 46.8 | 39.2 | 34.7 | 66.7 | 75.5 |
| | Women's Leather | 61.1 | 63.9 | 69.4 | 68.4 | 69.9 | 71.4 | 70.2 | 71.0 | 83.3 | 80.0 | 67.5 | 77.4 | 63.0 | 58.9 | 50.5 | 51.2 | 52.8 | 53.8 | 51.5 | 51.3 | 49.3 | 84.9 | 86.5 |
| | Rubber Tapper | 59.8 | 60.2 | 65.1 | 65.6 | 69.5 | 69.6 | 81.8 | 77.4 | 83.5 | 81.6 | 71.5 | 80.4 | 68.8 | 69.0 | 64.6 | 61.1 | 63.7 | 62.5 | 62.2 | 60.8 | 60.8 | 87.1 | 88.8 |

Legends

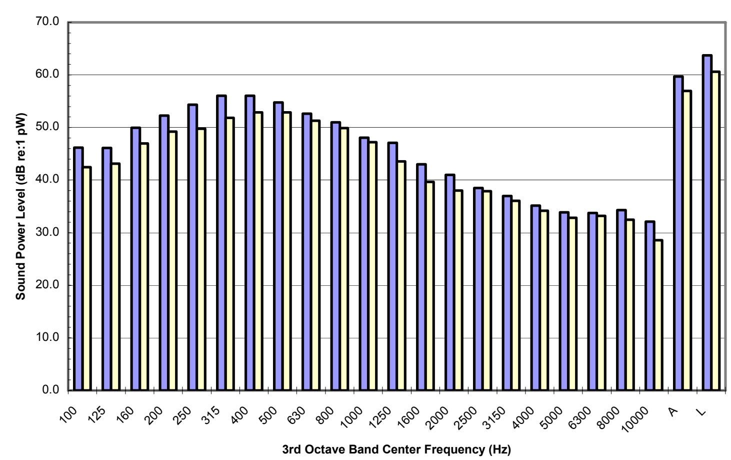
Average Human   Scaled "Shoed" Tapper   Scaled Rubber Tapper

