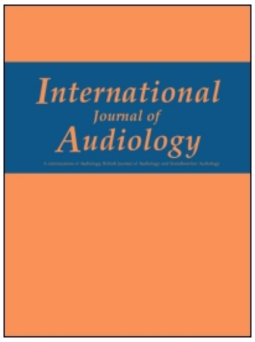


Taylor & Francis
Taylor & Francis Group

International Journal of Audiology

ISSN: 1499-2027 (Print) 1708-8186 (Online) Journal homepage: http://www.tandfonline.com/loi/iija20

What can 35 years and over 700,000 measurements tell us about noise exposure in the mining industry?

Benjamin Roberts, Kan Sun & Richard L. Neitzel

To cite this article: Benjamin Roberts, Kan Sun & Richard L. Neitzel (2017) What can 35 years and over 700,000 measurements tell us about noise exposure in the mining industry?, International Journal of Audiology, 56:sup1, 4-12, DOI: 10.1080/14992027.2016.1255358

To link to this article: https://doi.org/10.1080/14992027.2016.1255358

Taylor & Francis
Taylor & Francis Group

International Journal of Audiology 2017; 56: S4–S12

International Journal of Audiology

Original Article

What can 35 years and over 700,000 measurements tell us about noise exposure in the mining industry?*

Benjamin Roberts, Kan Sun & Richard L. Neitzel

Department of Environmental Health Sciences, University of Michigan, School of Public Health, Ann Arbor, MI, USA

The British Society of Audiology
The International Society of Audiology
NAS NORDIC AUDIOLOGICAL SOCIETY

Abstract

Objective: To analyse over 700,000 cross-sectional measurements from the Mine Safety and Health Administration (MHSA) and develop statistical models to predict noise exposure for a worker. *Design*: Descriptive statistics were used to summarise the data. Two linear regression models were used to predict noise exposure based on MSHA-permissible exposure limit (PEL) and action level (AL), respectively. Twofold cross validation was used to compare the exposure estimates from the models to actual measurement. The mean difference and *t*-statistic was calculated for each job title to determine whether the model predictions were significantly different from the actual data. *Study sample*: Measurements were acquired from MSHA through a Freedom of Information Act request. *Results*: From 1979 to 2014, noise exposure has decreased. Measurements taken before the implementation of MSHA's revised noise regulation in 2000 were on average 4.5 dBA higher than after the law was implemented. Both models produced exposure predictions that were less than 1 dBA different than the holdout data. *Conclusion*: Overall noise levels in mines have been decreasing. However, this decrease has not been uniform across all mining sectors. The exposure predictions from the model will be useful to help predict hearing loss in workers in the mining industry.

Key Words: Demographics/epidemiology; noise; hearing conservation; instrumentation

Introduction

Noise is one of the most common occupational exposures in the United States. Tak et al, (2009) estimated that 22 million workers were exposed to hazardous noise levels based on self-reported noise exposure. The National Institute for Occupational Safety and Health (NIOSH) estimates that over four million American workers are potentially exposed to hazardous noise >85 dBA and that the excess risk of noise-induced hearing loss (NIHL) at this exposure level ranges from 8% to 16% depending on the hearing loss metric and statistical model used (NIOSH, 1998). NIHL is among the top 10 leading work-related illnesses and injuries identified by NIOSH. The overall prevalence of hearing loss in the working population is estimated to be 11.4%, while the railroad and mining industries have the highest and second-highest prevalence (34.8% and 24.3%, respectively) (Tak & Calvert, 2008). NIOSH estimated that, on average, 100–200 coal, 50–150 metal and 10–40 non-metal workers per 100,000 full-time workers, experienced hearing loss each year. This accounted for around one fifth of the total reported injury cases in the mining sector (NIOSH, 2000). NIOSH also estimated that by the age of 50, 90% of miners will have developed a hearing loss >25 dB at the 1, 2, 3 and 4 kHz frequency (NIOSH, 2000).

The estimated economic cost of hearing loss varies widely. The WHO estimated the cost of hearing loss to be between 0.2% and 2% of gross domestic product (GDP) for developed countries (WHO, 1997). Emmett and Francis (2015) further found that hearing loss was independently associated with lower educational achievement and lower income than those without hearing loss. The cost of compensation for hearing loss in US military Veterans alone was over $1.2 billion in 2006 (Saunders & Griest, 2009). Recently, Neitzel et al, estimated that the United States could save between $52 and $152 billion each year if 20% of hearing loss from hazardous noise was prevented (Neitzel et al, In Press). Additionally, there is a growing body of evidence that noise exposure may be associated with a number of important non-auditory health effects, including cardiovascular disease (Basner et al, 2014). These effects may be particularly evident among miners, as mining has traditionally been considered one of the noisiest industries in the United States (Tak et al, 2009).

---

*A partial analysis of these data was presented at the 2016 National Hearing Conservation Association (NHCA) conference in San Diego, CA on February 19th 2016.

Correspondence: Richard L. Neitzel 6611D SPH Tower, 1415 Washington Heights, Ann Arbor, Michigan 48109-2029. E-mail: rneitzel@umich.edu

(Received 13 September 2016; revised 0 0000; accepted 24 October 2016)

ISSN 1499-2027 print/ISSN 1708-8186 online
DOI: 10.1080/14992027.2016.1255358

Abbreviations

AL	Action level
AIC	Akaike information criterion ;
dBA	A-weighted decibel
R2	Coefficient of determination
HCP	Hearing conservation programme
IQR	Interquartile range
JEM	Job exposure matrix
MSHA	Mine safety and health administration
NIOSH	National Institute for Occupational Safety and Health
NIHL	Noise-induced hearing loss
NAICS	North American Industrial Classification System
PEL	Permissible exposure limit
SOC	Standard occupation classification
TWA	Time-weighted average
WHO	World Health Organisation

