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Estimation of sound pressure level exposures from sound power level measurements of powered hand-tools using the diffuse-field point source model Eyring Theory

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ABSTRACT

As part of a long-term goal to reduce noise induced hearing loss in the construction industry, the National Institute for Occupational Safety and Health (NIOSH) estimated the A-weighted sound pressure level at the operator's ear ($L_{PA,est}$) from the A-weighted sound power (L_{WA}) measurements of 118 various model powered hand tools using the diffuse-field point source model Eyring theory. $L_{PA,est}$ from the model are compared to sound pressure measurements ($L_{PA,\ meas}$) acquired from a microphone located in the nominal hearing zone of a simulated powered hand tool operator. This paper provides a basis for the direct substitution of L_{WA} for $L_{PA,meas}$ and a comparison of $L_{PA,est}$ to $L_{PA,\ meas}$. The magnitude of L_{WA} is found to be a reasonable predictor of the magnitude of sound pressure level exposure, or $L_{PA,\ meas}$, that a powered hand tool operator might experience across a variety of acoustical environments. As such, L_{WA} magnitude can be used directly to select appropriate hearing protection and estimate worker' noise exposure.

Disclaimer: The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of company names of products does not constitute endorsement by the Centers for Disease Control and Prevention (CDC), NIOSH.

1 INTRODUCTION

As part of a long-term goal to reduce noise induced hearing loss in the construction industry, the National Institute for Occupational Safety and Health (NIOSH) instituted a program to estimate the A-weighted sound pressure level at the operator's ear ($L_{PA,est}$) from the A-weighted sound power (L_{WA}) measurements of powered hand tools.

A number of studies have shown construction workers' general noise exposures from portable power tools to range from 81 dBA to 113 dBA [1,2,3,4]. Although, these previous studies focused on personal, task-based, and area noise level measurements, they did show that power tools were a major contributor to construction site noise. Figure 1 contrasts power-tool-use-intensive construction occupations—such as plumbers, ironworkers, carpenters, and electricians—which show higher rates of abnormal hearing, with occupations less dependent on power tools, such as painters [5]. Lastly, a linear relationship between a power tool's sound power level and an operator's noise exposure has been shown [2].

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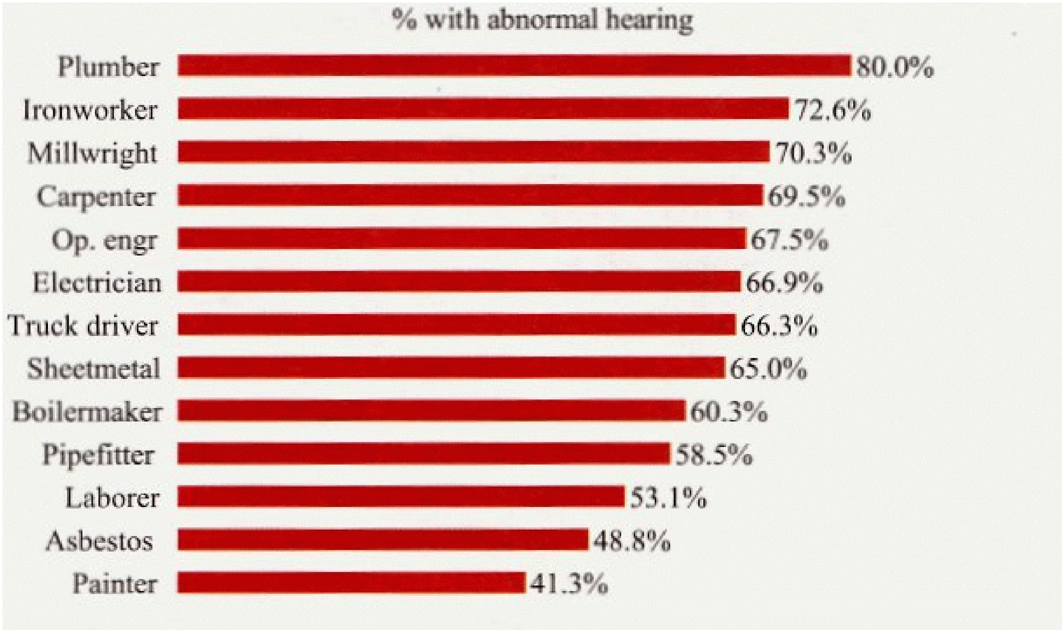

Figure 1: Percentage of various construction occupations found to have abnormal hearing.8

Studies conducted at the University of Washington found that 40% of the noise exposure measurements made on carpenters and laborers were over the state of Washington's Permissible Exposure Limit (PEL) of 85 dBA for 8 hours [3]. Twenty four percent of the measurements made on those who work in the so-called "quiet" trades, such as electricians, was also over this PEL [1].

Regulation of noise exposure in the construction industry currently falls under OSHA 29 CFR 1926.52. This regulation does not have the stringent requirements promulgated for other industries (OSHA 29 CFR 1910.95) to reduce noise exposure. For example, in fiscal year 2005, fines levied under 1926.52 (Occupational Noise Exposure) on the construction industry by federal OSHA inspectors amounted to 0.03% of total construction industry fines, while manufacturing industries made up 1.7% of total fines. In fiscal year 2005, 49,214 construction inspections by federal OSHA resulted in only 29 citations for noise totaling $20,122 in fines despite the well-documented existence of high noise exposure and high rates of NIHL in the construction industry [6]. OSHA is currently revising a previously released advanced notice of proposed rule making (ANPR) aimed at preventing hearing loss among construction workers [7]. However, that ANPR is listed on OSHA's web site as an archived document, "not representing current OSHA policy."

As there is no regulatory requirement in the construction industry to have a hearing conservation program (HCP) in place, the construction industry is the least likely across all industries to provide audiograms and monitor their employee's hearing. The low prevalence of HCPs in the construction sector necessitates providing, among other things, noise level information that can be readily used by the powered hand tool user to reduce their own risk of suffering a noise-induced hearing loss. The industry standard for describing noise emissions from equipment and machinery is sound power level (reported in Watts or dBA *ref* 10^{-12} Watts). In Europe, equipment and machinery are mandated to be labeled with either sound power level or a symbol/color indicating relative sound level [8]. In the US, there is an unenforced EPA regulation requiring similar labeling of equipment and machinery [9]. In anticipation of more restrictive noise level requirements on construction sites and the enforcement of existing labeling regulations in the US, this project examines an analytical model by which sound power level is related directly to sound pressure level.

