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Occupational exposure to diesel engine exhaust: A literature review

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Abstract

Background—Diesel exhaust (DE) is classified as a probable human carcinogen. Aims were to describe the major occupational uses of diesel engines and give an overview of personal DE exposure levels and determinants of exposure as reported in the published literature.

Methods—Measurements representative of personal DE exposure were abstracted from the literature for the following agents: elemental carbon (EC), particulate matter (PM), carbon monoxide (CO), nitrogen oxide (NO), and nitrogen dioxide (NO_2). Information on determinants of exposure was abstracted.

Results—In total, 3528 EC, 4166 PM, 581 CO, 322 NO, and 1404 NO_2 measurements were abstracted. From the 10,001 measurements, 32% represented exposure from on-road vehicles, and 68% from off-road vehicles (30% mining, 15% railroad, and 22% other). Highest levels were reported for enclosed underground work sites where heavy equipment is used: mining, mine maintenance, and construction, (EC: 27-658 μg/m^3). Intermediate exposure levels were generally reported for above ground (semi-)enclosed areas where smaller equipment was run: mechanics in a shop, emergency workers in fire stations, distribution workers at a dock, and workers loading/unloading inside a ferry (generally: EC< 50 μg/m^3). Lowest levels were reported for enclosed areas separated from the source such as drivers and train crew, or outside such as surface mining, parking attendants, vehicle testers, utility service workers, surface construction and airline ground personnel (EC<25 μg/m^3). The other agents showed a similar pattern. Determinants of exposure reported for enclosed situations were ventilation and exhaust after treatment devices.

Conclusions—Reported DE exposure levels were highest for underground mining and construction, intermediate for working in above ground (semi-)enclosed areas and lowest for working outside or separated from the source. The presented data can be used as a basis for assessing occupational exposure in population-based epidemiological studies and guide future exposure assessment efforts for industrial hygiene and epidemiological studies.

Keywords

diesel exhaust; occupational; review; exposure; determinant

Introduction

Diesel engines have a wide range of industrial applications, including on and off-road equipment used, for example, in the mining, railroad, construction, and transportation

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industries. The use and application of diesel engines in industrial processes became widespread between the 1930s and 1950s (HEI, 2002). The National Institute of Occupational Safety and Health (NIOSH) estimated that approximately 1.4 million workers in the United States (US) were occupationally exposed to diesel exhaust (DE) between 1981 and 1983 (NIOSH, 1983). A second study estimated that 3 million workers were exposed to DE in the 15 countries of the European Union between 1990–1993 (Kauppinen, et al., 2000).

DE contains a complex mixture of gases and particulates. Gaseous constituents include oxides of carbon, nitrogen, and sulfur, and low molecular weight hydrocarbons (Ris, 2007). The particulate fraction is primarily in the submicron range and consists of an insoluble elemental carbon (EC) core and an adsorbed surface coating of relatively soluble organic carbon (OC) . EC and OC typically constitute 33–90% and 7–49%, respectively, of the particulate mass(EPA, 2002). The assessment and characterization of DE is complicated because its chemical composition is affected by changes in engine technology and fuel composition over time (EPA, 2002).

Health effects of DE exposure include eye, throat and bronchial irritation, cough, phlegm, and neurophysiological symptoms (Lloyd, et al., 2001; Ris, 2007). In addition, DE is considered a probable human carcinogen by the International Agency for Research on Cancer (IARC) (1989). A general limitation of the almost 50 epidemiological studies investigating cancer in workers exposed to DE is the lack of quantitative data on historical exposure (Rogers, et al., 2005; Silverman, 1998).

This paper describes the major occupational uses of diesel engines and gives an overview of personal exposure levels to diesel exhaust and determinants of exposure as reported in the published literature. The data were developed as a basis for assessing occupational exposure to DE in population-based epidemiological studies. In addition, the data can guide future exposure assessment efforts for industrial hygiene and epidemiological studies.

Methods

Literature on occupational DE exposure was identified from MEDLINE, TOXLINE, NIOSHTIC, and the NIOSH Health Hazard Evaluation database using the search terms ‘diesel’, ‘diesel particulate matter’, ‘diesel exhaust’, ‘occupational’, and ‘exposure’. In addition, personal archives added literature not present in these databases. Literature from 1957 through 2007 was identified. Information on occupational DE exposure was abstracted. The information presented includes a brief description of the industry and processes and an overview of exposure measurements and reported determinants. The information is organized by on-road and off-road equipment. Off-road uses were further categorized into mining, railroad, and other applications.

The assessment of exposure to DE is complicated because no single constituent of DE is considered a unique marker of exposure(Lloyd, et al., 2001). In the past, investigators have used several non-specific components of DE as surrogates, such as respirable particulate matter (PM_R), carbon monoxide (CO), nitrogen oxide (NO), or nitrogen dioxide (NO_2). In the 1990s, two more specific surrogates for DE have been increasingly used: EC and submicron particulate matter (PM_s) (Steenland, et al., 1998). To evaluate both current and past exposure levels, EC, PM_R (including $PM_{2.5}$), PM_S, NO_2, NO, and CO were selected for this report. For these agents, all occupational personal measurement data reported in the literature were summarized in a database. Area samples that were likely representative of personal exposures were also included. Because most of the agents are not specific for diesel exhaust, an indication of the presence of diesel engines was required for inclusion. For practical reasons, only agents with a total of 5 or more measurements on all jobs combined in a study were included. Studies that did not report sample size were included when it could be inferred from the text that at least 5 measurements were likely for an agent. Efforts were made to exclude studies reporting the same exposure data.

The abstracted information on the measurements included industry, description of job/task/location, country, sample year (when not provided publication year was used), type of sample (area or personal), number of samples, sampling duration, sampling and analytic method, and summary statistics. All sampling durations except peak measurements were included and were categorized as <1 hour, 1–4 hours, or ≥4 hours. The arithmetic mean (AM) and standard deviation (SD) and geometric mean (GM) and geometric standard deviation (GSD) were included. Summary statistics were calculated when only individual measurement results were presented. When averages for similar jobs were presented in a single publication, these were combined into broader job categories by weighting the AMs and GMs by the number of measurements. For calculations, non-detectable (ND) values or averages were substituted by the detection limit divided by $\sqrt{2}$ (Hornung, et al., 1990). When means were presented without specifying the number of measurements, an unweighted average was calculated. In addition, the range of SDs or GSDs across jobs is presented. When the AM was not reported, it was estimated. When the GM and GSD were reported, a lognormal distribution was assumed and the AM was estimated using the formula (Aitchison, et al., 1969):

$$\mathrm{AM}=\mathrm{GM}\times \exp[1/2\times(\ln(\mathrm{GSD}))^2]$$

If only the range was provided, the GM was estimated by squaring the midpoint of the log transformed minimum and maximum levels and the GSD was estimated by squaring the range of the log transformed values divided by four (Hein, et al., 2008). The units of EC and PM are in μg/m^3, and CO, NO and NO_2 units are in ppm. When units of the gases were in mass/m^3, they were converted to ppm assuming standard room temperature and pressure.

Determinants of exposure are described that were either explicitly identified or implicitly identified by contrasting scenarios. Explicitly identified determinants for area measurements not representative of personal exposure, and measurements of other DE surrogates not selected for the measurement summary herein are also presented. When provided by the original paper, the exposure levels for the contrasting scenarios are given in the text. Statistical significance is indicated when reported by the original study investigators.

