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Dear JSHER Readers:

As an Editorial Review Board member, former editor, author and reader of this publication, I have mixed emotions as I write to inform you of our final issue. JSHER began both to enable the scholarship of teaching occupational safety and health to have a viable outlet and as an alternative research publication to the more established safety journals. While we have published some impactful articles in JSHER, neither goal established a compelling and lasting foundation, leading to lower readership and support. For the near future at least, we will maintain the JSHER archive on the ASSP website.

Last year, ASSP created its Council on Academic Affairs and Research, which reports to the Board of Directors. We believe this will raise the focus on research within the Society and ensure impact among the broad ASSP membership. The council is actively evaluating alternative means for scholarly output. As researchers, practitioner partners and consumers of research, we must work collaboratively to foster a more practical research agenda with new and meaningful outputs. The Society maintains a responsibility to enable members to be informed consumers of the vast array of information made available to us; our decisions based on this information have significant safety and health consequences. As we know, research underpins professional knowledge, advancement and practice, and it connects the profession with new sources of knowledge and ideas, enabling practical and meaningful solutions. ASSP is moving in this direction, but we have much work to do.

While writing this JSHER farewell, I reflected on my 2011 editorial in which I shared my ideologies about the integration of academics and research in the occupational safety and health discipline. My philosophy has not wavered in the intervening years. Please take a moment read that editorial and share your feedback.

Sincerely,
Michael Behm, Ph.D., CSP
Vice President, Council on Academic Affairs and Research

Dynamic 3D Blind Spot Mapping for Equipment Operations

Siyuan Song, Eric Marks and Gary Moynihan

ABSTRACT

Construction site characteristics tend to foster dynamic work environments with a multitude of interactions between moving equipment and pedestrian employees. Blind spot and obstructions can cause struck-by incidents between equipment and employees on construction sites. The research objective was to create a framework to identify and quantify areas not visible to construction equipment operators. A methodology including algorithms are provided to aid construction management personnel to calculate equipment operator blind spots given various situations and conditions. An indoor construction working environment was implemented to evaluate the effectiveness of the developed framework as part of the research methodology. An automated laser scanner was used to collect location-based data which was exported as a point cloud into a building information model. By identifying and quantifying equipment operator blind spots in 3D, construction site personnel can automatically detect and quantify non-visible areas for construction operators along equipment travel paths.

Keywords: *operator visibility, construction safety, struck-by incidents*

1. INTRODUCTION

Visibility-related issues, specifically blind spots of equipment operators, have been known to cause injuries and fatalities on construction sites (Teizer, et al., 2010). It is estimated that 5% of U.S. construction fatalities were visibility related (Teizer & Hinze, 2011). Virtual environments provide an opportunity for construction management personnel to identify higher risk hazards caused by moving construction equipment (Perlman, et al., 2014). Although sensing technology and other proactive strategies have been implemented to combat this problem, injuries and fatalities still result from limited construction equipment operator visibility (Lancaster, et al., 2007). A research need exists to explore more effective methods to solve the human-equipment interaction issue. One solution is to increase operator visibility through advanced equipment design by including nearby ground workforce equipment (Marks, et al., 2013). The research is aimed to create a framework to measure and calculate blind spots for pieces of construction equipment in construction working environments.

2. LITERATURE REVIEW

Construction workers encounter multiple hazards on construction sites. The dynamic environment of construction sites often fosters hazardous interactions between construction equipment and pedestrian workers. Previous research has identified situations in which construction equipment operators experienced limited visibility, and often are unable to identify pedestrian workers around a piece of construction equipment (Marks, et al., 2013). The following review discusses research concerning visibility measurement for construction equipment operators in order to design an optimal blind spot mapping and calculation framework. The following sections discuss construction safety statistics, visibility-related incidents, and visibility research for construction site personnel.

2.1 Human-Equipment Interactions on Construction Sites

The U.S. construction industry experienced 937 fatalities in 2015, accounting for 19% of all U.S. workplace fatalities that year (BLS, 2017). The total of 159 fatalities were categorized as struck-by incidents in which a piece of construction equipment or other objects struck a pedestrian worker. This value accounted for 17% of all U.S. construction fatalities in the U.S. in 2015 (BLS, 2017).

Visibility has been identified as an important cause in many safety incidents between construction equipment and pedestrian

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employees (Teizer, et al., 2010b). For example, excavator operators can experience up to 50% obstruction of their field-of-view during operation due to components of the equipment (Teizer, et al., 2010b). Other research identified the design of heavy equipment as an impact factor for the level of hazard experienced by construction employees (Lingard, et al., 2013). Non-visible were cited as a major issue on construction sites when specifically discussing struck-by incidents (Lingard, et al., 2013).

2.2 Construction Operator Visibility Quantification

Other researchers have explored measuring equipment operator visibility. Static operator blind spots were automatically identified through an algorithm that analyzes point cloud data (Teizer, et al., 2010a). Other researchers created a framework for quantifying and measuring the visibility of a forklift operation working in a manufacturing plant (Shen & Marks, 2016). This framework includes identifying blind spots obstructed by the forklift equipment components and materials that obstruct the view of the manufacturing environment (Shen & Marks, 2016).

Heat map generation is another tool that has been implemented for predictive safety planning in preventing struck-by and near miss interactions between workers-on-foot and construction equipment (Golovina, et al., 2016). Various legends and colors were used to represent safety barricades, equipment paths, pedestrian worker travel paths and equipment operator blind spots.

2.3 Blind Spot Measurement Methods

Ray tracing is a technique for generating an image by tracing the path of light through pixels in an image plane and simulating the effects of its encounter with virtual objects (Reshetov, et al., 2005). The use of a ray tracing algorithm to automatically measure the blind spot was validated on construction sites through outdoor testing (Teizer, et al., 2010a).

A new approach was developed to compute blind spots through point cloud data (Ray & Teizer, 2013). To compute the 3D blind spot of construction equipment, multiple laser scans were fused to create a comprehensive blind spot map (Ray & Teizer, 2013). A blind spot measurement tool was also created based on results of laser scanning (Marks, et al., 2013).

Choudhury, et al. (2014) created a visibility color map, defined as a surface color map of the space, where each view point of the space is assigned a color value that denotes the visibility measure of the target from that viewpoint. Measuring the visibility of a target from different viewpoints needs to consider factors such as distance, angle, and obstacles between the view point and the target (Choudhury, et al., 2014).

2.4 Research Needs Statement

Struck-by incidents resulting from limited visibility of construction equipment operators often result in injuries and fatalities. A need exists to further investigate methods for quantifying operator visibility, specifically along an equipment travel path in a construction working environment. This research uses collected laser scan data to quantify the dynamic blind spots of equipment operators. The innovation in this research is the quantification of the dynamic blind spot of construction equipment operators. By quantifying visibility information for construction operators, visibility-related hazards can be identified and mitigated proactively on construction sites.

3. METHODOLOGY

Due to the complexity and dynamic nature of typical construction sites, construction equipment operators often experience impeded visibility and may be unable to see a pedestrian worker. This research evaluates nonvisible areas in an indoor construction environment and establishes a framework for measuring blind spot from different perspectives. The non-visible area is defined as a blind spot for the equipment operator. The shaded area in Figure 1 represents a sample blind spot for an equipment operator that is obstructed by an object on the ground.

This research identified and quantified blind spot areas for equipment operators from a specific viewpoint. The visibility was analyzed from several viewpoints along an equipment travel path. This viewpoint can be due to moving pieces of construction equipment or pedestrians. Because the non-visible area changes for different locations of the viewpoint, different situations were discussed in the following sections. A 3D cube was selected to quantify visibility of an equipment operator. Any 3D object can be used, but a cube simplifies the process. Shaded areas in Figure 1 represent areas that are not visible to the equipment operator.

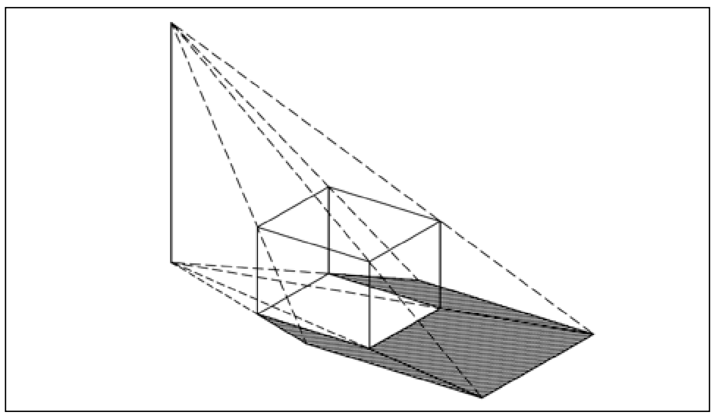


Figure 1. Conceptual model for analyzing nonvisible areas on construction sites

3.1 Identification of Blind Spots

Table 1 (p. 350) gives the definition of variables that are used in the remainder of this article. All variables can be found in Figure 2 and Figure 3 (p. 350).

A blind spot can be determined by finding the length (Y) and the width (D) of a non-visible area. The range of α and β are defined as $0° < \alpha < 180°$ and $0° < \beta < 180°$. Assume that input viewpoint height (m) and obstacle height (n) are given. From Figure 2, it can be noticed that when α larger than 90°, Y value will be infinity without a boundary. In this way, two situations have been discussed in the following sections:

Variable	Description
m	Viewpoint height
n	Object height
m - n	Vertical height differences between viewpoint and objects
a	Horizontal distance differences between viewpoint and objects
b	Chosen side length
α	Vertical angle between viewpoint and objects
β	Horizontal angle of chosen side
D	Non-visible area width
Y	Non-visible area length
L	The sum of horizontal distance differences and non-visible area length
R	Visual range

Table 1: Descriptions of variables used to quantify non-visible area

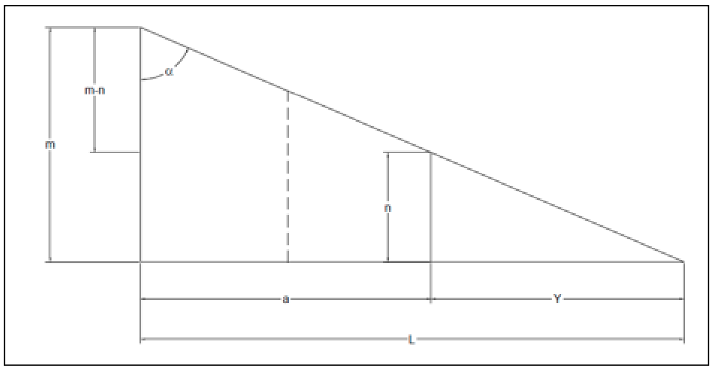


Figure 2: Side view of the conceptual model

Situation 1

When 0° < α < 90°, the conceptual model is an example of situation 1 (Figure 2). It can be seen from Equation 1 and Equation 2, the value of n and m are given, a value is the only variable that can affect Y value.

tanα = a/(m-n) ***Equation 1***

Y = n tanαα = n a/(m-n) ***Equation 2***

From the top view of the conceptual model (Figure 3), the D value can be calculated (using the law of cosines) by Equation 3 and Equation 4:

$$D^2 = L_1^2 + L_2^2 - 2L_1L_2 \cos\beta$$ ***Equation 3***

$$\begin{cases} L_1 = a_1 + Y_1 \\ L_2 = a_1 + Y_2 \\ \cos\beta = \frac{a_1^2 + a_2^2 - b^2}{2a_1a_2} \end{cases}$$ ***Equation 4***

From Equation 2, the Y value can be calculated if a value is given. In Equation 4, β value then can be calculated if b value is also given. Variables a and b are the impact factors of the D value. Also note that blind spot A can be determined after finding the Y and the D value. Areas of B and C can also be determined by following the same process.

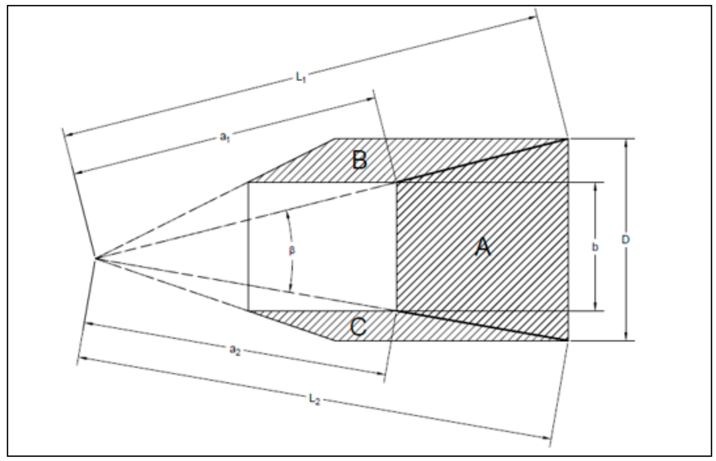


Figure 3: Top view of the conceptual model for analyzing blind spots

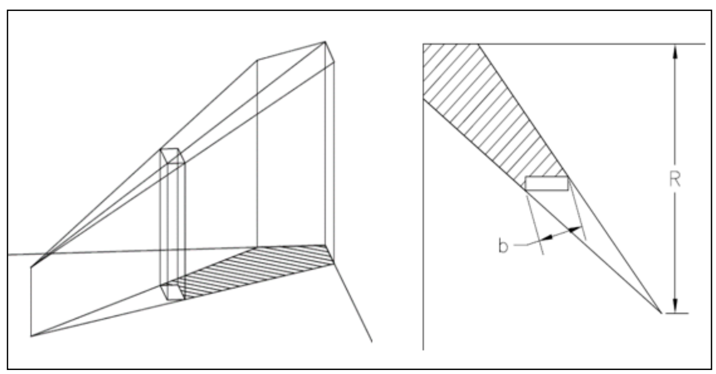


Figure 4: Model of situation 2 when 90° ≤ α < 180°

Situation 2

In Figure 4, when 90° ≤ α < 180°, the shaded area will lie on both the viewpoint and work zone boundaries (or visual range R). In this situation, b value and R value become the impact factors of the blind spot.

In sum, the blind spot area can be calculated by inputting the value of variables m, n, a, b and R. The developed approach should also allow adjusting for equipment operators with different body heights or selecting different viewpoints. Combining the methodology processes, a framework is created to measure the blind spot within different situations and is shown in Figure 5.