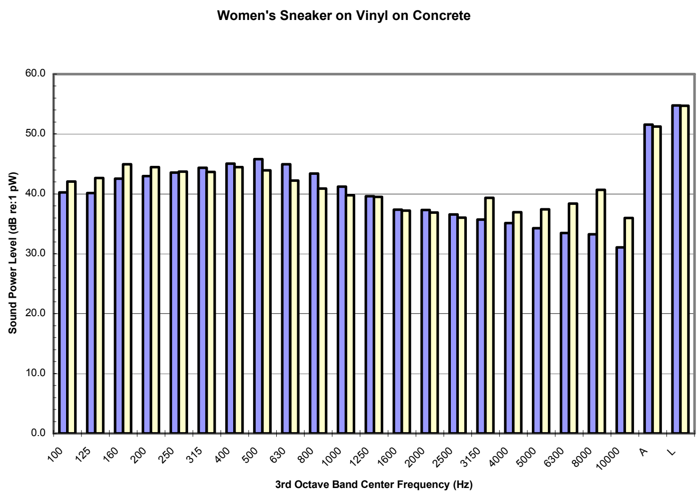
Vinyl on Concrete   Bare Concrete

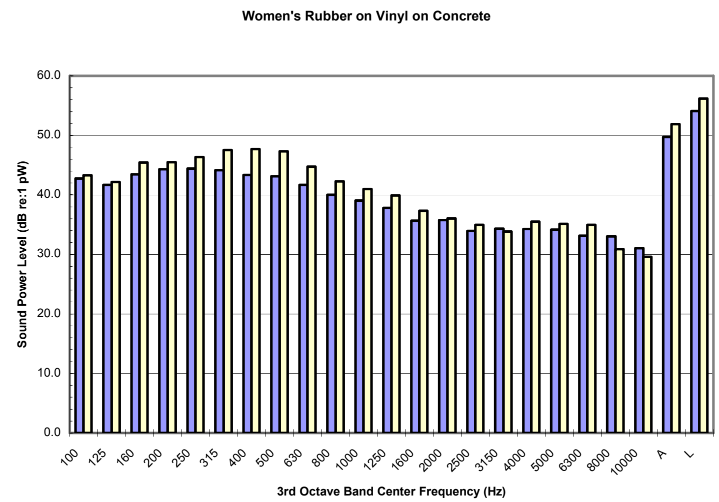
Men's Sneaker on Vinyl on Concrete

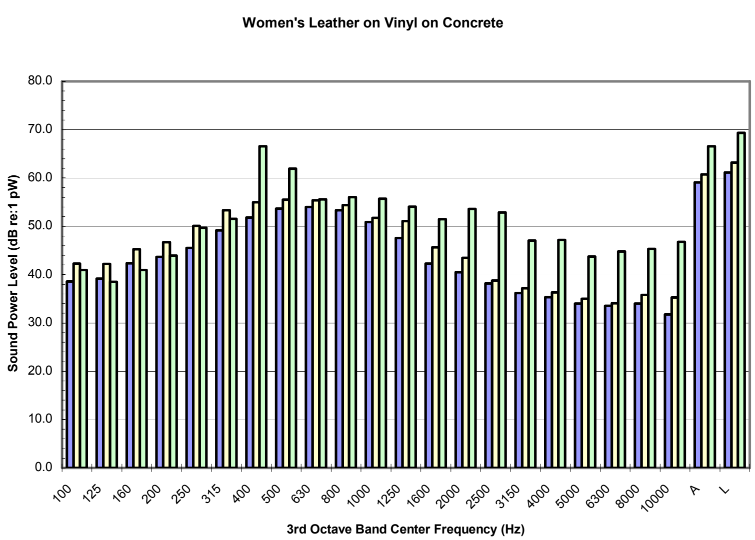


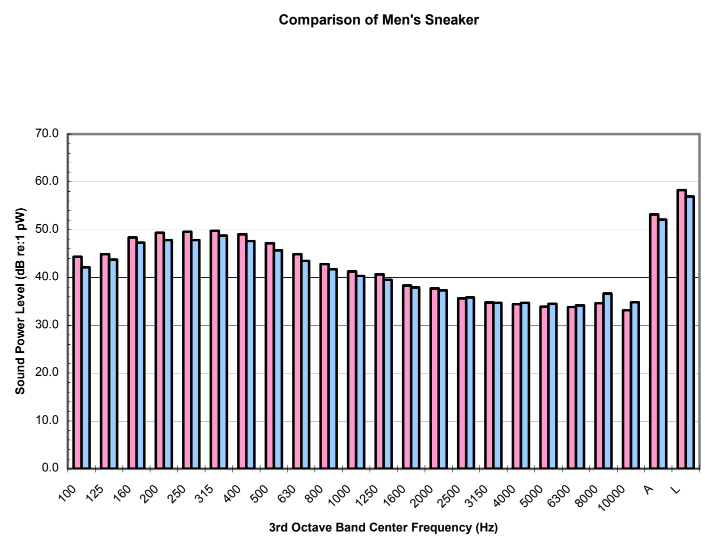

Men's Leather on Vinyl on Concrete



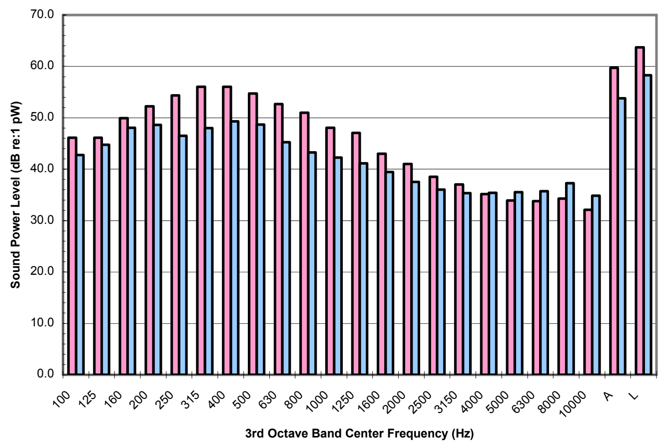

Women's Sneaker on Vinyl on Concrete
Sound Power Level (dB re:1 pW)
3rd Octave Band Center Frequency (Hz)