Results

Almost 300 papers and reports were reviewed. Fifty-seven studies reported on personal or representative area exposure measurements that did not overlap. Of these studies, 28% included samples taken after 2000 (5026 samples), 53% in the 1990s (3003 samples), 12% in the 1980s (1569 samples), and 7% in the 1970s (403 samples). In total, 10,001 samples were reported, of which 32% represented exposure from on-road vehicles. The remaining 68% was taken in the mining industry (30%), the railroad industry (15%), and other off-road operations (22%). Seventy-four percent of the samples were taken in the US. The rest were taken in Australia, Canada, Georgia and several European countries. The 10,001 samples consisted of EC measurements (35%), PM (42%, of which 8% were submicron and 34% were respirable), CO (6%), NO (3%), and NO_2 (14%).

EC was sampled by size selective sampling (submicron, respiratory or inhalable). Analysis was mostly performed by thermo-optical analysis as described in NIOSH method 5040

(Bakke, et al., 2001; Boffetta, et al., 2002; Burgess, et al., 2007; Cohen, et al., 2002; Davis, et al., 2007; Echt, et al., 1995; Garshick, et al., 2002; Liukonen, et al., 2002; McDonald, et al., 2002; NIOSH, 1993; NIOSH, 1998; NIOSH, 1998; NIOSH, 1998; NIOSH, 2006; Ramachandran, et al., 2005; Roegner, et al., 2002; Seshagiri, 2003; Stanevich, et al., 1997; Verma, et al., 2003; Wheatley, et al., 2004; Whittaker, et al., 1999; Woskie, et al., 2002; Zaebst, et al., 1991), but an alternative thermal technique based on coulometric detection was used by some studies (Adelroth, et al., 2006; Groves, et al., 2000; Leeming, et al., 2004; Lewne, et al., 2007). PM was assessed by size selective sampling (submicron or respiratory) and gravimetric analysis in all studies. CO was assessed by direct reading instruments (Hobbs, et al., 1977; NIOSH, 1994; NIOSH, 2005; NIOSH, 2006; Ulfvarson, et al., 1991; Whittaker, et al., 1999) or detector tubes (passive or active) (Bakke, et al., 2001; NIOSH, 1991; Seshagiri, 2003). NO and NO_2 were assessed mostly by passive diffusion sampling tubes (e.g. Palmes or Draeger) (Adelroth, et al., 2006; Ames, et al., 1982; Bakke, et al., 2001; Gamble, et al., 1978; Gamble, et al., 1987; Lewne, et al., 2006; Lewne, et al., 2007; NIOSH, 1986; NIOSH, 1991; NIOSH, 1991; NIOSH, 1991; NIOSH, 1992; NIOSH, 1993; Reger, et al., 1982), but also by direct reading instruments (Hobbs, et al., 1977; Ulfvarson, et al., 1991; Wheeler, et al., 1980; Whittaker, et al., 1999), and NIOSH method 6014 (NIOSH, 2005; Seshagiri, 2003; Verma, et al., 1999). Methods for EC, CO, and NO/NO_2 were not indicated or unclear in 3 studies ((NIOSH, 1986; Zaebst, et al., 1992), (Attfield, 1978) and (Zaebst, et al., 1992), respectively).

An evaluation of emission standards and environmental and occupational regulations regarding exposure to diesel particulate matter and exhaust gases is beyond the scope of this review. A comprehensive review of worldwide standards is summarized by an internet information service on diesel engine emissions (DieselNet).

On-road vehicles

Currently, almost all heavy duty trucks and buses, and an increasing fraction of medium duty trucks in the US use diesel engines (EPA, 2002). Heavy duty trucks first switched to diesel engines in the 1950s (Steenland, et al., 1990) and sales became predominantly diesel powered in the 1960s and 1970s (EPA, 2002). In the 1990s, the majority of medium duty truck sales and about 30% of light duty truck sales were diesel (EPA, 2002). The switch to diesel engines occurred earlier for large companies than for independent drivers or non-trucking companies (Steenland, et al., 1990). In the US, very few passenger cars or taxis are diesel-fueled, in contrast to about one third of the new passenger cars sales in Europe (Lloyd, et al., 2001).

EC exposure levels for truck, bus, and taxi drivers were generally 1–10 ug/m^3 (Table 1). Reported EC means were generally higher (20–40 μg/m^3) for mechanics in truck terminals, bus garages and stand alone maintenance shops (Table 1). EC levels reported for fire fighters were mostly non-detectable, but one study reported an AM of 40 μg/m^3 (Table 1). For other workers, including bus service workers involved in parking, cleaning and refueling, workers at a vehicle testing station, and parking attendants inside a booth, mean exposure levels of ≦11 μg/m^3 were reported. The other agents were measured less frequently, but showed a similar exposure pattern (Table 1).

Two large industrial hygiene surveys in the trucking industry reported significantly higher levels of EC and PM_R in trucks when windows were open vs closed (1.5 vs 1.3 and 19.9 vs 18.5 μg/m^3, respectively) (Davis, et al., 2007; Zaebst, et al., 1991) and during warm weather vs cold (7.0 vs 2.0 μg/m^3) (Zaebst, et al., 1991). A smaller study reported approximately 2-fold higher levels of EC and $PM_{2.5}$ for local drivers who worked during the day in a large city compared to long haul drivers driving in the evening on suburban and rural highways (AM: 6.7 vs 4.5 and 128.7 vs 56.0 μg/m^3, respectively) (Table 1) (Garshick, et al., 2002). A

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Swedish study also reported significantly higher NO_2 levels for both bus and truck drivers in the city than in a suburban area (0.04 vs 0.03 and 0.04 vs 0.03 ppm, respectively) (Lewne, et al., 2006). In this study, drivers of diesel and petrol powered taxis had similar exposure levels that were significantly lower than bus and truck drivers' exposure levels (0.025–0.027 vs 0.032–0.036 ppm) (Table 1) (Lewne, et al., 2006). This difference was explained by the long waiting periods taxis spent outside traffic intensive areas. Two large studies using identical sampling protocols and analytical methods showed that EC levels for truck drivers in 2001–2005 (Davis, et al., 2007) were about three times lower than in the 1980s (Zaebst, et al., 1991) (Table 1). In addition, the former of these studies reported a significantly positive correlation between EC level and truck age, which was attributed to higher seepage of DE into older truck cabs due to leaks from the cab's rubber seals (Davis, et al., 2007).

Colder weather compared to warmer weather resulted in higher personal EC exposure levels for mechanics (28 vs 4.8 $\mu g/m^3$) (Zaebst, et al., 1991) and statistically significantly higher area EC levels in a bus depot and truck repair shop (19–36 vs 5–6 $\mu g/m^3$) (Sauvain, et al., 2003), both of which were attributed to decreased ventilation. A study modeling exposure in trucking terminals showed that ventilation, terminal size, the number of workers, and general background levels were significant determinants of EC levels in work area air concentrations, and work location (shop higher than dock) was a significant determinant of both area and personal EC levels (levels not provided in the original article) (Davis, et al., 2006). Two studies, performed in the same bus garages in 1956 and 1979 in the U.K., using the same procedures, showed little difference between area levels of smoke from diesel buses entering and leaving the garage (Commins, et al., 1957; Waller, et al., 1985).

