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Exposure of Trucking Company Workers to Particulate Matter during the Winter

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Abstract

This study analyzed the workplace area concentrations and the personal exposure concentrations to fine particulate (PM_{2.5}), elemental carbon (EC), and organic carbon (OC) measured during the winter period in trucking companies. The averaged personal exposure concentrations at breathing zones of workers are much greater than those of the microenvironment concentrations. The highest difference between the area (microenvironment) and personal exposure concentrations was in the PM_{2.5} concentrations followed by the OC concentrations. The area concentrations of PM_{2.5}, EC, and OC at a large terminal were higher than those at a small one. The highest area concentrations of PM_{2.5}, EC, and OC were observed in the shop areas followed by pick-up and delivery (P&D) areas. The area concentrations and personal exposure to PM_{2.5}, EC, and OC in the shop and P&D areas which are highly affected by diesel engine exhaust emissions were much higher than those in the docks which are significantly affected by liquefied petroleum gas (LPG) engine exhaust emissions. The highest EC fraction to the total carbon (EC + OC) concentrations was observed in the shops, while the lowest one was identified in the offices. The personal exposure of the smoking workers to PM_{2.5} and OC was much higher than that of the non-smoking workers. However, the smoking might not significantly contribute to the personal exposure to EC. There were significant correlations between the PM_{2.5} and OC concentrations in both the area and personal exposure concentrations. However, significant correlations between the PM_{2.5} and EC concentrations and between the OC and EC concentrations were not identified.

Keywords

Diesel; Particulate; PM_{2.5}; Elemental and organic carbon; Exposure

1. Introduction

Many studies suggest that fine particulate matter (PM_{2.5}) which has a size less than 2.5 µm in aerodynamic diameter could lead to increase of adverse health effects such as respiratory disease and mortality (Greenwell et al., 2002; Ormstad, 2000; Abbey et al., 1999; Pope et al., 1995; Dockery et al., 1993). It was estimated that an increase of 10 µg/m³ in PM_{2.5} (as annual

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average) could be associated with increase of a relative risk for total mortality of 1.14 and 1.07, respectively (Neumann, 2001, Pepelko and Chen, 1993). A main source of ultrafine and fine particles in urban areas is attributed to emissions from motor vehicles, in particular, emissions from diesel fueled vehicles (Palmgren et al., 2003, Funasaka et al., 2000). Diesel engine exhaust particles (DEEPs) are one of the major components of urban particulates. It is well known that elemental carbon (EC) and organic carbon (OC) which include polycyclic aromatic hydrocarbons (PAHs) are major constituents of the DEEP (Adams et al., 2002; Funasaka et al., 2000; Norbeck et al., 1998). Diesel emissions including DEEPs, or diesel fumes, could have a potential toxicological significance, and some of them might produce mutagenic and carcinogenic effects such as lung cancer, respiratory symptoms such as asthma, bronchitis, and other respiratory ailments, and mortality (Hirano et al., 2003; Funasaka et al., 2000; Monn et al., 1997; Morgan et al., 1997; Seaton et al., 1995; Sagai, 1994; Pitts, 1983; Goldsmith, 1980). Thus the International Agency for Research on Cancer (IARC) classified diesel exhaust or emission as a probable human carcinogen in 1989 (IARC, 1989). However, the interpretation of past epidemiologic studies has been limited due to lack of direct measures of diesel exposure and insufficient years of follow up. Our research groups have identified a unique cohort of 55,750 long-term trucking company workers employed in 1985 and published the carcinogenicity studies of diesel exhaust in US railroad workers (Garshick et al., 2002, 1988 and 1987; Woskie et al., 1988a and 1988b). Although over 30 occupational epidemiological studies have been conducted, inadequacies in study design, especially the exposure assessment, have prevented the conclusion that exposure to diesel exhaust results in lung cancer. In this paper the authors analyzed the area concentrations identified at various workplaces of trucking companies and the workers' personal exposure to PM_{2.5}, EC, and OC during the winter in Michigan as a part of the diesel particle exposure and lung cancer study in US trucking companies.

2. Methods

Sampling of particulate matter for diesel exhaust exposure assessment was conducted at 1 large (>100 employees) and 1 small trucking terminal in Detroit, Michigan from February 16 to February 20, 2003. Personal exposure sampling, area sampling, and background sampling of particle (PM_{2.5}), elemental carbon (EC), and organic carbon (OC) were performed. The sampling strategy was to collect in-vehicle area (microenvironment) samples for pick up and delivery (P&D) truck drivers and long haul truck drivers where the sampler could be mounted in the vehicle next to the driver. For other jobs and work locations the area samplers were located centrally in the work area such as the freight dock or office. To obtain personal exposure concentrations at breathing zones of dockworkers (usually drivers), shop workers (mechanics), hostlers, and office workers, the personal air sampling vests, which were equipped with personal sampling pumps and filter cassettes, were worn by the workers themselves repeatedly during their work hours almost every day through the sampling period of 5 days. Since the workers have approximately 8–12 hr shifts, two sampling periods were used each day: approximately 10:00 am to 10:00 pm, and 10:00 pm to 10:00 am. An additional set of samples was collected concurrently at locations upwind (background) of the terminal to observe the air contaminants entering the facilities from other locations. Since the companies are unionized, job duties for each major job group are the same for all companies and there are only minor differences in job titles between companies. Major job titles, duties, and locations are reviewed in Table 1.