The Mine Safety and Health Administration (MSHA) was established by the Federal Mine Safety and Health Act of 1977 to promulgate and enforce health and safety regulations for the mining industry (Federal Mine Safety and Health Act, 1977). The permissible exposure limit (PEL) for noise was set at 90 dBA as an 8-hour time-weighted average (TWA) with a 5 dB time–intensity exchange rate for all sound levels from 90 to at least 140 dBA (Federal Mine Safety and Health Act, 1977). In addition, the Federal Mine Safety and Health Act established regulations regarding requirements for the use of noise controls and hearing protectors (and, in the case of coal mines, implementation of hearing conservation programmes, HCPs) that varied depending on the type of mine. In 1999, MSHA published a revised rule on occupational noise which harmonised the rules regarding HCPs and the implementation of noise controls in all mines in the United States. In addition, the new rules established an action level (AL) of 85 dBA as a TWA with a 5 dB exchange rate for sound levels between 80 and at least 130 dBA, as well as harmonised requirements for HCPs (30 CFR Part 62, 1999).

To help fulfil its mandate, MSHA conducts routine noise-monitoring inspections in mines of all types and amassed a dataset of over 700,000 noise dosimetry measurements from 1979 to 2014. Most of these measurements include information on the type of mine (facility, surface or underground), what was being mined (coal, metal or non-metal) whether the measurement was made using the PEL or AL criteria, and job title or task description for each measurement. In 2007, Joy and Middendorf (2007) conducted an analysis of noise measurements in coal mines from 1986 to 2004. This analysis yielded important insights into noise in US mines but was limited by the short (four year) time period for which data were available following implementation of MSHA's revised noise regulation in 2000. There has not been a comprehensive analysis of noise exposure in the mining industry since the analysis by Joy and Middendorf (2007). The continued high prevalence of hearing loss among workers in the mining industry warrants another careful analysis noise exposure in the mining industry (Masterson et al, 2016).

Measurements from this data set were analysed as part of a larger job exposure matrix (JEM) for occupational noise. Our study had two goals intended to increase our understanding of past and present noise exposure in the mining industry and to help predict future exposures so that adequate controls can be implemented to protect workers' health. The first goal of this analysis was to describe and evaluate trends in measured occupational noise levels among US miners from 1979 to 2014. The second goal was to use the measurements in the dataset to build a statistical model that could be used to estimate a worker's occupational noise exposure based on their job title and the type of mine.

Methods

Data collection and cleaning

This study was approved by The University of Michigan Institutional Review Board (HUM00083043). Data were requested from MSHA through a Freedom of Information Act request in May 2014. Data were received from MSHA in electronic format (Microsoft Excel spreadsheets and Microsoft Access databases) (Microsoft, Inc, Redmond, WA). The data were imported into STATA 14 (Stata Corp, College Station, TX) for data cleaning and analysis. The type of mineral being mined was coded using four-digit codes from the 2012 North American Industrial Classification System (NAICS) (Office of Management and Budget, 2009). The job titles were coded using the Bureau of Labour Statistic's 2010 Standard Occupation Classification (SOC) system (US Department of Commerce, 2010). The job titles were provided as string variables and contained numerous spelling errors and many different job titles that were considered synonymous. Regular expressions were used to efficiently identify patterns in the job titles so that SOC codes could be assigned (Stubblebine, 2007). Based on the assigned SOC code, each job title was also assigned a major occupational group according to the SOC structure (miners, maintenance, production, transportation/material moving and other). Information pertaining to specific companies or mining sites was removed from this analysis; all other identifiable information (sample ID, citation status, etc.) was also removed.

Measurements reported as a noise dose were converted to A-weighted measurements using the equation $SPL_{TWA} = 16.61 \times log_{10} \frac{Dose}{100} + 90$ (OSHA, 2013). Cases without any measurements or with TWA measurements <60 dBA and >120 dBA as a TWA were removed because these measurements were deemed unlikely to represent typical exposures. Any measurements with job titles that could not be converted to SOC codes, either because no job title was given or because the job title did not provide sufficient information, were removed to help minimise the misclassification of job titles. Finally, any measurements with a sample time >16 h were removed.

Statistical analysis

Histograms, box plots and other data visualisation methods were used to assess the distribution of measurements. Descriptive statistics were calculated for the entire data set. Descriptive statistics were then calculated and stratified by type of mine, miner SOC group and year. The percentage of measurements >85 and >90 dBA (the AL and PEL) was calculated before and after the implementation of the MSHA noise rule in 2000, stratified by the type of mine and mineral being mined.

Two fixed-effect linear regression models were developed to predict average noise exposure for a specific SOC. One model was developed to predict noise exposure using the MSHA PEL; the other was developed to use the MSHA AL. Both models contained covariates for the year (centred to 1979 for the PEL measurements and 2000 for the AL measurements), SOC code, mine type (surface, underground, and facility) and what type of mineral was being extracted (coal, metal, non-metal). Because of the large number of measurements, the holdout method (twofold cross validation) was used to split the data for both models into a training set which comprised 70% of the measurements and a validation set which was comprised of the other 30%. Model fit was evaluated using the coefficient of determination (R^2, where higher value indicate better model fit) and Akaike information criterion (AIC, where lower values indicate less information loss within nested models) (Picard & Cook, 1984). The mean predicted exposures were then calculated from the model in the training set for each SOC and subtracted from the mean value of the same SOC from the validation data set. A Student's *t*-test was used to determine whether there was a significant difference ($\alpha = 0.05$) between the predicted values from the training set and the values in the validation set.