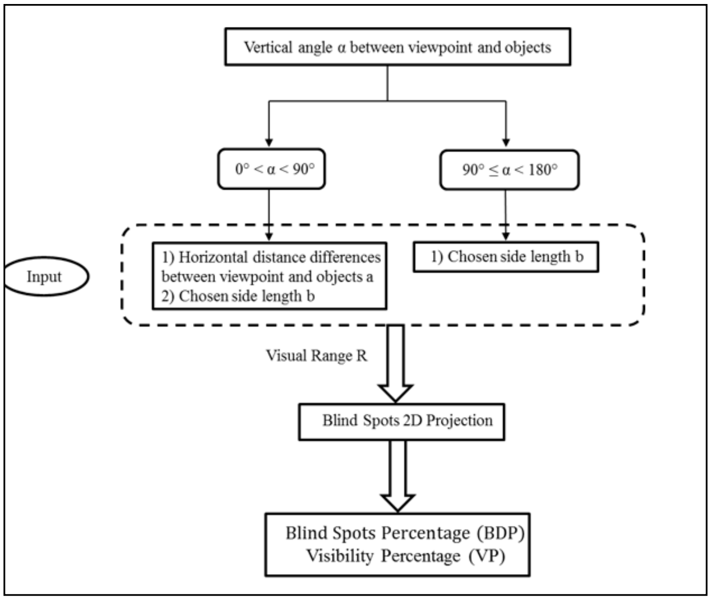


Figure 5: Blind spot measurement framework

3.2 Blind Spot Percentage

A construction site should decrease the percentage of blind spots to maintain a safe construction work environment. In this way, the research also wants to calculate the percentage of the total shaded area. By following the previous calculation processes, blind spot are shown in a 2D view which is depicted in Figure 6. The area of the shaded zone can be automated calculated by using Autodesk AutoCAD internal tool (area) by selecting specific objects as shown in Figure 6. Equation 5 can be used to calculate the blind spot percentage in a certain work environment:

Blind spots percentage (BDP) = (Total shaded area (TSA))/ Work zone area (WZA)) ***Equation 5***

Visibility percentage (VP) = 1 - BDP ***Equation 6***

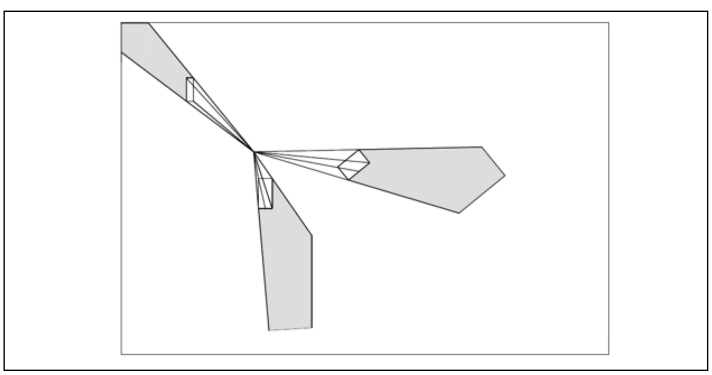


Figure 6: 2D view of blind spot of a construction site

4. CASE STUDY

Research has verified that an automated process that measures construction progress using 3D laser scanning technology is more accurate than image processing because point clouds establish a 3D environment to represent the construction site rather than fragmentary pictures (Zhang & Arditi, 2013). A 3D laser scanner was used to generate and collect several spatial point clouds as shown in Figure 7. From a certain viewpoint, objects can obstruct visibility in the construction environment. Walk-through views have been used to define the travel path and objects in an active construction site. A simplified BIM model was created in AutoCAD to define and calculated the blind spot as shown in Figure 8.

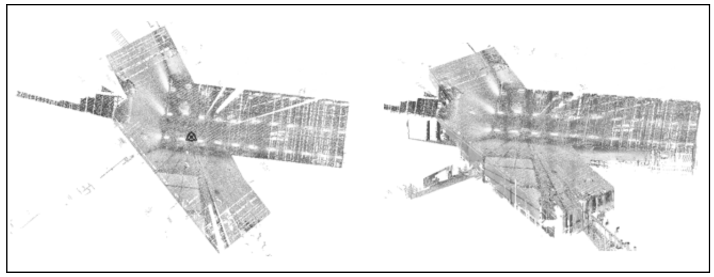


Figure 7: Sample laser scanning point cloud data of an indoor construction site

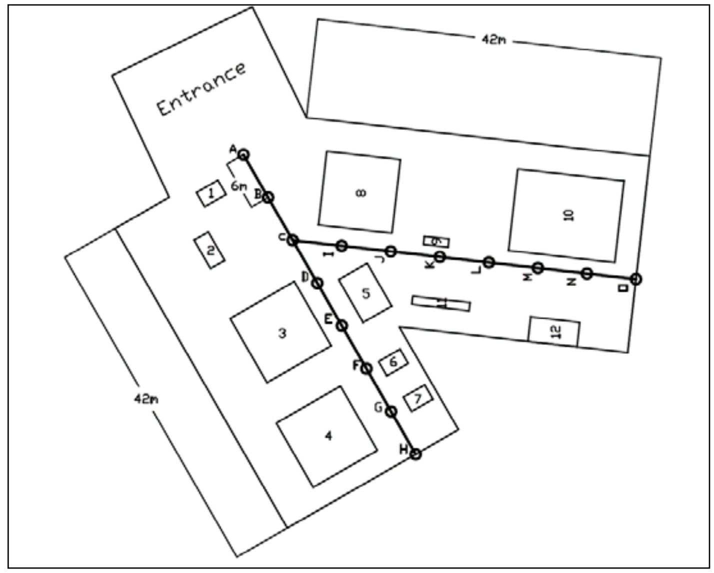


Figure 8: Simplified BIM model with 12 objects and two travel paths

It should be noted that each location was defined as the distance that equipment or workers move in 6 seconds. The authors assumed that the average speed of moving equipment in an indoor construction site is 1 meter per second for a safe work environment. The distance between two observation locations is 6 m. At each selected point along the two travel paths, a 6 m x 6 m x 6 m cube was projected along the ground surface to calculate the visibility percentage at the specific location. The process should also allow adjusting cube size based on different equipment moving speed, pedestrian's walking speed, construction environment and other possible conditions. Because the 3D grid was fixed to the cube, test locations were selected every 6 seconds of travel time. For the experimental trials, two travel path and 15 locations were selected. These paths are shown on Figure 10 (Path A-B-C-D-E-F-G-H and Path C-I-J-K-L-M-N-0). The 12 elements were extracted from the point cloud data and simplified into cuboid shapes shown in Figure 9 (p. 352). The 12 elements were selected from 12 arbitrary points along the equipment travel path to demonstrate the feasibility of the visibility measurement process. The length of the two travel paths is 42 meters, the dimensions of the 12 elements are defined in Table 2.

A 1.5 meter height viewpoint was selected to put in the center of each cube to modify a pedestrian or operator viewpoint. The methods provided in the methodology part were implemented to define the blind spot at the specific location. Results of the blind spot quantification are provided in Table 3.

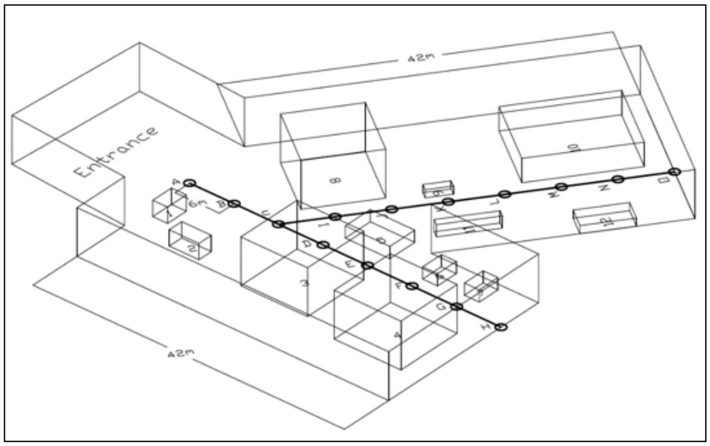


Figure 9: 3D view of equipment travel paths in BIM

Components	Length (m)	Width (m)	Height (m)
1	3	2	2
2	2	4	2
3	9	9	6
4	9	9	6
5	4	6	1.5
6	3	2	1.5
7	3	2	1.5
8	9	9	6
9	1	3	1
10	10	13	3
11	1	7	1.5
12	3	6	1

Table 2: Dimensions of construction site components

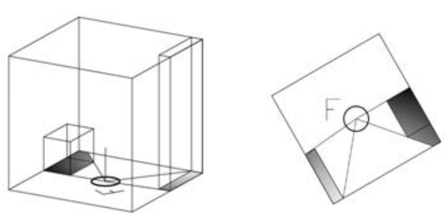
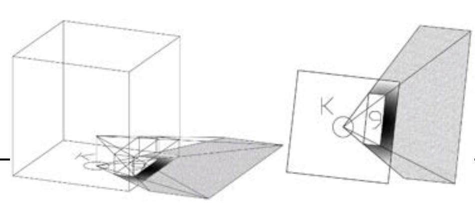
Travel Path	Location	Visibility	Example of objectives fixed in 6m×6m×6m cube.
Path 1	A	100%	
	B	100%	
	C	100%	
	D	91.1%	
	E	85.0%	
	F	86.3%	
	G	85.4%	
	H	94.9%	
Path 2	C	98.4%	
	I	91.2%	
	J	91.0%	
	K	87.7%	
	L	93.3%	
	M	84.6%	
	N	84.6%	
	O	99.2%	

Table 3: Summary of the visibility on the two travel paths at different locations

Table 3 includes the blind spot calculation of point F following situation 2 in the methodology section of this paper. Because the vertical angle between viewpoint and the object is larger than 90°, the chosen side length and the cube boundaries defined the blind spot in this situation. Point K is an example of situation 1 where the angle between viewpoint and the object is less than 90°. The shadowed area and grey area shows the blind spot without a boundary. Since a 6 m cube was fixed in location K, the shadowed area represents the blind spot.

5. CONCLUSION

Non-visible areas for construction equipment operators can result in unsafe working conditions that can lead to injuries or fatalities. Blind spots are created when an equipment operator's line of sight is obstructed by an object either on the construction equipment or in close proximity to the equipment. This research created a framework for quantifying and measuring the visibility of an indoor construction working environment.

Proactive safety controls such as personal protective equipment (PPE) and proximity detection devices can support the construction workers' safety with regards to struck-by incidents. Toole (2002) believes that all future construction projects will have detailed expectations on respective safety roles clearly articulated before the site work begins. The created framework can help with equipment travel path design and increase proximity detection device efficiency. By quantifying non-visible areas for construction operators, construction site managers can identify potential hazards associated with human-equipment interactions on construction sites. Future research will also want to create an automated blind spots measurement tool within BIM. Other areas of interest include assessing the automated method for obtaining an equipment operator blind spot with the manual methods discussed in the literature review section. ■

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Evaluation of Sabine's Formula on the Prediction of Reverberant Noise

Christopher Quinn-Vawter and William J. Brazile

ABSTRACT

Researchers modeled noise reverberation times (RT_{60}) using Sabine's formula in a building that housed enclosed and open workspaces to recommend noise controls to address problematic noise. The open floor plan in the building and the use of interior building materials with hard surfaces created this poor acoustic environment. To substantiate the modeled reverberation times, the researchers measured the reverberation times using a sound level meter and a noise signal. Five interior spaces with volumes ranging from 76 m^3 to 5,400 m^3 were modeled. Three of the spaces were entirely enclosed and two of the spaces had an open floor plan design. The RT_{60} predictions were then compared to the reverberation times measured in each location. The model performed well in the enclosed spaces, but did not perform well in the open space environments. As the room volumes increased, Sabine's formula model overestimated the reverberation times by larger margins. Using a repeated measures mixed model, it was found that room volume had a significant effect ($p = 0.01$) on the predicted reverberations times and that the reverberation times calculated by the model were significant ($p < 0.001$) predictors of the measured reverberation times.

Keywords: *noise, Sabine, Sabine's formula, reverberant noise, reverberation*

1. INTRODUCTION

1.1 Reverberation

A reverberant noise field is created when the sound reflects off of one or more surfaces before reaching the subject, in contrast to a free or direct field in which the sound travels directly from the source to the subject (AIHA, 2003; Anna, 2011; Bell & Bell, 1994). While the direct field generated by a source can be relatively easy to predict and control, the reverberant field created by the same source can be much more complex. For an occupational health professional (OHP) trying to develop noise controls in an environment such as a warehouse or high bay, being able to calculate the reverberant field effects can be a critical step in selecting effective noise controls. Depending on the acoustic characteristics of the space and the distance from the noise source(s), the reverberant field may contribute significantly more to a worker's noise exposure than the direct noise field (AIHA, 2003; Anna, 2011; Bell & Bell, 1994).

An OHP would be most likely to encounter reverberant noise problems when the reverberant field is either propagating high levels of noise from equipment or it is causing speech communication issues for workers (AIHA, 2003; Anna, 2011; Bell & Bell, 1994). Low-intensity reverberant fields, such as a high bay with light equipment use or a large office space, can still be a significant source of distraction and irritation for workers. Building spaces with high reverberation can create irritating environments for occupants and can interfere with communication, especially when workers try to talk to each other across a room (Kuttruff, 2002; Mechel, 2013).

Reverberant fields rely entirely on the characteristics of the room and the capacity of the materials to reflect or absorb the noise. These fields must be measured or modeled in each space to characterize and treat the reverberant noise, and are usually presented as reverberation decay times or a room constant (AIHA, 2003; Anna, 2011; Bell & Bell, 1994). The room constant for a single octave band represents the capacity of the room to absorb or reflect acoustic energy within that frequency range, and it is calculated using the noise absorption coefficient, or α value, of the building materials/surfaces present in the room.

An α value represents the percent of energy that is absorbed by a material and ranges from 0 (all reflected) to 1 (all absorbed). A material can have significantly different acoustic properties at different frequencies, making the α values critical to understanding a reverberant field in a room (AIHA, 2003; Bell & Bell, 1994). In general, a hard, smooth surface such as tile will be highly reflective and have very low α values while a soft or porous surface will have relatively high α values (Cox, 2009). The high variability in the reflectivity of materials in relation to the frequency makes it imperative to identify the materials in a room and the associated α values before attempting any reverberant noise controls in the room.

1.2. Reverberant Field Measurement

The reverberant field in a room is typically quantified by reverberation decay times (RT_{60}). The RT_{60} is measured as the time required for a sound frequency band to decrease by 60 dB after a loud sound pulse. RT_{60} times are measured at single

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octave bands centered at 125, 250, 500, 1,000, 2,000 and 4,000 Hz. These frequency ranges are most commonly associated with undesirable acoustic properties in interior spaces (AIHA, 2003; Bell & Bell, 1994; Kuttruff, 2002; Mechel, 2013). In a highly reflective environment, the sound wave is reflected off hard surfaces, losing energy very slowly and taking several seconds for the sound pressure level to drop by 60 dB leading to a long RT_{60} time. Conversely, in a highly absorptive environment, the sound wave will quickly transfer its energy to the absorptive surface materials, resulting in a short RT_{60} time (Cox, 2009).

Measuring RT_{60} times is done with one of two methods: the impulse method or the interrupted noise method (ASTM, 2009; Bell & Bell, 1994; Cox, 2009; ISO, 2012; Larson Davis, 2015). The interrupted noise method is widely accepted as the most accurate and most repeatable RT_{60} measurement. This method requires a large omnidirectional speaker system to generate a loud white noise signal evenly across 125 to 4,000 Hz (minimum) to build up and sustain the reverberant field in the room. Once the reverberant field is sustained, the speakers are shut off and the sound level meter (SLM) records the time for the sound pressure levels of each octave band to drop and calculates the corresponding RT_{60} times (ASTM, 2009; Bell & Bell, 1994; Cox, 2009; ISO, 2012; Larson Davis, 2015).

