ORIGINAL ARTICLE

Patterns and trends in OSHA occupational noise exposure measurements from 1979 to 2013

Stephanie K Sayler,[1] Benjamin J Roberts,[1,2] Michael A Manning,[1] Kan Sun,[1] Richard L Neitzel[1]

► Additional material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/oemed-2018-105041).

[1]Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, Michigan, USA
[2]Cardno ChemRisk, Chicago, Illinois, USA

Correspondence to
Dr Richard L Neitzel, Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor MI 48109, USA; rneitzel@umich.edu

Received 2 March 2018
Revised 18 September 2018
Accepted 7 November 2018
Published Online First 27 November 2018

To cite: Sayler SK, Roberts BJ, Manning MA, *et al. Occup Environ Med* 2019;**76**:118–124.

ABSTRACT

Objectives Noise is one of the most common exposures, and occupational noise-induced hearing loss (NIHL) is highly prevalent. In addition to NIHL, noise is linked to numerous non-auditory health effects. The Occupational Safety and Health Administration (OSHA) maintains the Integrated Management Information System (IMIS) database of compliance-related measurements performed in various industries across the USA. The goal of the current study was to describe and analyse personal noise measurements available through the OSHA IMIS, identifying industries with elevated personal noise levels or increasing trends in worker exposure over time.

Methods Through a Freedom of Information Act request, we obtained OSHA's noise measurements collected and stored in IMIS between 1979 and 2013 and analysed permissible exposure limit (PEL) and action level (AL) criteria measurements by two-digit industry code.

Results The manufacturing industry represented 87.8% of the 93 920 PEL measurements and 84.6% of the 58 073 AL measurements. The highest mean noise levels were found among the agriculture, forestry, fishing and hunting industry for PEL (93.1 dBA) and the mining, quarrying and oil and gas extraction group for AL (93.3 dBA). Overall, measurements generally showed a decreasing trend in noise levels and exceedances of AL and PEL by year, although this was not true for all industries.

Conclusions Our results suggest that, despite reductions in noise over time, further noise control interventions are warranted both inside and outside of the manufacturing industry. Further reductions in occupational noise exposures across many industries are necessary to continue to reduce the risk of occupational NIHL.

Key messages

What is already known about this subject?

- Noise is one of the most common environmental and occupational exposures, which results in high rates of noise-induced hearing loss (NIHL) and other adverse, systemic health effects in exposed populations.
- The Occupational Safety and Health Administration (OSHA) has established a 90 dBA permissible exposure limit (PEL) and an 85 dBA action level (AL) for noise exposure, and maintains the Integrated Management Information System (IMIS) database of PEL and AL compliance measurements for regulated industries.
- Previous research on this large dataset has shown a decrease in noise levels over time, but varying trends in noise exposure by industry.

What are the new findings?

- Although our analysis indicated overall reductions in measured OSHA compliance noise levels over time, these reductions appear to be driven by the manufacturing industry, which represents a disproportionately large number of the OSHA IMIS noise measurements.

How might this impact on policy or clinical practice in the foreseeable future?

- Our research suggests that further reductions in occupational exposure to noise across all industries may be necessary to reduce noise exposures to levels below which workers are at an increased risk of NIHL.
- Additionally, we suggest OSHA monitoring that encompasses a broader range of industries, outside of manufacturing and performing sampling on the basis of current employment trends.

INTRODUCTION

Noise is one of the most common environmental[1 2] and occupational[3] exposures, and noise-induced hearing loss (NIHL) is highly prevalent worldwide,[4 5] with enormous associated costs.[6–9] Noise is increasingly being linked to non-auditory health effects such as coronary heart disease,[10 11] hypertension,[12 13] myocardial infarction,[14 15] sleep disturbance, perceived stress, reduced quality of life[16 17] and possible mental health issues.[18] These non-auditory effects represent substantial and recognised threats to public health[19] (eg, cardiovascular disease is the number one cause of death in the USA[20]), in contrast to NIHL, which has historically received little attention.

The 1970 Occupational Safety and Health Administration (OSHA) Act established a permissible exposure limit (PEL) for noise of 90 A-weighted decibels (dBA) as an 8-hour time-weighted average (TWA). Workers exposed above this level were required to be protected using noise controls. In 1983, OSHA adopted an action level (AL) of 85 dBA TWA; workers exposed above this level must be enrolled in a hearing conservation programme (HCP), in which they are provided hearing protection, audiograms, training and noise exposure monitoring, among other requirements.[21] To ensure employer compliance with the PEL and AL, OSHA conducts noise monitoring of US workplaces. Measurement criteria (PEL vs AL) are determined at the inspector's discretion and likely based on perceived noise levels and any prior measurements. Although the PEL and AL share use of A-weighting, a slow time constant, an 8-hour criterion duration and a time-intensity exchange rate of 5 dB, they use different criterion levels (the level which results in 100% dose over the criterion duration, 90 dBA for PEL and effectively 85 dBA for AL) and threshold levels (90 dBA for the PEL vs 80 dBA for the AL). The lower threshold used in the AL results in AL measurements always being equal to or exceeding corresponding PEL measurements, as the AL incorporates noise levels from 80 to 90 dBA where the PEL treats values below 90 dBA as zero.