Results

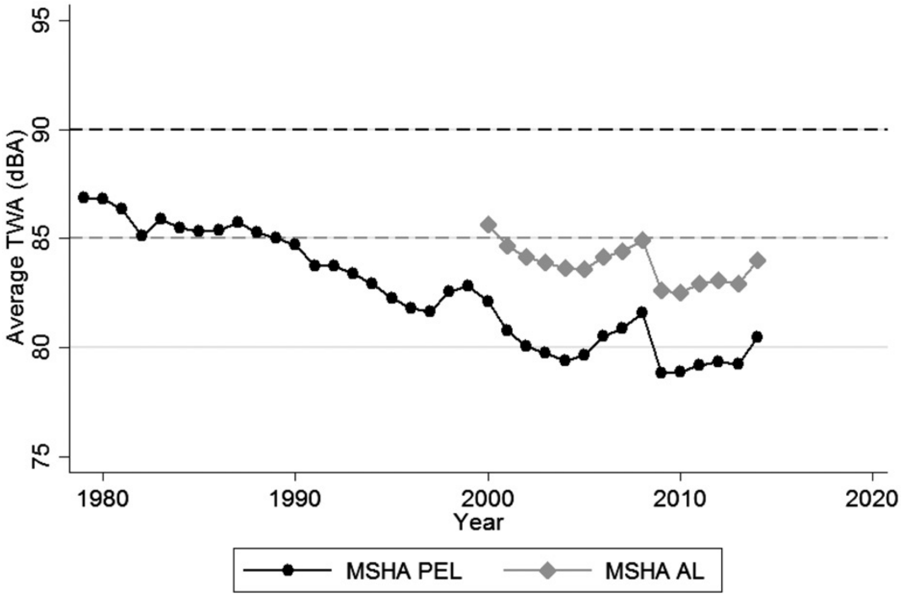
Prior to data cleaning, there were a total of 619,028 PEL measurements and 283,169 AL measurements available. Table 1 summarises the steps in the data cleaning process and the number of measurements eliminated for each exclusion criteria. The largest loss of PEL measurements was the result of missing information regarding what type of material was being mined. The largest loss of AL measurements occurred because the TWA measurements were below 60 dBA. In total, 120,159 (19.4%) PEL and 7421 (2.7%) AL measurements were removed from the data set, leaving 498,869 and 275,748 valid PEL and AL measurements. The mean PEL measurement prior to 2000 was 84.4 dBA with a standard deviation (SD) of 8.2 compared to a mean of 79.9 ± 8.6 dBA after 2000; this difference was highly significant ($p < 0.0001$). The mean AL (post-2000) was 83.7 ± 6.9 dBA.

Table 1. Number of permissible exposure limit (PEL) and action level (AL) measurements removed during data cleaning.

Exclusion criteria	*PEL*	*AL*	*Total*
Total			123,500
Missing any exposure information	4519	4519	4519
No job title	919	319	1238
Measurements <60 dBA	23,327	2042	25,339
Measurements >120 dBA	74	117	191
No information on what was being mined	91,231	0	91,231
No information on mine type	89	0	89
Sampling time >16 h	452	17	469
AL measurement prior to 2000	0	424	424

Figure 1 shows that the average TWA for PEL measurements have been steadily decreasing over time. AL measurements, made starting in 2000, followed a similar pattern, with higher measured levels than those indicated by the PEL due to the different measurement ranges used (80–130 dBA for the AL versus 90–140 dBA for the PEL). Table 2 summarises the changes in average noise exposure before and after the year 2000 stratified by what material was being mined and what type of mine the measurements came from. On average, the PEL measurements decreased by 4.5 dBA for measurements made after the implementation of MSHA's updated noise regulation in 2000. The greatest reduction in PEL exposures was seen in non-metal mines, where measurements decreased by 6.5 dBA, while coal and metal mines only by 2.7 and 2.8 dBA, respectively, and underground coal mines only decreased by 0.8 dBA. The average AL measurements ranged from 81.9 in surface non-metal mines to 87.9 dBA in underground metal mines.

Figure 2 summarises the percentage of measurements that exceeded the 85 dBA AL and 90 dBA PEL. Prior to the year 2000, 23.5% of all TWA measurements exceeded the MSHA PEL of 90 dBA, and underground metal mining had the highest noise exposures of all mine types, with 44.8% of the TWA measurements exceeding 90 dBA. Following the implementation of MSHA's revised noise regulation in 2000, 21.7% of measurements exceeded



85 and 90 dBA represents the Mine Safety and Health Administration's (MSHA) current Action level (AL) and permissible exposure limit (PEL) respectively

Figure 1. Average noise exposure in the coal, metal and non-metal mining sectors from 1979 to 2014.

Table 2. Comparison of mean time-weighted average measurements using the Mine Safety and Health Administration's permissible exposure limit (PEL) and action level (AL) in coal, metal and non-metal mining sectors.

	<2000 PEL			*≥2000 PEL*			*≥2000 AL*			
Mean	*SD*	*N*	*Mean*	*SD*	***N***	*Mean*	*SD*	***N***	*dBA*	*Decrease in PEL*
Overall	84.4	8.2	236,468	79.9	8.6	261,849	83.7	6.9	275,280	4.5
Coal mine										
Facility	84.7	8.3	961	79.5	9.0	23,960	82.9	7.6	25,988	5.2
Surface	82.6	8.0	1087	78.0	8.8	47,945	83.1	6.9	52,808	4.6
Underground	84.7	5.9	1342	83.9	6.6	79,608	86.5	5.5	80,551	0.8
Overall	84.0	7.4	3290	81.3	8.3	151,513	84.8	6.6	159,347	2.7
Metal mine										
Facility	82.6	8.1	4144	79.6	7.3	913	83.1	5.9	939	3.0
Surface	83.1	8.4	10,565	78.7	8.4	2345	82.6	7.0	2432	4.4
Underground	88.5	10.0	7252	85.7	9.8	2583	87.9	8.0	2579	2.8
Overall	84.8	9.3	21,961	81.9	9.5	5841	85.0	7.7	5950	2.9
Non-metal										
Facility	82.8	7.6	18,779	79.3	7.9	7775	83.1	6.3	7898	3.5
Surface	84.5	8.1	180,090	77.7	8.7	90,548	81.9	7.1	95,729	6.8
Underground	85.3	8.2	12,348	79.6	8.7	6172	83.7	6.8	6356	5.7
Overall	84.4	8.1	211,217	77.9	8.7	104,495	82.1	7.1	109,983	6.5