Women's Rubber on Vinyl on Concrete
Sound Power Level (dB re:1 pW)
3rd Octave Band Center Frequency (Hz)

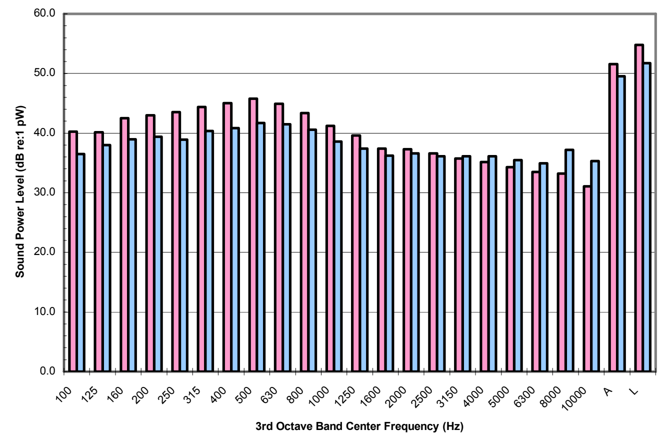

Women's Leather on Vinyl on Concrete
Sound Power Level (dB re:1 pW)
3rd Octave Band Center Frequency (Hz)


Comparison of Men's Sneaker
Sound Power Level (dB re:1 pW)
3rd Octave Band Center Frequency (Hz)

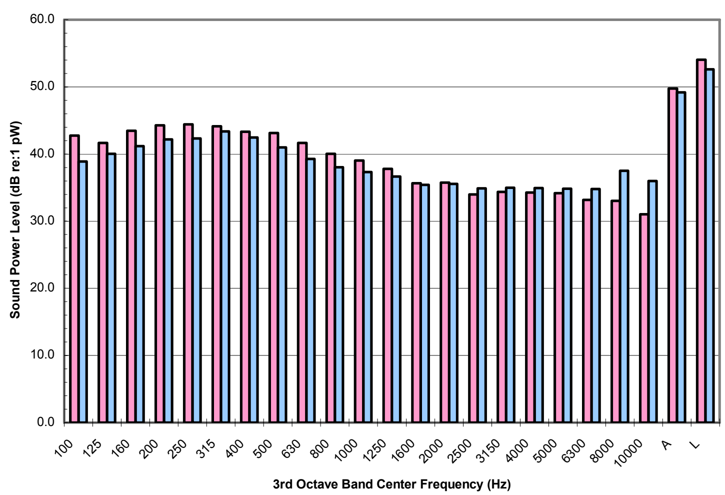
**Comparison of Men's Leather-Soled Shoe**