A study of three fire stations reported an observable trend in personal total PM exposure of workers inside two fire stations with closed windows with the number of times a truck made a run. This trend was not observed in a third fire station where windows were open (Froines, et al., 1987). Another study of fire fighters' exposure reported a reduction of EC levels by 76–91% after installation of ceramic filters on the tail pipes of fire engines (Roegner, et al., 2002).

Off-road applications

Off-road applications include the use of diesel powered heavy equipment, locomotives, fork-lift trucks, ships, tractors, and generators in the mining, railroad, construction, distribution, farming, and the military. The use of off-road diesel engines became widespread between the 1930s and 1950s (HEI, 2002). Off-road vehicle turnover is low and older engines are generally used longer in off-road than in on-road vehicles. In addition, in the US emission standards for non-road equipment are less stringent(DieselNet).

Mining

Mining operations can be either surface or underground. In surface mining, large excavating equipment is used to remove rock covering the mineral deposit. In underground mines, the mineral deposit is extracted through tunnels and shafts. Diesel powered vehicles may include vehicles for transportation of personnel, haulage trucks, load and dump vehicles, drills, graders, and utility trucks. Mining operations can be classified into coal and metal/nonmetal mines. In the US, diesel engines were first introduced in metal and nonmetal mines in 1939 and in coal mines in 1946 (MSHA, 1998). In the 1970s, the use of diesel engines greatly increased (Haney, et al., 1997; Lachtman, 1983). In 1998, the Mine Safety and Health Administration (MSHA) estimated that 18% of the 971 underground coal mines and 78% of the 261 underground metal/nonmetal mines in the US used diesel engines. Several states in the US ban, or significantly restrict, the use of diesel-powered equipment in underground coal mines. All 1673 surface coal mines and 10474 surface metal/nonmetal mines were estimated by MSHA to use diesel engines in 1998 (MSHA, 1998). In Europe, diesel engines were introduced for haulage in the 1920s and were extensively used by 1936 in both coal and non-coal mines (MSHA, 1998).

Of the 18 studies reporting exposure measurements, seven were performed in nonmetal mines, three in metal mines, seven in coal mines, and three studies did not specify the mine type (Table 2). For EC, PM_R and NO_2, mine types could be compared for a similar time period. No obvious differences in reported levels were observed.

Most studies focused on underground production workers who drilled and blasted at the mine face, loaded and scooped the ore and debris, and hauled the ore and debris to transportation equipment or conveyor belts that further transported it to surface processing areas. Maintenance workers included workers in underground repair shops, warehouse workers, and workers doing infrastructure maintenance located in haulage and travel ways. A comparison between the job categories was possible only for EC and PM_R. Reported EC levels were highest for underground production workers (AM: 148–658 ug/m^3) and lower for underground maintenance workers (AM: 53–144 ug/m^3) and underground unspecified and surface workers (AM: 13–66 ug/m^3) (Table 2). Highest levels for PM_R alsowere reported for underground mining and underground unspecified (AM: 710 – 3637 μg/m^3) and lowest for underground maintenance and surface (AM: 556–881 μg/m^3). A study reporting on specific jobs within underground mining found average EC exposure levels of 345 μg/$m^3$for ram car operators, 222 μg/m^3 for the belt crew, 225 μg/m^3 for continuous miners, 162 μg/m^3 for foremen, and 193 μg/m^3 for miners (Stanevich, et al., 1997). Another study reported that exposure levels to PM_R were similar for mining personnel (90–460 μg/m^3) and supervisors (130–480 μg/m^3) (Ambs, et al.).

The use of disposable DE filters was reported to decrease average area PM_s concentrations at a shuttle car in a coal mine from 1186 to 247 μg/m^3 (Ambs, et al.). In another coal mine, both reusable wire mesh filters and disposable paper filters resulted in lower ram car area PM_S levels than without filters (AM: 1200 vs 2060 μg/m^3 and 240 vs 890 μg/m^3, respectively) (Haney, et al., 1992). In a nonmetal mine, personal and area levels of respirable combustible dust in underground production workers and areas were 24% lower after installation of new oxidation catalytic converters (AM: 320 vs 420 μg/m^3) (Haney, et al., 1997). Increased underground ventilation resulted in 2–4 times lower EC exposure of nonmetal underground production workers compared to levels under the original mine ventilation conditions (Cohen, et al., 2002). Lower EC levels were reported for samples taken inside the closed cab of production equipment compared to outside the cab (AM: 27 vs 233 μg/m^3, respectively) (Leeming, et al., 2004). An Australian study reported higher PM_S levels under extreme load conditions than under normal conditions (400–600 vs 50–400 μg/m^3, respectively) (Pratt, et al., 1997).

Railroad transportation

In the US, diesel engines rapidly replaced steam engines in railroad locomotives between 1945 (10% diesel locomotives) and the 1950s (50% and 95% of engines were diesel in 1952 and 1959, respectively) (Garshick, et al., 1987; Garshick, et al., 2004; Laden, et al., 2006). In the 1960s, a second generation of more efficient diesel locomotives, which were reported to be less smoky, was introduced into many of the larger companies (Woskie, et al., 1988). The typical lifespan of a locomotive has been estimated to be more than 40 years, and many of the smaller railroads still use first generation engines built in the 1940s (EPA, 2002). Currently, a typical freight train crew consists of a conductor and engineer in the leading cab (Liukonen, et al., 2002; Verma, et al., 2003), sometimes supplemented with brakemen/switchmen for local or yard jobs (Liukonen, et al., 2002). In passenger trains, conductors often work in passenger compartments. Prior to the 1980s, tail-end brakemen and firemen also occupied the train (Liukonen, et al., 2002; Verma, et al., 2003; Woskie, et al., 1988). The conductor and tail-end brakeman were situated in the caboose, which was used for monitoring of the train, an office for the conductor, shift breaks, and mobile housing. Use of the caboose was discontinued in the mid-1980s due to the emergence of new technologies and reduction in crew size (Liukonen, et al., 2002). Ventilation systems in repair shops for locomotives have greatly improved since the 1950s (Woskie, et al., 1988).

Exposure to DE has been reported for train crew and for maintenance workers of rolling stock and non-rolling stock. The highest EC levels (AM: 39 $\mu g/m^3$) were reported for maintenance workers in a study that did not measure exposure for other jobs (Groves, et al., 2000) (Table 3). Three studies assessed exposure in both train crew and maintenance workers. Two of these reported higher levels of PM_R for maintenance workers of rolling stock (AM:196 $\mu g/m^3$ and median: 148 $\mu g/m^3$) than for the train crew (AM: 126 $\mu g/m^3$ and median: 111 $\mu g/m^3$, respectively) (Hammond, et al., 1988; Schenker, et al., 1992). The third study reported low levels of EC (AM < 4.6 $\mu g/m^3$) for both job categories (Verma, et al., 2003) and higher NO, but lower NO_2, levels for the train crew compared to maintenance workers of rolling stock (AM: 0.55 vs 0.26 ppm NO and 0.05 vs 0.10 ppm NO_2) (Verma, et al., 1999).