Currently, there are models for estimating sound pressure at the operator's position, $L_{PA,est}$, from a noise source located at some distance from the operator's ear [10,11]. The ISO standards model shown by Equation 1 uses the sound power L_{WA} and the quantity *Q*. *Q* is either determined experimentally or calculated from a measurement surface surrounding the tool/equipment under test.

$$L_{PA,est} = L_{WA} - Q \quad (dB) \tag{1}$$

While *Q* will vary with the directionality of the tool/equipment under test, the acoustical environment, and the distance from the source to the operator, Equation 1 assumes an omnidirectional source, a reflective acoustical environment, and a relatively steady distance between the source and receiver. The ISO standard 11203 does provide a range of *Q* values of 4-12 dB for hand-held machines. Using references, $L_{PA,est}$ (dBA ref. 20 μPa) and L_{WA} (dBA ref. 10-12 Watts).

The Australian government noise control guide of reference 4 provides a flowchart which gives:

$$L_{PA,est} = L_{WA} - 8 + (6 \; or \; 0) \quad (dB) \tag{2}$$

Where 6 is added if the sound power level measurement was taken in a highly reverberant acoustical environment or the age or loading of the machine is not representative of the conditions when the measurement was taken (i.e., the tool was new when tested but may now have many hours of wear or the tool is tested in the unloaded condition). This model does not specifically take into consideration source directivity, distance of the source to the operator's ear, or the effects of nearby reflective planes.

2 THEORETICAL MODEL

A model for estimating noise exposure from portable powered hand tools should consider the tool's sound characteristics, the environmental sound characteristics, and the proximity of the noise source to the operator's ears. These considerations are accounted for in the diffuse-field, point source Eyring theory model [12,13,14]. The diffuse-field point source model Eyring theory provides:

$$L_{PA,est} = L_{WA} + 10\log_{10}\left(\frac{Q_\theta}{4\pi r^2} + \frac{4}{R}\right), \tag{3}$$

where Q_θ is the tool or machine's directivity factor, *r* (m) is the radial distance between the sound source (the tool/machine) and the receiver (the tool operator's ear), and *R* (m^2) is the room constant. Eyring theory approximates the sound source as a point source having directivity, located in a room having a diffuse sound field at some distance from the receiver.

The first term inside the parenthesis of Equation 3 represents the effect of the direct sound field. The second term inside the parenthesis represents the effect of the reverberant sound field. Equation 3 can be rearranged to more easily show the direct and reverberant sound field's effect on the sound level. Moving L_{WA} to the left side of the equation yields,

$$L_{PA,est} - L_{WA} = 10\log_{10}\left(\frac{Q_\theta}{4\pi r^2} + \frac{4}{R}\right). \quad (4)$$

Now the left side term, ($L_{PA,est} - L_{WA}$), provides a convenient way to view the relationship between the difference in estimated sound pressure level and measured sound power level, and the direct and reverberant sound fields. A description of each of the direct and reverberant sound level variables, Q_θ, r, and R and their effect on the estimation of ($L_{PA,est} - L_{WA}$) is detailed below.

2.1 Directivity factor Q_θ

The sound source directivity of a powered hand tool is described by its directivity factor. This factor describes the tool's changing noise emission levels relative to the angle about the tool. For comparison, a tool acting as an omnidirectional or monopole source would have $Q_\theta = 1$. A sound source with a high directivity factor will have large variations of sound levels as the angle about the tool changes. In effect, $L_{PA,est}$ will vary with the angle between the tool and the operator's ear. Note that directivity does not affect the L_{WA} measurement. The directivity factor is a dimensionless quantity defined as:

$$Q_\theta = 10^{DI_\theta/10}, \quad (5)$$

where the directivity index is

$$DI_\theta = L_{PA\theta} - \overline{L_{PA}} + L_{rp} \quad \text{(dBA)}, \quad (6)$$

and $L_{PA\theta}$ is the sound pressure level measured at distance r and at angle θ from the source, $\overline{L_{PA}}$ is the level of space-averaged mean-square sound pressure level determined over the test hemisphere of area $2\pi r^2$ (8π in the case of this paper as r = 2 meters in the hemi anechoic chamber) surrounding the source, and L_{rp} is the sound pressure level correction factor to account for the sound source's location near reflecting planes.

If the tool is operated near reflecting surfaces (within 1/3 wavelength distances), those reflecting surfaces change the directivity index, which in turn changes the directivity factor. Table 1 specifies the values for L_{rp} for a powered hand tool under the influence of zero to three reflective surfaces [14,15]. The effect of directivity factor on ($L_{PA,est} - L_{WA}$) is shown in Figure 2.

Table 1: L_{rp} as a function of reflecting surfaces. L_{rp} increases with the number of reflecting planes the sound source is near (within 1/3 wavelength distances).

Geometric description of reflector	Number of reflective planes	L_{rp}
No reflective surfaces	0	0
Floor, wall, or hard ceiling	1	3
Interior Edge	2	6
Interior Corner	3	9