In most noise control scenarios, the simpler impulse method is sufficient to begin evaluating the acoustic properties of a room (Horvat, et al., 2008a, b; Vorlander & Bietz, 1994). With the impulse method, the constant reverberant field is replaced with a single loud sound pulse. The impulse sound may be generated by multiple different methods as long as the impulse is loud enough to be detected by the SLM over the background noise.(Horvat, et al., 2008; Larson Davis, 2015). The impulse may be created by methods such as popping a regular party balloon, a firecracker, a starter pistol or a specially designed clapper board. The simplicity and low cost of this method make it a good option for most OHPs faced with a reverberant noise problem.

1.3 Reverberant Field Prediction

To select an effective acoustical treatment, the OHP must have a way to model the reverberant field of the room. Sabine developed the first model for reverberant field prediction with Sabine's formula (Bell & Bell, 1994; Sabine, 1922). Sabine's formula requires knowing the room volume, the surface areas of all major materials in the room, and the associated α values for each material. The simplicity of Sabine's formula, however, leaves it susceptible to error as spaces become more complex. Using modern reverberation measurement equipment, the error range of Sabine's formula predictions varies from approximately 10% to 32% as a 125 to 4,000 Hz average (Astolfi, et al., 2008; Bistafa & Bradley, 2000; Passero & Zannin, 2010).

2. METHODS AND MATERIALS

The researchers evaluated the ability of Sabine's formula to adequately model reverberation in six spaces with room volumes ranging from 76 m^3 to 5,400 m^3. The subject spaces included two conference rooms (76 m^3 and 82 m^3) a classroom (620 m^3), an open-floor area with multiple offices (2,100 m^3), and an open-floor office area/atrium space (5,400 m^3). The conference rooms and classrooms were constructed of similar materials with some deviations; all had steel ceilings, tile floor covered with carpet and gypsum board walls. The conference rooms also had glass paned entryways and some decorative wood paneling. The open-floor office areas similarly were constructed of steel ceilings, gypsum board walls, and tiled floor (without carpet). The atrium space also had some brick construction, large glass panes and decorative wood paneling. It should be noted that the configuration of the three smaller spaces was vastly different as compared to the two larger spaces. The smaller spaces were well-defined "boxed in" areas (e.g., meeting rooms), whereas the larger spaces were two-story, multi-use office and laboratory areas.

2.1 Reverberant Noise Modeling

The reverberation times (RT_{60}) were calculated for each space at the octave band frequencies 125, 250, 500, 1,000, 2,000 and 4,000 Hz using Sabine's formula. Two versions of Sabine's formula were used for this study. For frequencies 1,000 Hz and below, Equation 1 was used (Bell & Bell, 1994; Bistafa & Bradley, 2000; Ducournaeau & Planeau, 2003; Sabine, 1992).

$$RT_{60} = 0.161V/A \qquad \textit{Equation 1}$$

For frequencies 2,000 Hz and above, Equation 2 was used (Bell & Bell, 1994; Bistafa & Bradley, 2000; Ducournaeau & Planeau, 2003; Sabine, 1992).

$$RT_{60} = 0.161V/((A+4mV)) \qquad \textit{Equation 2}$$

where
V = room volume (m^3)
A = total room absorption (Sabins)
m = air absorption coefficient

The air absorption coefficient (m) only has a significant impact on RT_{60} times for frequencies 2,000 Hz and higher. The value of m is dependent on the relative humidity and temperature of the room air (Bell & Bell, 1994; Knudsen, 1931). In this study, the values for m were selected using a relative humidity of 20%, near the relative humidity maintained by the climate control systems of the building. The total room absorption in Sabine's (A) was determined using Equation 3: (AIHA, 2003; Bistafa & Bradley, 2000; Ducournaeau & Planeau, 2003; Sabine, 1922).

$$A = \Sigma^{n}_{(i=1)}(S_1\alpha_1 + S_2\alpha_2 \ldots + S_n\, \alpha_n) \qquad \textit{Equation 3}$$

where:
Sn = area of the n^{th} surface in the room (m^2)
αn = absorption coefficient of the n^th surface in the room

The area of each surface type was determined using floor plans, measurements, notes and photographs taken during the site walkthroughs. When calculating surface areas, all materials contributing significantly to the total surface area of the room were measured (e.g., wood tables, doors, wall panels); smaller, highly variable surfaces were not measured (e.g., laboratory equipment, desktop computers). Each material was assigned its corresponding noise absorption coefficient, or α value, for single octave bands from 125 to 4,000 Hz. The material α values were obtained from available sound absorption coefficient tables (AIHA, 2003; Acoustic Project Co., 2014; Acoustical Surfaces Inc., 2015, 2016; Owens Corning, 2004). If α values for a specific room material were not available, the α values from the most similar material listed were used.

The information was entered into a spreadsheet created by Associates in Acoustics Inc. to perform room RT_{60} calculations (Associates in Acoustics Inc.). The modeling procedure was repeated for each of the six spaces.

2.2 Reverberant Noise Measurement

Each space within the building that was selected for the RT_{60} time model was also used for RT_{60} measurements after the models had been completed. RT_{60} measurements were taken using a class 1 Larson Davis model 831 SLM (Depew, NY). The SLM was mounted securely on a tripod with the microphone perpendicular to the floor at a height of 54 in. The sound impulse was generated using a Larson Davis BAS006 clapper board that can generate an average impulse noise over 80 dB from 125 to 8,000 Hz (Larson Davis, 2015).

The reverberation measurement procedure was based on the recommendations of Larson Davis, and the methodologies specified in American Society for Testing and Materials (ASTM, 2009) C423-09a and International Organization for Standardization (ISO, 2012) 3382 (Acoustics - Measurement of Room Acoustic Parameters) with modifications for use with available equipment. Because this study used only room RT_{60} times, modifications to the equipment in ISO 3382 included substituting the omnidirectional speaker system with the available clapper board and using multiple impulse locations per microphone location instead of multiple microphones per impulse location.

The impulses were generated in three different locations around the SLM for a total of three RT_{60} decay measurements per SLM position. The SLM was moved to a minimum of three different locations along the midline of the room to obtain a minimum of nine RT_{60} decay measurements per area. To provide the best conditions for the reverberation measurements and to generate the largest possible impulse decays, sampling was only performed when the building was empty and no loud equipment was operating. After sampling was completed, the arithmetic mean RT_{60} time was calculated for each single octave band being evaluated.

2.3 Statistical Analysis

For each of the measured single octave-band mean RT_{60} times, a 95% two-sided confidence interval (CI) was applied using a one-sample *t* test. The sample standard deviation for each RT_{60} time was taken from the value calculated by the Larson Davis reverberation time measurement software. The 95% CI from the measured times was then compared to the modeled times; the modeled times were considered successful if the prediction was within the bounds of the 95% CI.

To evaluate the predictive ability of the Sabine's formula model against potential influencing factors such as room volume and frequency, a repeated measures mixed model was used. Using JMP® statistical software from Statistical Analysis System (SAS®) Institute Inc., a mixed model was created setting the room volume, octave-band frequency, and modeled RT_{60} times as factors. The octave band frequency measurement was set as a repeated factor, and the room used for measurements was set as a random factor. The alpha level was set at 0.05 when investigating significant interactions between the factors.

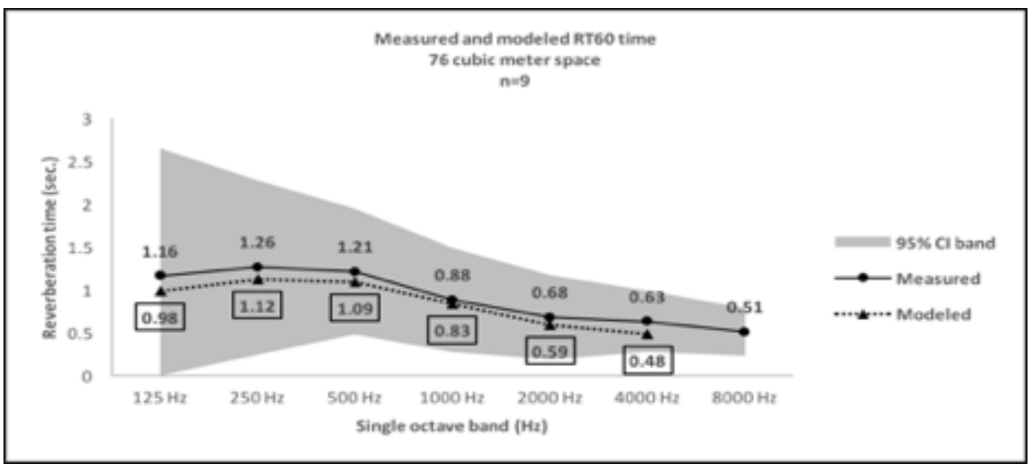

Figure 1: Measured and modeled RT_{60} times, 76 m^3 conference room

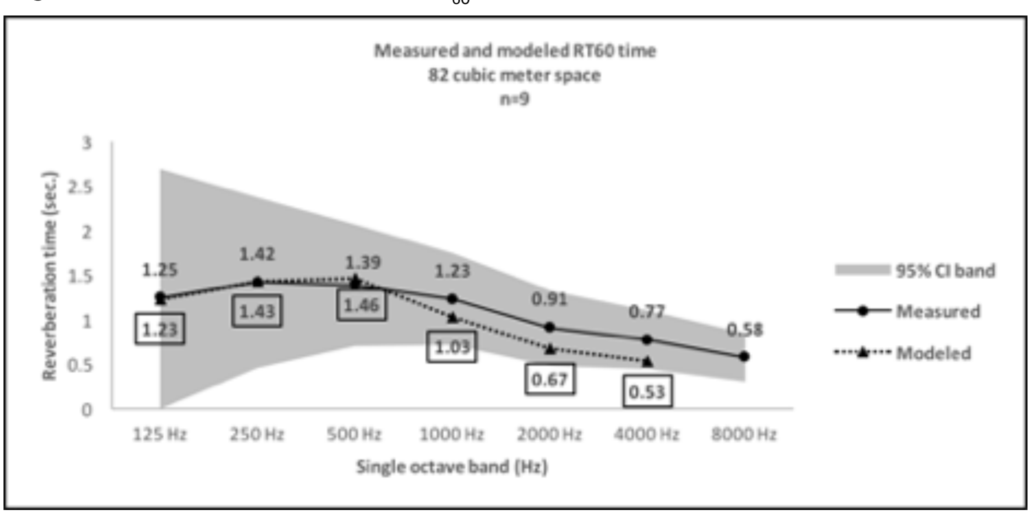

Figure 2: Measured and modeled RT_{60} times, 82 m^3 conference room

3. RESULTS

3.1 Measured and Modeled RT_{60} Times

The mean measured RT_{60} times and the modeled RT_{60} times at the single octave bands from 125 to 4,000 Hz are presented in Figures 1 through 5. The RT_{60} measurement at the 8,000 Hz octave band was included in the graphs, however, an RT_{60} time for 8,000 Hz was not modeled.

The results from the small 76 m^3 second floor conference room are summarized in Figure 1 (p. 356). The Sabine's formula model closely followed the measured reverberation times, ranging from 0.18 (at 125 Hz) to 0.05 (at 1,000 Hz) seconds below the measured times. All modeled reverberation times were well within the 95% CI band, though the CI was much larger at lower frequencies.

The results from the 82 m^3 second floor conference room are summarized in Figure 2 (p. 356). The Sabine's formula model again closely followed the measured reverberation times, ranging from 0.24 (at 2,000 and 4,000 Hz) to 0.02 (at 125 Hz) seconds below the measured times. All modeled reverberation times were within the 95% CI band, though the CI band was much larger at lower frequencies.

The results from the 620 m^3 first floor classroom are summarized in Figure 3. The Sabine's formula model follows the measured reverberation times though not as well as the smaller rooms, ranging from 0.56 (at 250 Hz) seconds above to 0.04 (at 1,000 Hz) seconds below the measured times. All modeled reverberation times from 125 to 2,000 Hz were within the 95% CI band, however, the modeled time exceeded the lower boundary of the CI at 4,000 Hz.

The results from the 2,100 m^3 third floor office area are summarized in Figure 4. The Sabine's formula model widely overestimated the reverberation times, ranging from 0.94 (at 1000 Hz) to 0.04 (at 4,000 Hz) seconds above the measured times. All modeled reverberation times from 125 to 2,000 Hz exceeded the upper 95% CI band, however, the modeled time fell within the CI at 4,000 Hz.

The results from the 5,400 m^3 first and second floor atrium and office area are summarized in Figure 5 (p. 358). The Sabine's formula model widely overestimated the reverberation times, ranging from 2.00 (at 1,000 Hz) to 0.02 (at 4,000 Hz) seconds above the measured times. All modeled reverberation times from 125 to 2,000 Hz exceeded the upper 95% CI band; again, however, the modeled time fell within the CI at 4,000 Hz.

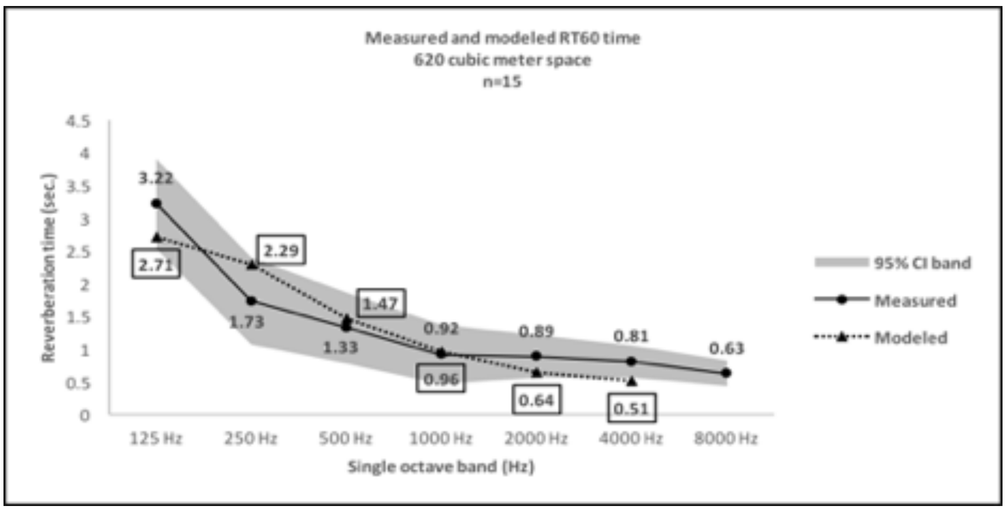

Figure 3: Measured and modeled RT_{60} times, 620 m^3 classroom

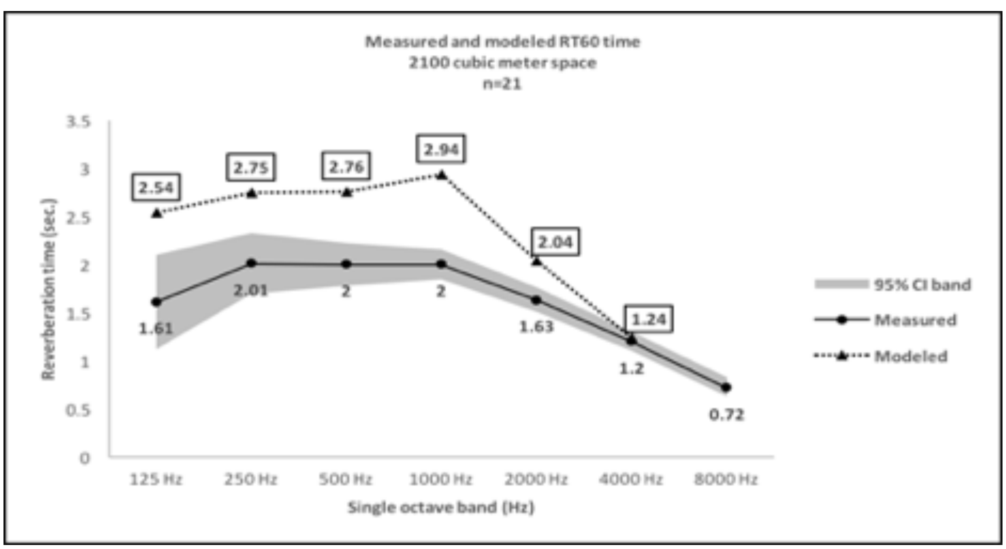

Figure 4: Measured and modeled RT_{60} times, 2,100 m^3 office area

3.2 Model Performance Factors

The percent error of the mean measured RT_{60} times compared to the modeled RT_{60} times are presented in Figure 6. The breakdown of percent error by octave band and room size appeared to indicate an increasing percent error of the model as the room size increased. There appeared to be no significant trend in the error within the octave bands, indicating that the error was dependent on the room volume rather than the frequency being measured and modeled.