2.1. Freight Terminal Description

There were three primary work sites with exposure to diesel exhaust at the selected sampling sites: vehicle cab, freight dock area, and the repair shop (Fig. 1). In all of these there can be emission sources within the area and emissions that infiltrate from the outside.

2.2. The Sampling Sites

“Company K” was the terminal from which our sampling crew was based. The overall facility was located in very industrial urban surroundings, approximately 500 meters north and occasionally downwind of a major steel production plant in Detroit, Michigan. The “no smoking” policy at the terminal was not enforced. Smoking was considered heavy in most areas of the terminal, including the dock and shop break rooms. “Company L” was the small terminal sampled near Detroit. The facility sat on about 9 acres of property. The overall facility was located in less urban and moderately industrial surroundings (other trucking terminals etc.) in the southeast part of Michigan. The “no smoking” policy at the terminal was enforced. Smoking was not considered heavy in most areas of the terminal. The more detailed description of the sampling sites and the number of the workers who participated in the personal exposure sampling was summarized in Table 2.

2.3. Summary of Sampling

In total, 126 PM_{2.5}, and 126 EC/OC were collected from a total of 18 local (P&D) drivers, 11 long-haul drivers, 20 dockworkers, 10 mechanics, and 4 hostlers. A total of 21 dock, 14 upwind (yard), and 7 shop area samples were collected. The sampling strategy was to collect personal samples for truck drivers and dock workers where the sampler could either be mounted on a forklift, in a tractor unit next to the worker, or on the worker themselves. Whenever possible, each subject was tested twice so that both between worker and day-to-day variability can be observed. Along with these samples, specific information on equipment design, make, model engine type, and route/operation schedules were either collected or noted, and may be used for future analyses.

2.4. Exposure Assessment Methods

2.4.1. PM_{2.5}—PM_{2.5} was measured using the Harvard Field Monitor (HFM) equipped with a slightly modified Vortex Timer 2 Sampling Pump (Casella, Amherst, NH), a GK2.05 SH (KTL) cyclone pre-selectors (BGI, Inc., Waltham, MA) and a 37mm Teflo filter (Pall Co., Ann Arbor, MI) with a pore diameter of 2µm. The filters were placed in 37mm three piece polystyrene cassettes (Millipore, Bedford, MA). The pumps were calibrated to 3.5 l/min which is the flow rate at which the cyclone conforms to US EPA (PM) Standards for a 50% cut point of 2.5µm. The mass collected on the filters was determined by gravimetric analysis using an analytic balance (Micro-Gravimetric M5, Mettler Instruments Corp, Hightstown, NJ). The filters were weighed before and after sampling in a room controlled for temperature and humidity. After sampling, filters were conditioned between 20 and 23°C and between 35 and 45% relative humidity (USEPA) for at least 48 hours, before being reweighed.

2.4.2. Elemental and Organic Carbon (EC and OC)—Elemental and organic carbon was measured using the same monitor system and cyclone pre-selector (SCC1.062 Triplex) as PM_{2.5} measurement and a 25mm Quartz tissue filter (Omega Specialty Instruments Co., Chelmsford, MA) with a pore diameter of 1.2µm. The same type of filter cassettes (25mm) and pump calibration (50% cut point of 1.0 µm) as PM_{2.5} measurement were used. Prior to field sampling, the Quartz tissue filters were pre-fired at 900°C for 5 hours and the foil used to line the Petri dishes for filter storage were pre-fired at 550°C for 15 hours. This was to prevent off gassing from the Petri dish material onto the filters. Upon returning from the field, the filters were stored at -20°C and analyzed for EC and OC using the National Institute for Occupational Safety and Health (NIOSH) 5040 thermo-optical analyzer method (OMS, 1993; Woskie et al., 1988a) at the laboratory of Dr. James Schauer (University of Wisconsin, Madison).

2.5. Quality Control

2.5.1. Filter Weighing—Quality control for the filter weighing included weighing the tare weight and re-zeroing after every 5 filters and reweighing a control filter at the end of each set of 10 filters. Our weighing precision was $\pm 3 \mu\text{g}$ for each filter.

2.5.2. Calibration—Three rotameters for field calibrations of all pumps were used. Flow measurements were obtained at the start and end of a sampling period. The rotameters were calibrated using a SKC (Eighty Four, PA) UltraFlow Calibrator (Model 709; SN 011347) and Buck Primary Gas Flow Calibrator (Model M-30; SN 030639) at the start and finish of the sampling trip. This was done to ensure that the calibration used for that trip was accurate for the local conditions. After the initial calibration, a label was placed on the side of the rotameter to indicate the appropriate flow. The flow used for final calculation was an average of the values obtained from these two calibrations. The barometric pressure, relative humidity, and temperature were all recorded in the room where the calibration took place. All real time instruments, including the Dust Trak and CO₂ monitors, were calibrated according to factory specifications.