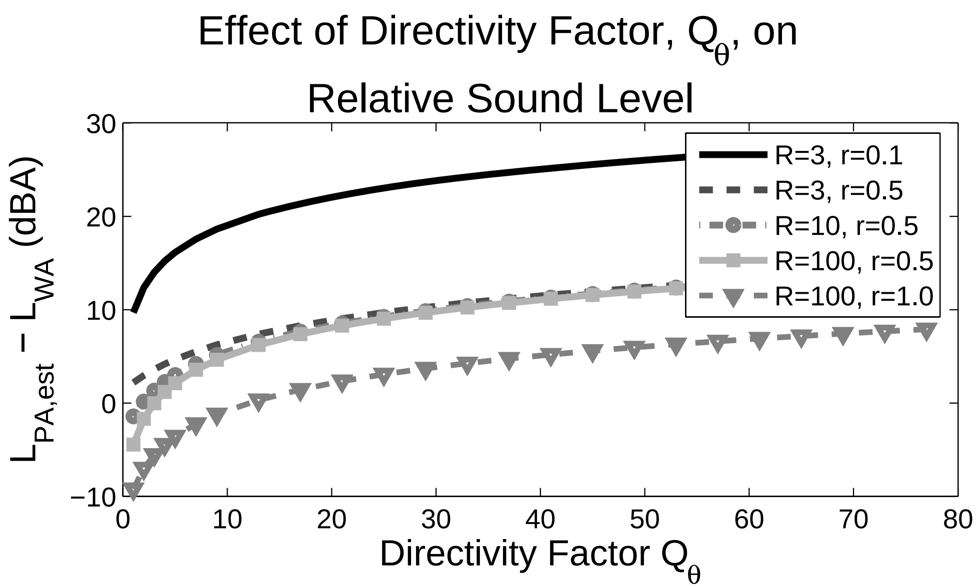

Figure 2: This diagram shows the effect of the directivity factor Q_θ on ($L_{PA,est} - L_{WA}$) for five combinations of acoustical environment and distance from the powered hand tool to the operator's ears. The top curve is for a highly reverberant acoustical environment with a powered hand tool in close proximity to the operator's ears, the middle three curves are for a powered hand tool at 0.5 (m) from the operator's ears in acoustical environments ranging from reverberant to absorptive, and the bottom curve is for an absorptive environment with a powered hand tool a long distance from the operator's ears r = 1.0 m. $L_{PA,est}$ (dBA ref. 20 μPa) and L_{WA} (dBA ref. 10-12 Watts)

The top curve demonstrates maximum ($L_{PA,est} - L_{WA}$) being found in a highly reverberant environment having a short distance from the powered hand tool to the operator's ears. The bottom curve shows the effect on ($L_{PA,est} - L_{WA}$) from a highly absorptive environment having a long distance between the powered hand tool and the operator's ears. The middle three curves have acoustical environments ranging from reverberant to absorptive with a typical distance from the powered hand tool to the operator's ears of $r = 0.5$ m.

The direct sound term dominates as Q_θ increases. Values of a given R have little influence on $L_{PA,est} - L_{WA}$ for $Q_\theta > 10$. A value of $Q_\theta > 10$ can be the result of the source having a high source directivity in combination with being in close proximity to several reflecting planes.

2.2 Distance From the Sound Source to the Operator's Ear, r

The distance from the powered hand tool to the operator's ears, r, greatly effects ($L_{PA,est} - L_{WA}$). Figure 3 shows ($L_{PA,est} - L_{WA}$) for Q_θ = 2, in three acoustic environments (reverberant R=1, intermediate R=10, and absorptive R=100) as r varies from 0.03 m to 1 m. As r approaches 0, the direct sound field dominates and ($L_{PA,est} - L_{WA}$) becomes greater than 20 dBA. ($L_{PA,est} - L_{WA}$) changes less than 10 dBA for all conditions of $r > 0.5$ m and R > 10 m^2, conditions typical of tool operations.

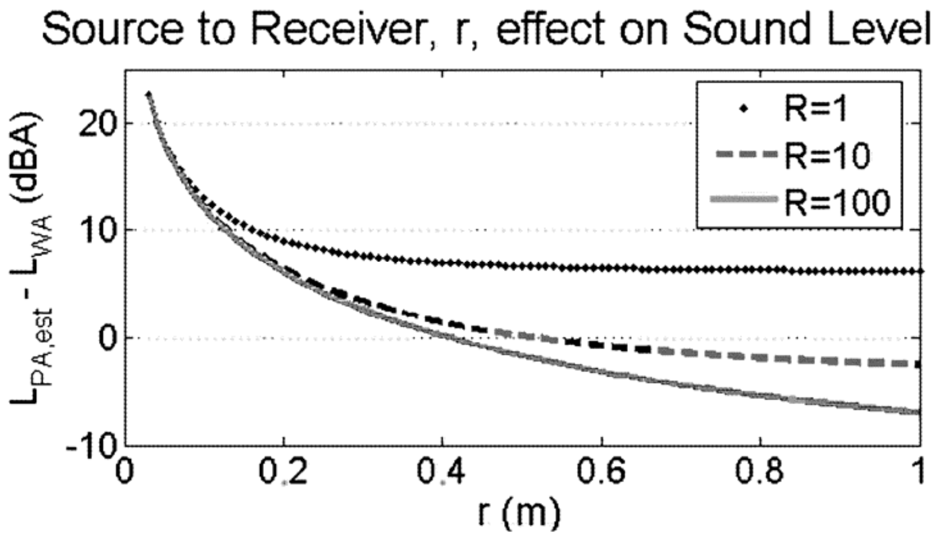

Figure 3: ($L_{PA,est} - L_{WA}$) is calculated from Equation 4 as the distance from operator's ears to the powered hand tool is varied from 0.03 to 1 m. $Q_\theta = 2$ and three values of R representing three different acoustical environments are used in the calculation.

2.3 Room Constant, R

The room constant, *R*, describes the magnitude of both surface area and sound absorption characteristics of a room or volume. The Eyring theory formula for *R* is applicable to enclosed rooms having an average surface absorption, a simple geometry, and a diffuse sound field. The formula for the room constant is:

$$R = \frac{-S\ln(1-\overline{\alpha})}{1-\overline{\alpha}} \tag{7}$$

where *S* is the total surface area of the room and $\overline{\alpha}$ is the average absorption coefficient of the room [13].

Table 2 lists room constants calculated using Equation 7 for various sizes of architectural spaces. A power tool and its operator will not typically be working inside a small volume such as a cabinet or small closet, consequently values for $R \leq 3$ m^2 are presented here strictly for comparative purposes. For general consideration, the range of $R > 3$ m^2 is used as the applicable range of room constants for establishing $L_{PA,est}$ with the point source model. Typical construction site noise exposures occur in the area between R = 1 and R = 100 (m^2).

Table 2: Room constants for various sizes and surface treatments of enclosed architectural spaces. Room constants greater than 3 m^2 are generally applicable to establishing $L_{A,\,est}$ levels.