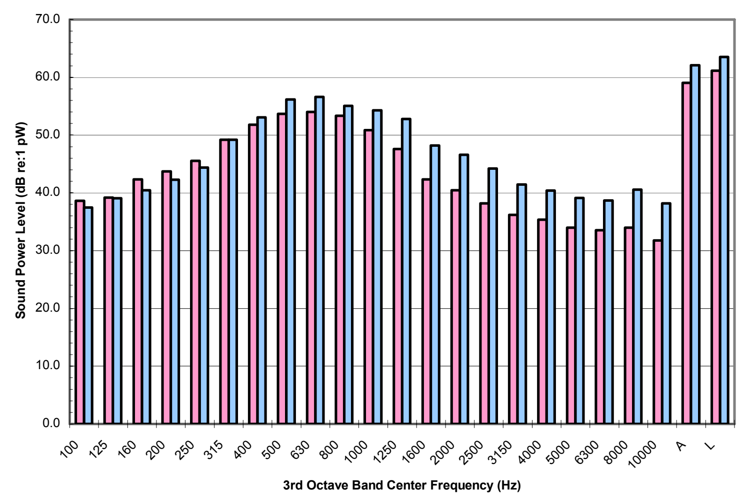

**Comparison of Women's Sneaker**




**Comparison of Women's Rubber-Soled Shoe**




**Comparison of Women's Leather-Soled Shoe**



# Appendix E:

# Results for Type 3204 Rubber-Tipped Tapping Machine

# Raw Data for Floor Profile 12

## Averaged Human Data

| | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (12) Vinyl/Concrete | **Men's Sneaker** | **44.3** | **44.9** | **48.3** | **49.4** | **49.6** | **49.7** | **49.1** | **47.2** | **44.9** | **42.8** | **41.3** | **40.7** | **38.3** | **37.7** | **35.7** | **34.8** | **34.4** | **33.9** | **33.8** | **34.6** | **33.2** | **53.2** | **58.3** |
| | 95% Confidence | 5.6 | 5.0 | 5.8 | 6.0 | 7.2 | 6.9 | 6.5 | 6.9 | 7.1 | 7.5 | 9.8 | 9.7 | 9.0 | 8.0 | 6.2 | 5.7 | 5.3 | 5.5 | 7.0 | 9.9 | 14.1 | 6.9 | 6.1 |
| | **Men's Rubber** | **43.3** | **43.7** | **46.4** | **46.5** | **46.4** | **48.1** | **49.7** | **49.0** | **46.1** | **42.9** | **42.4** | **42.4** | **40.2** | **38.1** | **36.3** | **35.3** | **33.8** | **33.1** | **32.4** | **32.7** | **30.0** | **53.5** | **57.5** |
| | 95% Confidence | 5.9 | 5.2 | 5.3 | 5.7 | 5.6 | 5.2 | 3.6 | 3.5 | 4.5 | 6.0 | 6.6 | 7.2 | 7.9 | 7.5 | 7.1 | 5.8 | 4.9 | 4.4 | 4.5 | 4.7 | 4.1 | 4.9 | 4.5 |
| | **Men's Leather** | **46.2** | **46.1** | **49.9** | **52.2** | **54.3** | **56.0** | **56.0** | **54.8** | **52.7** | **51.0** | **48.1** | **47.1** | **43.0** | **41.0** | **38.5** | **37.0** | **35.2** | **33.9** | **33.8** | **34.3** | **32.1** | **59.7** | **63.7** |
| | 95% Confidence | 5.1 | 4.7 | 5.4 | 6.6 | 7.4 | 8.4 | 8.6 | 7.1 | 4.3 | 4.7 | 5.6 | 9.3 | 11.8 | 12.3 | 11.3 | 9.9 | 6.3 | 4.3 | 4.6 | 4.4 | 3.8 | 5.6 | 6.2 |
| | **Women's Sneaker** | **40.3** | **40.2** | **42.5** | **43.0** | **43.5** | **44.4** | **45.0** | **45.8** | **44.9** | **43.4** | **41.2** | **39.6** | **37.4** | **37.3** | **36.6** | **35.7** | **35.1** | **34.3** | **33.5** | **33.2** | **31.1** | **51.6** | **54.8** |
| | 95% Confidence | 4.1 | 4.4 | 6.0 | 7.7 | 10.2 | 11.5 | 11.7 | 10.0 | 9.1 | 9.7 | 11.7 | 12.4 | 12.5 | 12.2 | 12.8 | 11.4 | 11.5 | 10.6 | 9.9 | 7.9 | 9.9 | 10.7 | 9.8 |
| | **Women's Rubber** | **42.7** | **41.7** | **43.5** | **44.3** | **44.4** | **44.1** | **43.3** | **43.1** | **41.7** | **40.0** | **39.0** | **37.8** | **35.7** | **35.8** | **34.0** | **34.3** | **34.3** | **34.2** | **33.1** | **33.0** | **31.0** | **49.7** | **54.1** |
| | 95% Confidence | 4.8 | 5.1 | 7.6 | 6.1 | 4.9 | 5.5 | 6.4 | 7.1 | 5.9 | 6.7 | 7.0 | 6.6 | 6.9 | 8.6 | 8.1 | 8.9 | 9.2 | 10.4 | 8.1 | 6.0 | 8.4 | 6.6 | 5.5 |
| | **Women's Leather** | **38.6** | **39.2** | **42.3** | **43.7** | **45.6** | **49.2** | **51.8** | **53.7** | **54.0** | **53.3** | **50.9** | **47.6** | **42.3** | **40.5** | **38.2** | **36.2** | **35.3** | **34.0** | **33.5** | **34.0** | **31.7** | **59.1** | **61.2** |
| | 95% Confidence | 3.0 | 3.0 | 3.4 | 3.8 | 4.1 | 4.3 | 3.9 | 2.7 | 3.7 | 4.7 | 5.2 | 5.8 | 5.3 | 4.5 | 4.9 | 5.9 | 5.8 | 4.9 | 4.5 | 4.3 | 4.2 | 3.7 | 3.2 |