OSHA has maintained PEL measurement data since 1979, and AL measurement data since 1983, in its Integrated Management Information System (IMIS). PEL and AL noise data collected between 1979 and 1999 were analysed previously by Middendorf, who found that most of the then-available 155 378 PEL and AL measurements occurred within the manufacturing industry.[22] Middendorf showed a decrease in non-compliant measurements (those exceeding 90 dBA using PEL criteria, and 85 dBA using AL criteria) between 1989 and 1998, but the final 5 years of the analysis indicated increasing PEL levels within manufacturing.[22] No other large-scale longitudinal analyses of trends in US occupational noise exposures appear to have been published, and comprehensive industry-specific temporal analyses appear to be available for only two industries: construction[23] and metals manufacturing.[24]

The goal of the current study was to provide an update on the previous analyses presented by Middendorf[22] through the inclusion of additional personal noise measurements made between 2000 and 2013. We also sought to identify industries with limited personal measurement data, elevated personal noise levels or stagnant or increasing trends in worker exposure over time.

METHODS

Data collection

Personal noise exposure records from full-shift dosimeter measurements in US workplaces by OSHA compliance officers from 1979 to 2013 were obtained through a Freedom of Information Act Request (number 733737) from OSHA. A total of 114 903 PEL and 78 372 AL measurements were received, without supporting information such as the reason for the measurement, geographical region, size of establishment or union presence. Datasets were obtained from OSHA as Microsoft Excel (Redmond, Washington, USA) files and were transferred to STATA V.14 (College Station, Texas, USA) for cleaning and analysis.

Data cleaning and management

Records were evaluated and removed if any of the following criteria were met: no dose value provided, average sound pressure level (L_{AVG}) ≤60 dBA or ≥120 dBA, full-shift sampling duration <6 or >16 hours. Additionally, any measurements with invalid (ie, indication that the measurement was 'blood', 'bulk' or other non-noise measurement), unclear, missing industry or occupation coding or labelled as an area measurement instead of a personal sample, were eliminated. These cleaning criteria differ slightly from those used previously by Middendorf,[22] who excluded inconsistently coded measurements and those measurements where the average sound pressure level was >1% different from the TWA (limiting measurements to those that were approximately 8 hours). Notably, Middendorf did not specify how area measurements were treated, while our analysis only included personal noise measurements. Noise exposure measurements recorded in accumulated noise dose were converted to equivalent full-shift TWA using Equation 1:

$$TWA = 16.61 \times \log_{10} \frac{\text{Dose (\%)}}{100\%} + 90\ \text{dBA} \quad (1)$$

Industry information was coded according to the 2012 North American Industry Classification System (NAICS).[25] Industry information was harmonised using publicly available cross-walks from the US Census Bureau.[26] The industry information for each measurement was collapsed to the first two digits of the NAICS codes (industry group) in order to maintain a moderate degree of industry specificity at the expense of job-level details. Codes for manufacturing (NAICS 31–33) were combined into one code (30), as were retail trade categories (NAICS 44–45 renumbered as 43) and transportation and warehousing (NAICS 48–49 renumbered as 47). All other two-digit industry categories remained as provided.

Data analysis

Data cleaning and analysis were completed using STATA V.14. After data cleaning, descriptive statistics on noise TWA and non-compliance (ie, exceedance) for the PEL and AL measurements were calculated by year and in 5-year bins overall and stratified by two-digit NAICS code.

Modelling and validation

Ordinary least squares (OLS) linear regression models were constructed to estimate 8-hour mean TWA exposures. These models used either the PEL or AL TWA as the outcome variable and the two-digit NAICS code and year (in 5-year bins) as predictor variables. As we have done previously,[27] we used the single 'hold-out' method described by Kohavi and Arlot and Celisse[28 29] to validate the estimates from our models. To do so, prior to modelling, we randomly (using a fixed seed to ensure replicability) divided both the AL and PEL measurements into a test set (75% of the dataset) and a validation set (the remaining 25%). We compared these results with the results of using 10-fold cross-validation.[29] The AL and PEL estimates from models based on our training dataset were stratified by two-digit NAICS code and compared with measurements in the validation set that were not used in modelling. Because of the large number of measurements in some two-digit NAICS codes, normal hypothesis testing would be overpowered and produce results that are statistically significant but not practically different.[30] Therefore, we compared the 10th, 50th and 90th percentiles of the estimated values and the hold-out values for each two-digit NAICS code. We considered the measurement tolerance of a type 2 sound level metre (±2 dB) as our threshold of meaningful difference when comparing the estimated results from the model and the hold-out values.[31 32] This method is more conservative than standard hypothesis testing.

RESULTS

Descriptive analysis

Overall, 20 983 PEL and 20 299 AL measurements were discarded during data cleaning, leaving 93 920 PEL and 58 073 AL measurements for analysis (table 1). Most PEL and AL

Table 1 Description of received and valid OSHA IMIS noise measurements by metric (PEL and AL) for the years 1979–2013

	PEL	AL
Measurements received	114 903	78 372
Total removed	20 983	20 299
Not full-shift	16 560	16 983
NAICS or SIC code could not be assigned	1520	2167
Measurement >120 or <60 dBA	1073	204
Area samples	830	944
AL measurement before 1983	–	1
Valid measurements used for analyses	93 920	58 073

AL, action level; IMIS, Integrated Management Information System; NAICS, North American Industry Classification System; OSHA, Occupational Safety and Health Administration; PEL, permissible exposure limit; SIC, Standard Industrial Classification.

measurements (33 543) were removed for not representing full-shift data. Measurements were also removed if a Standard Industrial Classification or NAICS code could not be assigned (4687), when the noise level fell outside of the range 60–120 dBA (1277) or when information indicated that a measurement was an area measurement (1774). One AL measurement was deleted because it was recorded prior to the promulgation of the AL criteria in 1983. The PEL and AL measurement distributions were roughly normal, although with a longer tail on the left side of the distribution.

