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Noise Exposure Reconstruction and Evaluation of Exposure Trends in Two Large Automotive Plants

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This study used a task-based approach to reconstruct employee noise exposures at two large automotive manufacturing plants for the period 1970–1989, utilizing historic noise measurement data, work history records, documented changes in plant operations, focus group discussions, structured interviews with long-tenure employees, and task-based job profiles. Task-based job noise exposure profiles were developed in the 1990s when the plants conducted task-based noise monitoring. Under the assumption that tasks and time-at-task profile within jobs did not change over time, these profiles were applied to historic jobs. By linking historic noise exposure measurements to job tasks, this approach allowed task-based reconstructed noise exposure profiles to capture variability of daily noise exposures. Reconstructed noise exposures, along with task-based noise exposure measurements collected at each plant during the 1990s, were analyzed to examine time trends in workplace noise levels and worker noise exposure. Our analysis of noise exposure trends revealed that noise levels for many jobs declined by ≥3 dBA from 1970 to 1998 as operational and equipment changes occurred in the plants and some noise control measures were implemented, but for some jobs, noise levels increased in the mid- to late 1990s, most likely because of an increase in production at that time. Overall, the percentage of workers exposed to noise levels >90 dBA decreased from 95% in 1970 to 54% in 1998 at one of the plants and decreased from 36% in 1970 to ~5% in 1999 at the other plant. These reductions indicate a degree of success for the hearing conservation program. However, the actual number of employees with noise exposure >90 dBA increased because of a substantial increase in the number of production employees, particularly in jobs with high noise levels, which shows a hearing conservation program challenge that companies face during periods of increased production. Future analysis of hearing levels in these plant populations will help determine whether noise level reduction translates into decreased hearing loss at these plants.

Keywords: automobile industry; noise; retrospective exposure assessment; task-based exposure

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INTRODUCTION

It is well known that excessive noise exposure causes hearing loss. Nonauditory effects, including psychological stress and hypertension, have been linked to noise exposure (National Institute for Occupational Safety and Health, 1998) and working in a high-noise environment can interfere with workplace safety (Picard *et al.*, 2008). Recent research has suggested that chronic exposure to typical workplace noise may be associated with an increased risk of acute myocardial infarction (Davies *et al.*, 2005). Approximately 30 million workers in the USA are exposed to potentially hazardous noise levels on the job (Franks *et al.*, 1996) with an estimated 9 million workers exposed daily to noise >85 dBA. More than 5 million of these workers are from manufacturing and utility industries (Simpson and Bruce, 1981). However, the actual number of noise-exposed workers may be substantially underestimated because of the lack of systematic national health surveillance to track noise exposure (Prince, 2002).

As the workforce ages, there may be increased interest among occupational noise and hearing loss researchers in conducting epidemiological studies to determine the contribution of noise exposure to hearing loss or other adverse health outcomes in older workers, particularly workers who have spent their career in noisy workplaces. Unfortunately, tracking and characterizing workers' noise exposure over their duration of employment is challenging because many companies do not perform noise measurements, do not keep records of measurements, or do not have enough measurements to permit useful analysis. Therefore, noise exposure reconstruction becomes necessary.

Several investigators (Seixas *et al.*, 1997; Stewart *et al.*, 1998; Sanderson *et al.*, 2001; Rice *et al.*, 2002) have published methods for reconstruction of air contaminant exposures. Additionally, some researchers have published studies in which noise exposure reconstruction was performed (Lee-Feldstein, 1993; Brühl *et al.*, 1994; Burgess *et al.*, 2004; Davies *et al.*, 2009; Neitzel *et al.*, 2011b). However, review of exposure reconstruction reported in the research literature indicates that reconstruction of employee noise exposure history has not been conducted as extensively as air contaminant exposure reconstruction.

This article describes reconstruction of employee noise exposure for the period 1970–1989 and examines trends in noise exposure among a cohort of noise-exposed workers from two large US automobile manufacturing facilities, a stamping facility, and a chassis manufacturing facility, owned by the same parent company. The main purpose of this exposure reconstruction was to provide estimates of noise exposure over time for use in an epidemiological investigation to evaluate risk of noise-induced hearing loss in populations working in these plants (Heyer *et al.*, 2011). We present an overall approach for the use of task-based job information and supplemental historic data from company hearing conservation programs to reconstruct noise exposure over time.

METHODS

Plant descriptions

The stamping plant (Plant A) began full operations in 1965 and manufactured automobile body parts, such as floor pans, doors, hoods, and fenders. Primary manufacturing processes were blanking, stamping, welding, and subassembly. Major noise sources included metal-to-metal impacts, compressed air releases, and noise from pumps and motors.

The chassis plant (Plant B) began full operations in 1957. Manufacturing changed considerably over time. From the 1960s to the mid-1970s, the plant had a large bolt-making operation. This was eliminated and replaced with rack and pinion manufacturing, steering column machining, and assembly. By the mid- to late 1990s, power steering pumps, recreational vehicle gear, and housing assemblies for pistons and gears were also manufactured. Principal manufacturing processes included machining, assembly, and heat treatment. Major noise sources included metal-to-metal impact, compressed air releases, noise from ventilation blowers, and noise from pumps and motors.

Jobs at each plant were delineated by alphanumeric job codes and corresponding job titles. Generally, workers in the same job title perform the same work. However, some job titles were further divided into job functions because of unique differences in job tasks. Employees at both plants worked 8-h shifts and 40 h per week. Both plants operated three 8-h production shifts per day. Production employees were represented by the United Auto Workers.

Data sources

We used several sources of data for reconstructing noise exposures. Historic documents included floor plans, reports, and memos of plant operation changes and engineering controls, noise control evaluations and recommendations, hearing protection information, hearing conservation program plans, and company noise policies. From personnel work history records, we obtained information about the names and codes used for jobs and work departments. Additionally, information from structured interviews and focus group meetings with experienced long-term hourly and supervisory employees, which was collected during a previous research study, provided historic details about department and production line locations, production changes, workplace noise levels, and the departmental organization and numbering system (Prince *et al.*, 2004). Information from these interviews also provided us with a temporal reference for changes in the plants from 1970 to 1990.