## Raw Tapper Data

| | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 | A | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (12) Vinyl/Cement | Men's Sneaker | 60.1 | 65.9 | 71.8 | 67.0 | 59.9 | 55.8 | 55.2 | 59.1 | 54.5 | 55.4 | 57.1 | 50.2 | 47.7 | 45.9 | 44.3 | 44.6 | 45.1 | 44.7 | 41.1 | 36.8 | 32.9 | 65.2 | 74.6 |
| | Men's Rubber | 61.2 | 66.7 | 72.5 | 71.2 | 66.2 | 64.1 | 61.4 | 64.0 | 57.8 | 59.0 | 60.9 | 53.2 | 50.3 | 45.5 | 43.3 | 40.4 | 40.8 | 42.6 | 42.0 | 41.8 | 37.0 | 68.8 | 77.0 |
| | Men's Leather | 61.3 | 64.8 | 71.1 | 70.9 | 69.6 | 69.9 | 68.1 | 68.4 | 79.2 | 75.5 | 63.0 | 69.9 | 57.0 | 53.4 | 49.6 | 50.1 | 50.7 | 51.6 | 50.6 | 48.0 | 42.6 | 80.4 | 82.9 |
| | Women's Sneaker | 60.1 | 66.2 | 71.9 | 67.0 | 59.9 | 56.0 | 55.3 | 58.6 | 53.1 | 55.1 | 57.2 | 50.7 | 47.7 | 44.6 | 44.1 | 48.4 | 47.3 | 49.6 | 50.2 | 49.0 | 41.1 | 65.5 | 74.7 |
| | Women's Rubber | 61.3 | 65.7 | 72.4 | 68.0 | 62.5 | 59.9 | 58.5 | 62.0 | 55.6 | 56.5 | 58.4 | 51.1 | 47.8 | 43.8 | 43.0 | 42.9 | 45.9 | 47.3 | 46.8 | 39.2 | 34.7 | 66.7 | 75.5 |
| | Women's Leather | 61.1 | 63.9 | 69.4 | 68.4 | 69.9 | 71.4 | 70.2 | 71.0 | 83.3 | 80.0 | 67.5 | 77.4 | 63.0 | 58.9 | 50.5 | 51.2 | 52.8 | 53.8 | 51.5 | 51.3 | 49.3 | 84.9 | 86.5 |
| | Rubber Tapper | 59.8 | 60.2 | 65.1 | 65.6 | 69.5 | 69.6 | 81.8 | 77.4 | 83.5 | 81.6 | 71.5 | 80.4 | 68.8 | 69.0 | 64.6 | 61.1 | 63.7 | 62.5 | 62.2 | 60.8 | 60.8 | 87.1 | 88.8 |