Using the repeated measures mixed model, the fit of the measured versus modeled RT_{60} times was evaluated and significant interacting factors with the model were identified. The measured versus modeled RT_{60} time correlation generated a p-value less than 0.0001, indicating that the reverberation times calculated by the model were significant predictors of the measured times.

The modeled RT_{60} time interaction with room volume generated a p-value of 0.01, indicating that the room volume had a significant effect on the predicted reverberation times and the Sabine's formula model became less effective as the room volume increased. The modeled RT_{60} time interaction with octave band frequency generated a *p*-value of 0.67, indicating that there was no significant interaction with the frequencies being modeled and measured. The Sabine's formula model had no significant trend for higher or lower percent errors at higher or lower frequencies. The graph in Figure 7 (p. 359) is a fit plot of the measured and modeled RT_{60} times plotted by the room volume in which each set of measurements were taken. The equation for each set of measurements is listed in the top left corner of the graph.

A fit line slope below 1 is representative of the Sabine's formula model overestimating the reverberation times; the farther away from 1, the larger the overestimation. A fit line slope of 1 is representative of the Sabine's formula model correctly predicting the reverberation times. A fit line slope greater than 1 is representative of the Sabine's formula model underestimating the reverberation times; the farther away from 1, the larger the underestimation. As the room volumes increased, the slopes moved farther below 1, indicating that the Sabine's formula model overestimated the reverberation times by larger margins as the room volume increased.

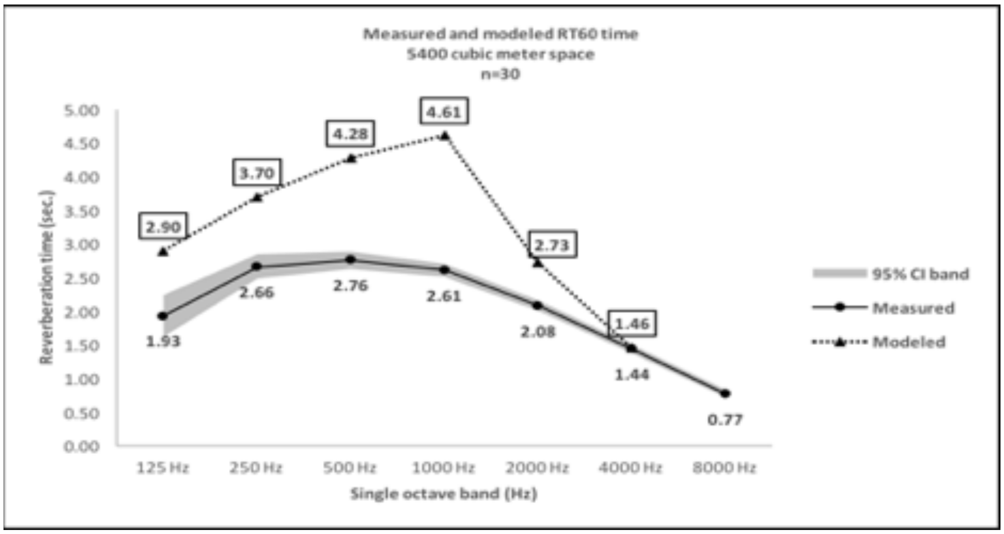

Figure 5: Measured and modeled RT_{60} times, 5,400 m^3 office area and atrium

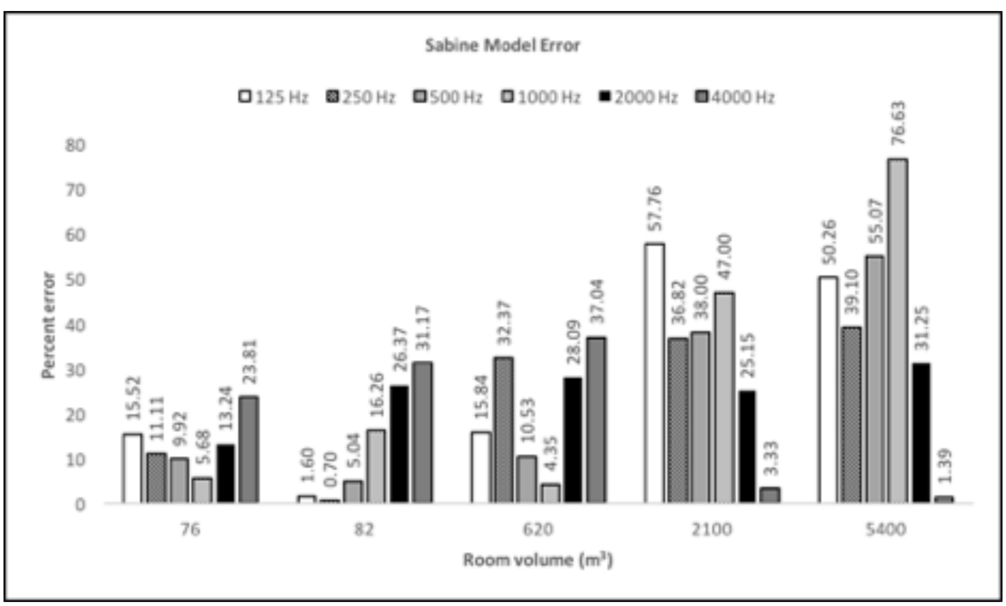

Figure 6: Sabine model error by room volume; rrror calculated using the mean RT_{60} measurements for each single octave band

4. DISCUSSION

4.1 Model Performance

The two larger interior spaces of the building that were modeled had multiple different factors all contributing to make the spaces very acoustically complex. These factors likely had a large impact on the model performance results observed in this study. The 76 m^3 to 620 m^3 conference rooms and classroom were all rectangular and fully enclosed by the walls, floor, and ceiling. The 2,100 m^3 third floor office area was also completely enclosed and essentially square in shape with the exception of some open hallways. The interior of the third-floor office space was much more complex than the smaller rooms. Clusters of offices were built in this area, and to work with the high-efficiency climate control and lighting systems, the offices did not have ceilings and were open to the common area. This created approximately one meter of open space between the offices and the steel ceiling framing and deck. The open ceilings of the offices acted as large diffusive elements, trapping a soundwave and reflecting it within the office until it dissipated (Cox, 2009; Kuttruff, 2002; Mechel, 2013; Möser, 2009). This diffusive action of the offices may have contributed a large amount of reverberant field reduction in the open office area.

While the other three areas had well-defined acoustic boundaries enclosing the square or rectangular rooms, the first floor atrium and second floor office area were much more open and complex. The large entryway atrium connected the first floor with the open-floor office area on the second floor. The second floor office area also had the same open-ceiling office design as the third floor, but contained a larger number of offices in addition to an open area of computer desks. The open floorplan and the layout of the space created multiple different pathways for a reverberant field to diffuse and dissipate before returning to an observer. The atrium may have had additional diffusive action on reverberation coming from the second floor.

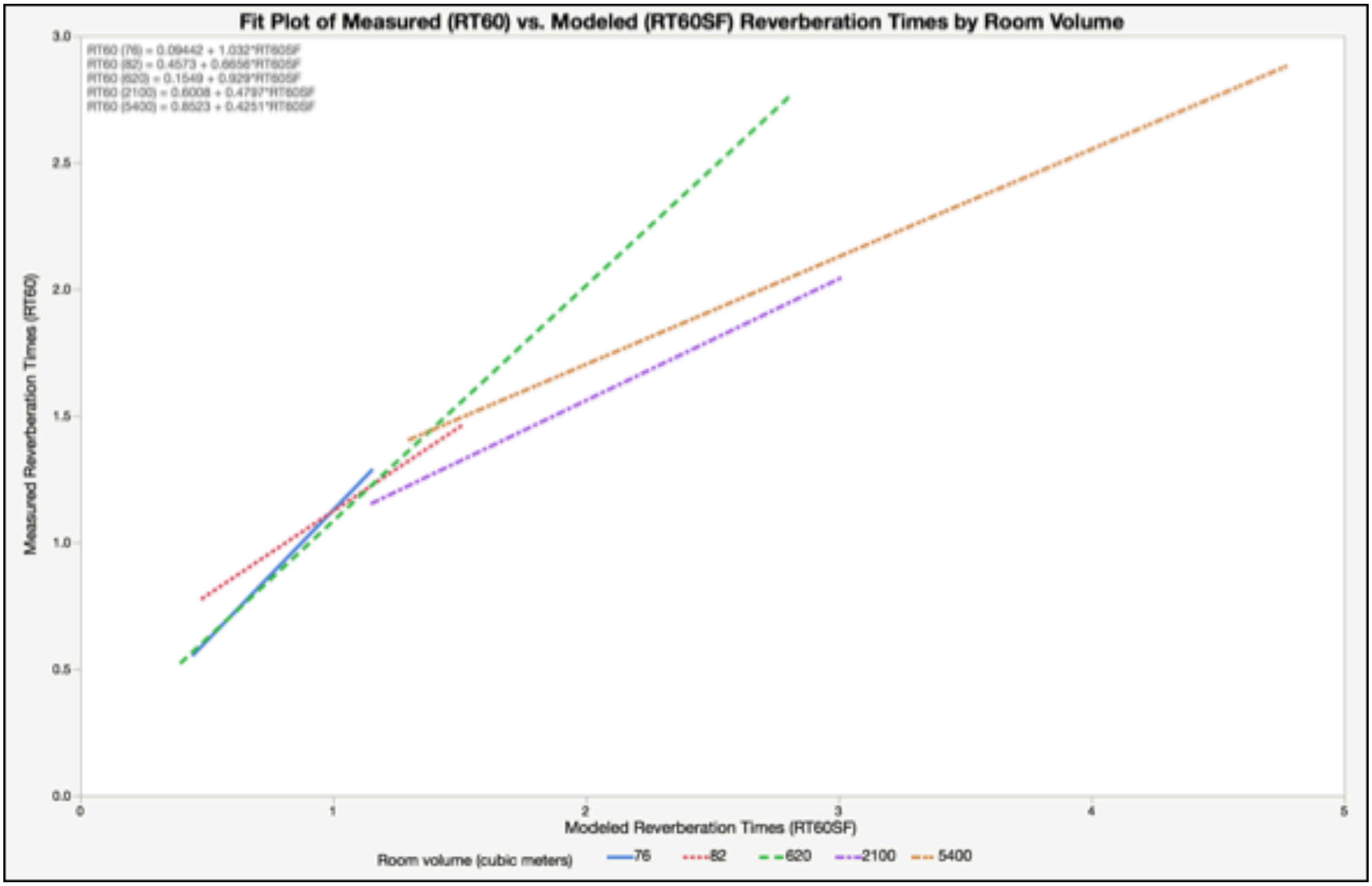

Figure 7: Fit plot of measured and modeled reverberation times by room volume

The Sabine's formula model performed well in the three smaller rooms, but proved to be far less accurate in the two largest spaces. When used in the 76 m^3 and 82 m^3 conference room, and the 620 m^3 classroom, the model followed the measured RT_{60} times well and only exceeded the 95% CI placed on the measured times at 4,000 Hz in the 620 m^3 classroom (Figures 1, 2 and 3). When used in the 2,100 m^3 third-floor office space and the 5,400 m^3 first floor atrium and second-floor office space, however, the model did not perform as well. In these two large spaces, the model only fell within the bounds of the 95% CI on the measured times at 4,000 Hz in both areas (Figures 4 and 5). At all other frequencies, the modeled RT_{60} times were well above the measured times in both spaces. In addition, Sabine's formula does not account for air absorption below 2 kHz. The farther sound travels, the greater the effect air absorption has on predicted reverberation times. Thus, not accounting for air absorption below 2 kHz could explain some of the error in the modeled versus measured results.

The RT_{60} time overestimation by the model in the largest spaces is confirmed by the analysis of the repeated measures mixed model. The trend of overestimation is summarized in Figure 7, the fit plot of the measured and modeled RT_{60} times plotted by the room volume in which each set of measurements were taken. The slope generated for the 2,100 m^3 room model was 0.48, and the slope generated for the 5,400 m^3 room model was 0.43. As the room volumes increased, the slopes moved farther below 1, indicating that the Sabine's formula model overestimated the reverberation times by larger margins as the room volume increased. The modeled RT_{60} time interaction with room volume generated a p-value of 0.01, indicating that the room volume had a significant effect on the predicted reverberation times and the Sabine's formula model became less effective as the room volume increased.

While the complex acoustic environment certainly contributed to the model error in the two largest spaces, the overall trend observed in all five rooms is consistent with previous studies using a Sabine's formula model. Researchers found in earlier studies that a Sabine's formula model consistently underestimated reverberation times in smaller spaces such as offices and classrooms, and overestimated reverberation times in larger spaces such as auditoriums and theaters (Astolfi, et al., 2008; Bistafa & Bradley, 2000; Passero & Zannin, 2010). The overestimation by Sabine's formula in large spaces was one of the equation's earliest problems identified by acoustic engineers; Carl Eyring developed what is now known as Eyring's formula to try to correct the problem in 1930. However, Eyring's formula is designed for use with a highly absorptive acoustic environment, and has increasing errors as the environment becomes more reflective (Bistafa & Bradley, 2000). Unfortunately, previous studies on the performance of Sabine's formula at different room volumes have, by necessity, used rooms of different materials and design (e.g., a classroom and a theater) (Passero & Zannin, 2010). The current study may be one of the first studies to use rooms that had similar construction materials and building techniques. However, the large differences in room configuration added multiple variables that make any conclusions of model performance based solely on room size tenuous. While there is clearly a significant interaction between the larger rooms and an overestimation of RT_{60} times by the model, it is likely due to a combination of factors involving both the volume of the room and effects of the room configuration.