Several studies indicate that the location of the exhaust stack in relation to the cab and air flow from outside the cab are important determinants of DE exposure. One study reported detectable EC levels in the trailing locomotive, but not in the front locomotive (Seshagiri, 2003). In addition, the presence of stacks preceding the cab versus not preceding the cab (GM: 10.1 vs 2.5 $\mu g/m^3$) (Liukonen, et al., 2002) and the configuration of the two locomotives in front of the train (both facing forward vs one facing backward: 4.8 vs 13.5 $\mu g/m^3$) (Seshagiri, 2003) were reported to be significant determinants of in-cab EC levels. Significantly higher in-cab EC levels were also reported when windows were open versus closed (GM: 4.9 vs 2.3 $\mu g/m^3$) (Liukonen, et al., 2002) and during summer compared to winter (17.1 vs 2.9 $\mu g/m^3$) (Seshagiri, 2003). Higher exposure levels to PM_R, adjusted for cigarette smoke, were reported in the summer compared to winter for yard and passenger engineers/firers and passenger brakemen/conductors, but lower levels were reported for freight engineers/firers, hostlers moving trains in and out of repair shops, and freight and yard brakemen/conductors. In this study, overall, season was a significant determinant (Woskie, et al., 1988). Other determinants were also investigated in this study. PM_R levels unadjusted for smoking were higher for brakemen/conductors than for firers/engineers (AM: 112–233 vs 74–122 $\mu g/m^3$) (Hammond, et al., 1988). Among brakemen/conductors, the highest PM_R levels were reported for yard brakemen/conductors and hostlers compared to passenger and freight brakemen/conductors (AM: 192–233 vs 112–128 $\mu g/m^3$), which was attributed to the greater amount of time the former workers spent outdoors near operating trains. Company also significantly affected adjusted PM_R exposure levels, possibly due to differences in the facility, equipment, maintenance procedures, and fuel (Hammond, et al., 1988; Woskie, et al., 1988). In another study, levels during two 20–30 minute trips in tunnels were 7–110 ppm for CO and 39–70 ppm for NO compared to average 8-hour levels of <1.0 for CO and 0.11–0.34 ppm for NO during freight operations (Hobbs, et al., 1977).

For repair shop workers, higher personal PM_R levels were reported for cold compared to warm weather conditions (AM: 231–254 vs 118–127 $\mu g/m^3$) (Hammond, et al., 1988). In addition, area levels of visible smoke, the number of detectable NO_2 samples, and peak CO levels were higher in a roundhouse when the doors were shut than when they were open (Madl, et al., 2002).

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Other off-road uses

Several studies have assessed DE exposure among construction workers. EC levels were higher for underground construction, i.e. tunnels, than for above ground construction (AM: 132–314 vs 4–13 μg/m^3) (Table 4). A Swedish study that assessed exposure levels in both types of construction sites reported significantly higher levels in underground locations for all measured agents (AM: 132 vs 13 μg/m^3 for EC, 121 vs 34 μg/m^3 for PM_S and 0.22 vs 0.02 ppm for NO_2) (Table 4) (Lewne, et al., 2007). A study in the US reported significantly higher EC exposure levels during tunnel construction phases of a large highway construction project for enclosed versus non-enclosed construction sites (AM: 41 vs 24 μg/m^3) (Blute, et al., 1999). Other significant determinants of EC exposure were the type of diesel powered machine (crane > generator > lift > earth mover), the distance from the diesel source (less than 10 ft > 10–20 ft > more than 20 ft), and the number of other diesel sources (2 and more > less than 2) (Blute, et al., 1999) (levels not shown in original article). The highest EC levels in this study of mostly above ground heavy and highway construction sites were found during the installation of drop ceiling and wall tiles, concrete pouring, concrete finish work, laying of conduit/pipe in trenches, and excavation work (Woskie, et al., 2002).

Another major off-road use of diesel engines is fork-lift trucks, which may also be powered by propane, gasoline, or electricity. Before 1980, almost all fork-lift trucks used in truck docks were propane or gasoline powered (Zaebst, et al., 1991). Average reported EC levels for dockworkers in the vicinity of diesel powered fork-lifts, including fork-lift truck operators, were generally between 4 and 36 μg/m^3, except for one study reporting 122 μg/m^3 (Table 4). Significantly lower EC exposure levels in dockworkers were reported when exhaust filters were used compared to no filters (GM: 2 vs 24 μg/m^3), and significantly lower NO_2 levels were reported when an overhead fan was used in the dock compared to no forced ventilation (GM: 0.14 vs 0.21 ppm) (Zaebst, et al., 1992). Another source of DE at docks may be on-road trucks, which back up against the docks for loading and unloading. EC levels reported for docks in which only non-diesel powered fork-lift trucks were used, resulting presumably primarily from on-road trucks, were low (0.9–4.2 μg/m^3) (NIOSH, 1993; Zaebst, et al., 1992) compared to the levels shown in Table 4.

Exposure to DE has been assessed for airline baggage screening workers using tugs that may be diesel powered and for mechanics involved in maintenance of equipment and trucks used for refueling of aircraft (AM: 11 μg/m^3 EC) (NIOSH, 1994; NIOSH, 2005). Two studies investigated DE exposure in ship docks. One study reported a mean EC exposure level of 49 μg/m^3 for workers using diesel powered tugs and container lorries for loading and unloading freight from a ferry that was ventilated by opening the bow and stern doors (Groves, et al., 2000). The second study in marine terminals reported an average EC exposure level of 5.7 μg/m^3, which ranged from 2.5 μg/m^3 for crane operators to 12 μg/m^3 for shop workers (NIOSH, 2006).

Discussion

Several advisory or regulatory authorities in North America and Europe, including IARC, NIOSH, MSHA, the Health Effects Institute, and the US Environmental Protection Agency (EPA), have concluded that sufficient evidence exists that exposure to DE causes an increased risk of cancer (Rogers, et al., 2005). These evaluations were based on sufficient toxicological animal studies and limited evidence from almost 50 occupational epidemiologic studies. Among other limitations, the lack of quantitative exposure assessment has consistently been cited as a fundamental problem in determining causality from the existing epidemiological studies (Rogers, et al., 2005). The purpose of this review was to provide a comprehensive overview of quantitative occupational exposure levels to

DE that will allow for more accurate and consistent occupational exposure assessments in population-based epidemiologic studies.

For EC, the highest exposure levels were reported for underground mining (27–658 μg/m^3), tunnel construction (132–314 μg/m^3), and underground mine maintenance workers (53–144 μg/m^3). For maintenance workers of on-road and railroad equipment, distribution workers, fire fighters, and ship dock workers, exposure levels generally ranged from ND to 50 μg/m^3. Relatively low levels were reported for drivers of on-road vehicles, train crews, above ground mining, parking attendants, vehicle testers, utility service workers, above ground construction, and airline ground personnel (<25 μg/m^3). For airline personnel, jet exhaust may be another source of EC and more research is needed to investigate its contribution (Schauer, 2003). EC is currently the preferred surrogate for DE in industries other than coal mines (Leeming, et al., 2004), since it is relative simple to measure, has few chemical interferences and is the major component of diesel particulate matter (Groves, et al., 2000; Schauer, 2003).

There was little information available on PM_S to compare with the EC levels. Exposure levels of miners and underground construction workers were highest (154–1600 and 121 μg/m^3, respectively), followed by mechanics, above ground construction workers, and taxi drivers (10–35 μg/m^3). PM_S has only a few interferences from non-diesel sources, i.e. oil mist and cigarette smoke (Hammond, et al., 1988). PM_R is a less suitable surrogate for DE since it is generated from more non-diesel sources, i.e. oil and grease mists, cigarette smoke, emissions from other combustion sources, and respirable inorganic matter such as mechanically aerosolized geological and fibrous materials (Hammond, et al., 1988). These non-diesel sources are a likely explanation for the reported PM_R levels that were substantially higher than PM_S levels in all situations. Nonetheless, for PM_R, the highest levels also were reported for workers in underground mining and underground construction (710–3637 and 1160–1700, respectively).