## University of Hartford Acoustics Laboratory

**Spring 2008 Footfall Noise Characterization**

**Sponsor: Paul S. Veneklasen Research Foundation**

### Sound Power Levels of Tapper Sounds (dB, re: 1 picoWatt)

| Shoe Type | Center Freq. (Hz): | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 |
|---|---|---|---|---|---|---|---|---|---|---|
| Men's Sneaker | Average | -0.16595 | 2.361512 | 2.345986 | -3.20926 | -10.4212 | -12.7925 | -21.5639 | -16.0602 | -17.4809 |
| | Standard Dev | 4.337003 | 9.670682 | 13.27866 | 12.49964 | 7.511495 | 6.913795 | 14.66784 | 9.024225 | 17.11136 |
| Men's Rubber | Average | 0.820572 | 2.850042 | 2.258797 | -0.67658 | -5.44314 | -7.20329 | -18.2205 | -13.5796 | -14.4267 |
| | Standard Dev | 5.529143 | 8.54162 | 11.19794 | 10.22762 | 6.818898 | 8.099098 | 12.9401 | 9.63967 | 16.13826 |
| Men's Leather | Average | -0.17723 | 2.771507 | 2.436701 | 1.541691 | -1.1097 | -0.87903 | -10.2501 | -5.4562 | -4.51495 |
| | Standard Dev | 3.537602 | 5.260529 | 8.484952 | 6.259495 | 3.413416 | 9.286311 | 22.27224 | 12.01465 | 6.942395 |
| Women's Sneaker | Average | -0.63835 | 1.8637 | 1.457191 | -5.49294 | -12.7075 | -14.4104 | -24.281 | -18.4327 | -20.5004 |
| | Standard Dev | 7.647556 | 13.17652 | 14.83003 | 17.41678 | 13.29886 | 10.43623 | 7.577575 | 11.62297 | 16.30012 |
| Women's Rubber | Average | -0.20714 | 2.627117 | 3.200681 | -0.45817 | -6.08765 | -7.55534 | -17.1068 | -11.7813 | -13.55 |
| | Standard Dev | 6.709701 | 11.49828 | 14.39082 | 15.33039 | 14.02072 | 12.50469 | 16.53238 | 14.76107 | 23.58418 |
| Women's Leather | Average | 0.358289 | -0.05646 | 0.878584 | 0.129891 | -1.34613 | -0.4012 | -9.62853 | -4.58121 | -2.22091 |
| | Standard Dev | 3.662416 | 4.169408 | 5.479444 | 3.954078 | 5.035994 | 10.79248 | 25.1921 | 14.84107 | 9.301362 |

| Shoe Type | Center Freq. (Hz): | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 | 6300 | 8000 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Men's Sneaker | Average | -18.9922 | -16.4349 | -22.5068 | -21.0233 | -22.2264 | -20.6182 | -17.2399 | -17.2826 | -16.4424 | -19.0745 | -20.7375 | -25.23013 |
| | Standard Dev | 13.6304 | 13.86188 | 13.46676 | 10.64102 | 9.015904 | 8.31106 | 8.896365 | 8.724653 | 9.572826 | 11.1446 | 9.170669 | 11.646617 |
| Men's Rubber | Average | -15.8661 | -14.5389 | -19.5773 | -18.6511 | -19.8396 | -19.4176 | -17.3192 | -18.0684 | -17.3553 | -17.6296 | -18.8631 | -23.18962 |
| | Standard Dev | 14.16395 | 13.00384 | 12.31494 | 10.56272 | 10.86355 | 10.26786 | 10.13411 | 8.908782 | 8.777404 | 13.06718 | 12.64696 | 15.216186 |
| Men's Leather | Average | -7.649 | -7.90849 | -11.4697 | -11.8024 | -13.3113 | -13.1759 | -10.9061 | -11.9617 | -10.6656 | -11.3111 | -11.8696 | -16.81383 |
| | Standard Dev | 11.83035 | 7.77923 | 13.37774 | 12.33895 | 15.31089 | 15.12237 | 13.91434 | 17.74896 | 18.22428 | 22.90991 | 23.58713 | 26.450546 |
| Women's Sneaker | Average | -21.3946 | -18.117 | -24.7797 | -23.285 | -24.4838 | -21.4999 | -16.6949 | -16.8487 | -16.1653 | -16.1336 | -16.0062 | -22.71219 |
| | Standard Dev | 13.51279 | 17.67968 | 12.86939 | 13.058 | 10.13806 | 8.74946 | 11.9633 | 10.22298 | 9.870358 | 13.73676 | 15.56325 | 17.677752 |
| Women's Rubber | Average | -14.3207 | -11.5767 | -17.0415 | -15.4115 | -17.0477 | -16.279 | -14.4193 | -14.9043 | -13.9759 | -14.9289 | -16.6606 | -20.94178 |
| | Standard Dev | 20.56918 | 21.02178 | 21.97845 | 18.83978 | 18.77314 | 17.19168 | 17.0397 | 14.83993 | 14.50959 | 13.26518 | 15.93946 | 16.159645 |
| Women's Leather | Average | -4.70435 | -4.23443 | -6.77322 | -7.46051 | -9.08754 | -9.84418 | -8.76436 | -9.74184 | -7.75544 | -9.63855 | -9.09711 | -12.08739 |
| | Standard Dev | 16.12681 | 12.40638 | 20.71884 | 19.12104 | 22.32862 | 22.00086 | 20.2259 | 23.83194 | 23.49479 | 29.23533 | 29.28797 | 30.468805 |