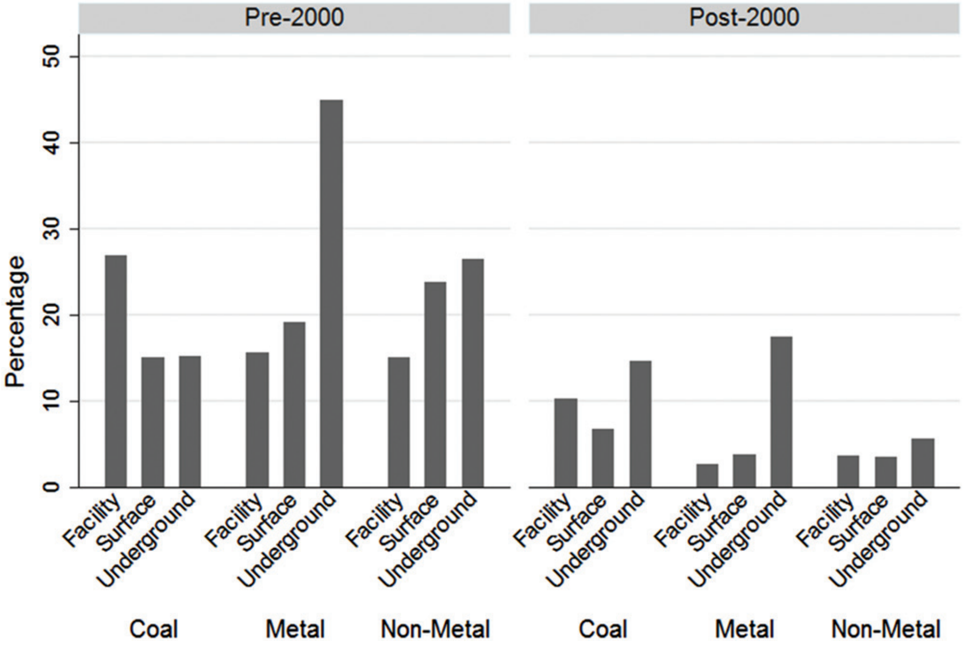


Figure 2. Percentage of measurements exceeding 90 dBA before and after the implementation of the Mine Safety and Health Administration's (MSHA) revised noise regulation in different types of facilities in the coal, metal, and non-metal mining sectors.

the AL and 7.0% exceeded the PEL. After the year 2000, underground metal mining continued to have the greatest percentage of measurements (17.4%) that exceeded the PEL, while underground coal mining had the greatest percentage of measurements (48.4%) that exceeded the AL.

Table 3 shows the percentage of PEL TWA measurements pre- and post-2000 that exceeded a range of cut points (85, 90, 105 and 115 dBA), stratified by material mined and mine type. The percentage of measurements exceeding each of the four cut points dropped after the year 2000 across all mine types and materials mined, with the largest reductions in measurements exceeding these cut points seen in underground non-metal mines and the smallest reductions seen in underground coal mines.

There were a total of 45 different job titles in this data set. Appendix 1 provides the mean, standard deviation and number of measurements for each job title before and after the year 2000. The measurements for the 45 job titles were collapsed into broad occupational groups based on their assigned SOC codes. Figure 3 provides a box plot of the distribution of measurements for each broad occupational group. The mining exposure group had the highest median exposure both before and after the implementation of MSHA's noise standard in 2000. The miner, production, and

Table 3. Percentage of permissible exposure limit (PEL) measurements above certain thresholds before and after the year 2000 in coal, metal and non-metal mining sectors.

	<2000					*≥2000*				
	≥85 dBA	*≥90 dBA*	*≥105 dBA*	*≥115 dBA*	*N*	*≥85 dBA*	*≥90 dBA*	*≥105 dBA*	*≥115dBA*	*N*
Overall	53.3	23.5	0.5	0.0	236,568	21.7	7.0	0.1	0.0	386,130
Coal mine										
Facility	57.0	26.3	0.0	0.0	961	28.5	10.3	0.1	0.0	25,991
Surface	45.3	15.1	0.2	0.0	1087	21.5	6.8	0.1	0.0	52,817
Underground	54.5	15.2	0.1	0.0	1342	48.4	14.7	0.2	0.1	80,584
Overall	52.3	18.5	0.1	0.0	3390	36.3	11.4	0.1	0.0	159,392
Metal mine										
Facility	43.4	15.6	0.4	0.0	4144	12.9	2.6	0.0	0.0	1852
Surface	45.9	19.1	0.4	0.0	10,565	12.9	3.9	0.0	0.0	4777
Underground	65.9	44.8	4.9	0.1	7252	27.9	17.4	0.7	0.0	5162
Overall	52.1	26.9	1.9	0.0	21,961	19.5	9.6	0.3	0.0	11,791
Non-metal										
Facility	43.3	15.1	0.2	0.0	18,779	13.0	3.6	0.0	0.0	15,673
Surface	54.1	23.8	0.4	0.0	180,090	10.5	3.5	0.1	0.0	186,277
Underground	57.8	26.5	0.8	0.0	12,348	15.0	5.7	0.0	0.0	12,528
Overall	53.4	23.2	0.4	0.0	211,217	11.0	3.7	0.1	0.0	214,478