For the gases, the highest mean levels generally were reported for workers in underground mining and underground construction. Similar to PM, the pattern of the gases among industries was generally consistent with the EC levels. However, relatively high mean concentrations for some of the gases also were reported in situations where reported EC levels were low, e.g. for DE exposed airline personnel, train crews, and utility service workers. These higher levels are likely the result of emissions from other combustion sources.

The results of this review suggest that enclosure of the work site and the type of diesel equipment used are the most important determinants affecting occupational DE exposure. Highest levels were found in underground mining, maintenance, and construction, where heavy equipment is used in enclosed underground work sites. Situations for which intermediate exposure levels were reported mostly involved smaller equipment, probably run intermittently, in above ground (semi-)enclosed areas that were more easily ventilated by natural or mechanical ventilation, i.e. mechanics in a shop, emergency workers in fire stations, distribution workers at a dock, and workers loading/unloading vehicles inside a ferry. Determinants that have been repeatedly reported for both above and underground (semi-)enclosed situations were ventilation (Cohen, et al., 2002; Davis, et al., 2006; Hammond, et al., 1988; Madl, et al., 2002; Sauvain, et al., 2003; Zaebst, et al., 1992; Zaebst, et al., 1991) and the use of exhaust after treatment devices (Ambs, et al., ; Haney, et al., 1992; Haney, et al., 1997; Roegner, et al., 2002; Zaebst, et al., 1992). Lowest levels were found for workers in enclosed areas separated from the source or for workers who were outside. Airflow from outside the train or truck cab was reported to result in higher exposure levels for train crew and on-road drivers than exposure levels within a closed cab (Davis, et al., 2007; Liukonen, et al., 2002; Seshagiri, 2003; Zaebst, et al., 1991), suggesting that DE exposure in these situations occurs mostly via the outdoor air. The railroad studies indicated that the exposure is derived from preceding stacks of the same train (Liukonen, et al., 2002; Seshagiri, 2003). For drivers of on-road vehicles, higher levels were reported for inner city drivers than for drivers in rural or suburban areas, suggesting that emissions from other vehicles are probably responsible for most of the exposure (Garshick, et al., 2002; Lewne, et al., 2006).

Assessing occupational exposures in epidemiological studies in the general population is challenging. For chronic diseases such as cancer, the relevant exposure periods are usually decades ago, and exposure measurements for the relevant exposure period are often not available. In addition, exposures can vary widely depending on individual work environments. Thus, the availability of a comprehensive database of historical quantitative exposure levels including determinants of exposure is likely to result in a more accurate and consistent exposure assessment than when the assessment is based only on expert judgment.

However, there are some limitations to this approach. Because DE is a complex mixture of compounds, several agents were selected, complicating comparison across studies focusing on different agents. In addition, the composition of DE varies with engine technology, fuel type, operating conditions, and the presence of emission control systems, which have all changed over time (EPA, 2002; Lloyd, et al., 2001). PM_R and the gases were selected to investigate time trends, since the more specific surrogates of DE, such as EC, were not developed until the 1990s. Recently, more advanced chemical techniques are being developed. However, these are not yet suitable for application in epidemiological and exposure studies because of the extensive number of samples and low air volume of the samples typical in these studies (Schauer, 2003). Regulation of emissions has decreased emission levels (Bunn, et al., 2002; Laden, et al., 2006), yet the use of diesel engines has increased. However, not enough exposure data were available to assess the effect of these changes. Consequently, the incorporation of time trends in exposure assessment will be problematic. Another limitation of the complex composition of DE, is that the relevant toxic agent, which varies by health effect (Scheepers, et al., 1992), may not be proportional to the chosen agent of study.

A further limitation of using published literature is the extraction and interpretation of exposure information from reports written by different authors for different purposes. The description of the measured jobs, the number of measurements, the duration of the measurements, and the exposure conditions was often unclear or absent. In addition, published reports may have been biased towards worst case scenarios and may not represent what is typical for the industry with regard to both the types of jobs reported and the concentrations measured. Finally, measurements on other industrial uses, such as farming and the military, have not been reported.

In spite of these limitations, contrast in exposure levels was found when comparing different jobs and industries, and several determinants of exposure have been identified. The data described in this study can be used to assess exposure levels based on job and industry title and certain exposure characteristics in population-based epidemiologic studies. Furthermore, these data can guide future exposure assessment efforts as well as the selection of study populations for future epidemiologic studies.