Room Type	Acoustical Surface Type	R (m^2)	S (m^2)	$\overline{\alpha}$ (0-1)	Room Size L x W x H (m^3)
Small Cabinet	Concrete	0.1	1.5	0.05	0.5 x 0.5 x 0.5
Small Cabinet	Hard	0.2	1.5	0.1	0.5 x 0.5 x 0.5
Large Cabinet	Concrete	0.3	6	0.05	1 x 1 x 1
Large Cabinet	Hard	0.7	6	0.1	1 x 1 x 1
Closet	Concrete	1.3	24	0.05	2 x 1.3 x 2. 85
Closet	Soft	3	24	0.2	2 x 1.3 x 2. 85
Small Room	Hard	6	52	0.1	3 x 3 x 2.85

Small Room	Soft	15	52	0.2	3 x 3 x 2.85
Small Office	Hard	13	110	0.1	6.7 x 3 x 2.85
Small Office	Soft	30	110	0.2	6.7 x 3.8 x 2.85
Conference Room	Hard	30	260	0.1	8 x 10 x 2.85
Conference Room	Soft	130	260	0.3	8 x 10 x 2.85
Ball Room	Hard	350	3000	0.1	30 x 30 x 10
Ball Room	Soft	840	3000	0.2	30 x 30 x 10
Hemi Anechoic Chamber	Absorptive Surfaces, Reflective Floor	1180	800	0.513	8 x 4 x 3
Open-Field	Hard Ground	∞	∞	1.0	∞

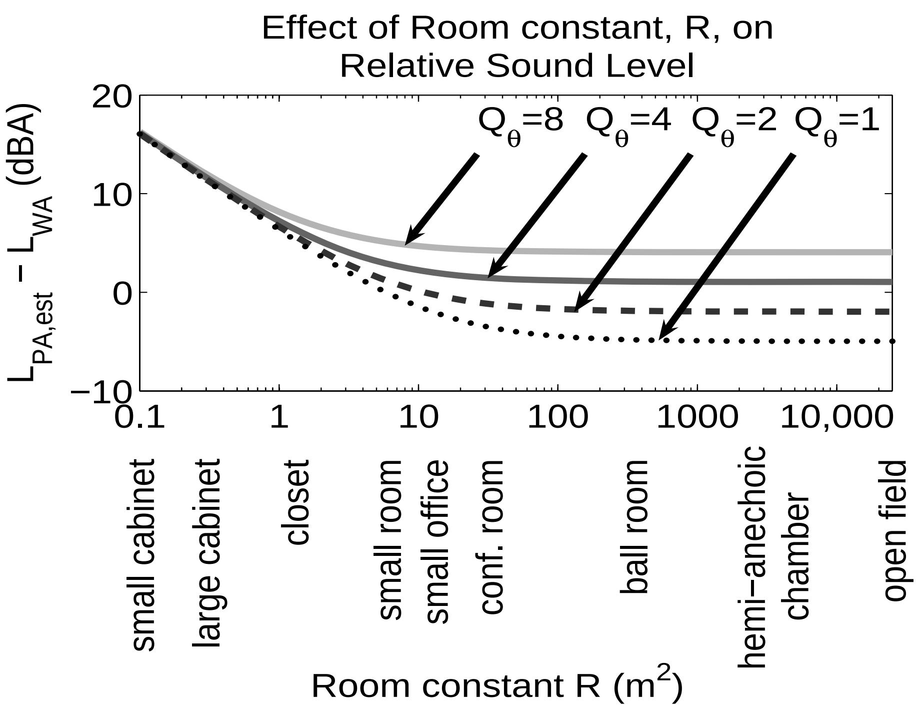

Figure 4: From Equation 4, ($L_{PA,est} - L_{WA}$) is calculated as the Room Constant, R, is varied from 0.1 to 25,000 (m2), Qθ = 1, 2, 4, and 8, and r = 0.5 (m). LPA, est (dBA ref. 20 µPa) and LWA (dBA ref. 10-12 Watts)

3 METHODS

The sound pressure level (L_{PA}) used to calculate L_{WA} for 118 powered hand tools was measured using a 10-microphone array over a hemispherical measurement surface, in accordance with ISO 3744. The hemi-anechoic chamber, measurement setup, and data processing, analysis, and presentation of L_{PA}, L_{WA}, and $L_{PA,meas}$ are described in detail in the project's study protocol, searchable website database, and other subsequent documents [16,17,18,19,20]. The determination of the values of Q_{θ}, r, and R for the tests are detailed below. Note that an 11th microphone was positioned at what would be in the tool operator's hearing zone. $L_{PA,meas}$ was measured using this 11th microphone and likewise, r was measured from the 11th microphone to the powered hand tool.

Each powered hand tool of similar type was oriented in the same direction for each of the measurements so that the directivity could be compared within powered hand tool types. Q_{θ} at the operator's ears was calculated for an angle passing through the operator's ears over one reflecting plane using the sound pressure data from the 10-microphone array and Equation 5. Influences on directivity due to the powered hand tool direct noise emissions and the indirect emissions resulting from the reflecting plane are included in calculating Q_θ (see Equations 5 and 6).

A total of 234 sound power level tests were conducted with a variation in the loading conditions and the distance, r, between the powered hand tool and an 11th microphone. 127 tests were conducted with r=0.89 m (99 unloaded, 28 loaded) and 107 tests were conducted with r=0.50 m (18 unloaded, 89 loaded). The use of two different distances, r, provided a variation of that parameter for the purpose of validating its effect on the model. The loading condition was in accordance with ANSI S12.15 [19]. However, where the standard specified testing in the full speed, no load condition, the tools were tested in both the unloaded condition and the loaded condition. The loaded/unloaded tool data were gathered as part of another study of the effects of loading conditions on sound power level [21].