Noise over time

From 1979 to 2013, overall PEL and AL averages were 88.7 and 91.6 dBA respectively, with PEL measurement variability being generally higher than AL variability (SD from 6.2 to 9.5 dBA for PEL vs 6.1 to 7.5 dBA for AL measurements). The highest PEL and AL levels occurred during the first 5-year bin (1979–1984), with a PEL of 90.8±6.2 dBA and an AL of 94.2±6.3 dBA, although AL measurements were only available for part of that time window (from 1983 to 1984). For the most recent year group (2010–2013), approximately one-third of PEL measurements exceeded 90 dBA, while nearly four-fifths of AL measurements exceeded 85 dBA (table 2). Both PEL and AL measurements showed an overall decreasing trend in noise levels and exceedances by year, with the exception of a small increase in PEL averages from 2011 to 2013 (figure 1). This trend is also demonstrated in table 2, where each 5-year bin average is lower

Table 2 Description of OSHA compliance noise measurements by two-digit NAICS industry code, year group and metric (PEL and AL) for the years 1979–2013

	PEL (n=93 920)			AL (n=58 073)		
NAICS two-digit industry (code)*	**N**	**Mean (SD)**	**>90 dBA (%)**	**N**	**Mean (SD)**	**>85 dBA (%)**
Overall	93 920	88.7 (8.2)	50.5	58 073	91.6 (6.8)	85.7
Accommodation and food services (72)	309	83.1 (8.9)	22.3	305	86.9 (7.1)	71.5
Administrative and support and waste management and remediation services (56)	720	86.9 (9.9)	42.1	643	89.4 (8.4)	76.4
Agriculture, forestry, fishing and hunting (11)	345	93.1 (6.8)	77.7	148	93.1 (8.3)	87.2
Arts, entertainment and recreation (71)	179	82.8 (8.8)	19.0	208	86.4 (7.3)	60.6
Construction (23)	2377	90.6 (9.1)	57.8	965	91.3 (8.4)	79.8
Educational services (61)	154	78.6 (8.5)	8.4	233	84.2 (7.1)	45.5
Finance and insurance (52)	14	78.0 (9.8)	14.3	19	81.6 (5.4)	26.3
Healthcare and social assistance (62)	94	80.8 (9.5)	17.0	127	85.9 (8.7)	56.7
Information (51)	434	86.0 (8.1)	35.2	277	89.4 (7.2)	77.3
Management of companies and enterprises (55)	4	90.5 (3.2)	25.0	0	-	-
Manufacturing (31–33)	82 456	88.9 (7.9)	51.7	49 157	92.0 (6.4)	87.9
Mining, quarrying and oil and gas extraction (21)	86	89.2 (6.7)	54.7	38	93.3 (3.5)	97.4
Other services (except public administration) (81)	1779	85.8 (9.2)	35.4	1591	89.4 (7.3)	76.4
Professional, scientific and technical services (54)	699	86.6 (9.6)	42.4	489	88.5 (8.5)	69.7
Public administration (92)	424	84.2 (9.5)	32.3	494	88.3 (8.2)	69.8
Real estate rental and leasing (53)	111	86.9 (9.6)	43.2	80	87.7 (7.6)	71.3
Retail trade (44, 45)	1186	85.0 (9.0)	32.2	1154	88.3 (8.1)	71.3
Transportation and warehousing (48, 49)	946	85.3 (10.2)	36.3	834	87.6 (8.0)	66.2
Utilities (22)	165	83.2 (8.2)	20.6	137	86.4 (7.3)	61.3
Wholesale trade (42)	1438	87.8 (8.5)	45.4	1174	90.8 (6.6)	84.2
Year group	**N**	**Mean (SD)**	**>90 dBA (%)**	**N**	**Mean (SD)**	**>85 dBA (%)**
1979–1984	41 720	90.8 (6.2)	60.6	1832†	94.2 (6.3)	93.2
1985–1989	14 856	89.0 (8.2)	52.2	13 865	93.0 (6.1)	91.2
1990–1994	9736	86.8 (8.8)	41.1	10 283	91.9 (6.6)	88.1
1995–1999	6248	86.6 (9.2)	41.6	7082	91.1 (6.9)	83.5
2000–2004	8114	86.0 (9.3)	38.7	9469	90.8 (6.7)	83.5
2005–2009	8402	85.7 (9.3)	36.5	9879	90.7 (7.0)	82.1
2010–2013	4844	85.1 (9.5)	32.7	5663	89.8 (7.5)	78.2

*NAICS code 55 (management of companies and enterprises) was excluded because there were too few measurements for modelling.
†AL measurements only included for years 1983–1984.
AL, action level; NAICS, North American Industry Classification System; OSHA, Occupational Safety and Health Administration; PEL, permissible exposure limit.