We obtained historic noise measurement results from area noise surveys in 1970–1971 and 1985–1986 at Plant A and in 1971 at Plant B. We had limited information about the methods and instruments used for noise measurements. However, historic documents noted that the company performed area noise measurements using basic Type 2 sound level meters. These instruments did not integrate noise measurements and the results were typically reported as a range. In the 1990s, task-based noise exposure assessments were conducted at the plants using methods previously described by Hager (1998). For those noise surveys, short duration task measurements were primarily made using Type 2 sound level meters, but dosimeters were sometimes used for highly mobile tasks when a handheld sound level meter was impractical. Task-based noise surveys were completed in 1991, 1995, and 1998 at Plant A and in 1990, 1992, 1995, and 1997 at Plant B. These task-based data provided task and time-at-task information for developing pre-1990 job time-at-task profiles and to study noise exposure trends.

Noise exposure reconstruction

We used the following steps to reconstruct noise exposures:

1. Subdivide reconstruction time periods based on substantial production changes;
2. Link sound level measurements to production areas in reconstructed plant floor plans;
3. Merge historic department/job combinations with job time-at-task profiles;
4. Link historic sound levels to tasks in reconstructed job time-at-task profiles;
5. Calculate time-weighted average (TWA) for reconstructed job time-at-task profiles.

Subdivide reconstruction time periods based on substantial production changes. Production, process, or equipment changes that were judged to likely result in noise level changes were an important product from historic reports of plant operation changes and from structured interviews with experienced long-term employees. On the basis of when these key changes occurred, the period 1970–1989 was subdivided into shorter periods for each plant, as shown in Table 1. Because plant operations remained essentially the same within these shorter periods, we assumed that noise levels within each of these shorter periods remained steady.

Link sound level measurements to production areas in reconstructed plant floor plans. Plant floor plans from the 1990s revealed the location of production lines and departments at that time. However, it was known from discussions with plant personnel that the location of production lines and departments were sometimes different in 1970–1989. Additionally, some production lines did not exist prior to 1990, and some had been eliminated by 1990.

For Plant A, notes from plant-wide noise surveys conducted in 1971 and 1985 provided the department number, production line number, and plant grid location for each measurement. By cross-referencing this information with historic floor plans that included grid identification and production lines, we determined the boundaries for departments and the location of major production lines within departments for each time period. Knowing these boundaries helped us to link other historic noise measurements collected during 1970–1971 and 1985–1986 to work departments or production lines.

The 1971 noise survey at Plant B provided department and grid location information. However, this information was not available for other years and could only be used to help determine department boundaries for the period 1971–1976. Therefore, a different approach was necessary for later periods. Through structured interviews, long-term employees reviewed plant floor plans from the 1990s and then identified the location of production departments during previous periods.

Once department boundaries were established for each historic period, we linked each historic sound level measurement to a department using

Table 1. Key production, process, or equipment changes (1970–1989).

Facility	Time period	Production, processes, or equipment changes
Plant A	1970–1984	• No changes considered to substantially change noise levels
	1985–1989	• Major new production line began operation
		• Four new press lines added
		• One small press area in weld assembly department eliminated
		• Introduction of automated technology at major press department
Plant B	1971–1976	• Several noisy transfer operations removed
		• High-speed bolt-maker machines introduced
	1977–1978	• A major press replaced by storage area
		• Introduction of rack and pinion line, wire draw line, transfer machine, and drills
	1979–1983	• Building expansion
		• Expansion of rack and pinion lines
		• New yoke machines added
		• Screw machines replace plating
	1984–1989	• Parts manufacturing for new vehicles started
		• Pickle house, most bolt-maker machines, and some tube mills eliminated
		• Addition of new pump area

the department, production line numbers, or grid location references from the historic sound level measurements. Plant A had 1340 sound level measurements for the period 1970–1984 and 304 sound level measurements for 1985–1989. Plant B had 352 noise measurements for the period 1971–1976. No noise measurements were available at Plant B for the period 1977–1990.

Merge historic department/job combinations with job time-at-task profiles. In the 1990s, plant-wide task-based noise monitoring was performed at both plants. Because structured interviews with long-term employees and supervisors at each plant indicated that job tasks had not changed substantially over time, we decided that the tasks and time-at-task profiles from the 1990s job time-at-task profiles could be used for historic job profiles. From work history records, a complete list of all department, job code, and job function combinations that existed during each reconstruction period at each plant was compiled. These historic department, job code, job function combinations were merged with job time-at-task profiles from the 1990s. When a direct match by department, job code, and job function did not occur, tasks and time-at-task details for reconstruction period job profiles were extrapolated from job profiles in the 1990s in the following sequence:

1. same department and job code combination
2. same job code in a similar department
3. similar job code in the same department
4. similar job code in similar department.

For Plant B, where there were production changes, long-term employees provided input regarding typical job tasks and task durations, retrospectively. When these differed from the details of the 1990s, long-term employee input took precedence.

Link historic sound levels to tasks in reconstructed job time-at-task profiles. To develop task-based noise exposure profiles, historic sound level measurements had to be linked to the tasks in the reconstructed job time-at-task profiles. We grouped work tasks in the reconstructed profiles into two categories, stationary tasks or mobile tasks, on the basis of interviews with long-term employees and job descriptions from the 1990s. Stationary tasks were performed at a specific location within a department. In contrast, mobile tasks were performed across an entire department, multiple departments, and, in a few cases, the entire plant. Because most departments had multiple historic sound level measurements, it was impossible to know which specific measurements best represented the noise level for each task. Therefore, we averaged all historic sound level measurements that logically represented the sound level for each task [equation (1)], on the basis of the location(s) of the measurements and the location(s) where the task was likely performed. Depending on task mobility and task location(s), from 2 to 1310 (median = 54) individual historic sound level measurements were averaged for each task. The resulting average was considered to be the sound level for the task in the job time-at-task profile.

$$\text{Task sound level average } (L_{\text{SLAi}}) = q\,\text{Log}_{10}\left[\frac{1}{N}\sum_{i=1}^{N}10^{L_{\text{SLi}}/q}\right] \quad (1)$$

Here, q = 10, N = total number of historic sound level measurements linked to task, and L_{SLi} = historic A-weighted sound levels linked to task.