The value of R in the hemi-anechoic chamber was calculated using Equation 7. S was obtained by measuring the surface area of the reflective floor and the outer surface area of the acoustical wedges on the walls and ceiling. $\overline{\alpha}$ was estimated by measuring the reverberation time and applying the results to Equation 8:

$$\overline{\alpha} = 1 - e^{\left(\frac{4mV}{S} - \frac{55.3\,V}{c\,T_{60}\,S}\right)} \tag{8}$$

where T_{60} (s) is the reverberation time, V (m^3) is the volume of the hemi-anechoic chamber, c (m/s) is the speed of sound, $2m$ (Np/m) is the energy air absorption exponent, S (m^2) is the total surface area, and $\overline{\alpha}$ is the average sound absorption coefficient [13]. T_{60} was obtained by discharging a cap gun in the chamber and measuring the time for sound pressure level to decay by 60 dB in the hemi-anechoic chamber.

4 DATA ANALYSIS

For each of the 240 test runs, the respective L_{WA}, Q_θ, r, and R was applied to Equation 4 to obtain the $L_{PA,est}$ calculation. The resulting value of $L_{PA,est}$ was then compared to $L_{PA,meas}$. The $L_{PA,est}$ - $L_{PA,meas}$ difference was calculated for each tool in the loaded and unloaded condition. The mean, standard deviation, and confidence interval of the difference were calculated for each tool type. Similarly, the difference and statistical analysis were performed on the same data set for L_{WA} - $L_{PA,meas}$.

In some instances as noted in the results section, the measured sound pressure level was adjusted to reflect values of R=10 m^2 and r=0.5 m. With R=10 m^2, a more conservative and realistic condition of that found on construction sites is modeled. The adjusted value also sets the sound pressure level to sound power level difference closer to zero (as can be seen in Figure 4 for R=10 m^2 vs. R=1180 m^2, for Q_θ=2). While all calculations for estimated and adjusted L_{PA} used the Q_θ calculated for that particular tool relative to the 11th microphone position, the overall Q_θ was approximately 2. The adjustment is made by:

$$\begin{aligned} L_{PA,meas}(Adjusted) = L_{PA,meas} &+ 10\log\left(\frac{Q_\theta}{4\pi 0.5^2} + \frac{4}{10}\right) \\ &- 10\log\left(\frac{Q_\theta}{4\pi (r_{used\ in\ test})^2} + \frac{4}{1180}\right) \end{aligned} \tag{9}$$

Recall that the hemi-anechoic environment had R=1180 m^2 and it is more likely the construction site environment will have some R considerably less that 1180 m^2. The L_{WA} - $L_{PA,meas(Adjusted)}$ data set were analyzed in a similar fashion to the L_{WA} - $L_{PA,meas}$ data.

5 RESULTS

Q_θ for the powered hand tools tested in the unloaded condition had an average of 1.98 ± 0.17 (0.90, 2.88). Q_θ for tools tested in the loaded condition had an average of 2.30 ± 0.55 (0.79, 3.82). Exact values of Q_θ were used in all calculations. Values of r=0.89 m and r=0.50 m that were used during the tests were also used in all calculated results presented in Figures 5 and 6. Adjusted values of r=0.5 m were used in calculating results presented in Figure 7. Similarly, R of the hemi-anechoic environment was determined to be 1180 m^2 and was used in Figure 5 and 6 calculations while the adjusted value of R=10 m^2 was used in Figure 7 calculations.

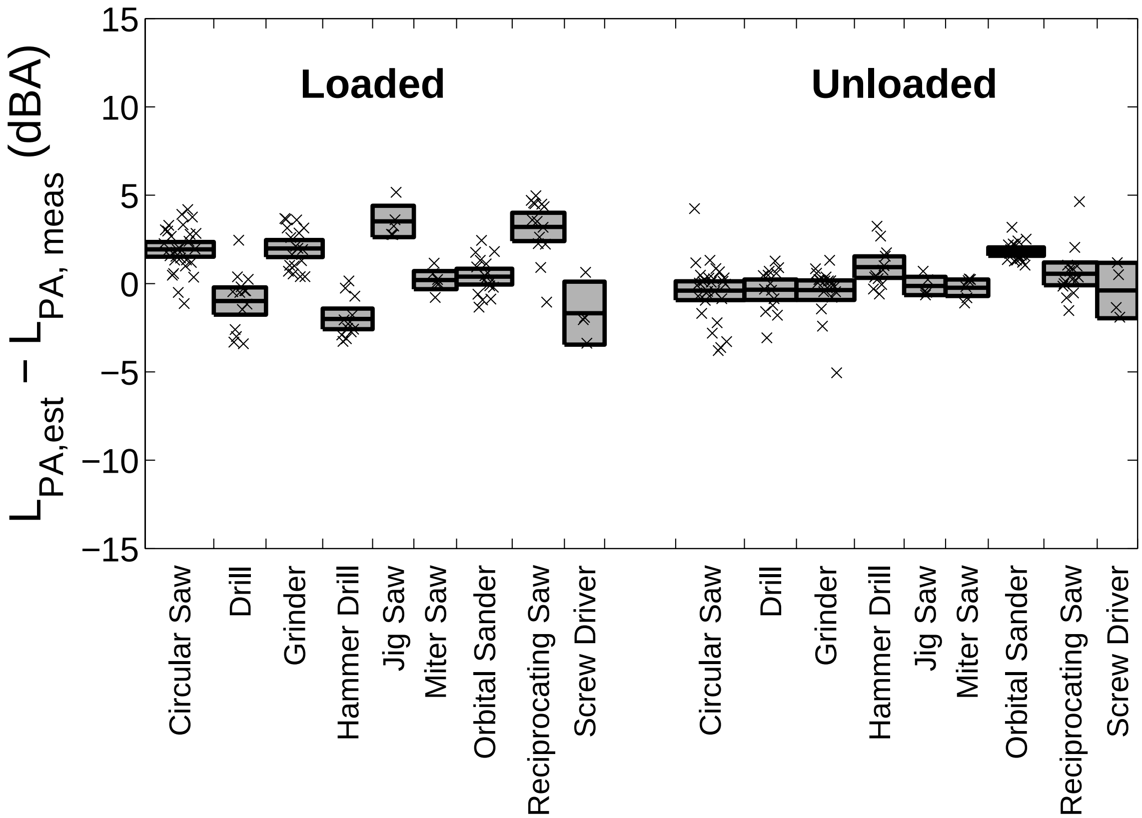

Figure 5: The difference between the estimated sound pressure level calculated from the model and actual measured sound pressure level is typically between 6 dB and -4 dB for both the loaded and unloaded condition.