One interesting and unexpected observation from this study relates to the reverberation measurements in the small conference rooms. The 95% CI at 125 Hz and 250 Hz was relatively large in both conference rooms, becoming smaller at 500 Hz and higher (Figures 1 and 2). This may have been caused by several different factors, the first of which was the clapper board used to create the impulse noise for the measurements. All impulsive noise sources have an inherent variability in the directionality of the impulse noise they generate. This variability becomes much larger at lower frequencies, and all sources but the sophisticated omnidirectional speaker systems have difficulty generating repeatable and consistent low frequency impulses (Horvat, et al., 2008a, b). This variability does not have much impact on measurements in a large space because the impulse has a large volume in which to dissipate and becomes more uniform before being reflected back to the microphone. In a smaller room, the impulse does not have this additional volume to become a more uniform field before being reflected back to the microphone, and the variability in the low frequency fields may have much more impact on the variability of the measurements (Horvat, 2008b).

Another possible explanation is related to the behavior of low frequency soundwaves when they encounter an object. The conference rooms in the building were walled with drywall mounted to a steel frame with fiberglass insulation placed in the open areas between studs to reduce sound transmission through the wall. Low frequency noise easily passes through drywall, and walls must be specially designed with either sound-absorbing materials or additional framing and drywall panels to prevent sound transmission when using drywall (USG, 2013). The walls in the building conference rooms were built with a single panel of drywall screwed directly to the metal framing. A low frequency soundwave may be able to pass through the single drywall panel and reflect off the metal frame back into the room, or if it does not encounter the metal framework, it may pass through the other side of the wall and leave the room with minimal reflection back (AIHA, 2003; Bell & Bell, 1994; USG, 2013). These different factors may have contributed to the large variability in low frequency measurements observed in the small conference rooms but not in any of the larger spaces.

This model performance study had several notable limitations. The first, and largest, limitation was the small sample size of five rooms that were used in the study. The second was the differences in room configuration and design. The small sample size and the vastly different space configurations, from the standard rooms of the conference rooms and classroom to the highly irregular combined atrium and office space, made it very difficult to determine if the changes in model performance were due to room volume or caused more by the changes in room shape.

Another limitation is one inherent in all reverberation models: the accuracy of the α values used for all the different room materials (Cox, 2009). The material α values are a vital foundation of a Sabine's formula model and any other reverberant field model, and the changing absorption at different frequencies is a major contributor to reverberant fields (AIHA, 2003; Bell & Bell, 1994; Cox, 2009; Sabine, 1922). Highly reflective materials with low α values are especially susceptible to significant errors in models. Concrete has a listed α value of 0.01 at 125 Hz in most commonly used α value tables (AIHA, 2003). If the concrete in the room being measured behaved slightly different and had an actual α value of 0.013 instead of the 0.01 used in the model, a 30% error has already been introduced at 125 Hz. If the room had a large concrete area, the incorrect α value could have a large impact on the final model even though the α value used in the model is only 0.3% lower (1% vs. 1.3%). This limitation is very difficult to address in models. Beyond using α values for the exact material in the room, or an extremely similar material, there is very little that can be done practically to prevent these errors (Cox, 2009).

5. CONCLUSION

This project provided a unique opportunity to evaluate the method available to most OHPs to measure and predict reverberant noise: Sabine's formula and the impulse noise method of reverberation measurement. These methods are relatively simple and require no specialized equipment other than a clapper board or other impulse generating device that can be purchased for no more than two or three hundred dollars. This is a sharp contrast to the popular methods of reverberation measurement that require speaker and amplification systems costing several thousand dollars and advanced computer programs to model the acoustic fields.

Sabine's formula has fallen out of favor with acoustic engineers, being replaced with the much more precise computer programs. While no longer used in precise acoustic applications, Sabine's formula is likely to meet the needs of any OHP faced with a reverberant noise problem. The model performed well in room volumes 620 m^3 and below, and would have likely performed better in the large volume rooms if they did not have such complex acoustic environments. The Sabine's formula model will likely overestimate RT_{60} times even in an acoustically simple room if the volume is large enough. The model was still slightly underestimating times at 620 m^3 indicating that it would perform well in larger volume spaces, though the authors were not able to identify the room volume at which Sabine's formula begins to overestimate reverberation times. In addition, based on the modeled versus measured RT_{60} results, it is recommended to apply Sabine's formula to well-defined spaces, rather than to acoustically complex spaces as was done for the two larger spaces in this study to help increase the accuracy of the modeled RT_{60} times.

Future work evaluating the performance of a Sabine's formula model when applied to different room volumes should use rooms of similar acoustic complexity if possible. Using rooms of a similar design would eliminate significant variables in the room acoustics, and allow stronger conclusions about observed trends when using the Sabine's formula model. The current researchers were able to use rooms of similar materials and construction methods, but had a wide range of room configurations. One possibility to study rooms of similar materials and configurations but different volumes may be to use warehouses or similar storage areas if possible. Another potential study design could use both the impulse noise method and the interrupted noise method of reverberation measurement to further investigate differences between the two methods that may influence measurements in different room volumes or configurations. ■

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Prioritizing Components of Safety Management Systems

Elyas Jazayeri, Huang Liu and Gabriel B. Dadi

ABSTRACT

Although improving, the construction industry has a significant share of fatalities, according to Occupational Safety and Health Administration statistics. While many owners and contractors have established policies and procedures to reduce risk and incident frequencies, the degree to which they are practiced has received little attention. The concept of operational excellence seeks to create predictable and reliable behaviors. Operational excellence is defined as doing the right thing, the right way, every time, even when no one is watching. To apply the operational excellence concept to construction safety, researchers have developed an operational excellence model (OEM) to measure and improve construction project safety performance. The OEM contains 13 elements that are essential to safety, termed safety drivers. It would be simplistic to assume that each driver has equal weight in the model, thus this article establishes appropriate weights for each safety driver through construction safety expert opinions using an analytic hierarchy process. The primary contribution to the body of knowledge is prioritizing components of a safety management system to provide practitioners and researchers guidance on areas that most impact safety performance.

Keywords: *operational excellence, operational excellence model (OEM), construction safety, safety culture*

1. INTRODUCTION

According to the U.S. Bureau of Labor Statistics (BLS, 2014), there were 11.8 fatal incidents per 100,000 full-time construction workers in the U.S. in 2014. U.S. construction industry fatalities represented over 20% of all private industry workplace fatalities in 2016 (OSHA, 2016). The number of fatalities in the construction industry illustrates the significant risk that workers face daily (OSHA, 2013).

Construction worker injuries significantly impact projects beyond the loss of the individual's time. Injuries typically lead to delays, productivity losses, revenue losses and other negative outcomes that affect overall project performance directly and indirectly (Koskela & Howell, 2002). Vitharana, et al. (2015) believe this is due to the higher rate of self-employed workers and migrant and/or seasonal workers who are unfamiliar with construction processes. O'Toole (2002) mentions other factors such as lack of proper training, lack of safety enforcement, poor safety conditions of project sites and lack of proper safety equipment. Coleman (1991) found that approximately 90% of fatal incidents were preventable and that the root cause of 70% of these incidents was a lack of safety management. According to Liu, et al. (2015), unsafe behaviors are primary contributors to most incidents, and many unsafe behaviors are related to poor construction safety culture.

The recordable injury rate (RIR) for the industry has decreased approximately 33% from 2008 to 2010 (Hinze, et al., 2013). However, the long-standing goal of many construction organizations is a zero-injury work environment, so improvement is still needed (Koskela & Howell, 2002). Although there has been improvements in safety performance, it has not been attributed to any specific factors or parameters (Hinze, et al., 2013).

The primary objective of this research is to prioritize components of a safety management system based on input from subject-matter experts. The safety management system components are compiled in an operational excellence model for construction project safety. The components are prioritized using an analytic hierarchy process (AHP). With this knowledge, practitioners and researchers can identify gaps in safety management and, thus, focus on areas with the greatest opportunity to improve safety performance. The following sections will describe operational excellence (OE), the development of the OE model and the approach toward meeting the primary objective of this research.

2. BACKGROUND

2.1 Definition of Operational Excellence

OE has become a popular concept only used across various industries when addressing improvements in production, safety, quality and cost performance, yet it is often ill defined. The fundamental idea of OE is that predictable operations lead to desirable results. Many industries such as the chemical processing industry have explored operational excellence to maintain a safe work environment. Liu, et al. (2017) define it as doing the right thing, the right way, every time, even when

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no one is watching. The basic premise of OE is that predictable and desired behaviors lead to excellent results. OE has been frequently defined, and researchers have proposed different characteristics for their OE definitions. As an example, Johnson (2005) identified 10 characteristics for his OE model, Walter (2002) proposed a model with 15 parameters, Rains (2012) established a model with 11 factors, and Klein and Vaughen (2008) developed a model with 11 characteristics.

The OE model (OEM) structure was adapted from a six sigma critical to quality (CTQ) tree that translates broad needs to specific and measurable requirements (Van Aartsengel & Kurtoglu, 2013). At the highest level of the tree is the customer need or the question that is to be answered. The tree then breaks down into subcomponents all the way to a final level of a measurable, defined outcome.

To achieve a conceptually valid model, a two-step approach to validation was conducted. First, the research team held eight internal face-to-face review sessions and webinars. Once the model was agreed on by the team, external subject experts from safety consultant groups such as DuPont, Zurich, Construction Industry Institute (CII) member companies, and the Construction Users Roundtable (CURT) were consulted for their advice. Subject-matter experts were all safety managers, safety directors or project managers with years of experience in the construction industry. An extensive survey of the importance of model elements helped identify a conceptually valid model.

3. OPERATIONAL EXCELLENCE MODEL

The model includes four levels to accurately describe operational excellence in the construction safety context: 1) safety driver (SD); 2) critical to safety (CTS); 3) critical to expectation (CTX); and 4) specification or measurement (S/M). SDs are major factors to achieve safety which result in the desired outcome of operational excellence. CTSs are more specific elements that help define their respective SD. CTXs are behaviors and/or processes that should be implemented to accomplish its CTS. The S/Ms help quantify a level of achievement for the behaviors and/or processes in the CTXs. An initial list of SDs was established from previous research and literature review. Model validation was conducted through a survey of subject-matter experts (Liu, et al., 2017). The final version of the OEM included 12 SDs, 75 CTSs, 256 CTXs and 293 S/Ms. Previous research by the team identified 12 safety drivers. More details on this model can be found in Liu, et al. (2015).

3.1 Employee Engagement (SD 1)

Employee engagement is a workplace approach designed to ensure that employees are dedicated to their organization's values, motivated enough to contribute to work aligned with organizational prosperity, and able to improve their own sense of happiness and comfort at the same time (Seijts & Crim, 2006). Its goal is to generate an emotional commitment to improving work and safety processes.

3.2 Human Performance & Factors (SD 2)

Human performance is a process of "selection, analysis, design, development, implementation and program evaluation to cost-effectively influence human behavior and accomplishment" (Winter, 2015). It is a combination of three essential processes: performance analysis, cause analysis and intervention selection that can be applied to any individual, small and large organizations (Pershing, 2006). Any item like hardware, software and equipment that influence people's behavior, choices and attitudes are included in engineering control such that they are designed for universal use and understanding. By reducing misinterpretation of information, training and assignments, human errors can be reduced and expected behaviors become more frequent.

3.3 Organizational Learning (SD 3)

Organizational learning is an organization-wide continuous process that improves its collective ability to accept, make sense of and respond to changes, both internally and externally (Kasemsap, 2015). Organizational learning is more than information held by its employees. It requires systematic integration and collective interpretation of new knowledge that leads to collective action and involves risk taking as experimentation (Green & Stankosky, 2010). Effective organizational learning requires both formal and informal approaches. Formal approaches include suggestions, investigation reports and lessons learned systems. Informal approaches include conversations such as those between workers, management and safety huddles.

3.4 Owner's Role (SD 4)

Owner organizations have a critical role in safety on construction projects. The owner model establishes a safety culture for all parties and at the same time sets expectations for all parties involved in the project. The owner model should also monitor and analyze safety to achieve safety objectives.

3.5 Recognition & Rewards (SD 5)

When people engage in behavior, three possible consequences may happen: their behaviors may be recognized or rewarded afterward; they may be punished or fired; or nothing could be done. Workers should be recognized and/or rewarded for involving and engaging in desired behaviors. Often, people engage in discretionary behaviors to get rewarded. The amount of effort toward discretionary behaviors can be described using expectancy theory (Poter & Lawler, 1968). Recognition and rewards could be project-based, individual-based or team-/craft-based.

3.6 Risk Awareness, Management & Tolerance (SD 6)

Risks are future events whose exact favorable or unfavorable outcome is unknown. In the world of construction health and safety, risk is the potential for harm created by unknown hazards. The Institute for Risk Management (2016) defines risk management as “systematic process of understanding, evaluating and addressing these risks to maximize the chances of objectives being achieved and ensuring organizations, individuals and communities are sustainable.” Risk awareness encompasses the nature and presence of risk in all aspects of a firm’s construction operations and the need for risk to be addressed in all management processes. Risk awareness also represents an understanding of the nature and presence of risks. Risk tolerance addresses how much risk an individual is willing to incur and for how long in the performance of a task combining these risk elements, the driver of risk awareness, management and tolerance is the systematic process of understanding, evaluating, and addressing safety and health risks to minimize worker exposure to risks and possibility of harm.

3.7 Shared Values, Beliefs & Assumptions (SD 7)

Each individual maintains their own values, beliefs and assumptions that influence how they respond to various situations. People develop these characteristics from interacting and operating within situations and discovering their own solutions to problems. Groups of individuals often maintain similar values, beliefs and assumptions, often referred to as their culture (Schein, 1986). Even though there is some commonality, values, beliefs and assumptions can vary both within a group and between groups. It is of particular concern when there is significant disagreement between the values, beliefs and assumptions of management, supervision, safety professionals and craft workers.

3.8 Strategic Safety Communication (SD 8)

Achieving operational excellence requires that an organization develop and implement an approach to safety communication. The safety message needs to be identified and communicated in a consistent manner through a variety of channels to prevent conflicts.

3.9 Subcontractor Management (SD 9)

The prime contractor is responsible for selecting the subcontractors and ensuring that their work complies with the project’s safety requirements. In addition, subcontractors often comprise the majority of workers and hours on-site. With site responsibility lying with the prime contractor, it is imperative that there be contractual and procedural requirements to measure and control the efforts made for safety.

3.10 Training & Competence (SD 10)

Work is being performed by diverse skills and individuals in the construction industry. Operational excellence in training and competence requires construction companies to ensure that their workers do have competencies necessary to have incident free work site. It is obligatory that contractors know what competencies are required and how to assess whether the new person has those essential skills.

3.11 Transformational Leadership (SD 11)

Actions and behaviors of the leader communicate beliefs, values, and desired behavior within the organization, and that makes leadership critical to culture change. Transformational leadership is a style of leadership that moves toward transforming an organization’s culture (Schein, 1985). With an appropriate culture in place, the expectation becomes that behaviors are desired and predictable.

3.12 Worksite Organization (SD12)

Worksite organization is an approach that requires that everything has a place and everything is in its place. The result is increased efficiency, productivity, and hazard reduction and or elimination. It is one of the major tools in the 5S System outlined in the Toyota Production System (Monden, 2011).