Tasks in the reconstructed profiles that specified the use of manual hand tools, powered hand tools, or welding equipment did not have historic sound level measurements. Likewise, tasks occurring in the garage or outside the plant did not have historic measurements. We assumed that sound levels for these tool tasks or locations changed very little over time. Therefore, we used the average sound levels from measurements in the 1990s for these tools, tasks, or locations as the sound levels for the corresponding tasks in the reconstructed job time-at-task profiles.

Because Plant B did not have historic sound level measurements except for the period 1971–1976, a different approach was necessary for the three periods from 1977 to 1989. For these periods, structured interviews with long-term employees were used to identify departments where noise levels had likely changed and to identify when new departments or jobs had been established. Noise exposure data from 1971 to 1976 were used for tasks in corresponding department–job combinations in subsequent periods when there was no indication of department noise level changes. For departments in which there was an indication that noise exposures had changed after 1971–1976, noise level measurements from the 1990s were used for tasks in the corresponding department–job combinations from the earlier period. Noise exposure data from the 1990s were also used for corresponding jobs within new departments.

Calculate TWA for reconstructed job time-at-task profiles. The 8-h TWA noise exposure for each reconstructed job time-at-task profile was calculated using equation (2).

$$\text{Reconstructed TWA job noise exposure profile } (L_{\text{TWAi}}) = q\,\text{Log}_{10}\left[\frac{1}{T}\sum_{i=1}^{N}t_i \times 10^{L_{\text{SLAi}}/q}\right] \quad (2)$$

Here, q = 10, T = 8, hours worked during the work shift, N = total number of tasks in job profile, t_i = duration of the ith task (time-at-task), and L_{SLAi} = A-weighted sound level average for the ith task [from equation (1)].

An example reconstructed job noise exposure profile is provided in Table 2.

Because not all jobs existed in all time periods, we separately performed analysis on the subset of jobs that did exist across all periods. For this analysis, we grouped closely related jobs at each plant on the basis of similar job name, job code, and job function, resulting in 15 job groups that existed in all periods for each plant. At Plant A, each job group consisted of job noise exposure profiles from one to five job codes (mean = 2.2, standard deviation, SD = 1.0); and at Plant B, each job group consisted of job noise exposure profiles from 2 to 10 (mean = 5.3, SD = 2.6). The representative noise exposure level for each job group was calculated by averaging the job noise exposure profile TWAs for the grouped jobs using equation (3).

Table 2. Example reconstructed job noise exposure profile, 1970–1984.

Department	Job code	Job function	Job tasks[a]	Time-at-task, h[a]	Task sound level, dBA[b]
930	2882	Repair	Lunch and break	1.0	86.2
			Weld department repairs	2.0	95.9
			Press department repairs	3.5	97.6
			Tool and die area activity	1.5	89.2
TWA noise exposure for Job Code 2882 in Department 930				8.0	95.7[c]

[a]Based on task and time-at-task profiles from task-based noise surveys conducted in 1991.
[b]Calculated using equation (1).
[c]Calculated using equation (2).

Average TWA for job group

$$\left(L_{\text{GAi}}\right) = q\,\text{Log}_{10}\left[\frac{1}{N}\sum_{i=1}^{N}10^{L_{\text{TWAi}}/q}\right] \qquad (3)$$

Similarly, q = 10, N = total number of profiles for job group within the time period, and L_{TWAi} = TWA for each job noise exposure profile [from equation (2)].

Additionally, we examined whether noise level trends in jobs differed from employees' noise exposures over time by merging the reconstructed job noise exposure profiles with work history records. To calculate a worker's average noise exposure for each reconstruction time period, the TWA job noise exposure profile results for each job the employee held were first merged with the employee's work history data, which provided the start and stop date for each job. The worker's average noise exposure during the reconstruction time period was then calculated using equation (4).

Average noise exposure of worker during reconstruction time period

$$\left(L_{\text{AVGi}}\right) = q\,\text{Log}_{10}\left[\frac{1}{D}\sum_{i=1}^{N}d_i \times 10^{L_{\text{TWAi}}/q}\right] \qquad (4)$$

Here, q = 10, D = total number of days an employee worked during the time period, d_i = number of days for ith job, d_i = number of days for ith job, and L_{TWAi} = TWA exposure level for ith job [from equation (2)].

RESULTS

Job exposure changes over time

At Plant A, 395 (87%) of reconstructed profiles had calculated TWA levels >90 dBA, during the period 1970–1984 (Fig. 1). The number of profiles with TWAs ≥90 dBA decreased over time. This decrease was particularly evident from 1970–1984 to 1985–1989. By 1997–1998, only 33% of the profiles had TWA levels ≥90 dBA. Forty-one (9%) profiles at Plant A during 1970–1984 had calculated TWA noise levels of 85–90 dBA. However, a large increase in the number of profiles in this range was observed by 1985–1989. Relatively small increases occurred in subsequent periods. Job profiles with TWA levels <85 dBA ranged from 3.2% of the total profiles in 1985–1989 to 13.1% in 1994–1996.

At Plant B, 171 (39%) of the reconstructed profiles had calculated TWAs ≥90 dBA during the period 1971–1976. The number of profiles with a TWA ≥90 dBA (Fig. 2) decreased to 80 profiles by 1977–1978 and remained at or below this number, except for 1990–1991, when it was slightly higher. The calculated TWA noise levels for 249 (57%) profiles at Plant B during 1971–1976 were 85–90 dBA. This number decreased to 154 by 1977–1978 but subsequently increased in each period until 1992–1993, after which the total number started to decline slightly. Job profiles with TWA <85 dBA represented 4% of the total profiles at Plant B in 1971–1976 but increased to ~37% of the total profiles by 1992–1993.