Table 3: The mean, standard deviation, and confidence interval of the difference between estimated sound pressure level and measured sound pressure level for tools tested in the loaded and unloaded condition. The number of different types of models tested of a particular tool is shown in parenthesis next to the tool type.

$L_{PA,\ est}$ - $L_{PA,\ meas}$	Loaded test condition	Unloaded test condition
Tool Type (number tested)	Mean ± Stand. Dev. (Confidence Interval)	Mean ± Stand. Dev. (Confidence Interval)
Circular Saw (28)	1.94 ± 1.30 (1.52, 2.36)	-0.41 ± 1.67 (-0.95, 0.13)
Drill (14)	-0.99 ± 1.65 (-1.77, -0.22)	-0.35 ± 1.23 (-0.93, 0.23)
Grinder (18)	1.98 ± 1.17 (1.50, 2.46)	-0.37 ± 1.39 (-0.92, 0.18)

Hammer Drill (12)	-2.00 ± 1.14 (-2.59, -1.41)	0.93 ± 1.18 (0.32, 1.54)
Jig Saw (5)	3.52 ± 0.98 (2.63, 4.41)	-0.14 ± 0.57 (-0.66, 0.38)
Miter Saw (6)	0.20 ± 0.65 (-0.31, 0.71)	-0.24 ± 0.58 (-0.70, 0.22)
Orbital Sander (17)	0.39 ± 1.06 (-0.06, 0.84)	1.81 ± 0.57 (1.57, 2.05)
Reciprocating Saw (14)	3.21 ± 1.70 (2.41, 4.01)	0.55 ± 1.42 (-0.09, 1.19)
Screw Driver(4)	-1.68 ± 1.67 (-3.47, 0.11)	-0.40 ± 1.47 (-1.97, 1.17)

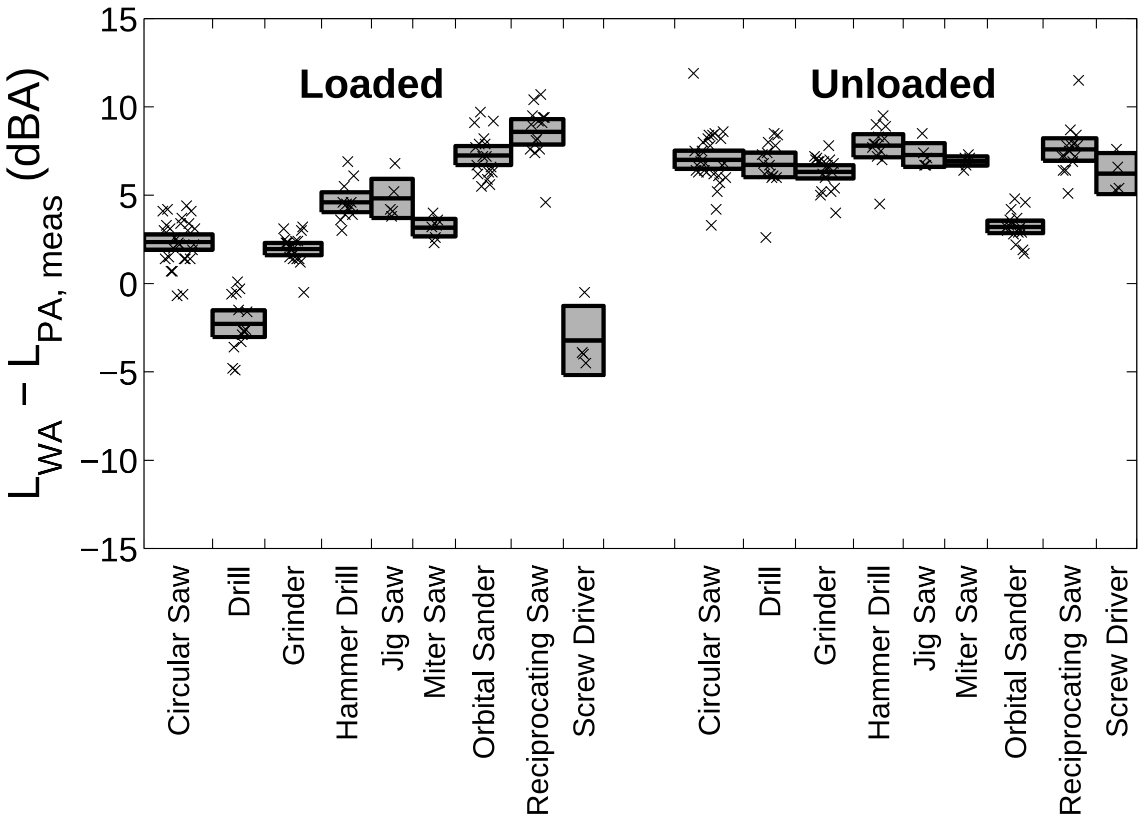

Figure 6: The difference between the magnitude of the sound power level and the measured sound pressure level at the operator's ears is compared across different tool types and loading conditions.

Table 4: The mean, standard deviation, and confidence interval of the difference between the sound power level and the measured sound pressure level for tools tested in the loaded and unloaded condition. The number of different types of models tested of a particular tool is shown in parenthesis next to the tool type.