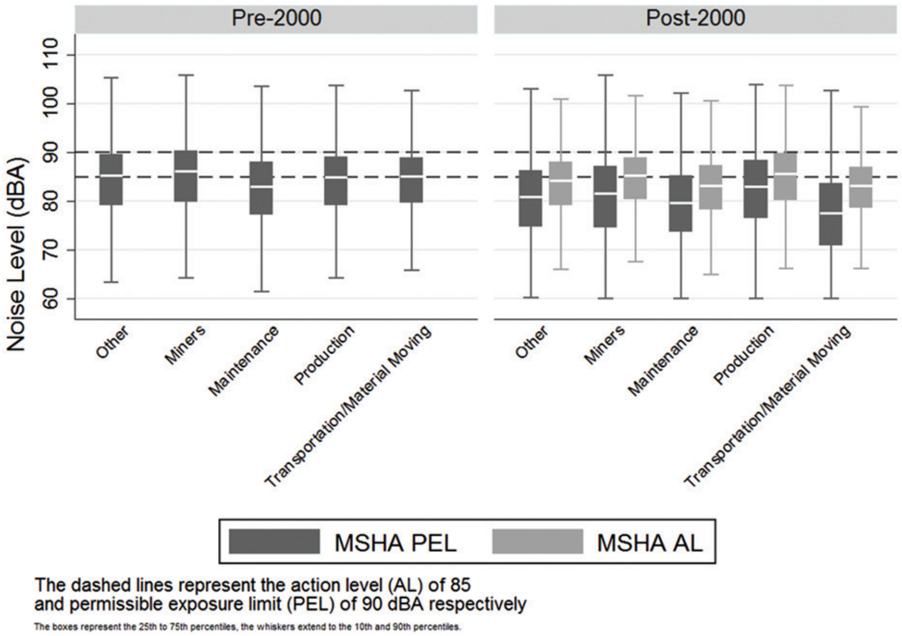


Figure 3. Distribution of measurements for each exposure group before and after the year 2000 for all mining sectors.

other groups all had very similar medians, but the miner group had a larger number of statistical outliers than the other group suggesting that the likelihood of exposures greater than 105 dBA is higher in this group.

The regression coefficients for PEL and AL models, created using the training dataset are presented in Appendix 2. The PEL model contained measurements from 1979 through 2014, while the AL model contained measurements from 2000 through 2014. In both models, the year variable was centred to the first year that measurements were collected. The adjusted-R^2 for the models were 0.1540 for the PEL and 0.1339 for the AL model. When controlling for job title, material being mined and the type of mine, both models predicted that noise exposure has decreased over time (-0.331 and -0.243 dBA per year for the PEL and AL models). This indicates that on average noise levels in the mining industry have decreased by about 0.3 and 0.2 dBA each year for PEL and AL measurements. Coal mines were predicted to be noisier than metal and non-metal mines in the PEL model, but metal mines were found to be noisier than coal and non-metal mines in the AL model. Underground mines were found to be noisier than facility and surface mines in both the PEL and AL models. Roof bolters were estimated to have the highest exposure in the PEL model while landscaping and grounds keeping workers were estimated to have the highest exposure in the AL model.

The overall mean for the predicted values from the training data set PEL model was 82.0 ± 3.4 dBA compared to a mean of 82.0 ± 8.7 dBA for the validation data set. The interquartile range (IQR) for the predicted values was 5.0 dBA compared to 12.2 dBA for the validation data. For each job title, predictions from the PEL model were on average 0.9 dBA different than the actual measurements in the validation data set. The results of the *t*-tests found that six job titles had significantly different ($p < 0.05$) predicted and actual mean exposures. Only three job titles had a mean difference greater than 2 dBA and these job titles had a smaller number of measurements compared to other job titles in the dataset. The overall mean for the predicted values from the AL model was 83.7 ± 2.5 dBA, while the validation data had a mean of 83.7 ± 6.9 dBA. The IQR was 3.4 and 8.7 dBA for the predicted and validation data sets, respectively. For each job title, predictions from the AL model were on average 0.7 dBA different than the validation values. Two job titles were found to have predicted values significantly different from the validation values, the difference between the predicted and validation values for both job titles were less than 2 dBA.

Discussion

The results from this analysis indicate that mean noise exposure in the mining industry has been decreasing every year. This concurs with the results from Joy and Middendorf (2007), who found that the overall annual median noise dose declined 67% for surface coal mining and 24% for underground coal mining from 1986 to 2004. The reductions in exposure noted in our analyses are likely due, at least in part, to the implementation of MSHA's revised noise regulation in 2000 and to improvements in mining technology and noise control (Kovalchik et al, 2007; Smith et al, 2011). However, this reduction in noise exposure does not appear to be evenly distributed among different types of mines, nor has it been completely monotonic. Workers in underground coal mines in particular had a smaller decrease in noise exposure than workers in other mine types mining other materials when comparing measurements before and after the implementation of MSHA's noise standard. There was also a small increase in the percentage of facility coal miners exposed to noise > 105 dBA and underground coal miner exposed to noise > 115 dBA. Our analysis does not allow us to know why this increase has occurred or if it is statistically significant. However, it is possible that as mining technology becomes more automated and requires less workers a small subgroup of miners may be exposed to very high levels of noise as they operate machinery.

Regardless of what types of materials were being mined, workers in underground mines were found to have the highest noise exposure. This is not surprising, as underground mine work involves use of noisy heavy equipment in tightly enclosed, reverberant spaces (Peterson et al, 2006). This suggests that additional resources should be directed to design and implement new noise control technologies that can be used in underground mines. Prior to 2000, coal, metal and non-metal mines had a similar mean exposure level; however, after the year 2000, non-metal mines experienced a much larger decrease in noise exposure than coal and metal mines. A portion of this difference can be attributed to the smaller percentage (5.9%) of underground mine measurements from the non-metal mining sector that were taken post-2000 compared to underground coal (52.5%) and metal (44.2%) mines. The mean exposure in underground mines in the non-metal mining sector was still 2–3 dBA lower than coal or metal mining. This difference could be caused by the differences in tools and techniques for extracting coal and metals compared to non-metals (Peterson et al, 2006) or perhaps by differing production demands.