Although we observed a downward trend in the number of job noise exposure profiles with TWA

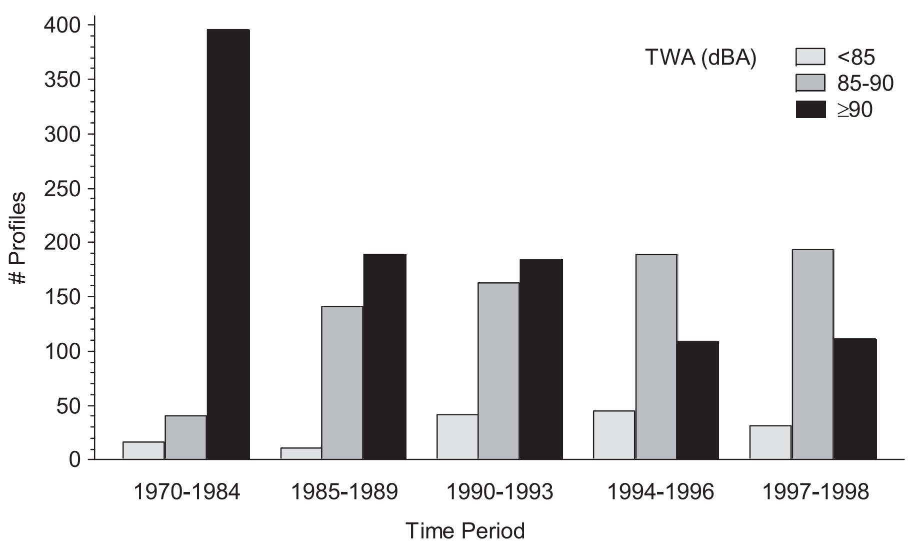

Fig. 1. Number of job noise exposure profiles per exposure level category at Plant A.

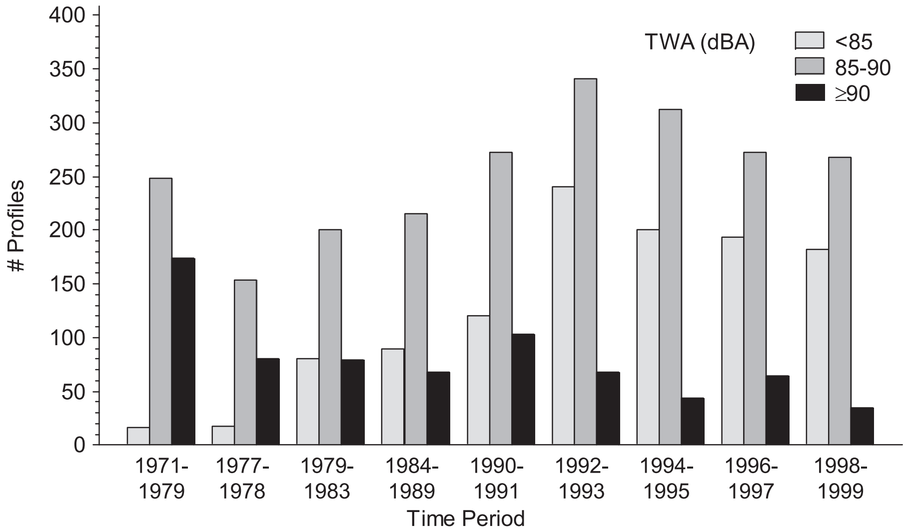

Fig. 2. Number of job noise exposure profiles per exposure level category at Plant B.

noise levels ≥90 dBA, it was unclear from this analysis whether this trend occurred consistently across different jobs because not all jobs existed in all time periods. To explore this further, we restricted our analysis to jobs that existed in all periods. Noise level trends for the 15 job groups at Plant A are presented in Fig. 3. More than 82% of production employees who worked at the plant from 1970 to 1998 were in these 15 job groups. Calculated TWA noise exposure levels in 14 job groups were ≥90 dBA in 1970–1984. However, by 1997–1998, only 5 of the job groups still had TWA noise levels >90 dBA. In nearly all the groups TWA noise levels decreased by at least 3 dBA over time. The largest decreases, ~7 dBA, were observed in the two groups with the most production employees, namely, 'Automation Tender Major Press Lines' and 'Automation Tender Major Welding Lines'.

Noise level trends for the 15 job groups at Plant B are presented in Fig. 4. More than 71% of all production employees who worked at the plant from 1971 to 1998 were in these 15 job groups. The calculated TWA noise exposure levels for nine job groups were ≥90 dBA in 1971–1976. In 1998–1999, no job group had TWA noise levels ≥90 dBA. Noise levels decreased for all 15 job groups over time and decreased by >3 dBA for eight job groups. The largest decreases (4.5–4.8 dBA) were observed in the job groups 'Industrial Lift Truck Operator/Tow Tractor Driver', 'Inspector', and 'Cleaner'.

In most job groups at both plants, noise levels decreased over time. However, noise levels sometimes increased from one period to the next. The increases were usually ≤1 dBA, but in a few instances, noise levels increased by ~4 dBA.

Employee noise exposure changes over time

The percentages of workers by category of noise exposure (<85, 85–89, and ≥90 dBA) for each time period are presented in Fig. 5 for Plant A and in Fig. 6 for Plant B. Nearly 95% of workers in Plant A were exposed to noise levels ≥90 dBA during 1970–1984. In each subsequent period, the percentage of workers with noise exposures ≥90 dBA decreased, with the exception of 1997–1998. At Plant B, only 36% of production workers were exposed to noise levels ≥90 dBA in 1971–1976. This percentage decreased in each subsequent period until 1992–1993 and then remained at 5–7% for subsequent periods. For both plants, we observed an overall increase over time in both the number and the percentage of workers with exposures of 85–90 dBA. Of particular note was an increase in the percentage of workers with exposures <85 dBA at Plant B, from <5% in 1971–1976 to ~30% in 1998–1999.