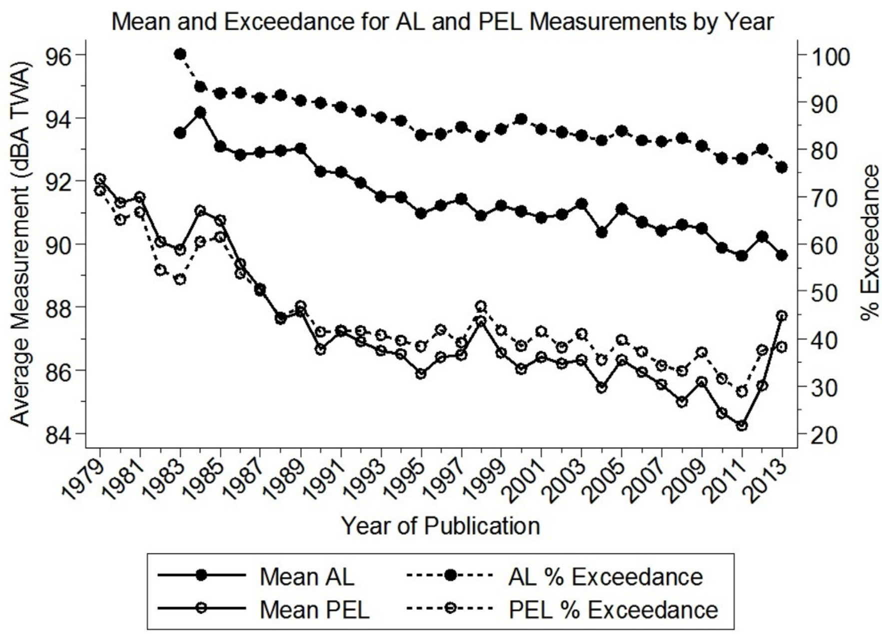

Figure 1 Time-weighted average (TWA) and exceedance of permissible exposure limit (PEL, 90 dBA) and action level (AL, 85 dBA) for Occupational Safety and Health Administration Integrated Management Information System noise measurements by year (1979–2013).

than the previous 5-year bin for both PEL and AL measurements. The small uptick in 2011–2013 in the PEL values in figure 1 is absent in the year bins in table 2. Both the PEL and the AL decreased at an average rate of 0.13 dBA per year (data not shown).

Noise by industry

Measurements were available for 24 two-digit NAICS codes, which were reduced to 20 categories after collapsing the manufacturing, retail trade and transportation and warehousing industries (table 2). Manufacturing (NAICS 31–33) represented 87.8% of the PEL and 84.6% of the AL measurements. The highest levels were found in agriculture, forestry, fishing and hunting (NAICS 11) with a mean PEL level of 93.1±6.8 dBA, and in mining, quarrying and oil and gas extraction (NAICS 21) with a mean AL level of 93.3±3.5 dBA. The finance and insurance industry (NAICS 52) had the lowest PEL and AL measurements, 78.0±9.8 and 81.6±5.4 dBA, respectively, although these estimates are based on only 33 measurements over 35 years. Only four measurements were available for the management of companies and enterprises industry (NAICS 55). Almost 70% of AL measurements in manufacturing exceeded 90 dBA (table 2). Among the six industries with the largest number of measurements, the transportation and warehousing industry (NAICS 48–49) had the lowest mean AL and the second lowest mean PEL, along with the largest proportion of measurements under 85 dBA.

Regression analysis

Regression results are presented in table 3. Both the PEL and AL models had poor model fit (R^2_{ADJ}=8.7% and 5.8%, respectively), which would be expected for a dataset of exposure measurements from diverse industries. Using NAICS 52 (finance and insurance) and the first 5-year bin (1979–1984) as the reference levels (PEL=79.1 dBA, AL=84.6 dBA), all PEL and AL model coefficients were statistically significant, with the exception of healthcare and social assistance (NAICS 62) and educational services (NAICS 61). Coefficients for industry ranged from 3.0 to 15.9 dBA for the PEL (SE: 2.5–2.7 dBA) and 2.1–11.0 dBA for the AL (SE: 1.7–2.0 dBA), while 5-year group coefficients and errors were significantly lower overall than industry coefficients (−1.8 through −5.6 dBA for PEL and −1.1 through −4.0 dBA for AL, SE: 0.1–0.2 dBA). The largest reductions in noise levels (ie, differences in the negative slope coefficients by each year bin) occurred during earlier year groups, and decreases grew increasingly smaller with each subsequent year group for both PEL and AL (table 3).

While overall noise levels generally decreased over time, when accounting for both time and industry, we observed a wide degree of variability by NAICS code (figure 2). Some industries showed stable noise levels (eg, PELs in utilities and construction), while others had increasing noise levels over time (eg, PELs in agriculture, and ALs in the transportation and warehousing and utilities industries). Because the largest number of measurements were present in NAICS 31–33 (ie, manufacturing), we conducted a subanalysis to examine whether the observed decrease in noise levels over time was driven solely by manufacturing or occurred across all industries (data not shown). The adjusted PEL model excluding NAICS 31–33 found that since the 1985–1989 year group there was no statistically significant decrease in noise levels. This is surprising given that the large number of measurements in the model would be expected to be overpowered and produce statistically significant results. By comparison, the AL model did not find a consistent decrease in noise levels over time when manufacturing industries were excluded.