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Table 1

Occupational exposure measurements to diesel exhaust from on-road vehicles: elemental carbon (EC, μg/m^3), submicron and respiratory particulate matter (PM_S and PM_R, μg/m^3), and CO, NO and NO_2 (ppm)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Reference
Drivers								
Truck – local	EC_S	>4	56	5 (0.9)	0.9 (4.0)	US	1980s	(Zaebst, et al., 1991)
Truck – local	EC_S	>4	576 (a)	2 (2.3)	1 (2.8)	US	2001–2005	(Davis, et al., 2007)
Truck – local	EC_R	>4	5	7^e	6 (1.6)	US	1999	(Garshick, et al., 2002)
Truck – local	EC_{NI}	>4	4 (a)	5 (0.1)	5 (1.0)	US	1985	(NIOSH, 1986)
Truck - long haul	EC_S	>4	72	5 (0.4)	0.4 (3.8)	US	1980s	(Zaebst, et al., 1991)
Truck - long haul	EC_S	>4	349 (a)	1 (0.8)	1 (2.3)	US	2001–2005	(Davis, et al., 2007)
Truck - long haul	EC_R	>4	5	5^e	4 (2.0)	US	1999	(Garshick, et al., 2002)
Truck - long haul	EC_{NI}	>4	4 (a)	22 (13.2)	19 (2.0)	US	1985	(NIOSH, 1986)
Truck	EC_I	1->4	3	10 (6.0)	9 (1.8)	US	1992	(NIOSH, 1993)
Bus	EC_R	>4	5	10^e	9 (1.3)	Estonia	2002 (p)	(Boffetta, et al., 2002)
Bus	EC_R	>4	39	2.0 (1.3)	1.4 (3.3)	US	2002 (p)	(Ramachandran, et al., 2005)
Bus	EC_I	>4	4	2>LOD: 11–20		US	1998	(NIOSH, 1998)
Bus and truck$^{\infty}$	EC_I	>4	20	11^e	6 (2.9)	Sweden	2002–2004	(Lewne, et al., 2007)
Taxi$^{\infty}$	EC_I	>4	8	8^e	7 (1.6)	Sweden	2002–2004	(Lewne, et al., 2007)
Mechanics								
Truck	EC_S	>4	80	27 (4.1)	4 (12.1)	US	1980s	(Zaebst, et al., 1991)
Truck	EC_R	>4	10	4^e	4 (1.6)	US	1999	(Garshick, et al., 2002)
Ambulance depot	EC_R	>4	3	31	29 (1.6)	UK	2000(p)	(Groves, et al., 2000)
Bus	EC_R	>4	53	39	31 (2.1)	UK	2000(p)	(Groves, et al., 2000)
Bus	EC_R	>4	15	39^e	38 (1.3)	Estonia	2002 (p)	(Boffetta, et al., 2002)
Truck/bus (+inspection)	EC_I	>4	40	21^e	11 (3.2)	Sweden	2002–2004	(Lewne, et al., 2007)
Bus	EC_I	>4	4	ND	ND	US	1998	(NIOSH, 1998)
Others								
Firefighter	EC_I	>4	27	24 (max)		US	2002(p)	(Roegner, et al., 2002)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Reference
Firefighter	EC_I	>4	18	40 (20.3)	35 (1.7)	US	1995(p)	(Echt, et al., 1995)
Firefighter	EC_I	>4	12	10 (max)		US	1997	(NIOSH, 1998)
Firefighter	EC_I	<1	8	ND	ND	US	1998	(NIOSH, 1998)
Service worker bus	EC_I	>4	4	2>LOD: 0.3–15		US	1998	(NIOSH, 1998)
Vehicle testing	EC_R	>4	11	11	11 (1.8)	UK	2000(p)	(Groves, et al., 2000)
Parking attendant (booth)	EC_R	>4	34 (a)	1.1 (0.6)	1.1 (1.8)	US	2002 (p)	(Ramachandran, et al., 2005)
Drivers								
Taxi $^{\infty}$	PM_S	>4	8	12^e	11 (1.3)	Sweden	2002–2004	(Lewne, et al., 2007)
Bus and truck $^{\infty}$	PM_S	>4	20	15^e	14 (1.6)	Sweden	2002–2004	(Lewne, et al., 2007)
Truck – local	PM_R	>4	5	129^e	120 (1.5)	US	1999	(Garshick, et al., 2002)
Truck – local	PM_R	>4	545 (a)	28 (39)	20 (2.1)	US	2001–2005	(Davis, et al., 2007)
Truck - long haul	PM_R	>4	4	56^e	55 (1.2)	US	1999	(Garshick, et al., 2002)
Truck - long haul	PM_R	>4	334 (a)	53 (328)	23 (2.5)	US	2001–2005	(Davis, et al., 2007)
Bus	PM_R	>4	5	600^e	580 (1.5)	Estonia	2002 (p)	(Boffetta, et al., 2002)
Mechanics								
Truck/bus (+inspection)	PM_S	>4	40	28^e	23 (1.9)	Sweden	2002–2004	(Lewne, et al., 2007)
Truck	PM_R	>4	10	203^e	152 (2.1)	US	1999	(Garshick, et al., 2002)
Bus	PM_R	>4	15	1100^e	1020 (1.6)	Estonia	2002 (p)	(Boffetta, et al., 2002)
Bus	PM_R	NI	232	240 (260)		US	1987 (p)	(Gamble, et al., 1987)
Bus	PM_R	>4	41	267	224 (1.8)	UK	2000(p)	(Groves, et al., 2000)
Ambulance depot	PM_R	>4	3	127	118 (1.6)	UK	2000(p)	(Groves, et al., 2000)
Others								
Vehicle testing	PM_R	>4	10	156	149 (1.4)	UK	2000(p)	(Groves, et al., 2000)
Driver								
Truck – local	NO	>4	4 (a)	0.23 (0.05)	0.22 (1.3)	US	1985	(NIOSH, 1986)
Truck - long haul	NO	>4	4 (a)	0.27 (0.10)	0.25 (1.5)	US	1985	(NIOSH, 1986)
Driver								

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Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Reference
Taxi[∞]	NO_2	>4	12	0.03[e]	0.02 (0.7)	Sweden	2002–2004	(Lewne, et al., 2007)
Bus and truck[∞]	NO_2	>4	30	0.03[e]	0.03 (0.7)	Sweden	2002–2004	(Lewne, et al., 2007)
Truck	NO_2	>4	40	0.04 (0.02)		Sweden	1997–1999	(Lewne, et al., 2006)
Taxi	NO_2	>4	20	0.03 (0.01)		Sweden	1997–1999	(Lewne, et al., 2006)
Bus	NO_2	>4	42	0.03 (0.01)		Sweden	1997–1999	(Lewne, et al., 2006)
Mechanics								
Truck/bus (+inspection)	NO_2	>4	60	0.05[e]	0.05 (0.9)	Sweden	2002–2004	(Lewne, et al., 2007)
Bus	NO_2	NI	232	0.24 (0.26)		US	1987 (p)	(Gamble, et al., 1987)

S = submicron, R = respirable, I =inhalable; NI: not indicated; (a): area sample representative of personal exposure;

[e] AM estimated from GM and GSD or from range; (p): publication year, sampling year not available;