At both plants, the percentage of workers with high noise exposures decreased over time. However, at Plant A, the number of workers with noise exposures ≥90 dBA increased from ~850 employees in 1970–1984 to ~1600 employees in 1997–1998. This corresponded with an increase in the number of production workers from ~900 in the 1970s and 1980s to 1700 workers in 1990–1993 and ~2950 workers after 1994. The number of production workers at Plant B increased from ~500 in

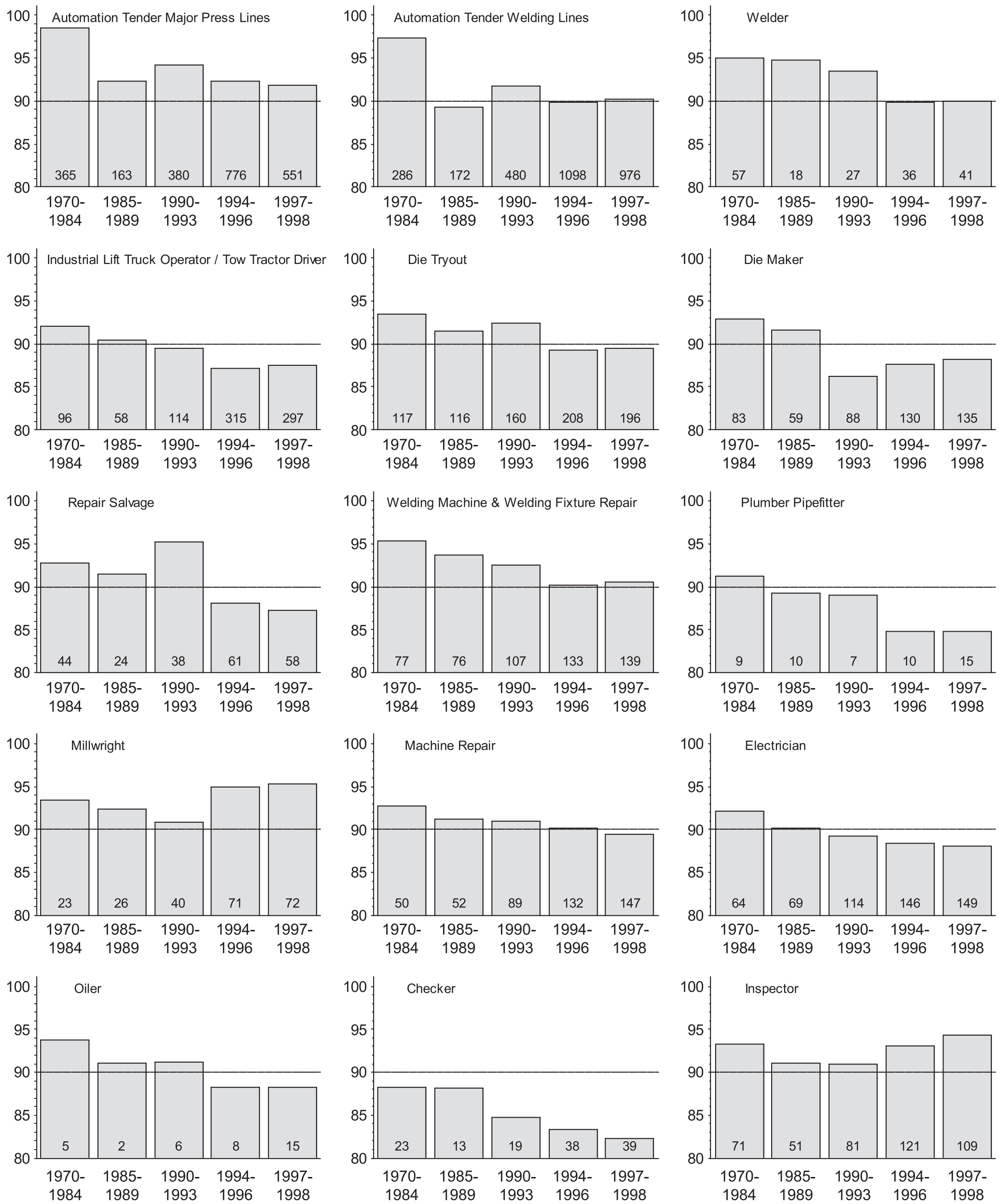

Fig. 3. Noise level trend for Plant A job groups (average number of employees shown in bars).

the 1970s to 1000 by 1990–1991 and then to ~3000 by the mid-1990s; but the number of workers with noise exposure ≥90 dBA remained relatively constant, ranging from 159 to 249 workers.

DISCUSSION

The goal for this occupational noise exposure reconstruction was to estimate employees' exposures over time. Ideally, we would have had multiple historic personal noise exposure measurements collected from representative workers for each job. However, this level of detailed information was not available to us and is rarely available for exposure reconstruction. Therefore, we relied on historic noise measurement data, work history records, documented changes in plant operations, results of focus group discussions and structured