4. METHODOLOGY

4.1 Analytic Hierarchy Process

AHP was the method utilized to establish weights for each safety driver in the model. AHP was established in 1971 by T. L. Saaty and has been applied to many decision-making problems in manufacturing industries such as selecting a suitable machine in a manufacturing factory (Skibniewski & Chao, 1992). Its popularity eventually led to the creation of an American Society for Testing and Materials (ASTM, 1995) standard (E 1765-95) for using AHP in multi-attribute decision analysis. The method divides a complex system into hierarchical elements. The elements are evaluated for their importance against one another through pair-wise comparisons. The results of the comparisons become measurable in a comparison matrix. The eigenvector of the matrix is calculated which shows the comparative weight among the elements of the specific hierarchy (Lin & Yang, 1996).

Numerous previous studies applied the AHP methodology when evaluating the significance of multiple options. The availability, low complexity and possibility of being used in many fields make AHP a popular method (Podgórski, 2015). The compatibility of AHP with any decision-making research makes it popular in a variety of fields.

One of the first applications of AHP in operational health and safety was in research conducted by Jervis and Collins (2001). The aim of their research was to show managers which field they should invest in to get a return on their investment. According to Aminbaksh, et al. (2013), suitable prioritization through AHP is necessary for management, planning, and budgeting of safety-related risks.

Al-Harbi (2001) presented this method to prequalify contractors in project management by prioritizing criteria in prequalifying decisions. Teo and Ling (2006) conducted a study that applied AHP to achieve a high level of safety on construction projects. In a recent study in operational safety and health, Podgórski (2015) demonstrated selection of leading key performance indicators in an operational safety and health management system by applying AHP method for the selection of leading indicators.

Overall, this method used in a variety of industries, but in construction and specifically in construction safety, use of AHP is not widespread. One of the premiere construction journals in the U.S., *Journal of Construction Engineering and Management,* has published only seven articles with AHP used as the primary method in the last 5 years. Although the focus of this article is prioritizing the safety drivers, the process of decision making and prioritization by AHP method will also be discussed.

According to ASTM, there are five major steps to complete an AHP (ASTM 1995). These five steps are; construction of hierarchic structure, pairwise comparison, aggregation of comparison matrices, relative weight computation, and consistency ratio. All steps are included in this paper to illustrate the AHP method for academics as well as practitioners in construction safety.

Step 1: Construction of Hierarchic Structure. The primary objective of the analysis is the importance of an individual safety driver versus the other safety drivers. All safety drivers that were previously mentioned are the hierarchic structure matrix. Therefore, there are 12 columns and 12 rows with each representing a safety driver.

Step 2: Pairwise Comparison. The main goal of AHP is to obtain the relative weights of safety drivers through a series of pairwise comparisons. To conduct pairwise comparisons, a comparison matrix must be constructed to record results of comparison sets. A measurement scale of 1 to 5 is developed to quantify the relative importance of each driver. The detailed description of this process will be presented in the results section of this article.

Step 3: Aggregation of Comparison Matrix. AHP is built on comparison matrices created by a group of decision makers or experts. In this study, twenty-one experts present their judgements on the importance of safety drivers in the operational excellence model that has been developed. The aggregation of comparison matrices translate judgements of multiple experts into a single judgement that is shown in each cell of the matrix. To do so, the aggregation of individual judgements (AIJ) is being used (Saaty, 1989). The way to compute AIJ is to use the geometric mean of the values assigned by experts to the individual comparison matrix to make an aggregated comparison matrix. For example, if $a_{ij}^{1}, a_{ij}^{2}, \ldots, a_{ij}^{n}$ stand for comparison results of SD *i* versus SD *j* by the experts 1, 2, …, n respectively, the entry of SD *i* versus SD *j* to the group comparison matrix can be calculated by the following equation:

$$a_{ij}^{g} = \prod_{k=1}^{n} a_{ij}^{k}$$

Where a_{ij}^{g} is the value at row *i* and column *j* of the group comparison matrix, and a_{ij}^{k} is the raw value at row *i* and column *j* of the comparison matrix by the *kth* expert.

Step 4: Relative Weight Computation. Eigenvector is one of the popular methods of computing relative weight. The theory of eigenvector is that each entry a_{ij} of the comparison matrix *A* is exactly the ratio of weight w_i to w_j. For an *n×n* comparison matrix, the calculation of w_i, the relative weight for the *ith SD* element, can be obtained by the following equation:

$$w_i = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}$$

Where a_{ij} is the raw value at row *i* and column *j* of the comparison matrix, w_i is the weight of the *ith* element, and the equation below indicates the sum of all raw values in column *j* that is used to normalize column *j*.

$$\sum_{k=1}^{n} a_{kj}$$

Step 5: Consistency Ratio (CR). In the AHP method, there is a way to verify that the pairwise comparisons have consistency. Consistency shows that there is a logic behind all the comparison pairwise cells. As an example, an expert thinks that SD1 is more important than SD2, and the same expert thinks that SD2 is more important than SD3. If the experts follow the same train of thought to judge that SD1 is more important than SD3, then consistency exists, otherwise, inconsistency exists in the responses. Therefore, Saaty (1988) developed a measure of deviation of consistency called the consistency ratio, which will be discussed in detail in the results section of this paper.

To establish the factors of pair-wise comparisons in the matrix, all factors in the matrix should be formed. Each of the factors in the matrix is the mean of the respondent's judgement about that specific factor. The structure of the pair-wise comparison matrix is shown in Table 1.

Alternatives	**Alternative 1**	**Alternative 2**	**….**	**Alternative n**
Alternative 1	1	Desirability of Alt. 1 Versus Alt. 2	….	Desirability of Alt. 1 Versus Alt. n
Alternative 2	Desirability of Alt. 2 Versus Alt. 1	1	….	Desirability of Alt. 2 Versus Alt. n
….	….	….	….	….
Alternative n	Desirability of Alt. n Versus Alt. 1	Desirability of Alt. n Versus Alt. 2	….	1

Table 1. Structure of pair-wise comparison

The judgment matrix has 144 cells since it is 12 by 12. Each cell is filled with the mean of the respondent's answers to each question based on the proposed scale in the survey. According to Chang, et al. (2007), there are rules related to each cell that should be followed. Each cell should have a value greater than zero, cells comparing the same alternative should have a value of 1, and opposite cells should have a value inversely proportional. These rules are written as follows:

$$a_{ij} > 0, \quad a_{ii} = 1, \quad a_{ij} = {}^{1}/_{a_{ji}}$$

Based on these constraints, only 66 pair-wise questions are needed for each respondent to fill out the whole matrix. 144 cells are in the judgement matrix. Twelve are 1 because a_{ii}=1. Of the 132 cells remaining, 66 are the inverse of the others based on the constraint $a_{ij}=1/a_{ji}$. The total number of pair-wise comparisons needed for the AHP can be written as:

$$n\,(n-1)/2$$

To calculate the priority vector, the weights for the drivers, first synthesizing the pair-wise comparison should be performed. Synthesizing can be calculated by dividing each cell by the sum of its column. As an example, for the cell a_{ii}, it would be:

$$A = \begin{bmatrix} a_{ii} & \cdots & a_{ij} \\ \vdots & \ddots & \vdots \\ a_{ji} & \cdots & a_{jj} \end{bmatrix} \quad {}^{a_{ii}}/_{\sum_{ji}^{ii} a_{ii}}$$

Once the synthesized matrix is computed, priority vectors could be calculated by getting the average of each row. Assume *b* is the synthesized form of *a*, the calculation will be:

$$\begin{bmatrix} b_{ii} & \cdots & b_{ij} \\ \vdots & \ddots & \vdots \\ b_{ji} & \cdots & b_{jj} \end{bmatrix} = \begin{matrix} (\sum_{n=i}^{j} b_{in})/n \\ \cdots \\ (\sum_{n=i}^{j} b_{jn})/n \end{matrix}$$

At this time, the priority vector is calculated and should add to 1.

The last part of the process is to verify and validate the judgements with a consistency ratio to see if the results are consistent. This analysis is discussed and presented in the results section of this article.

5. ANALYSIS

5.1 Survey Description

The objective of the study is to prioritize the safety drivers based on input from subject matter experts on an OE model. The weighting of the elements was achieved by conducting a survey, data collection, data validation and data analysis.

A survey questionnaire was developed as the primary data collection instrument. The structure was based on pair-wise questions, and respondents were asked to compare any two safety factors with each other. Their answer was based on the degree of comparison between two safety drivers on a 1 to 5 scale from equal to strongly more important, or from -1 to -5 in the case which the second item is more valuable than the first item in the question. Although Saaty suggested a 9-point scale in the AHP process, Franek and Kresta (2014) believe that using different scales do not have an impact on the ranking of criteria. As an example, one of the survey questions is, "How much more valuable is subcontractor management than recognition and reward?" If the respondent believes that subcontractor management is strong compared to recognition and reward, a 4 would be the appropriate response. If the respondent thinks that recognition and reward is strongly valuable compared to subcontractor management, s/he should put a -4.

Table 2 shows the numerical rating which was provided to survey participants. In analysis, the authors used 1/2, 1/3, 1/4, and 1/5 instead of -2, -3, -4 and -5, since all cells should have a value of more than zero. The reason that negative numbers were used instead of fractions is because pilot test feedback showed that using fractions in the questionnaire was confusing. A brief explanation of each safety driver was provided in the survey to enable respondents to recall each safety driver's description while answering the questions. There were 66 questions about safety drivers and some demographic questions about respondent's background and their field of work.

The survey was hosted electronically through Qualtrics, an online survey software, and distributed among safety professionals with an instruction guide and cover letter attached to clarify the survey goals and objectives and minimize confusion. The target group for this research was safety managers, safety supervisors, and safety related positions in owner, consulting, and contractor firms.

5.2 AHP Matrix

The collected data was entered into a comparison matrix in Microsoft Excel to perform the weighting calculations. To verify the results of the Excel calculations, the researchers checked their results against software created by Thomas Saaty called Expert Choice that performs AHP. Figure 1 shows the AHP matrix that was used in this research. As an example, the intersection of SD4 and SD2 is 2.11, which means that the average of all responses for this cell is 2.11. The number demonstrates that respondents believe that SD4 is 2.11 times more important that SD2.

z	Equal	Moderate	Strong	Very Strong	Extreme
If X is more important than Y	1	2	3	4	5
If X is less important than Y	1	-2	-3	-4	-5

Table 2. Pair-wise comparison scale

Degree of Comparison

Equal	Moderate	Strong	Very Strong	Extreme
1	2	3	4	5

	SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SD11	SD12
SD1	1.00	0.33	0.33	0.31	0.33	0.42	0.44	0.38	0.41	0.45	0.49	0.40
SD2	3.05	1.00	0.62	0.47	0.49	0.83	0.75	0.60	0.88	0.79	0.68	0.63
SD3	3.05	1.60	1.00	0.48	0.42	0.54	0.51	0.46	0.54	0.66	0.56	0.51
SD4	3.21	2.11	2.08	1.00	0.73	0.92	0.94	0.62	0.78	0.86	0.97	0.62
SD5	3.06	2.03	2.37	1.37	1.00	0.85	0.90	0.55	0.59	0.89	0.54	0.57
SD6	2.38	1.21	1.84	1.09	1.18	1.00	0.77	0.52	0.60	0.66	0.53	0.48
SD7	2.29	1.32	1.95	1.06	1.11	1.31	1.00	0.50	0.55	0.70	0.75	0.54
SD8	2.60	1.67	2.17	1.62	1.82	1.92	2.00	1.00	0.55	0.83	0.60	0.52
SD9	2.45	1.14	1.86	1.29	1.69	1.68	1.83	1.80	1.00	0.78	0.68	0.53
SD10	2.21	1.26	1.52	1.17	1.12	1.52	1.43	1.21	1.28	1.00	0.73	0.48
SD11	2.05	1.48	1.79	1.03	1.86	1.89	1.33	1.66	1.47	1.37	1.00	0.66
SD12	2.52	1.59	1.95	1.62	1.75	2.09	1.86	1.91	1.89	2.07	1.51	1.00

		Relative Weight
0.033	SD1	1.000
0.061	SD2	1.859
0.055	SD3	1.690
0.083	SD4	2.536
0.082	SD5	2.492
0.070	SD6	2.129
0.075	SD7	2.300
0.101	SD8	3.084
0.101	SD9	3.086
0.090	SD10	2.755
0.110	SD11	3.350
0.138	SD12	4.205

Figure 1. AHP matrix

5.3 Demographic Info

The survey was deployed to individuals primarily in organizations belonging to CII, CURT and members of the research team. Subject-matter experts were safety managers, safety directors, or project managers with years of experience in the construction industry. The online survey system facilitated the data collection process. A total of 21 completed responses were collected. Although the survey was time consuming, all the participants voluntarily participated in this study. The survey had the option to pause, save, and resume. The combination of the save feature and voluntary nature of the survey limits the impact of fatigue on respondents. Participants were provided with descriptions of each factor on the top of each page of the survey.

Figure 2 illustrates the types of organizations the respondents are employed by. The majority of respondents were contractors (67%) with the remainder primarily owners (28%). Many of the safety drivers queried were issues addressed by contractors, so the balance of respondents leaning toward contractors is acceptable.

Figure 3 breaks down the respondents based on the type of work that their firm primarily performs. The majority work in the power or industrial sector of the industry. With the primary sources of data to be CII and CURT member companies, this is to be expected, as their membership is primarily heavy industrial owners and contractors. There was also representation in the commercial and infrastructure sectors of the construction industry. These are also typically organizations that dedicate significant resources and attention to safety, so their expertise is considered industry-leading. Subsequently, their responses bring a high level of credibility.

6. RESULTS

6.1 Consistency Ratio

The AHP process described to this point does not guarantee the validation of the data itself. To validate the AHP result, a consistency ratio has been developed which shows whether data is consistent. This ratio validates consistency of responses across all pair-wise comparisons. Saaty (1988) suggests a con-

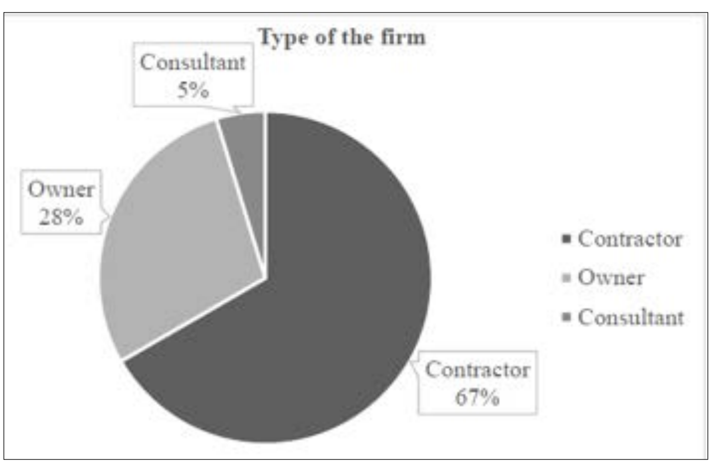

Figure 2. Type of firm

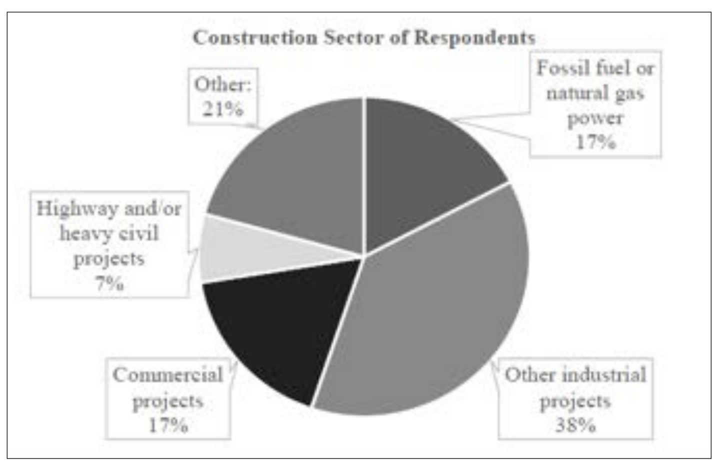

Figure 3. Construction sector of respondents

sistency ratio with the threshold of 0.1. If the consistency ratio is less than the threshold, it is considered a consistent result. If the consistency ratio is more than 0.1, the judgments should be revised by decision-makers. First, the pair-wise comparison matrix is created based on the averages of the responses from the survey. This matrix is shown in Table 3.