Following the implementation of MSHA's revised noise regulation, noise exposures dropped for all broad occupational groups. Pre-2000, between 15% and 45% of all PEL measurements exceeded the 90 dBA PEL, while post-2000, 3–17% exceeded 90 dBA. Following the introduction of the revised regulation, the median AL exposures in both miner and production groups exceeded the 85 dBA AL, suggesting that workers in these groups should be the focus of further efforts to reduce noise exposure in the mining industry.

The mean training data set predictions from the linear models were very close to the mean measurements in the validation data set despite having a relatively low adjusted-R^2 (0.1540 and 0.1339 for the PEL and AL models, respectively). This occurred because the large number of samples present in both models and the validation training sets results in a very stable and unbiased mean exposure estimate for each job title (Seixas & Sheppard, 1996). This is the primary advantage of working with large data sets and makes the predictions generated by these models useful for both establishing a past exposures and helping predict future exposures for groups of workers. However, it is very important to recognise that there is an inherent variability in an individual worker's exposure from day to day due to a number of factors, including the implementation of controls, workload and personal work habits (Kromhout et al, 1993). As a result, the predictions from the model should not be used in place of noise monitoring. The best use of the model would be to predict mean yearly exposures to noise for groups of workers in each of the mine types and materials mined in order to help predict the risk of developing hearing loss in the future.

There are some limitations that need to be considered when using this model. The first is the possibility of error in exposures estimates due to misclassification of some job titles. We attempted to reduce this risk by using the SOC database to standardise job titles, and by removing measurements where a SOC code could not be assigned. It is also important to consider that grouping workers by job titles does not guarantee that all those workers have similar exposures (Rappaport et al, 1993). Another limitation is that 123,031 measurements could not be included in this analysis because they met the exclusion criteria. The majority (91,231) of these measurements were excluded because they did not provide any information on what material was being mined. We could not identify an efficient method to find the missing information for these measurements and chose to exclude them because of the overall size of the dataset would prevent the exclusion of these measurements from introducing significant error to the analysis. If information on material being mined was missing in a non-random fashion, this could have introduced bias into the estimates presented here. We also removed 25,339 measurements for being below 60 dBA. Removing these measurements likely resulted in slightly higher mean exposures in our analysis, but we believe this is justified because it is very unlikely that an eight-hour TWA at a mine site would be < 60 dBA (the noise level of an average conversation). We believe that the effects of these excluded measurements on our analyses are likely small due to the size of the dataset.

Despite these limitations, the analysis herein signifies a substantial expansion of the previous work by Joy and

Middendorf (2007) and provides an up-to-date examination of noise exposure in the mining industry. The main strength of this analysis is the size and scope of this data set makes it possible to calculate very accurate group exposure estimates. Another strength of this analysis is that the use of the SOC system provides a standardised method for future studies to classify job titles in a harmonised manner so that exposure information can be more easily compared between studies. Additionally, by stratifying exposure groups by the type of mine and what mineral is being extracted, it is possible to discern exposure differences between different mining sectors and mine types so that sector- and mine-specific controls can be implemented to reduce noise exposure. Finally, the models presented here can be used to predict a worker's mean yearly noise exposure based on their job title, type of mine they were employed at, and the year of their employment. This information could help identify workers at increased risk of developing NIHL and help prioritise resources to implement engineering controls and ensure that the worker is enrolled in a HCP.

Acknowledgements

We would like to thank Stephanie Sayler, Rachel Long and Taichi Murata for their assistance in collecting data for this project.

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

This work was supported by the National Institute for Occupational Safety and Health.

Grant # R21OH0 10482: Development of a US/Canadian Job Exposure Matrix (JEM) for Noise.

ORCID

Benjamin Roberts http://orcid.org/0000-0001-7451-925X

References

Basner M., Babisch W., Davis A., Brink M., Clark C., et al. 2014. Auditory and non-auditory effects of noise on health. *Lancet*, 383, 1325–1332.

Emmett G. & Francis H.W. 2015. The socioeconomic impact of hearing loss in U.S. adults. *Otol Neurotol*, 36, 545–550.

Joy G.J. & Middendorf P.J. 2007. Noise exposure and hearing conservation in U.S. coal mines-a surveillance report. *J Occup Environ Hyg*, 4, 26–35.

Kovalchik P.G., Smith A.K., Matetic R.J., Lynn A.A.. 2007. A dual sprocket chain as a noise control for a continuous mining. In *Noise-Con*. Reno, NV: Institute of Noise Control Engineering. Retrieved May 20, 2016: http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/adsca.pdf.

Kromhout H., Symanski E. & Rappaport S.M. 1993. A comprehensive evaluation of within- and between-worker components of occupational exposure to chemical agents. *Ann Occup Hyg*, 37, 253–270.

Masterson E.A., Bushnell P.T., Themann C.L., Morata T.C. 2016. Hearing impairment among noise-exposed workers – United States, 2003-2012. *MMWR Morb Mortal Wkly Rep*, 65, 389–394.

MSHA, 1977. *Federal Mine Safety and Health Amendments Act of 1977* Public Law 95-164-Nov. 9, 1977, Washington, D.C.: US Congress. Retrieved May 20, 2016: http://www.gpo.gov/fdsys/pkg/STATUTE-91/pdf/STATUTE-91-Pg1290.pdf.

Neitzel R.L., Swirnburn, T.K., Hammer M.S. Economic impact of hearing loss and reduction of noise-induced hearing loss in the US. *J Speech Lang Hear Res*, In Print.

NIOSH, 1998. *Criteria for a Recommended Standard: Occupational Noise Exposure*, DHHS (NIOSH) Publication No. 98-126.Cincinnati, Ohio. Retrieved May 20, 2016: http://www.cdc.gov/niosh/docs/98-126/pdfs/98-126.pdf.