Due to the large amount of data from manufacturing, we also conducted the regression analysis using three-digit NAICS code for measurements within manufacturing (NAICS 31–33, online supplementary table 3). Overall, the predicted measurements are very similar; however, this analysis allowed us to evaluate noise levels in different manufacturing environments. The explanatory power of the models (as measured by an adjusted-R^2) increased slightly, as would be expected when adding additional fixed effects to a model. When model fit (ie, AIC) was compared between the corresponding models for the PEL and AL, models that included three-digit NAICS codes for manufacturing had

Table 3 Linear regression model predicting mean OSHA noise level by measurement criteria (PEL and AL) using two-digit NAICS industry code and year range as predictors for the years 1979–2013.

	PEL (R^2_{ADJ}=8.7%)			AL (R^2_{ADJ}=5.8%)		
NAICS two-digit industry (code)*	β	SE	P values	β	SE	P values
Intercept	79.1	2.5	<0.001	84.6	1.7	<0.001
Finance and insurance (52)	Reference			Reference		
Accommodation and food services (72)	7.8	2.5	0.002	4.7	1.8	0.007
Administrative and support and waste management and remediation services (56)	11.7	2.5	<0.001	7.7	1.7	<0.001
Agriculture, forestry, fishing and hunting (11)	15.9	2.5	<0.001	10.5	1.8	<0.001
Arts, entertainment and recreation (71)	7.7	2.6	0.003	4.2	1.8	0.019
Construction (23)	14.9	2.5	<0.001	9.5	1.7	<0.001
Educational services (61)	3.0	2.6	0.240	2.1	1.8	0.243
Healthcare and social assistance (62)	3.8	2.6	0.151	3.2	1.8	0.079
Information (51)	8.6	2.5	0.001	7.0	1.8	<0.001
Manufacturing (31–33)	11.8	2.5	<0.001	9.7	1.7	<0.001
Mining, quarrying, and oil and gas extraction (21)	13.3	2.7	<0.001	11.0	2.0	<0.001
Other services (except public administration) (81)	9.6	2.5	<0.001	7.2	1.7	<0.001
Professional, scientific and technical services (54)	10.2	2.5	<0.001	5.4	1.7	<0.001
Public administration (92)	8.7	2.5	0.001	6.4	1.7	<0.001
Real estate rental and leasing (53)	12.4	2.6	<0.001	5.1	1.9	<0.001
Retail trade (44, 45)	9.4	2.5	<0.001	6.7	1.7	<0.001
Transportation and warehousing (48, 49)	8.7	2.5	<0.001	5.3	1.7	0.002
Utilities (22)	6.7	2.6	0.009	4.2	1.8	0.021
Wholesale trade (42)	11.7	2.5	<0.001	8.8	1.7	<0.001
Year group						
1979–1984	Reference			Reference		
1985–1989	–1.8	0.1	<0.001	–1.1	0.2	<0.001
1990–1994	–3.9	0.1	<0.001	–1.9	0.2	<0.001
1995–1999	–4.2	0.1	<0.001	–2.7	0.2	<0.001
2000–2004	–4.9	0.1	<0.001	–3.1	0.2	<0.001
2005–2009	–5.2	0.1	<0.001	–3.2	0.2	<0.001
2010–2013	–5.6	0.1	<0.001	–4.0	0.2	<0.001

*NAICS code 55 (management of companies and enterprises) was excluded because there were too few measurements for modelling.
AL, action level; NAICS, North American Industry Classification System; OSHA, Occupational Safety and Health Administration; PEL, permissible exposure limit.

significantly better fit than those with only two-digit codes (Δ_{PEL}=3425.6; Δ_{AL}=1888.3).

Model validation

The difference between the 10th, 50th and 90th percentiles of the predicted values from the PEL model developed from the training dataset were compared with the observed values from the validation set (see online supplementary table 1). Ten of 21 (4719 (52.6%) two-digit NAICS codes had 50th percentile differences >2.0 dBA. All of the two-digit NAICS codes had a 10th percentile difference >2.0 dBA while 14 (73.6%) had 90th percentiles that differed by >2.0 dBA. Differences between the 10th, 50th and 90th percentiles of the predicted AL values from the training dataset are compared with the hold-out values in online supplementary table 2. Four of 19 (21.1%) of the two-digit NAICS codes had 50th percentile differences >2.0 dBA. Similar to the PEL model, all of the 10th percentile differences and 15 of 19 (78.9%) of the 90th percentile differences exceeded 2.0 dBA. Model validation using 10-fold cross-validation found slightly poorer agreement between the model predictions and the observed values (see online supplementary tables 4 and 5). Validation results for the PEL and AL models that included three-digit manufacturing codes are also available for both the hold-out (see online supplementary tables 6 and 7, respectively) and 10-fold validation methods (see online supplementary tables 8 and 9, respectively).

DISCUSSION

Our study evaluated over 150 000 OSHA compliance noise measurements and found significant differences in exposures by industry and over time. We found differences in exposure trends over time within industry, indicating that not all industries are benefiting equally from OSHA noise regulations. The manufacturing industry represented a large percentage of measurements (86.6%), which has also been observed in a study of IMIS exposure data for lead.[33] Given the decreasing number of workers in this industry over the time period assessed (1979–2013),[34] these findings suggest that OSHA compliance efforts regarding noise exposure may not be adequately targeting other noisy industries. Additionally, the large proportion of recent measurements that exceeded the PEL and AL (32.7% and 85.7%, respectively) indicate the continued need for surveillance and regulatory enforcement of noise exposure limits, as well as opportunities for noise control and abatement.