[∞] Mostly diesel powered vehicles

Table 2

Occupational exposure measurements of diesel exhaust in the mining industry: elemental carbon (EC, μg/m^3), submicron and respiratory particulate matter (PM_S and PM_R, μg/m^3), and CO, NO and NO_2 (ppm)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Ref
Underground								
Production (NM/NI)	EC_S	1->4	13	163 (141)	84 (4.3)	US	2001–2002	
Production (NM)	EC_R	NI	6 (a)	148 (136)	85 (3.5)	UK	2004(p)	(Leeming, et al., 2004)
Production (NM)	EC_R	>4	343	202 (32–144)	111 (1.4–4.8)	US	2002(p)	(Cohen, et al., 2002)
Production (NM)	EC_S	>4	38	219 (65–193)		US	1997(p)	(Stanevich, et al., 1997)
Production (C)	EC_R	>4	4	241[e]	202 (1.8)	Estonia	2002 (p)	(Boffetta, et al., 2002)
Production (M)	EC_R	>4	15	637 (75–508)		US	1999	(McDonald, et al., 2002)
Production (NI)	EC_I	<1–4	12	538 (512)		US	2007 (p)	(Burgess, et al., 2007)
Maintenance (NM)	EC_S	>4	8	53 (46)		US	1997(p)	(Stanevich, et al., 1997)
Maintenance (NM)	EC_R	>4	269	144 (17–462)	66 (1.7–4.6)	US	2002(p)	(Cohen, et al., 2002)
Mining, NS (C)	EC_R	NI	7 (a)	66 (28)	62 (1.5)	UK	2004(p)	(Leeming, et al., 2004)
Mining, NS (M)	EC_{NI}	NI	27	27		Sweden	2006 (p)	(Adelroth, et al., 2006)
Surface								
Prod./Maint. (NM)	EC_R	>4	164	13 (2–89)	2 (1.8–6.2)	US	2002(p)	(Cohen, et al., 2002)
Prod./Maint. (NM)	EC_S	>4	23	23 (15–54)		US	1997(p)	(Stanevich, et al., 1997)
Underground								
Production (NM)	PM_S	>4	7	154 (68)	142 (1.6)	US	1991	(NIOSH, 1991)
Production (NM)	PM_S	>4	8	651 (356)	578 (1.7)	US	1991	(NIOSH, 1993)
Production (C)	PM_S	>4	337	186[e]		Australia	1990–1994	(Pratt, et al., 1997)
Production (C)	PM_S	>4	30 (a)	714 (120–410)		US	1991 (p)	(Cantrell, et al., 1991)
Production (C)	PM_S	>4	24 (a)	635 (110–270)		US	1992 (p)	(Watts, et al., 1992)
Production (C)	PM_S	>4	181 (a)	620 (20–480)		US	NI	(Ambs, et al.)
Production (C)	PM_S	>4	≥ 5 (a)	582		US	1992(p)	(Haney, 1992)
Production (C)	PM_S	>4	16 (a)	1012 (753)	699 (2.7)	US	1992p	(Haney, et al., 1992)
Mining, NS (M)	PM_S	>4	30 (a)	1600 (1020)		US	1988	(NIOSH, 1992)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Ref
Mining, NS (M)	PM_S	>4	14	389 (264)		US	1988	(NIOSH, 1991)
Underground								
Production (NM)	PM_R	>4	305	2128 (130–2510)	1610	Germany	1999–2003	(Dahmann, et al., 2007)
Production (M/NM)	PM_R	>4	≥ 5 (a)	847		US	1992(P)	(Haney, 1992)
Production (M)	PM_R	>4	15	1941 (452–1839)		US	1999	(McDonald, et al., 2002)
Production (C)	PM_R	>4	2	3437[e]	3300 (1.3)	Estonia	2002 (p)	(Boffetta, et al., 2002)
Production (C)	PM_R	>4	20	1379[e]	1249 (1.4–1.7)	Czech R.	1999–2000	(Scheepers, et al., 2003)
Production (C)	PM_R	>4	≥ 5 (a)	1629		US	1992(p)	(Haney, 1992)
Production (C)	PM_R	>4	16	1453[e]	940 (1.7–2.5)	US	1976–1980	(Wheeler, et al., 1980)
Maintenance (NM)	PM_R	>4	107	556 (40–830)	364	Germany	1999–2003	(Dahmann, et al., 2007)
Mining, NS (NM)	PM_R	NI	180	710 (710)		US	1978 (p)	(Gamble, et al., 1978)
Mining, NS (NM)	PM_R	NI	≥5	3637		US	1976–1977	(Attfield, 1978)
Mining, NS (M)	PM_R	NI	≥5	940		US	1976–1977	(Attfield, 1978)
Mining, NS (C)	PM_R	>4	78	1483 (870–1720)		US	1982 (p)	(Reger, et al., 1982)
Mining, NS (C)	PM_R	>4	60	2000 (1700)		US	1982 (p)	(Ames, et al., 1982)
Surface								
Prod./Maint. (C)	PM_R	>4	68	881[e]	651 (1.6–2.3)	Czech R.	1999–2000	(Scheepers, et al., 2003)
Underground								
Production (NM)	CO	1–>4	5	2.0 (0.6)	1.9 (1.4)	US	1991	(NIOSH, 1991)
Mining, NS (NM)	CO	NI	≥ 5 (a)	8.9		US	1976–1977	(Attfield, 1978)
Mining, NS (M)	CO	NI	≥ 5 (a)	6.1		US	1976–1977	(Attfield, 1978)
Underground								
Production (NM)	NO	>4	9	14.7 (2.8)	14.5 (1.2)	US	1991	(NIOSH, 1991)
Production (NM)	NO	>4	7	4.2 (1.7)	3.9 (1.5)	US	1991	(NIOSH, 1991)
Production (NM)	NO	>4	6	4.7 (1.0)	4.6 (1.2)	US	1991	(NIOSH, 1993)
Mining, NS (M)	NO	>4	54 (a)	11.0 (5.7)		US	1988	(NIOSH, 1992)
Mining, NS (M)	NO	>4	25	0.7 (0.6)		US	1988	(NIOSH, 1991; NIOSH, 1992)
Surface								
Prod./Maint. (M)	NO	>4	12	0.3 (0.2)		US	1988	(NIOSH, 1992)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Ref
Underground								
Production (NM)	NO_2	>4	9	2.9 (0.5)	2.9 (1.2)	US	1991	(NIOSH, 1991)
Production (NM)	NO_2	>4	7	0.8 (0.4)	0.7 (1.6)	US	1991	(NIOSH, 1991)
Production (NM)	NO_2	>4	6	0.7 (0.1)	0.7 (1.1)	US	1991	(NIOSH, 1993)
Production (NM)	NO_2	NI	183	1.9 (1.6)		US	1978 (p)	(Gamble, et al., 1978)
Production (C)	NO_2	>4	41	0.2[e]	0.1 (1.5–2.8)	US	1976–1980	(Wheeler, et al., 1980)
Production (C)	NO_2	>4	76	0.2 (0.1 –0.1)		US	1982 (p)	(Reger, et al., 1982)
Production (M)	NO_2	NI	29	0.2		Sweden	2006 (p)	(Adelroth, et al., 2006)
Production (M)	NO_2	>4	54 (a)	1.5 (0.9)		US	1988	(NIOSH, 1992)
Production (M)	NO_2	>4	25	5.5 (3.9)		US	1988	(NIOSH, 1991)
Mining, NS (C)	NO_2	>4	60	0.2 (0.1)		US	1982 (p)	(Ames, et al., 1982)
Surface								
Prod./Maint. (M)	NO_2	>4	12	0.04 (0.03)		US	1988	(NIOSH, 1992)

S = submicron, R = respirable, I =inhalable; NI: not indicated; NS, job not specified; NM: nonmetal, M: metal, C: coal; (a): area sample representative of personal exposure; ≥ 5 : at least 5 samples for all jobs combined in the study;

[e]AM estimated from GM and GSD or from range; (p): publication year, sampling year not available

Table 3

Occupational exposure measurements of diesel exhaust in the railroad industry: elemental carbon (EC, μg/m^3), submicron and respiratory particulate matter (PM_S and PM_R, μg/m^3), and CO, NO and NO_2 (ppm)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Ref
Train crew								
Driver, assistant, shunter driver	EC_R	>4	19	20 (18.7)	16 (2.0)	Russia	2002 (p)	(Boffetta, et al., 2002)
Hostler	$EC_{R/I}$	>4	5	4 (1.3)	3 (1.5)	Canada	1999–2000	(Verma, et al., 2003)
Engineer/driver, conductor/trainmen	$EC_{R/I}$	>4	76 (a)	5 (1.1–15.8)	3 (1.5–3.5)	Canada	1999–2000	(Verma, et al., 2003)
Nonoperating crew trailing locomotive	EC_I	>4	47 (a)	10 (12)	6	Canada	2003	(Seshagiri, 2003)
Engineer's operating console	EC_I	1–> 4	49 (a)	6	4 (3)	US	1996–1998	(Liukonen, et al., 2002)
Maintenance								
Rolling equipment	$EC_{R/I}$	>4	48	5 (4.9–8.8)	3 (2.4–2.7)	Canada	1999–2000	(Verma, et al., 2003)
Rolling equipment	EC_R	>4	64	39	17 (1.9)	UK	2000(p)	(Groves, et al., 2000)
Train crew								
Driver, assistant, shunter driver	PM_R	>4	17	858 (354)	797 (1.5)	Russia	2002 (p)	(Boffetta, et al., 2002)
Engineer, brakeman	PM_R	>4	47	111 (p50)		US	1992 (p)	(Schenker, et al., 1992)
Engineer, firer, conductor, brakeman, hostler	PM_R	NI	206	126		US	1981–1983	(Hammond, et al., 1988)
Maintenance								
Rolling equipment	PM_R	>4	55	250	203 (1.9)	UK	2000(p)	(Groves, et al., 2000)
Rolling equipment	PM_R	>4	191	148 (p50)		US	1992 (p)	(Schenker, et al., 1992)
Rolling equipment	PM_R	>4	120	196		US	1981–1983	(Hammond, et al., 1988)
Non rolling equipment	PM_R	>4	14	71		US	1981–1983	(Hammond, et al., 1988)
Train crew								
Nonoperating crew trailing locomotive	CO	>4	280 (a)	4.50 (max)		Canada	2003	(Seshagiri, 2003)
Locomotive and caboose	CO	>4	16 (a)	<1		US	1974–1976	(Hobbs, et al., 1977)
Train crew								
Nonoperating crew trailing locomotive	NO	>4	46 (a)	1.13 (0.87)	0.82	Canada	2003	(Seshagiri, 2003)
Locomotive	NO	>4	9 (a)	0.55		Canada	1996	(Verma, et al., 1999)
Locomotive/caboose	NO	>4	16 (a)	0.23		US	1974–1976	(Hobbs, et al., 1977)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Ref
Maintenance								
Rolling equipment	NO	>4	18	0.26		Canada	1996	(Verma, et al., 1999)
Train crew								
Nonoperating crew trailing locomotive	NO_2	>4	181 (a)	0.3 (max)		Canada	2003	(Seshagiri, 2003)
Locomotive on board	NO_2	>4	9 (a)	0.05		Canada	1996	(Verma, et al., 1999)
Locomotive and caboose	NO_2	>4	16 (a)	0.03		US	1974–1976	(Hobbs, et al., 1977)
Maintenance								
Rolling equipment	NO_2	>4	18	0.10		Canada	1996	(Verma, et al., 1999)