L_{WA} - $L_{PA, meas}$	Loaded test condition			Unloaded test condition		
Tool Type (number tested)	Mean	Standard Deviation	Confidence Interval	Mean	Standard Deviation	Confidence Interval
Belt Sander (1)	3.80	-	-	7.60	-	-
Circular Saw (28)	2.35	1.35	0.43	7.01	1.59	0.51
Drill (14)	-2.28	1.60	0.76	6.71	1.48	0.70
Grinder (18)	1.95	0.87	0.35	6.32	0.96	0.38
Hammer Drill (12)	4.60	1.09	0.56	7.80	1.28	0.66
Impact Wrench (1)	5.20	-	-	6.80	-	-
Jig Saw (5)	4.82	1.23	1.10	7.28	0.74	0.67
Miter Saw (6)	3.17	0.63	0.50	6.93	0.33	0.26

Orbital Sander (17)	7.25	1.29	0.54	3.21	0.84	0.35
Reciprocating Saw (14)	8.59	1.53	0.72	7.59	1.40	0.63
Screw Driver(4)	-3.23	1.84	1.96	6.23	1.09	1.16

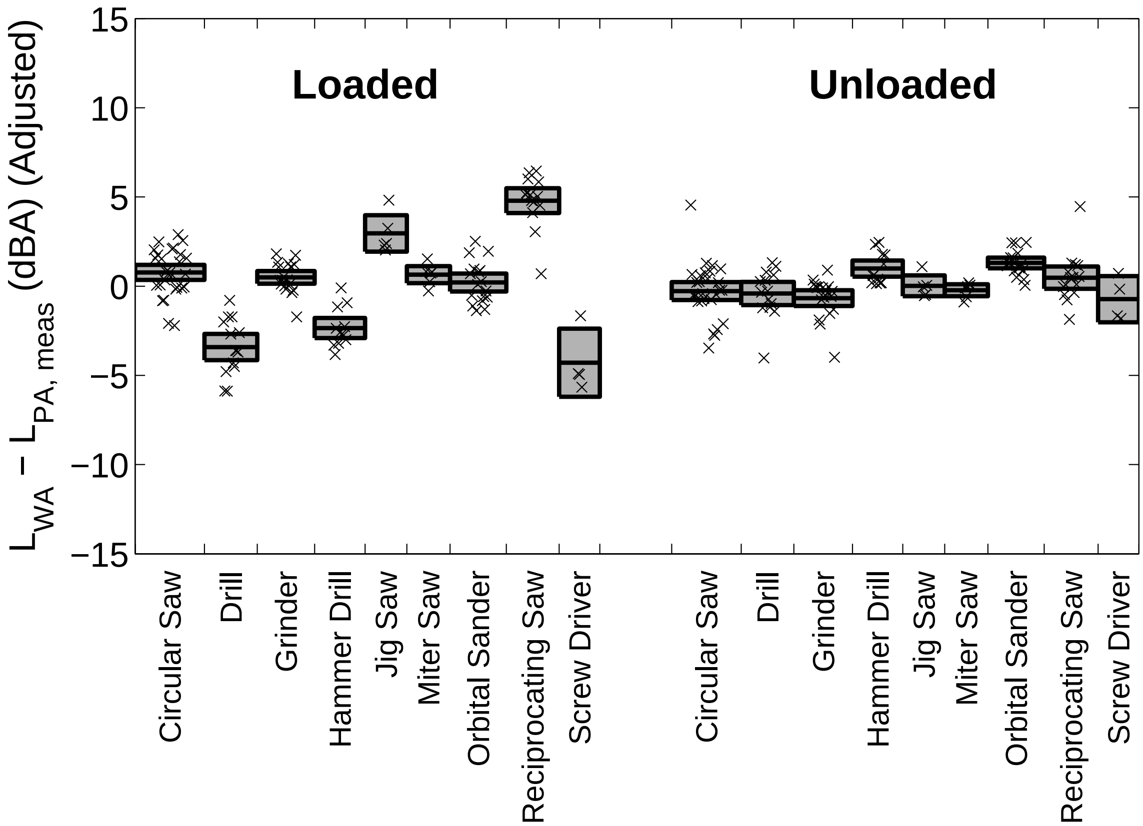

Figure 7: The difference between the magnitude of the sound power level and the measured sound pressure level was adjusted for R=10 m2 and r=0.5 m. The graph demonstrates that sound power level magnitude may be a useful metric for estimating the sound pressure level exposures to operators of powered hand tools.

Table 5: The mean, standard deviation, and confidence interval of the difference between sound power level and adjusted measured sound pressure level for tools tested in the loaded and unloaded condition show that the sound power level can estimate the noise exposure in the loaded and unloaded conditions within 5 dB on average. The number of different types of models tested of a particular tool is shown in parenthesis next to the tool type.

L_{WA} - $L_{PA, meas}$	Loaded test condition	Unloaded test condition
Tool Type (number tested)	Mean ± Stand. Dev. (Confidence Interval)	Mean ± Stand. Dev. (Confidence Interval)
Circular Saw (28)	2.35 ± 1.35 (1.92, 2.78)	7.01 ± 1.59 (6.50, 7.52)
Drill (14)	-2.28 ± 1.60 (-3.04, -1.52)	6.71 ± 1.48 (6.01, 7.41)
Grinder (18)	1.95 ± 0.87 (1.60, 2.30)	6.32 ± 0.96 (5.94, 6.70)
Hammer Drill (12)	4.60 ± 1.09 (4.04, 5.16)	7.80 ± 1.28 (7.14, 8.46)
Jig Saw (5)	4.82 ± 1.23 (3.72, 5.92)	7.28 ± 0.74 (6.61, 7.95)
Miter Saw (6)	3.17 ± 0.63 (2.67, 3.67)	6.93 ± 0.33 (6.67, 7.19)
Orbital Sander (17)	7.25 ± 1.29 (6.71, 7.79)	3.21 ± 0.84 (2.86, 3.56)
Reciprocating Saw (14)	8.59 ± 1.53 (7.87, 9.31)	7.59 ± 1.40 (6.96, 8.22)
Screw Driver(4)	-3.23 ± 1.84 (-5.19, -1.39)	6.23 ± 1.09 (5.07, 7.39)

6 DISCUSSION

Figure 5 shows the difference between the $L_{PA,est}$ calculated using the model from Equation 4 and the $L_{PA,meas}$. The graph separates the loaded and unloaded test conditions and groups the models according to tool types. A value of zero dBA on the y-axis coincides with the sound pressure model perfectly estimating the actual sound pressure level exposure without error. Points below zero dBA on the y-axis indicate areas where the model underestimates $L_{PA,est}$ and above zero indicates an overestimation. The data show more variation for tools tested in the loaded condition versus those tested in the unloaded condition. The greater variability when testing tools in the loaded condition may be expected as the tool is typically changing distances relative to the microphone used to gather $L_{PA,meas}$. This would be true also for gathering data in the field, further exemplifying the need to make broad-based noise exposure assessments using the magnitude of L_{WA} (versus archiving a limited library of field sound pressure level measurements and consequently using that archive to estimate noise exposures across an entire population of tools, acoustical environments, and tool operators). Table 3 provides the magnitude of the mean, standard deviation, and confidence interval for each tool type and loading condition shown in Figure 5. The mean of the difference in sound levels for each tool type are more nearly zero for the unloaded condition data, again showing the greater variability for the loaded condition test data.