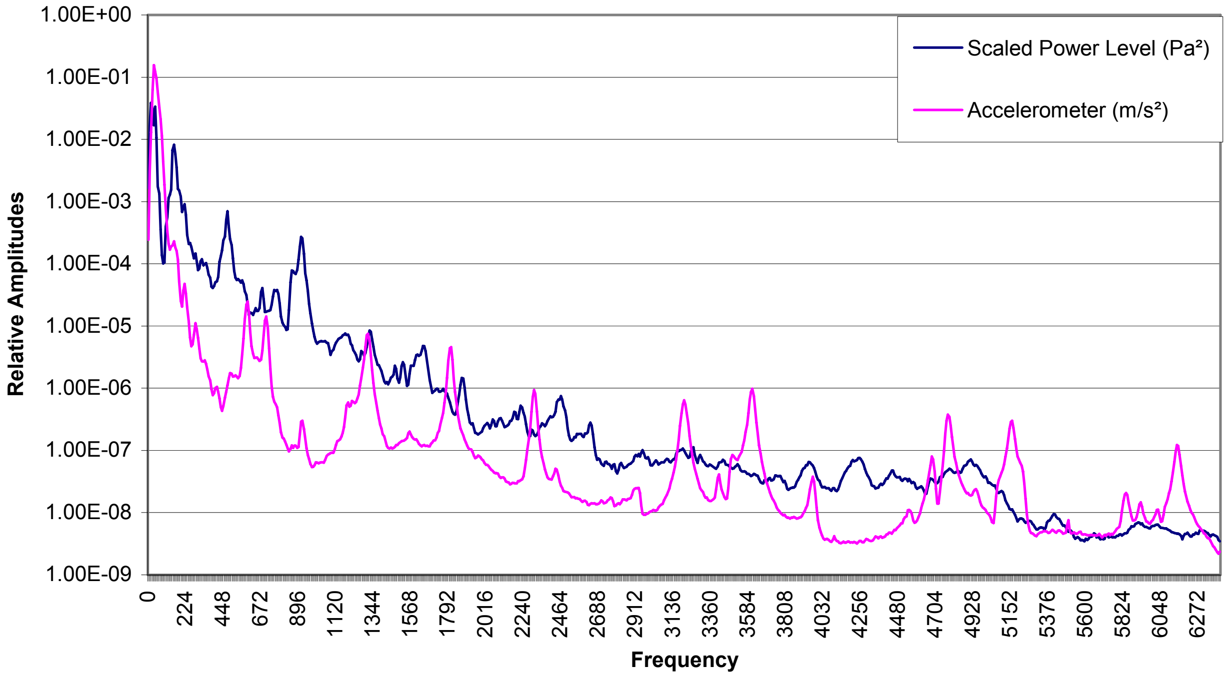
# Appendix F:

# Additional

# Vibratory Results

# Appendix F: Additional Vibratory Results

**Example with Poor Correlation - Wool Carpet on Pad**




**Example with Decent Correlation - Carpet on Concrete**