NIOSH, 2000. Injuries, Illnesses, and Hazardous Exposures in the Mining Industry, 1986-1995: A Surveillance Report, DHHS(NIOSH) Publication No. 2000-117. Washington, D.C. Retrieved May 20, 2016.

Office of Management and Budget, 2009. *2007 North American Industry Classification System (NAICS)—Updates for 2012; Notice*, US Congress. Retrieved May 20, 2016: http://www.census.gov/eos/www/naics/federal_register_notices/notices/fr07ja09.pdf.

OSHA, 2013. *OSHA Technical Manual - Noise*, Washington, D.C. U.S. Department of Labor, Occupational Safety and Health Administration Retrieved May 20, 2016: https://www.osha.gov/dts/osta/otm/new_noise/index.pdf.

Peterson J.S., Kovalchik P.G. & Matetic R.J. 2006. Sound power level study of a roof bolter. *Trans Soc Min Metall Explor*, 320, 71–177.

Picard R.R. & Cook R.D. 1984. Cross-validation of regression models. *J Am Stat Assoc*, 79, 575–583.

Rappaport S.M., Kromhout H. & Symanski E. 1993. Variation of exposure between workers in homogeneous exposure groups. *Am Ind Hyg Assoc J*, 54, 654–662.

Saunders G. & Griest S. 2009. Hearing loss in veterans and the need for hearing loss prevention programs. *Noise Health*, 11, 14–21.

Seixas N.S. & Sheppard L. 1996. Maximizing accuracy and precision using individual and grouped exposure assessments. *Scand J Work Environ Health*, 22, 94–101.

Smith A.K., Zimmerman J.J., Michael R., Kovalchik P.G. 2011. Modified tail section reduces noise on a continuous mining machine. *Min Eng*, 63, 83–85.

Stubblebine T. 2007. *Regular Expressions Pocket Reference*. 2nd ed., Sebastopol (CA): O'Reilly Media.

Tak S. & Calvert G.M. 2008. Hearing difficulty attributable to employment by industry and occupation: an analysis of the National Health Interview Survey–United States, 1997 to 2003. *J Occup Environ Med*, 50, p46–56.

Tak S., Davis R.R. & Calvert G.M. 2009. Exposure to hazardous workplace noise and use of hearing protection devices among US workers–NHANES, 1999-2004. *Am J Ind Med*, 52, 358–371. p

US Department of Commerce, 2010. *2010 SOC User Guide*, Alexandria, VA. Retrieved May 20, 2016: http://www.bls.gov/soc/soc_2010_user_guide.pdf.

WHO, 1997. *Prevention of noise-induced hearing loss.*, Retrieved May 20, 2016: http://www.who.int/pbd/deafness/en/noise.pdf.

Appendix 1. Comparison of permissible exposure limit (PEL) measurements before and after 2000 by job title.

	<2000 PEL			*≥2000 PEL*		
SOC	*Mean*	*SD*	***N***	*Mean*	*SD*	***N***
Maintenance						
Electrical power-line installers and repairers				75.6	6.7	9
Maintenance and repair workers, general	83.4	7.3	3240	79.9	8.0	10,030
Maintenance workers, machinery	84.8	7.0	967	82.6	7.8	1290
Mobile heavy equipment mechanics, except engines	81.0	7.6	5347	77.7	7.7	8122
Overall	82.2	7.6	9554	79.2	8.0	19,451
Miners						
Continuous mining machine operators	84.9	8.4	166,788	79.7	8.8	160,092
Earth drillers, except oil and gas	84.3	7.5	4135	80.5	8.3	11,577
Explosives workers, ordnance handling experts and blasters	83.4	7.8	436	80.0	7.8	858
Extraction workers	80.0	8.8	2543	77.4	8.6	1023
Roof bolters, mining	90.2	7.5	310	86.0	5.0	20,485
Overall	84.8	8.4	174,212	80.4	8.7	194,035
Production						
Crushing, grinding, and polishing machine setters, operators and tenders				80.3	8.9	415
Cutting and slicing machine setters, operators and tenders	84.4	7.6	1,446	83.7	7.9	2,813
Drilling and boring machine tool setters, operators, and tenders, metal and plastic	84.5	5.8	1346			
Foundry mould and coremakers				76.8	9.0	37
Helpers–production workers	81.9	7.2	125	79.9	6.7	76
Inspectors, testers, sorters, samplers and weighers	80.6	8.3	536	74.0	8.0	713
Machinists	76.5	8.0	151	75.7	8.6	103
Packaging and filling machine operators and tenders	81.5	8.2	86	78.9	7.4	75
Pourers and casters, metal	79.3	7.8	46	79.9	8.9	39
Production workers, all other	83.4	7.0	79	80.9	6.8	69
Supervisors of production workers	84.6	7.9	1382	84.3	6.4	332
Welders, cutters, solderers and brazers				78.9	8.3	543
Woodworkers, all other				86.1	6.0	1,020
Woodworking machine setters, operators and tenders, except sawing	81.6	8.4	221	79.5	7.0	133
Overall	83.6	7.6	5,418	82.0	8.5	6,368
Transportation/material moving						
Conveyor operators and tenders				80.1	6.9	1,798
Heavy and tractor-trailer truck drivers	83.7	7.2	29,269	76.9	8.5	22,637
Labourers and freight, stock and material movers, hand	81.3	7.5	1397	78.2	8.4	1934
Pump operators, except wellhead pumpers				78.4	8.0	164
Tank car, truck and ship loaders	87.0	8.6	895	79.1	9.7	789
Overall	83.7	7.3	31,561	77.2	8.5	27,322
Other						
Dispatchers, except police, fire and ambulance				74.1	8.8	152
Engineers	80.3	8.3	313	78.9	9.0	32
Gaming change persons and booth cashiers				70.9	7.4	88
Industrial production managers				78.7	7.6	2,997
Janitors and cleaners, except maids and housekeeping cleaners	85.0	7.4	8,532	81.8	7.8	4,612
Landscaping and groundskeeping workers				82.8	7.4	481
Life, physical and social science technicians	78.2	8.2	976	73.8	7.1	407
Mining and geological engineers, including mining safety engineers				73.1	7.1	47
Occupational health and safety technicians				73.3	10.1	6
Stock clerks and order fillers	80.1	8.1	470	76.8	6.7	49
Ushers, lobby attendants and ticket takers				72.3	7.9	6
Overall	84.0	7.9	10,291	80.1	8.1	8,877

Appendix 2. Regression coefficients for the permissible exposure limit (PEL) and action level (AL) models.