Next, the synthesized matrix is calculated by dividing each cell of the matrix by its column sum. As an example, the first cell at the top left of the pair-wise comparison matrix table is 1.0. The sum of the other factors in its column is 29.81 (1 + 3.05 + 3.05 + 3.21 + 3.06 + 2.38 + 2.29 + 2.60 + 2.45 + 2.21 + 2.05 + 2.52 = 29.81). The cell value is divided by the column sum, 1.0/29.87 = 0.03. This value becomes the first cell at the top left of the synthesized matrix as shown in Table 4.

The next step is to calculate priority vectors. The priority vector is calculated by the sum of each row by its number of cells in each row. For SD1 as an example, its priority vector is calculated as (0.03 + 0.02 + 0.02 + 0.02 + 0.02 + 0.03 + 0.03 + 0.03 + 0.04 + 0.04 + 0.05 + 0.06)/12 = 0.03. A weighted sum matrix then needs to be created by multiplying the priority vector for each row by its cell numbers from that row. The matrixes on p. 369 illustrate the weighted sum matrix calculated for this project.

The next step is calculating the largest eigenvalue of the pair-wise comparison matrix, λ_{max}. Each weighted sum matrix component should be divided by its priority vector.

λ_{max} is computed by averaging all the previous calculations.

λ_{max}=(14.00+12.83+11.67+13.00+12.75+12.42+11.75+12.50 +12.60+12.55+12.45+12.35)/12=12.57

$$\frac{0.42}{0.03}=14.00,\quad \frac{0.77}{0.06}=12.83,\quad \frac{0.70}{0.06}=11.67,\quad \frac{1.04}{0.08}=13.00,\quad \frac{1.02}{0.08}=12.75,$$
$$\frac{0.87}{0.07}=12.42,\quad \frac{0.94}{0.08}=11.75,\quad \frac{1.25}{0.10}=12.50,\quad \frac{1.26}{0.10}=12.60,\quad \frac{1.13}{0.09}=12.55,$$
$$\frac{1.37}{0.11}=12.45,\quad \frac{1.73}{0.14}=12.35$$

A primary component of the consistency ratio is the consistency index given by:

CI=(λ_{max}-n)/(n-1) CI=(12.57-12)/(12-1)=0.05

The last step in calculating the CR is finding the compatible random consistency index (RI). Saaty (1988) suggested values for the RI depending on the size of the pair-wise comparison matrix. Table 5 reports those values from Saaty (1988). With an n = 12, the appropriate RI is 1.48. The consistency ratio can then be calculated as CR=CI/RI=0.05/1.48=0.034 (Table 5, p. 370).

The consistency ratio is 0.034. Any values less than 0.1 are considered to be acceptable and consistent according to Saaty (1988). Given the outcomes of this analysis, the survey produced valid and consistent results. The above steps could be useful for academics and practitioners for decision-making in this field.

Drivers	SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SD11	SD12
SD1	1.00	0.33	0.33	0.31	0.33	0.42	0.44	0.38	0.41	0.45	0.49	0.40
SD2	3.05	1.00	0.62	0.47	0.49	0.83	0.75	0.60	0.88	0.79	0.68	0.63
SD3	3.05	1.60	1.00	1.48	0.42	0.54	0.51	0.46	0.54	0.66	0.56	0.51
SD4	3.21	2.11	2.08	1.00	0.73	0.92	0.94	0.62	0.78	0.86	0.97	0.62
SD5	3.06	2.03	2.37	1.37	1.00	0.85	0.90	0.55	0.59	0.89	0.54	0.57
SD6	2.38	1.21	1.84	1.09	1.18	1.00	0.77	0.52	0.60	0.66	0.53	0.48
SD7	2.29	1.32	1.95	1.06	1.11	1.31	1.00	0.50	0.55	0.70	0.75	0.54
SD8	2.60	1.67	2.17	1.62	1.82	1.92	2.00	1.00	0.55	0.83	0.60	0.52
SD9	2.45	1.14	1.86	1.29	1.69	1.68	1.83	1.80	1.00	0.78	0.68	0.53
SD10	2.21	1.26	1.52	1.17	1.12	1.52	1.43	1.21	1.28	1.00	0.73	0.48
SD11	2.05	1.48	1.79	1.03	1.86	1.89	1.33	1.66	1.47	1.37	1.00	0.66
SD12	2.52	1.59	1.95	1.62	1.75	2.09	1.86	1.91	1.89	2.07	1.51	1.00

Table 3. Pair-wise comparison matrix

Drivers	SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SD11	SD12	Priority Vector
SD1	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.06	0.03
SD2	0.10	0.06	0.03	0.04	0.04	0.06	0.05	0.05	0.08	0.07	0.07	0.09	0.06
SD3	0.10	0.10	0.05	0.04	0.03	0.04	0.04	0.04	0.05	0.06	0.06	0.07	0.06
SD4	0.11	0.13	0.11	0.08	0.05	0.06	0.07	0.06	0.07	0.08	0.11	0.09	0.08
SD5	0.10	0.12	0.12	0.11	0.07	0.06	0.07	0.05	0.06	0.08	0.06	0.08	0.08
SD6	0.08	0.07	0.09	0.09	0.09	0.07	0.06	0.05	0.06	0.06	0.06	0.07	0.07
SD7	0.08	0.08	0.10	0.08	0.08	0.09	0.07	0.04	0.05	0.06	0.08	0.08	0.08
SD8	0.09	0.10	0.11	0.13	0.14	0.13	0.15	0.09	0.05	0.07	0.07	0.08	0.10
SD9	0.08	0.07	0.10	0.10	0.13	0.11	0.13	0.16	0.09	0.07	0.08	0.08	0.10
SD10	0.07	0.08	0.08	0.09	0.08	0.10	0.10	0.11	0.12	0.09	0.08	0.07	0.09
SD11	0.07	0.09	0.09	0.08	0.14	0.13	0.10	0.15	0.14	0.12	0.11	0.10	0.11
SD12	0.08	0.09	0.10	0.13	0.13	0.14	0.13	0.17	0.18	0.19	0.17	0.14	0.14

Table 4. Synthesized matrix

6.2 Matrix Weights

Table 6 (p. 370) produces the individual weights and the relative weights for each safety driver based on the results of the AHP survey and analysis.

The most heavily weighted driver is the owner's role while recognition and rewards received the least weight from survey respondents. In comparing the differences between these two, the owner's role had a relative weight 4 times that of recognition and reward. While the majority of respondents were from contractor organizations who are motivated by what the owner pays for, this still strongly suggests the need to have owners play a part in valuing safety

$$0.03\begin{pmatrix}1.00\\3.05\\3.05\\3.21\\3.06\\2.38\\2.29\\2.60\\2.45\\2.21\\2.05\\2.52\end{pmatrix}+0.06\begin{pmatrix}0.33\\1.00\\1.60\\2.11\\2.03\\1.21\\1.32\\1.67\\1.14\\1.26\\1.48\\1.59\end{pmatrix}+0.06\begin{pmatrix}0.33\\0.62\\1.00\\2.08\\2.37\\1.84\\1.95\\2.17\\1.86\\1.52\\1.79\\1.95\end{pmatrix}+0.08\begin{pmatrix}0.31\\0.47\\0.48\\1.00\\1.37\\1.09\\1.06\\1.62\\1.29\\1.17\\1.03\\1.62\end{pmatrix}+0.08\begin{pmatrix}0.33\\0.49\\0.42\\0.73\\1.00\\1.18\\1.11\\1.82\\1.69\\1.12\\1.86\\1.75\end{pmatrix}+0.07\begin{pmatrix}0.42\\0.83\\0.54\\0.92\\0.85\\1.00\\1.31\\1.92\\1.68\\1.52\\1.89\\2.09\end{pmatrix}$$

$$+0.08\begin{pmatrix}0.44\\0.75\\0.51\\0.94\\0.90\\0.77\\1.00\\2.00\\1.83\\1.43\\1.33\\1.86\end{pmatrix}+0.10\begin{pmatrix}0.38\\0.60\\0.46\\0.62\\0.55\\0.52\\0.50\\1.00\\1.80\\1.21\\1.66\\1.91\end{pmatrix}+0.10\begin{pmatrix}0.41\\0.88\\0.54\\0.78\\0.59\\0.60\\0.55\\0.55\\1.00\\1.28\\1.47\\1.89\end{pmatrix}+0.09\begin{pmatrix}0.45\\0.79\\0.66\\0.86\\0.89\\0.66\\0.70\\0.83\\0.78\\1.00\\1.37\\2.07\end{pmatrix}+0.11\begin{pmatrix}0.49\\0.68\\0.56\\0.97\\0.54\\0.53\\0.75\\0.60\\0.68\\0.73\\1.00\\1.51\end{pmatrix}+$$

$$0.14\begin{pmatrix}0.40\\0.63\\0.51\\0.62\\0.57\\0.48\\0.54\\0.52\\0.53\\0.48\\0.66\\1.00\end{pmatrix}=\quad 0.06\begin{pmatrix}0.42\\0.77\\0.70\\1.04\\1.02\\0.87\\0.94\\1.25\\1.26\\1.13\\1.37\\1.73\end{pmatrix}$$

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57

Table 5. Random consistency index (data from Saaty, 1988)

on a project. In addition, respondents placed a strong emphasis on keeping a site clean and organized, as worksite organization was the second highest weighted driver.

Although the need for an organized site is typically realized, it is important to note that it is valued over items such as training employees and understanding risk on a project site. Another interesting outcome was that subcontractor management received the second lowest weighting. Contractors control the safety behaviors of their direct hires, however, they have less control over subcontractor's employees yet are still responsible for their safety on a project. Given that the majority of survey respondents were contractors, one might expect to see a higher emphasis placed on managing subcontractors.

7. LIMITATIONS

One of the anticipated limitations of this study was the effect of fatigue and bias of participants because of the length of the survey. The survey platform had a feature of pause, save, and continue, which let participants finish the survey based on their own desired pace, so it reduced the bias and fatigue impact on the survey result. In addition, the effort relies on the opinions of subject matter experts. Thus, individual biases are present in the responses provided. The other limitation of the study was that there was no precise AHP software that could handle 12 by 12 matrix for AHP analysis, so the research team developed a customized 12 by 12 Excel matrix.

8. CONCLUSION

The objective of the study was to prioritize the safety drivers based on input from subject matter experts. This was achieved through an AHP which involved conducting a survey, collecting, validating and analyzing data. The survey of 21 owner and contractor safety professionals provided the expertise in weighting the various safety drivers. Survey respondents strongly believed that owners play a significant part in safety outcomes on a project site as well as keeping a jobsite organized. Subcontractor management and recognizing and rewarding employees did not have a strong influence on jobsite safety according to survey respondents. This study allows for the appropriate evaluation of the OEM on specific project assessments. Future research in this area will assess project adherence to the OEM. The statistical relationship between OEM score and project safety performance will be established. In addition, understanding the impact of each of these safety drivers will help industry practitioners know where their projects may be excelling and where they may need to dedicate additional resources.

Overall, this research helps professionalize safety in a similar regard to previous efforts on productivity and front-end planning. Practitioners can evaluate their project's commitment to safety in the hopes that the industry can continue momentum toward zero incident jobsites. Further, highly weighted practices indicate an area of importance based on the feedback from the panel of experts. For practitioners who wish to devote more effort to project safety, those highly weighted practices would be desirable starting points. For other practitioners whose programs may be strong in those areas, some of the lower weighted practices may help improve safety further. The other important finding aspect is the model itself. Safety practitioners need an easy-to-use, practical and effective tool to quickly identify ways to improve safety. The model meets this need by providing a systematic approach to addressing this issue. Future research will apply this model to various projects to validate its effectiveness and efficiency. ■

Drivers	SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SD11	SD12	Priority Vector
SD1	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.06	0.03
SD2	0.10	0.06	0.03	0.04	0.04	0.06	0.05	0.05	0.08	0.07	0.07	0.09	0.06
SD3	0.10	0.10	0.05	0.04	0.03	0.04	0.04	0.04	0.05	0.06	0.06	0.07	0.06
SD4	0.11	0.13	0.11	0.08	0.05	0.06	0.07	0.06	0.07	0.08	0.11	0.09	0.08
SD5	0.10	0.12	0.12	0.11	0.07	0.06	0.07	0.05	0.06	0.08	0.06	0.08	0.08
SD6	0.08	0.07	0.09	0.09	0.09	0.07	0.06	0.05	0.06	0.06	0.06	0.07	0.07
SD7	0.08	0.08	0.10	0.08	0.08	0.09	0.07	0.04	0.05	0.06	0.08	0.08	0.08
SD8	0.09	0.10	0.11	0.13	0.14	0.13	0.15	0.09	0.05	0.07	0.07	0.08	0.10
SD9	0.08	0.07	0.10	0.10	0.13	0.11	0.13	0.16	0.09	0.07	0.08	0.08	0.10
SD10	0.07	0.08	0.08	0.09	0.08	0.10	0.10	0.11	0.12	0.09	0.08	0.07	0.09
SD11	0.07	0.09	0.09	0.08	0.14	0.13	0.10	0.15	0.14	0.12	0.11	0.10	0.11
SD12	0.08	0.09	0.10	0.13	0.13	0.14	0.13	0.17	0.18	0.19	0.17	0.14	0.14

Table 6. Safety driver weights

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Evaluation of Noise Reduction Engineering Controls on an Air Impact Wrench

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ABSTRACT

Noise affects millions of workers in the U.S. One of the primary sources of noise is machinery. Developing effective approaches that can reduce the sound level generated by machinery is, therefore, of great interest to occupational safety and health (OSH) professionals and industries, and will help reduce the prevalence of occupational hearing loss. This research was designed to evaluate the sound level generated by an air impact wrench and the effect of increasing distance. More importantly, this research evaluated the noise reduction efficiencies of using fiberglass insulation materials to muffle the noise from the wrench exhaust air outlet, which was enclosed in either a wood box or a plastic bottle. Our data showed that the pneumatic impact wrenches produced an average of 107 dBA at the source. Increasing the working distance from the source to 5 ft. significantly reduced the sound level ($p \leq 0.05$). Enclosing the impact wrench exhaust outlet with either a wooden box or plastic bottle filling with fiberglass insulation materials also significantly reduced the sound level ($p \leq 0.05$). Our results demonstrated that a high level of noise produced by machineries can be effectively reduced by increasing working distance and/or simple engineering control approaches.