Figure 6 illustrates the relative difference between the L_{WA} and the $L_{PA,meas}$ as gathered in the hemi-anechoic environment. The figure is presented to show the difference before any adjustment is made to $L_{PA,meas}$. Substituting the magnitude of L_{WA} for $L_{PA,meas}$ results in an underestimation of noise exposure (i.e., values below zero on the y-axis). Conversely, all values above zero represent an overestimation of noise exposure. Table 4 shows the relative difference between the L_{WA} and the $L_{PA,meas}$ before adjustments. It can be argued that using the magnitude of L_{WA} directly to estimate $L_{PA,meas}$ and consequently, choosing appropriate hearing protection, would result in overprotecting the worker. However, considering the data used to evaluate the Eyring theory model were taken in a highly sound absorptive environment, $L_{PA,meas}$ would tend to be lower, thus underestimating a worker's real-world noise exposure. If all construction projects and powered hand tool use took place in an open-field environment over a reflecting plane the unadjusted model would be sufficient. However, that environment is ideal in minimizing powered hand tool noise exposure. The typical acoustical environment of a construction site would be a more enclosed and reverberant environment. Therefore, $L_{PA,meas}$ is adjusted as described above to provide a more conservative and realistic estimate of a worker's noise exposure when operating powered hand tools.

Figure 7 shows the difference between the L_{WA} and the $L_{PA,meas\ (Adjusted)}$. As in Figure 6, values below zero on the y-axis underestimate a worker's exposure and values above zero overestimate exposure. However, in Figure 7, overestimation becomes less likely since the adjustment typically increases the sound pressure levels in order to better model the acoustical environment of a construction site. Table 5 shows that the mean of the difference in sound levels after the adjustment: a comparison of Table 4 and Table 5 shows that the mean of the difference in sound level is closer to zero dBA. These results demonstrate that the magnitude of L_{WA} can be used to estimate noise exposures of tool operators.

6.1. Field Condition Effects

Q_θ values measured in the lab will vary in the field when the powered hand tool is operated near more than one reflecting plane. Given the general Q_θ value in the lab equaled approximately 2 and that it could range as high as 8 due to additional reflecting planes, the model could underestimate ($L_{PA,est} - L_{WA}$) by as much as 6 dBA (or 10 Log (2/8)).

The r used in the lab is similar to the r in the field. All the data is adjusted to r=0.5 m, the nominal value to be expected for powered hand tool operation. As such, little difference in field to lab ($L_{PA,est} - L_{WA}$) would be expected as a function of r.

For a given sound source, ($L_{PA,est} - L_{WA}$) changes very little for R>100 m^2. However, taking the same sound source, with fixed Q_θ and r, and moving it through acoustical environments from R=10 m^2 up through R=100 m^2, reduces ($L_{PA,est} - L_{WA}$) by as much as 3 dBA. Even greater reductions occur when comparing operation of a non-directional source in a highly reverberant environment to a highly absorptive environment. By this logic, the aggregate reduction in ($L_{PA,est} - L_{WA}$) could be as much as 3 dBA (6 dBA–3 dBA) for the operation of a given powered hand tool across any number of acoustical environments found on construction sites.

In Figures 2-4, the relative sound level ($L_{PA,est} - L_{WA}$) is plotted for various ranges of the parameters Q_θ, r, and R, for the purpose of understanding how the Eyring theory models $L_{PA,est}$, a tool operator's exposure, using the L_{WA}. The ranges of Q_θ, r, and R theoretically applicable to a tool operator using a powered hand tool on a construction site are $0 < Q_\theta < 80$, $0.03 < r < 1$ m, and $R > 3$ m^2. The entire ranges of all combinations of Q_θ, r, and R presented in these figures can theoretically be produced, yet gathering $L_{PA,meas}$ for each of these combinations is cost prohibitive if not logistically impossible. From Figures 2-4, the variation of ($L_{PA,est} - L_{WA}$) due to different combinations of Q_θ, r, and R within the above stated applicable ranges are approximately +28 to -10 dBA, +23 to -7 dBA, and +6 to -5 dBA respectively. The extreme values of ($L_{PA,est} - L_{WA}$) from the theoretical analysis are physically possible, but may be infrequent for many construction workers. From Figures 6 and 7, the variation in ($L_{PA,est} - L_{WA}$) is +5 to -12 dBA and +6 to -6.5 dBA respectively. From Figure 7, for each tool type the mean value of $L_{PA,est} - L_{WA}$ had a range of +5 to -5 dBA, which may be more representative of actual field use on a construction site.

7 CONCLUSIONS

The theoretical and laboratory results show the two quantities $L_{PA,est}$ and L_{WA} are more nearly equal when consideration is given to the variety of acoustical environments for powered hand tools use.

ISO standard 11203 (given here as Equation 1) advocates subtracting 4 to12 dB from measured sound power level to estimate sound pressure level exposures. Equation 2, giving the rule of thumb provided in the Australian government noise control guide [11], subtracts 2 to 8 dB from measured sound power level to estimate sound pressure level exposure. Using these methods will invariably underestimate the noise hazard the worker's being exposed to and if hearing protection is chosen accordingly, lead to under-protecting the worker--increasing hearing loss. Given a reasonable $L_{PA,meas}$ estimator such as L_{WA}, it becomes feasible to provide the most comprehensive and economical noise exposure data set for powered hand tool operators. Of course, an accurate estimate is only viable where the L_{WA} magnitude is obtained appropriately and then made conveniently available to the tool user or safety professional through tool labeling or internet accessible database.

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