Model validation results indicated that the PEL and AL models were able to predict the median noise exposure within 2.0 dBA of the observed values for 11 of 21 and 19 of 21 two-digit NAICS codes, respectively. One likely reason for the difference

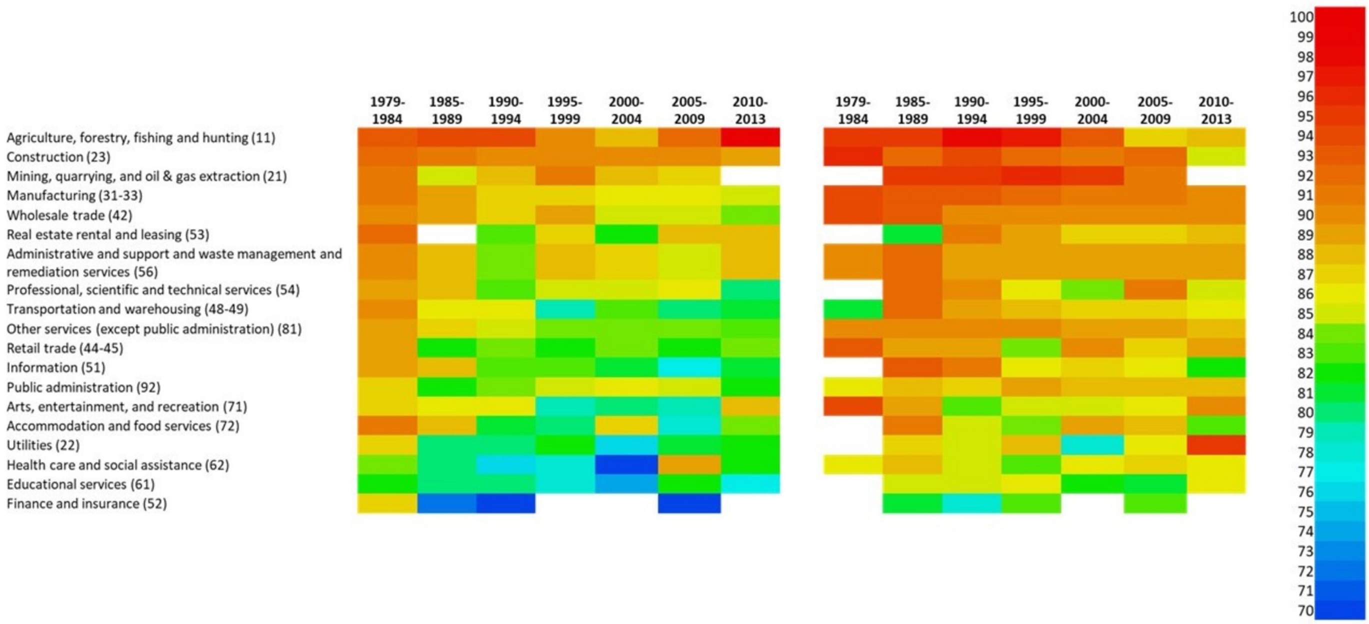

Figure 2 Gradient map illustrating the OSHA IMIS average noise time-weighted average (TWA, in dBA) for permissible exposure limit (PEL, left) and action level (AL, right) by two-digit NAICS industry category and year range for the years 1979–2013, where white blocks indicate <5 noise measurements. NAICS 55 (management of companies and enterprises) excluded from figure due to small sample size.

in model performance is that AL measurements were more evenly spread across the study period, while the PEL measurements were clustered in the earlier time groups. As indicated in table 2, over 41 720 PEL measurements were made from 1979 to 1984, compared with just 1832 AL measurements. Because noise levels generally decreased over time (figure 1), it would be expected that the large number of PEL measurements earlier in time would increase the variance of noise levels and lead to poorer agreement between the model estimates and hold-out data. The increased discordance between the models' estimates for the 10th and 90th percentile reflects the fact that the model predictions cluster around the mean, while the hold-out data do not. While the models can be used to make fairly accurate predictions of the median exposure for a worker in a certain industry during a certain time period, model predictions should not be used in place of personal noise monitoring.

Our findings suggest that a large degree of the reduction in occupational noise levels over time in the OSHA IMIS database resulted from noise reductions in manufacturing. Figure 2 illustrates that some industries (eg, utilities and construction) appeared to have minimal reductions in noise levels over time, and some even had apparent increases (eg, transportation and warehousing and agricultural industries). These results are consistent with those found by Middendorf in his earlier assessment of OSHA compliance measurements,[22] as well as evaluations of noise in construction[23] and manufacturing.[24] This is of particular concern, since the prevalence of NIHL in many industries remains high (agriculture, forestry, fishing and hunting, 11.1%; construction, 16.3%; manufacturing, 13.7%; transportation, warehousing and utilities, 7.9%).[35]