	PEL Model			*AL Model*		
	Coefficient	*SE*	p	*Coefficient*	*SE*	p
Intercept	95.54	0.0819	<0.001	90.270	0.061	<0.001
Centred year	−0.331	0.00167	<0.001	−0.243	0.004	<0.001
SOC						
Roof bolters, mining		Reference			Reference	
Carpenters	−6.078	0.478	<0.001	−4.070	0.452	<0.001
Cement masons and concrete finishers	−3.119	0.582	<0.001	−0.566	0.735	0.441
Construction labourers	−4.126	0.332	<0.001	−2.768	0.356	<0.001
Continuous mining machine operators	−3.078	0.075	<0.001	−2.171	0.062	<0.001
Conveyor operators and tenders	−5.294	0.235	<0.001	−3.904	0.188	<0.001
Crushing, grinding and polishing machine setters, operators and tenders	−2.379	0.468	<0.001	−3.165	0.363	<0.001
Cutting and slicing machine setters, operators and tenders	0.820	0.166	<0.001	2.533	0.159	<0.001
Dispatchers, except police, fire and ambulance	−10.53	0.804	<0.001	−12.370	0.572	<0.001
Drilling and boring machine tool setters, operators and tenders, metal and plastic	−7.281	0.266	<0.001	.	.	.
Earth drillers, except oil and gas	−2.009	0.107	<0.001	−1.400	0.094	<0.001
Electrical power-line installers and repairers	−6.894	3.586	0.055	−5.640	2.892	0.051
Electricians	−5.249	0.178	<0.001	−4.821	0.149	<0.001
Engineers	−8.956	0.523	<0.001	−3.738	1.322	0.005
Explosives workers, ordnance handling experts and blasters	−4.753	0.276	<0.001	−2.714	0.268	<0.001
Extraction workers	−6.69	0.179	<0.001	−5.538	0.235	<0.001
First-line supervisors of construction trades and extraction workers	−6.59	0.149	<0.001	−5.858	0.172	<0.001
Foundry mould and coremakers	−7.661	1.673	<0.001	−6.261	1.321	<0.001
Gaming change persons and booth cashiers	−13.87	0.982	<0.001	−14.170	0.688	<0.001
Heavy and tractor-trailer truck drivers	−4.182	0.086	<0.001	−2.655	0.080	<0.001
Helpers–production workers	−6.367	0.672	<0.001	−4.436	0.977	<0.001
Industrial production managers	−5.629	0.187	<0.001	−5.523	0.148	<0.001
Inspectors, testers, sorters, samplers and weighers	−7.858	0.278	<0.001	−9.320	0.265	<0.001
Janitors and cleaners, except maids and housekeeping cleaners	−2.072	0.113	<0.001	0.098	0.129	0.448
Labourers and freight, stock and material movers, hand	−5.952	0.181	<0.001	−5.535	0.179	<0.001
Landscaping and groundskeeping workers	0.744	0.440	0.091	1.076	0.354	0.002
Life, physical and social science technicians	−8.794	0.270	<0.001	−7.093	0.375	<0.001
Machinists	−8.518	0.596	<0.001	−5.866	0.770	<0.001
Maintenance workers, machinery	−0.726	0.218	0.001	0.160	0.223	0.474
Maintenance and repair workers, general	−2.900	0.111	<0.001	−2.611	0.097	<0.001
Mining and geological engineers, including mining safety engineers	−11.96	1.441	<0.001	−12.660	0.999	<0.001
Mobile heavy equipment mechanics, except engines	−6.047	0.110	<0.001	−5.025	0.103	<0.001
Occupational health and safety technicians	−11.64	3.586	0.001	−8.387	2.892	0.004
Packaging and filling machine operators and tenders	−6.284	0.751	<0.001	−2.829	0.926	0.002
Painters, construction and maintenance	−4.655	2.316	0.044	−0.905	4.572	0.843
Pourers and casters, metal	−4.972	1.047	<0.001	−0.754	1.246	0.545
Production workers, all other	−4.731	0.745	<0.001	−3.617	0.907	<0.001
Pump operators, except wellhead pumpers	−5.945	0.785	<0.001	−5.579	0.613	<0.001
Stock clerks and order fillers	−9.029	0.438	<0.001	−5.172	1.051	<0.001
Supervisors of production workers	−5.579	0.243	<0.001	−2.060	0.423	<0.001
Tank car, truck and ship loaders	−2.170	0.248	<0.001	−2.897	0.274	<0.001
Ushers, lobby attendants and ticket takers	−14.05	3.586	<0.001	−13.630	2.640	<0.001
Welders, cutters, solderers and brazers	−3.864	0.418	<0.001	−4.289	0.329	<0.001
Woodworkers, all other	0.179	0.303	0.554	0.310	0.243	0.203
Woodworking machine setters, operators and tenders, except sawing	−3.869	0.514	−0.001	−2.177	0.678	0.001
Material mined						
Coal		Reference			Reference	
Metal	−0.741	0.069	<0.001	1.014	0.104	<0.001
Non-metal	−1.095	0.043	<0.001	−1.492	0.037	<0.001
Mine type						
Underground		Reference			Reference	
Facility	−4.024	0.053	<0.001	−2.670	0.052	<0.001
Surface	−3.992	0.043	<0.001	−3.197	0.042	<0.001