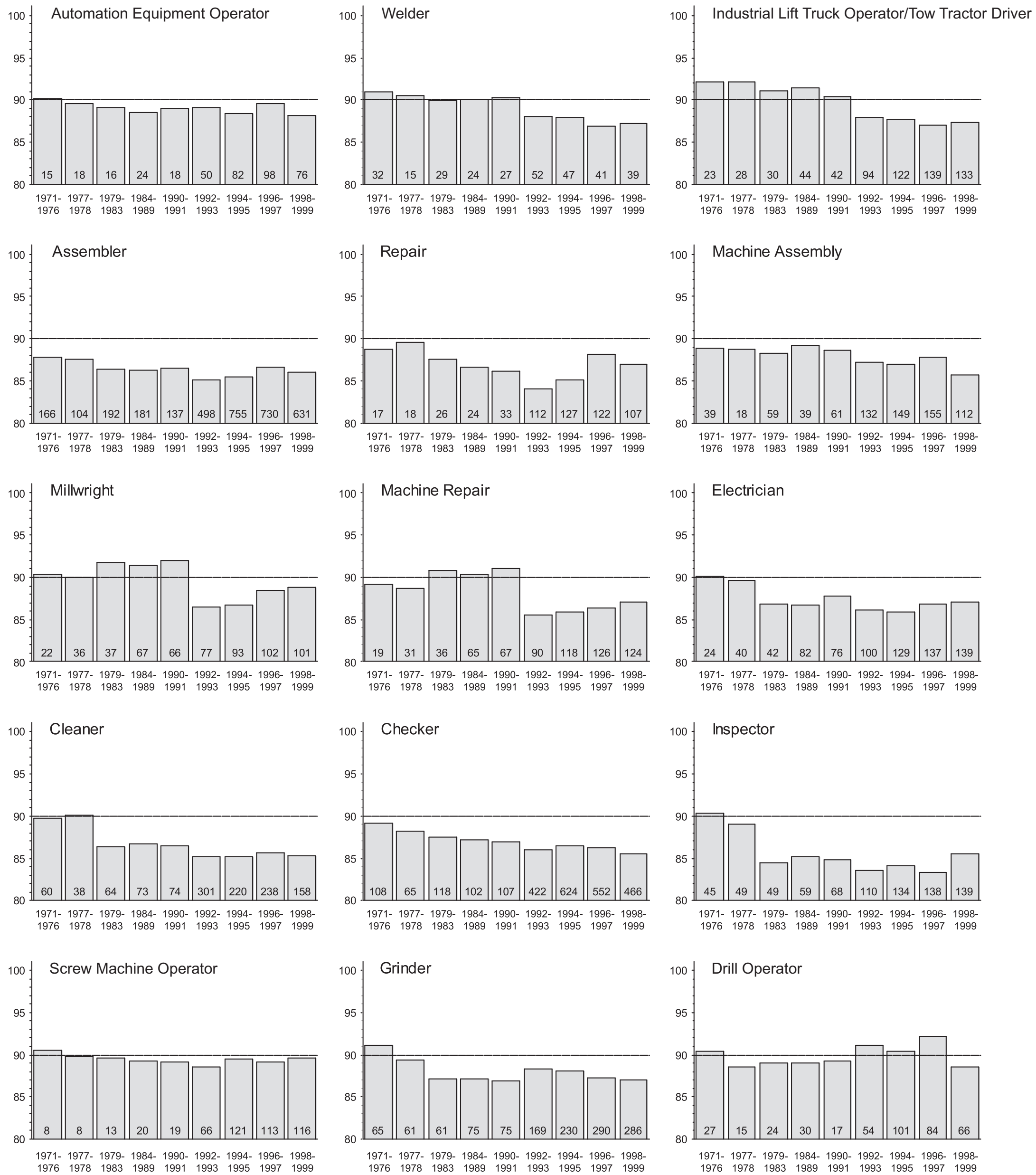

Fig. 4. Noise level trend for Plant B job groups (average number of employees shown in bars).

interviews with long-tenure employees, task-based job profiles, and professional judgment to reconstruct employee noise exposures. Reconstructed noise exposures, along with separate task-based noise exposure measurements collected during the 1990s, allowed us to examine trends over time in workplace noise exposure levels.

Operational and equipment changes in these plants over time likely affected noise levels. Historic company documents show that the plants attempted to initiate noise controls beginning in the early 1970s; however, little information was available to substantiate the extent and effectiveness of controls. A corporate program to guide the decision-making process for purchasing equipment that generated noise levels <84 dBA was established in the early 1980s. Both plants increased automation over time, which might

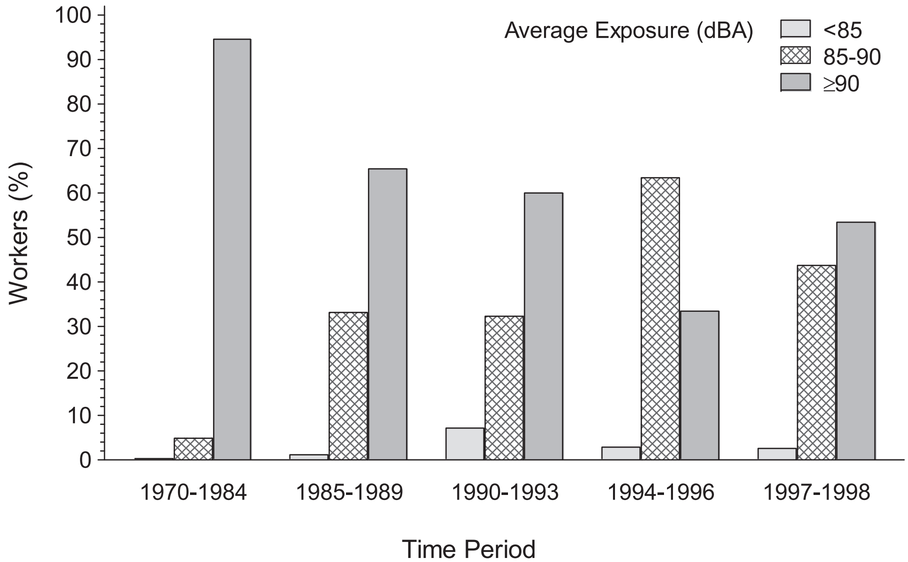

Fig. 5. Percentage of workers at Plant A by noise exposure category by time period.