S = submicron, R = respirable, I =inhalable; NI: not indicated; (a): area sample representative of personal exposure; (p): publication year, sampling year not available;

‡Only results from trailing locomotive, no detectable samples in leading locomotive

Table 4

Occupational exposure measurements of diesel exhaust from other off-road vehicles: elemental carbon (EC, μg/m^3), submicron and respiratory particulate matter (PM_S and PM_R, μg/m^3), and CO, NO and NO_2 (ppm)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Ref
Construction								
Tunnel	EC_I	>4	10	314^e	163 (1.5–3.0)	Norway	1996–1999	(Bakke, et al., 2001)
Tunnel	EC_I	>4	12	132^e	87 (2.5)	Sweden	2002–2004	(Lewne, et al., 2007)
Heavy/highway	EC_R	>4	261	13	8 (2.7)	US	1994–1999	(Woskie, et al., 2002)
Above ground	EC_I	>4	22	13^e	8 (2.8)	Sweden	2002–2004	(Lewne, et al., 2007)
Electric utility installation	EC_I	>4	120	4		US	1996–1997	(Whittaker, et al., 1999)
Tunnel	PM_S	>4	12	121^e	119 (1.2)	Sweden	2002–2004	(Lewne, et al., 2007)
Above ground	PM_S	>4	22	34^e	28 (1.9)	Sweden	2002–2004	(Lewne, et al., 2007)
Tunnel	PM_R	>4	40	1160 (361)		Sweden	1991 (p)	(Ulfvarson, et al., 1991)
Tunnel	PM_R	>4	336	1700^e	1100 (1.4–2.4)	Norway	1996–1999	(Bakke, et al., 2001)
Heavy/highway	PM_R	>4	260	766	254 (2.5–4.2)	US	1994–1999	(Woskie, et al., 2002)
Tunnel	CO	>4	78	9^e	5.7 (1.5–2.6)	Norway	1996-1999	(Bakke, et al., 2001)
Tunnel	CO	>4	52	5 (3.7)		Sweden	1991 (p)	(Ulfvarson, et al., 1991)
Electric utility installation	CO	>4	27	1 (0.6–0.6)		US	1996–1997	(Whittaker, et al., 1999)
Tunnel	NO	>4	53	2.6 (1.5)		Sweden	1991 (p)	(Ulfvarson, et al., 1991)
Electric utility installation	NO	>4	27	0.2 (0.2–0.4)		US	1996–1997	(Whittaker, et al., 1999)
Tunnel	NO_2	>4	18	0.22^e	0.19 (0.58)	Sweden	2002–2004	(Lewne, et al., 2007)
Tunnel	NO_2	>4	82	0.86^e	0.54 (1.5–4.5)	Norway	1996–1999	(Bakke, et al., 2001)
Tunnel	NO_2	>4	53	0.88 (0.68)		Sweden	1991 (p)	(Ulfvarson, et al., 1991)
Above ground	NO_2	>4	33	0.02^e	0.02 (1.06)	Sweden	2002–2004	(Lewne, et al., 2007)
Electric utility (outside)	NO_2	>4	24	0.32 (0.2–0.2)		US	1996–1997	(Whittaker, et al., 1999)
Dock/distribution								
Dockworkers	EC_S	>4	54	24 (0.4–2.5)	2 (1.3–27.2)	US	1991(p)	(Zaebst, et al., 1991)

Description	Agent	Duration	n	AM (SD)	GM (GSD)	Location	Year	Ref
Dockworkers	EC_S	>4	≥5	#	7	US	1990	(Zaebst, et al., 1992)
Fork-lift truck	EC_R	>4	39(a)	36[e]	27	UK	2004(p)	(Wheatley, et al., 2004)
Dockworkers	EC_R	>4	27	122	66 (3.3)	UK	2000(p)	(Groves, et al., 2000)
Dockworkers	EC_R	>4	12	9[e]	7 (2)	Georgia	1999	(Garshick, et al., 2002)
Dockworkers	EC_I	>4	5	4 (1.8)	4 (1.5)	Georgia	1992	(NIOSH, 1993)
Fork-lift truck	PM_R	>4	39(a)	#	106	UK	2004(p)	(Wheatley, et al., 2004)
Dockworkers	PM_R	>4	11	359[e]	276 (2.1)	Georgia	1999	(Garshick, et al., 2002)
Dockworkers	PM_R	>4	25	442	380 (369)	UK	2000(p)	(Groves, et al., 2000)
Dockworkers	NO_2	>4	≥5	#	0.18	US	1990	(Zaebst, et al., 1992)
Airline personnel								
Baggage and screening	EC_I	>4	72	11 (5.4)		US	2004	(NIOSH, 2005)
Baggage and screening	CO	>4	61	2.4[e]		US	2004	(NIOSH, 2005)
Mechanics and refuelers	CO	>4	10	5 (1.5)	4.7 (1.3)	US	1992	(NIOSH, 1994)
Baggage and screening	NO	>4	40	0.13 (0.07)		US	2004	(NIOSH, 2005)
Baggage and screening	NO_2	>4	40	0.12 (0.07)		US	2004	(NIOSH, 2005)
Loading/unloading ship								
Marine terminal	EC_I	>4	168	6 (0.9–9.0)		US	2003–2005	(NIOSH, 2006)
Ferry	EC_R	>4	20	49	37 (2.5)	UK	2000(p)	(Groves, et al., 2000)
Ferry	PM_R	>4	16	295	198 (2.7)	UK	2000(p)	(Groves, et al., 2000)
Marine terminal	CO	>4	60	2.5		US	2003–2005	(NIOSH, 2006)

S = submicron, R = respirable, I =inhalable; NI: not indicated; (a): area sample representative of personal exposure; ≥ 5 : at least 5 samples for all jobs combined in the study;

[e] AM estimated from GM and GSD or from range; (p): publication year, sampling year not available,

[#] AM could not be calculated