Trends in employment must be considered when reviewing these results. For example, the US construction industry employed approximately 5 933 000 workers in 2013, and that number has been generally increasing since 1979. By comparison, the number of US manufacturing workers decreased markedly over that same time period, to about 12 083 000 workers in 2013.[34] Although the construction workforce was approximately half the size of the manufacturing workforce in 2013, it only represented 3% of the measurements that year vs 83% for manufacturing. Middendorf noted similar disparities in the IMIS database related to rates of noise sampling and employment numbers for the years 1979–1999.[22]

LIMITATIONS

Although our dataset was large, over 40 000 measurements (21%) received from the OSHA IMIS system had to be removed prior to analysis. Additionally, we inexplicably received fewer measurements from our FOIA request than did Middendorf (193 275 vs 209 750, respectively).[22] This resulted in a similar number of measurements as those analysed by Middendorf,[22] although our study covered more than a decade of additional OSHA compliance measurements. While we received fewer measurements, our averages across many of the fields were consistent with those found by Middendorf, who also found low levels in retail, transportation and finance, and higher levels in construction and mining.[22] We were not able to identify the cause of differences between the noise dataset we received from OSHA and that received by Middendorf from a prior FOIA request. This large discrepancy is problematic and requires further correspondence with OSHA in order to determine if data cleaning is now done prior to the release of the FOIA data which was not done previously. Additionally, our FOIA request contained no information on geographical region, size of establishment or union presence, which may have been useful in further assessing reasons for excessive noise exposure in certain industries. This is likely one of the reasons for the poor observed model fit. The reduction in industry specificity resulting from using the two-digit NAICS codes in order to maximise the number of measurements within each NAICS group is another likely cause of poor model fit. Finally, by not including fixed effects for job title there is a significant amount of relevant information that is not included in the model.

Aside from receiving fewer cases, our data cleaning methods, and specifically our elimination of measurements<6 hours in duration, reduced the number of measurements available for industries that may rely more heavily on short-term, task-based noise monitoring (eg, construction). We believe our approach is valid, since it is not appropriate to directly compare task-based measurements to 8-hour exposure limits.[36] However, this approach may have yielded non-random bias, where industries that rely heavily on task-based monitoring for certain jobs contained an oversampling of jobs where full-shift monitoring is more frequently performed. These industries may also have a reduced number of measurements overall where task-based noise monitoring is more heavily used by OSHA inspectors.

The sampling strategy used by OSHA compliance officers to collect OSHA IMIS data adds a degree of uncertainty to our results. While we do not have information on the specific sampling strategy used to collect these noise measurements, previous research on chemicals suggests that IMIS measurements likely represent worst-case exposures that are not typical of the overall industry.[33 37 38] However, worst-case monitoring provides valuable information regarding the top percentiles of noise-exposed workers, who are most likely to be affected by NIHL and other noise-related health impacts. Some authors regard the IMIS data as not representative exposure of the working population in the USA.[39] We attempted to address this issue statistically by assessing the distribution of exposures (10th, 50th and 90th percentiles). Non-random temporal bias may also exist in OSHA inspection and sampling practices, where jobs or industries are specifically targeted due to government initiatives or public interest at the time. Additionally, measurement criteria (PEL vs AL) are determined at the inspector's discretion, and may contribute to random or non-random bias in the data set.

CONCLUSIONS

Although our analysis indicated overall reductions in measured compliance noise levels over time, these reductions appear to be driven by the manufacturing industry, which represents a disproportionately large number of the OSHA IMIS noise measurements. While the exposure reductions in the manufacturing industry are significant and should not be ignored, additional OSHA noise monitoring appears to be warranted in other industries with high rates of NIHL and a large number of employed workers (eg, construction).

Contributors RLN conceived of and planned the study, and has overall responsibility for the content. SKS assisted with planning and execution of the study and led the manuscript preparation efforts. BJR, MAM and KS conducted the analyses and contributed to the manuscript preparation efforts.

Funding This study was funded by the National Institute for Occupational Safety and Health, grant number R21OH0 10482: Development of a US/Canadian Job Exposure Matrix (JEM) for Noise.

Competing interests None declared.