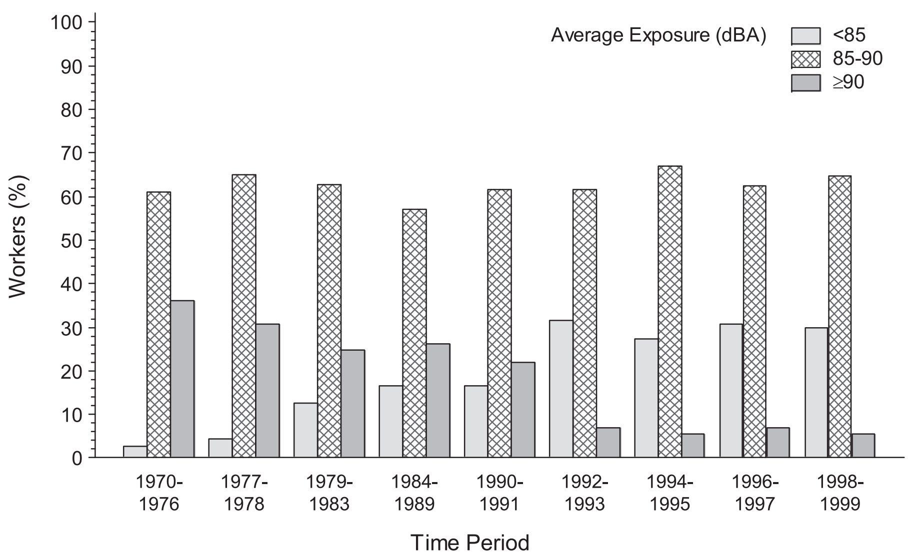

Fig. 6. Percentage of workers at Plant B by noise exposure category by time period.

have allowed employees to manage and monitor production at a greater distance from noise sources. New product lines could have incorporated quieter equipment and increased automation. A study examining noise exposure trends in a large automotive plant found that noise levels in the plant successively decreased even though there was an increase in production (Brühl *et al.*, 1996). Reduced noise levels were attributed to noise reduction measures on presses, increased automation, and quality improvements that resulted in the elimination of a high-noise-generating process. Middendorf (2004) suggested that implementation of engineering or administrative controls and process changes in the manufacturing sector reduced the number of workers near high-noise sources, which may have partially led to a decrease in the need for and number of Occupational Safety and Health Administration (OSHA) noise inspections from 1985 to 1998.

We observed a downward trend in the number of job profiles with calculated TWAs ≥90 dBA (Figs 1 and 2). This trend was particularly evident from the 1970s through the 1980s. As the number of job profiles with noise levels ≥90 dBA decreased, the number of profiles with noise levels < 90 dBA increased. We attributed this to noise reductions or changes in production, which resulted in some job profiles moving from higher to lower noise level categories. However, tracking the number of job profiles in noise exposure categories may not sufficiently reveal trends because jobs came into or went out of existence over time. Therefore, we examined noise exposure in jobs that existed throughout the entire time period of the study.

Our analysis of noise trends in job groups (Figs 3 and 4) indicated that the plants successfully decreased noise over time. For most jobs, noise levels decreased in each successive period. However, beginning in the 1990s, the noise level in a few jobs increased slightly, relative to the immediate preceding period. A substantial increase in the number of employees also occurred during the 1990s. The workforce size increase corresponded with an increase in production volume and equipment, which were likely to increase noise within the plant, affecting some jobs disproportionately more than others. Interestingly, noise levels in the 'Repair Salvage' job group in Plant A increased 3.8 dBA from 1985–1989 to 1990–1993. Upon closer review of the job tasks in this job group, we found that the increase was due to very high noise levels (99.8 and 106.3 dBA) for two tasks in one of the 'Repair Salvage' job profiles included in the job group during 1990–1993. The same tasks were performed in other time periods; however, they were performed in a different area where noise levels were substantially less. This example shows how substantially high task noise levels influence exposures and the estimation of mean noise levels for the entire job group, in addition to also illustrating a challenge in interpreting job-based noise level trends.

Although overall noise levels and the proportion of workers with noise exposures ≥90 dBA decreased over time, an unexpected finding from our analysis was that the number of workers with noise exposures ≥90 dBA increased in the 1990s, particularly at Plant A. This decrease in the proportion of employees exposed to high noise levels highlights an important accomplishment for the hearing conservation program. However, the increase in the number of workers exposed to high noise levels illustrates the difficulty and challenge that large manufacturing companies can encounter when trying to reduce noise exposures during periods of growth in production.

Although multiple factors could motivate companies to reduce noise exposures, perhaps one of the more important incentives was OSHA noise standards, which required the use of hearing protection, engineering controls (OSHA, 1974), and establishment of a hearing conservation program (OSHA, 1983). Davis and Sieber (1998) attributed an increase in hearing protector usage across American manufacturing plants from 1972 to 1989 to the implementation of noise regulations. The reduction in noise levels over time at these plants was likely to have been influenced by OSHA noise standards, as evidenced by documents from the early 1970s and 1980s, which indicated that the company was attempting to implement measures to reduce noise levels to meet the legal limits. These measures included noise control evaluations and written hearing conservation programs. In addition to compliance with OSHA noise standards, other factors that may contribute to noise reduction include a desire to reduce workers' compensation costs (Gray and Mendeloff, 2002) and equipment manufacturers reducing the noise generated by equipment.

Previous analysis of the hearing conservation program at these two plants indicated that Plant B had better compliance with the OSHA hearing conservation standard than Plant A (Prince, 2004). However, Plant A had more substantial noise reduction. These examples demonstrate that patterns of noise control and exposure are complex; and plant level compliance can differ for plants within the same corporation (Gray and Shadbegian, 2005).