Keywords: *noise; pneumatic wrench; sound level; engineering control; working distance*

1. INTRODUCTION

Noise is a health and safety epidemic globally. A recent report from the National Institute for Occupational Safety and Health (NIOSH) suggests that close to 28 million or 14% of U.S. adults ages 20 to 69 suffer from hearing loss, and worldwide one-third of adults has measurable hearing loss to some degree (Murphy, Eichwald, Meinke, Chadha & Iskander, 2018). In addition to the notorious health effect of noise-induced hearing loss (NIHL), increasing noise exposure can interfere with communication, increase physiological and psychological stress, and pose a great risk to safety (Canton & Williams, 2012; Leon Bluhm, Berglind, Nordling & Rosenlund, 2007; Padmakumar, et al., 2017).

An air impact wrench, also called a pneumatic torque wrench, is a ubiquitous tool powered by air. The wrench has high efficiency and safety features, including higher power-to-weight ratio, high torque output with minimal exertion, lower self-destruct when jammed or overloaded, lower vibration, and no risks of sparks or electrocution (Majumdar, 1996). The tool is widely used in industries where an accurate and high torque output are required to install or remove a nut and bolt, such as construction, automotive industry, and equipment assembly, maintenance and repair.

However, air impact wrenches often produce high levels of noise. According to the NIOSH Power Tools Database, most impact wrenches generate about 110 dB of sound power level (NIOSH). Therefore, developing effective noise reduction controls are of significant interest to industries and EHS professionals. This research tested the noise reduction efficiencies of using fiberglass insulation material to muffle the noise from the exhaust air outlet, which was further enclosed by a wood box or a plastic bottle. Our data show both exhaust air outlet enclosure designs can significantly reduce sound level at the source by 4.8 dBA and 7.2 dBA, respectively.

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2. MATERIALS & METHODS

2.1 Air Impact Wrench

A ½-in. aluminum air impact wrench (#EQ12A), manufactured by the Central Pneumatic Earthquake Co. (Camarillo, CA, USA; Figure 1A), was acquired to use as a noise source generator. The wrench has an air consumption capacity of 6 cubic feet per minute flow (CFM) at 90 pounds per square inch of pressure (PSI) and generate up to 8,000 blows per minute (BPM). The wrench was pressurized by a Porter Cable air compressor (Porter-Cable, Jackson, TN, USA).

2.2 Engineering Design of Noise Reduction

The exhaust air outlet, located on the underside of the impact wrench, generates a high level of noise due to high-pressure air flow (Figure 1B). Two noise reduction designs were developed to reduce the sound level generated at the exhaust air outlet. Fiberglass insulation material (8 oz.) was placed over the exhaust air outlet to muffle the noise (Figure 1C), and then enclosed with either a plastic bottle (Figure 1D) or a wood box (Figure 1E). A hole directly in the bottom of a plastic bottle was made to encapsulate the impact wrench's exhaust and fiberglass insulation (Figure 1D). The wood box (6 in. L × 2.5 in. H × 1.5 in. W) was built using scrap wood sheets with ¼-in. width (Figure 1E).

2.3 Noise Measurement

A calibrated 3M SoundPro DL-2 #BIP010010 (Quest Technologies Inc., Kennesaw, GA, USA) was used to measure the sound pressure level. Pre- and post-use calibrations along with four calibration spot checks during the experiment were performed using a 3M Quest Acoustic calibrator QC-10/QC-20 (#QIK020050). Environmental conditions at the time of the experiment were 77 °F, 74% humidity, and a 5-mph wind. The torqueing activity of the wrench was consistently maintained at the maximum blow speed (8,000 BPM) for each test. The

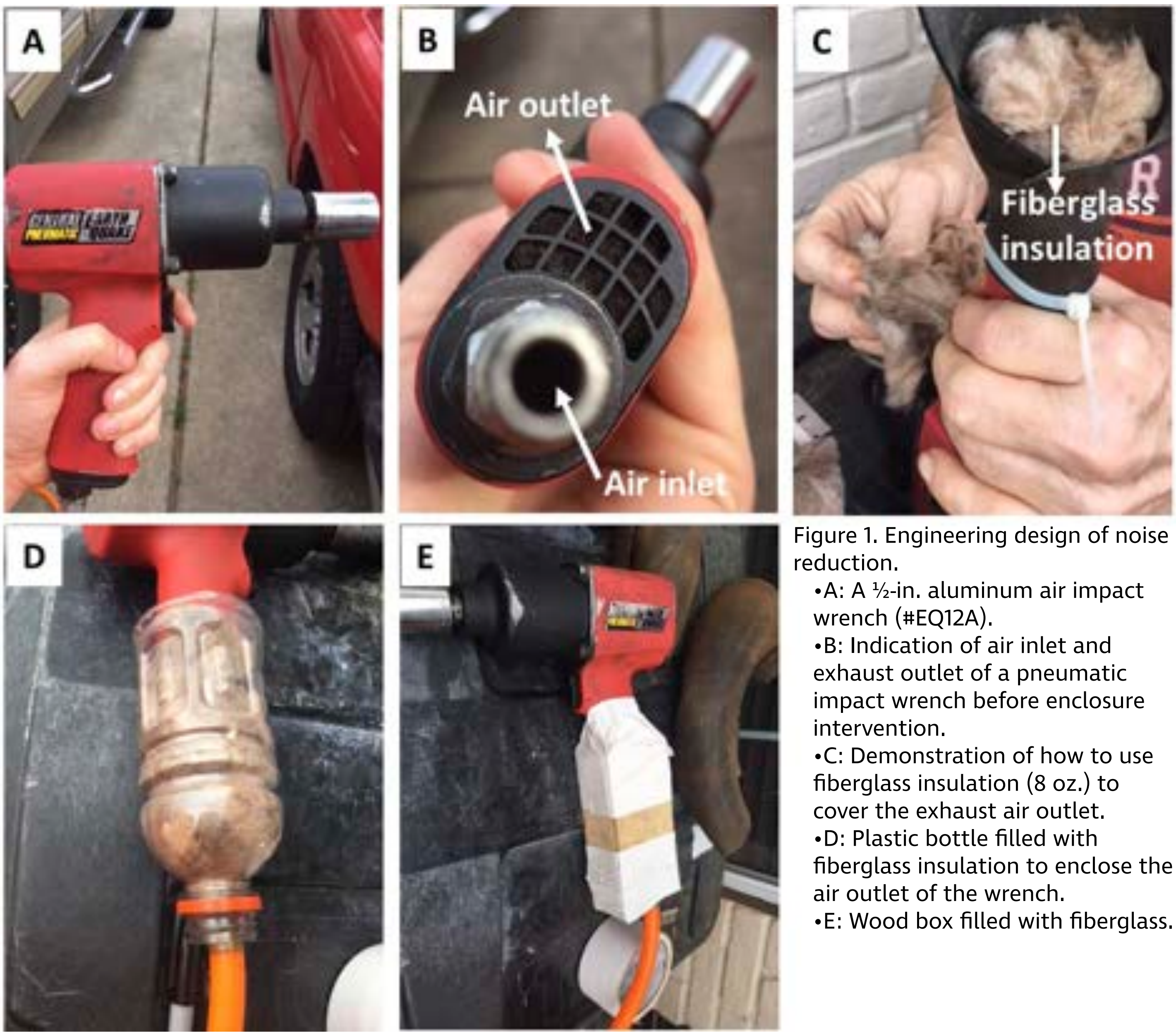

Figure 1. Engineering design of noise reduction.

- A: A ½-in. aluminum air impact wrench (#EQ12A).
- B: Indication of air inlet and exhaust outlet of a pneumatic impact wrench before enclosure intervention.
- C: Demonstration of how to use fiberglass insulation (8 oz.) to cover the exhaust air outlet.
- D: Plastic bottle filled with fiberglass insulation to enclose the air outlet of the wrench.
- E: Wood box filled with fiberglass.

sound levels were measured four separate times directly at the source of the exhaust, 2 ft away from the impact wrench exhaust outlet, and 5 ft from the impact wrench exhaust outlet with and without each noise reduction design.

2.4 Data Analysis

Data is presented as the mean ± standard error of the mean. The effect of each noise reduction design and the distance from the noise source was analyzed using two-way ANOVA. Multiple comparisons using the Tukey test were performed to determine differences between groups. A $p \leq 0.05$ was considered as statistically significant.

3. RESULTS

3.1 Engineering Control Reduces Noise Levels

Before the engineering control intervention, the sound level of the pneumatic impact wrench was 107.1 dBA at the source. The sound levels were significantly reduced to 95.4 dBA at 2 ft from the impact wrench exhaust outlet and 91.2 dB at 5 ft from impact wrench exhaust outlet ($p \leq 0.05$; Figure 2). Using fiberglass insulation material to muffle the noise from the exhaust air outlet and enclosing the exhaust outlet with either a wood box or plastic bottle, the researchers were able to reduce the noise level at the source by 4.8 dBA and 7.2 dBA, respectively ($p \leq 0.05$; Figure 2).

3.2 Engineering Control Increases the Reference Duration

Using the equation ($T = 8 / (2^{(L-90)}/5)$) provided at 29 CFR 1910.95 App A “Noise exposure computation” (OSHA), the reference duration (T) for each noise level was computed. As shown in Table 1, the average allowable exposure time (that is reference duration) at the source was 0.7 hours, while enclosing the exhaust air outlet using the wood box design filled with fiberglass insulation materials (8 oz.) can double the reference duration, and the plastic bottle design can almost triple the time (Table 1). The two designs can increase the reference duration by an average of 132%. When the distance was increased from the noise source, both engineering controls were still able to increase the reference duration, but the increment was reduced with increased distance (Table 1).

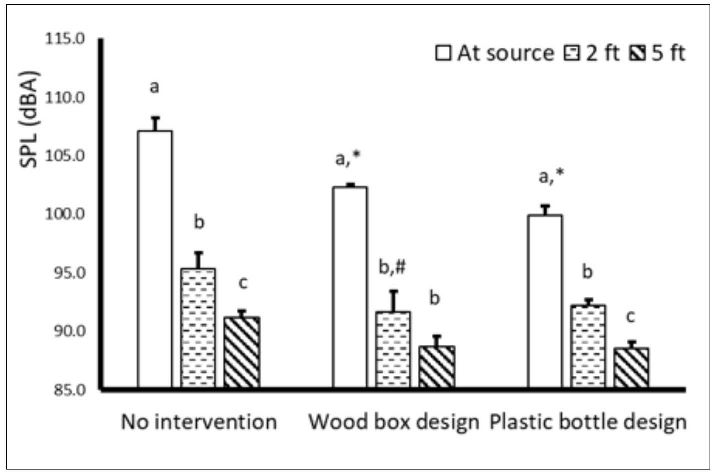

Figure 2. Sound pressure level (SPL) of the pneumatic impact wrench without and with different exhaust air outlet enclosure designs. The noise level (dBA) at the source, 2 ft and 5 ft away from the source was measured using a calibrated sound level meter.

4. DISCUSSION

Excessive exposure to noise affects billions of people worldwide, and has resulted in over 27 million U.S. adults alone losing their hearing annually (Murphy, et al., 2018; Nelson, Nelson, Concha-Barrientos & Fingerhut, 2005). Air-powered tools are widely used in construction, manufacturing, automotive and various other industries. Air impact wrenches have many advantages including high efficiency and safety features (Majumdar, 1996), but produce high levels of noise (NIOSH).

Here we tested a simple engineering noise control approach to muffle the noise from the exhaust air outlet of the wrench, with fiberglass insulation material, which was enclosed with either a wood box or a plastic bottle. Our data show these either exhaust enclosure design can significantly reduce the noise level at the source by an average of 6 dBA. According to OSHA’s Guidelines for Noise Enforcement [29 CFR 1910.95(b)(1)], a control able to reduce the noise level by 3 to 5 dB would be considered significant (OSHA). Therefore, an average of 6 dBA reduction suggests our engineering designs are very effective.

Many pneumatic impact power tools produce high levels of noise while operating (NIOSH), which poses a great risk of noise-induced hearing

	No Intervention		Wood box design		Plastic bottle design		Increased T, %
	dBA	T, hours*	dBA	T, hours	dBA	T, hours	
At source	107.1	0.7	102.3	1.4	100.0	2.0	+ 132.5
2 ft.	95.4	3.8	91.7	6.3	92.2	5.9	+ 61.2
5 ft.	91.2	6.8	88.7	9.6	88.5	9.8	+ 43.2

* The reference duration (T, hours) was calculated using equation $T = 8 / (2^{(L-90)/5})$ provided at 29 CFR 1910.95 App A “Noise exposure computation” (OSHA).

Table 1. Computed reference duration (T, hours) at each noise level, and the percentage of exposure time increased after the engineering noise control

loss to employees. In our study, the noise level of the original pneumatic impact wrench tested was 107.1 dBA at the source (Figure 2). At this noise level, the operator would only be allowed to use the wrench for 0.7 hours, and during the rest of the 8-hour shift the operator could not be exposed to other noise source greater than 80 dB, per OSHA standard 29 CFR 1910.95 App A (OSHA).

However, this assumption often is impracticable and unachievable. For example, a recent 10-year prospective study suggested the construction workers are estimated to have an average annualized equivalent continuous noise exposures (LEQ) of 87±3.6 dBA (Seixas, et al., 2012). In fact, many industrial environments have a noise level over 85 dB (Olayinka & Abdullahi, 2009), an action level per the OSHA requirement (OSHA).

Therefore, to increase the operator's allowable time exposure and productivity, the practical approaches for the employer to reduce noise level include the implementation of engineering controls and/or providing hearing personal protective equipment (PPE). Here we tested the efficiency of using fiberglass insulation material to muffle the noise from the pneumatic impact wrench exhaust air outlet and applied using a wood box or plastic bottle enclosure design (Figure 1). We found both designs significantly reduced the noise level at the source ($p \leq 0.05$; Figure 2) and, thereby, more than doubled the average allowable operation time (Table 1).

In addition to the evaluation of noise at the source (primarily affecting operators), we evaluated the noise level at 2 ft and 5 ft away from the source, which is expected to impact adjacent co-workers. As shown in Figure 2, both enclosure designs were able to reduce the noise level by an average of 3.4 dBA and 2.6 dBA at 2 ft and 5 ft, respectively, suggesting these engineering designs would be effective to protect co-workers per OSHA's noise enforcement guidelines (OSHA). Accordingly, the computed reference duration would be increased by 61% and 43%, respectively (Table 1), suggesting the consequence of noise reduction by these engineering designs will make other controls (that is, administrative control and PPE) more practicable and achievable.

In summary, this study provides evidences to support the premise that muffling the noise from the exhaust air outlet of an air-powered tool by using fiberglass insulation materials and an enclosure box will be very effective. This engineering control design is simple and inexpensive, and is able to be implemented by many plants and on many pneumatic tools. The design can effectively reduce the level of noise exposure to operators and adjacent co-workers, and contribute to their hearing conservation programs. Additional designs and testing to ensure that the enclosure box is more ergonomic friendly and less interfering handle grips will warrant the application of these noise reduction engineering designs. ■

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