Patient consent Not required.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1 EPA. Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. 1974. EPA Report 550/9-74-004.
2 WHO. In: Berglund B TL, Schwela D, eds. *Guidelines for Community Noise*. Geneva: World Health Organization, 1999.
3 NIOSH. Criteria for a Recommended Standard: Occupational Noise Exposure. *Revised Criteria* 1998;1998:105.
4 Nelson DI, Nelson RY, Concha-Barrientos M, *et al*. The global burden of occupational noise-induced hearing loss. *Am J Ind Med* 2005;48:446–58.
5 Sataloff R, Sataloff J. *Occupational Hearing Loss*. 3rd ed. New York: Taylor and Francis, 1996.
6 Dobie RA. Economic compensation for hearing loss. *Occup Med* 1995;10:663–8.
7 Neitzel RL, Swinburn TK, Hammer MS, *et al*. Economic Impact of Hearing Loss and Reduction of Noise-Induced Hearing Loss in the United States. *J Speech Lang Hear Res* 2017;60:182.
8 Tufts JB, Weathersby PK, Rodriguez FA. Modeling the Unites States government's economic cost of noise-induced hearing loss for a military population. *Scand J Work Environ Health* 2010;36:242–9.
9 WHO. Prevention of Noise-Induced Hearing Loss: Report of an Informal Consultation Held at the World Health Organization. *Geneva, Switzerland: (World Health Organization* 1997.
10 Gan WQ, Davies HW, Demers PA. Exposure to occupational noise and cardiovascular disease in the United States: the National Health and Nutrition Examination Survey 1999-2004. *Occup Environ Med* 2011;68:183–90.
11 Virkkunen H, Kauppinen T, Tenkanen L. Long-term effect of occupational noise on the risk of coronary heart disease. *Scand J Work Environ Health* 2005;31:291–9.
12 Katsouyanni K, Cadum E. Dudley, Marie-Louise Savigny P, Seiffert I, Al. *E. Hypertension and exposure to noise near airports: the HYENA study. Env Heal Perspect* 2008;116:329–33.
13 Leon Bluhm G, Berglind N, Nordling E, *et al*. Road traffic noise and hypertension. *Occup Environ Med* 2007;64:122–6.
14 Ising H, Babisch W, Kruppa B, *et al*. Subjective work noise: a major risk factor in myocardial infarction. *Soz Praventivmed* 1997;42:216–22.
15 Selander J, Nilsson ME, Bluhm G, *et al*. Long-term exposure to road traffic noise and myocardial infarction. *Epidemiology* 2009;20:272–9.
16 Passchier-Vermeer W, Passchier WF. Noise exposure and public health. *Environ Health Perspect* 2000;108 Suppl 1:123–31.
17 Seidman MD, Standring RT. Noise and quality of life. *Int J Environ Res Public Health* 2010;7:3730–8.
18 Lercher P, Evans GW, Meis M, Kofler WW. Ambient neighbourhood noise and children's mental health. *Occup Environ Med* 2002;59:380–6.
19 Hammer MS, Swinburn TK, Neitzel RL. Environmental noise pollution in the United States: developing an effective public health response. *Environ Health Perspect* 2014;122:115–9.
20 Centers for Disease Control and Prevention (CDC). Prevalence of heart disease–United States, 2005. *MMWR Morb Mortal Wkly Rep* 2007;56:113–8.
21 OSHA. Occupational Noise Exposure: Hearing Conservation Amendment; Final Rule. *Fed Reg* 1983;48:9738–85.
22 Middendorf PJ. Surveillance of occupational noise exposures using OSHA's Integrated Management Information System. *Am J Ind Med* 2004;46:492–504.
23 Neitzel RL, Stover B, Seixas NS. Longitudinal assessment of noise exposure in a cohort of construction workers. *Ann Occup Hyg* 2011;55.
24 Neitzel RL, Galusha D, Dixon-Ernst C, Rabinowitz PM, *et al*. Methods for evaluating temporal trends in noise exposure. *Int J Audiol* 2014;53 Suppl 2(Suppl 2):S76–S83.
25 Office of Management and Budget. 2007 North American Industry Classification System (NAICS) - Updates for 2012. *National Archives and Records Administration* 2009.
26 US Census Bureau. North American Industry Classification System Concordances n.d.
27 Roberts B, Sun K, Neitzel RL. What can 35 years and over 700,000 measurements tell us about noise exposure in the mining industry? *Int J Audiol* 2017;56:4–12.
28 Kohavi R. A study of cross-validation and bootstrap for accuracy estimation and model selection. *Int Jt Conf Artif Intell* 1995.
29 Arlot S, Celisse A. A survey of cross-validation procedures for model selection. *Stat Surv* 2010;4:40–79.
30 Gelman A. P values and statistical practice. *Epidemiology* 2013;24:69–72.
31 ANSI. *ANSI S1.4-1-2014 Electroacoustics - Sound Level Meters - Part 1: Specifications*, 2014.
32 Office of Health Compliance Assistance. *Chapter VI - Noise Survey Data. OSHA Ind. Hyg. Tech. Manual, OSHA Instr. CPL 2-2.20A*. Washington DC: Office of Health Compliance Assistance, US DOL, Occupational Safety and Health Administration, 1984.
33 Henn SA, Sussell AL, Li J, *et al*. Characterization of lead in US workplaces using data from OSHA's integrated management information system. *Am J Ind Med* 2011;54:356–65.
34 Bureau of Labor Statistics. Employment, hours, and earnings from the current employment statistics survey (national). *US Dep Labor n.d*.
35 Masterson EA, Bushnell PT, Themann CL, *et al*. Hearing Impairment Among Noise-Exposed Workers — United States, 2003–2012. *MMWR Morb Mortal Wkly Rep* 2016;65:389–94.
36 Seixas NS, Sheppard L, Neitzel R. Comparison of task-based estimates with full-shift measurements of noise exposure. *Aiha J* 2003;64:823–9.
37 Hamm MP, Burstyn I. Estimating occupational beryllium exposure from compliance monitoring data. *Arch Environ Occup Health* 2011;66:75–86.
38 Sarazin P, Burstyn I, Kincl L, *et al*. Trends in OSHA Compliance Monitoring Data 1979-2011: Statistical Modeling of Ancillary Information across 77 Chemicals. *Ann Occup Hyg* 2016;60:432–52.
39 Lavoue J, Friesen MC, Burstyn I. Workplace measurements by the US Occupational Safety and Health Administration since 1979: descriptive analysis and potential uses for exposure assessment. *Ann Occup Hyg* 2013;57:77–97.