Study advantages

One of the major advantages of this study was the availability of task-based noise exposure profiles from noise surveys conducted at the plants in the 1990s, which provided a structure for noise reconstruction. We used the tasks and time-at-task details from the 1990s' profiles for historic job profiles because many jobs remained in existence over time and interviews with long-term experienced employees or focus group discussions (Prince, 2004) indicated that job profiles had not changed substantially over time. By using task-based reconstructed noise exposure profiles, we were able to capture variability of noise exposures from different tasks or work locations during the work shift, which reflects a typical daily noise exposure pattern for many workers, particularly workers who do not have stationary jobs. Few studies have compared task-based noise exposure assessments to full-shift noise dosimetry or other exposure assessment methods. Virji *et al.* (2009) found that task-based noise exposure estimates exhibited good agreement with full-shift dosimetry. Additionally, task-based methods had better accuracy and agreement with measured noise levels compared with exposure assessment methods such as subjective rating or estimated exposures on the basis of external trade mean levels (Neitzel, 2011a). In contrast, Seixas *et al.* (2003) found poor agreement between task-based and dosimetry methods. These different results suggest that additional research comparing noise exposure assessment methodologies is needed.

Our approach differed from noise exposure reconstruction approaches taken by other researchers who did not have or use task data. Burgess *et al.* (2004) estimated historic noise exposures for British nuclear workers. In that study, a panel of experienced industrial hygienists created noise contours for nuclear plants by estimating average area noise levels on the basis of historic noise sampling results and process information. Researchers then used job title information to estimate individual employee noise exposures. For a cohort study of the association between high noise exposure and risk of cardiovascular disease in British Columbia sawmill workers, researchers obtained noise exposure data from research measurements, compliance measurements, and industry measurements and then developed a predictive statistical model to quantitatively estimate historic noise exposures (Davies *et al.*, 2009). In a 5-year study of hearing loss within an automobile company, workers' noise exposure history was determined based on job location and noise measurements at the job location, but noise exposure history prior to 1985 was estimated indirectly using work history records and previous sound survey results (Lee-Feldstein, 1993). Although some elements of these other noise reconstruction studies, such as the use of historic noise measurement results to estimate exposures (Burgess *et al.*, 2004) or identification of workers' job locations (Lee-Feldstein, 1993), were similar to ours, approaches that are not task based are not able to account for the differences in task noise exposures.

Another advantage in this study was the availability of a substantial number of historic sound level measurements to calculate and reconstruct historic task-based noise exposures, unlike exposure reconstruction in which historic exposure estimates are extrapolated solely from current measurements (Deadman *et al.*, 1997) or statistical models (Davies *et al.*, 2009). We also had detailed work history records of employees, which included start dates, termination dates, department codes, and job codes. Merging detailed work history records with task-based noise exposure profiles allowed us to create a job exposure matrix for individual workers. Detailed worker noise exposure history resulting from this noise exposure reconstruction was used for an epidemiologic study to evaluate the effectiveness of hearing conservation program components (Heyer *et al.*, 2011).

Study limitations

The exposure reconstruction process has elements of uncertainty, requiring that researchers prudently use whatever information is available to reduce the uncertainty. On the basis of information from historic records and previous structured interviews with long-term employees, we assumed that plant operations and, therefore, noise levels did not change during the time periods between key production, process, or equipment changes at each plant. However, historic data could be incomplete and errors in extrapolated noise levels could occur if noise level changes were not measured or operational changes were not documented. Another source of potential error includes differences in noise levels between work shifts. Historic noise measurement results did not indicate during which shift the measurements were taken. However, a historic document from the mid-1980s indicated that more equipment operated during the first shift and advocated that noise measurements should be collected during that shift.

Errors in assigning tasks and time-at-task profiles to historic jobs cannot be ruled out. We used task and time-at-task details from the 1990s' job time-at-task profiles for historic job profiles. This decision was largely based on the recollection of long-term employees (Prince *et al.*, 2004), who indicated that job profiles had not substantially changed over time. However, increased automation and changes in some production lines over time do present the possibility that tasks or time-at-task profiles might have also changed over time. Even though the long-term employees had not been asked to recall exact tasks, time-at-task estimates, even when obtained directly from workers, are subject to variability, and mobile jobs may have even greater variability (Virji *et al.*, 2009). A study of task recall among construction workers found recall of time-at-task details ranged from 53 to 100% 6 months after tasks were actually performed (Reeb-Whitaker *et al.*, 2004). Because we knew from work history records the departments where employees worked, errors from potentially incorrect assignment of tasks or time-at-task profiles may be somewhat mitigated, particularly for stationary employees, because the noise level for many tasks were more closely related to the location of the task rather than the task itself. Although most production employees were stationary or worked in a single department, the risk of error from incorrect assignment of task or time-at-task profiles could be greater for highly mobile employees who had worked across several departments.

Task-specific exposure levels were not available before 1990; therefore, misclassification of exposures cannot be ruled out (Rabinowitz *et al.*, 2007). We used historic sound level measurements to represent the noise exposure of workers at the location of the measurements. This approach works when task noise levels are primarily from equipment or operations in a specific work area. However, the contribution of noise from the task could be underestimated if the task itself is the primary contributor to workers' noise exposures. We attempted to take this into account by identifying tasks, such as tool use, where the task itself was the major contributor to exposure. Because historic measurements did not include sound levels for manual and powered hand tools, we extrapolated tool sound levels from surveys conducted in the 1990s. Historic documents did not indicate that the company had obtained power tools that used noise reduction technology, so we assumed that noise generated by tools did not change substantially over time.

CONCLUSION

The availability of historic noise level measurements, documented changes in plant operations, detailed work history records, and task-based noise exposure profiles provided a structure to reconstruct historic noise exposures at two automotive manufacturers using task-based methods. An important advantage of using a task-based approach is the ability to capture variability of noise exposures from different work tasks or locations where tasks were performed. An examination of noise exposure trends over time using the results of our noise reconstruction, along with task-based noise measurements collected in the 1990s, indicated that noise levels in the plants declined over time for most jobs. Additionally, the percentage of employees with noise exposure ≥90 dBA also declined over time, but the total number of employees with noise exposures '≥90 dBA actually increased due to a substantial increase in the number of production workers'. One of the factors probably influencing these noise level reductions was the companies' efforts to comply with OSHA noise regulations.

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