3. Results and Discussion

3.1. PM_{2.5} Area Concentrations

Fig. 2 represents workplace area concentration distributions of PM_{2.5} identified at trucking companies in Detroit. The dock area is used to load and unload freight to be delivered operating forklifts that use liquefied petroleum gas (LPG) as a fuel. The PM_{2.5} concentrations at a large terminal, K, were higher than those at a small one, L. That is because the activity level at the large terminal during the period of this investigation was relatively busy as compared to that at the small one. In addition, as “no smoking” policy was not enforced at terminal K, a lot of workers (dock workers and mechanics) smoked even during their works. Therefore, environmental tobacco smoke at terminal K could be also responsible for higher PM_{2.5} concentrations as compared to those in the dock of terminal L which the “no smoking” policy was enforced. The PM_{2.5} concentrations at dock (inside) areas would be significantly affected by air exchange rates depending upon a ventilation system or environment and a degree of dock blocking by trailer-trucks, with loaded or unloaded cargo, parked outside the dock. In fact, the air exchange rate at the dock could be varied from day to day or week to week. The PM_{2.5} concentrations at the yard samplers, which are located in upwind areas, considered as a background within their company sites were less than those at the dock. However, the yard concentrations could be affected by frequency of truck operation within the investigation sites, stationary emissions or traffic situations passing near the investigation sites, and the meteorological situations such as local wind speed and direction. Because of these complex factors, the average concentrations of PM_{2.5} identified at the yard were much higher than those at the office that did not have significant sources of fine particulate matter. PM_{2.5} concentrations were measured in long haul areas by attaching a sampler to the passenger side chair or dash board inside heavy duty tractor-trailer trucks operated between cities, mostly by highway, were similar to or slightly lower than those measured at the dock areas. However, the particulate components would be significantly different from each other.

The long haul area is highly affected by diesel emissions, highway traffic emissions, or drivers' cigarette smoke, while the dock area is greatly affected by LPG emissions from forklifts and cigarette smoke of forklift drivers (Mazurek et al., 1990; Szidat et al., 2004). This fact was identified from the difference in organic carbon concentration between two areas. The PM_{2.5} concentrations in P&D microenvironments were much higher than those in dock or long haul microenvironments (see Table 1 for terms of P&D and long haul). The cause of the high concentrations might be due to the local air pollution, local traffic emissions, diesel emissions

from the sampling vehicles, drivers' cigarette smoke, and driving with closed windows. In particular, the second highest concentration of the whole investigated workplaces was observed in one P&D truck operated by a smoking driver. The driver might have the habit of limited ventilation during or after his smoking because of severe cold or ignorance of adverse health effects concerning smoke. The highest PM_{2.5} concentrations of the investigated areas were identified in shop areas. The arithmetic mean (AM) concentrations of 5 measurements at the shop areas almost reached to the national ambient air quality standard (NAAQS: 65 ug/m³), based on 24-hour average, of PM_{2.5} in the USA. The 8-hour time weighted average (TWA: 85.3 ug/m³) of the five measurements exceeded the NAAQS. In addition, the 8-hour TWA concentrations of the P&D tractors and shop areas exceeded the indoor value of PM_{2.5} (40 ug/m³), recommended by US Environmental Protection Agency (EPA), not to have adverse health effects indoors for short term periods.

3.2. EC and OC Area Concentrations

Fig. 3a and 3b shows 8-hour TWA concentrations of elemental carbon (EC) and organic carbon (OC), respectively, collected from areas of trucking companies in Detroit, Michigan, USA during the winter of 2003. The TWA EC and OC concentrations were approximately 7.5% and 56.0% of the TWA PM_{2.5} concentrations, respectively, in the whole areas. Thus the area TWA of the total carbon (EC + OC) was approximately 63.5% of that of the PM_{2.5} concentrations. The area concentration patterns of EC were similar to those of OC. The highest concentrations of both EC and OC were observed in the shop areas which repair and maintain tractors using diesel as a fuel and also fuel diesel into the tractors. Repair, maintenance, and fueling activities in shop were conducted with frequent close of shop doors due to the cold weather in the investigation sites. Thus the shop areas could be considered as an indoor area in part. Therefore, the shop areas might have indoor sources of diesel emissions and result in increases in the concentrations of EC and OC in the shop areas. In addition, compressed air was frequently used for cleaning or removal of the particulate matter or diesel exhaust accumulated on the tractors (Funaska et al., 2000; Groves and Cain, 2000). Some mechanics who work in the shop areas smoked. Even smoking does not significantly increase EC concentrations, 0.49% (Hildemann et al., 1991), but these activities could significantly increase the concentrations of particulate matter including EC and OC.

The second highest area concentrations of EC and OC were identified from P&D areas followed by long haul areas. Both P&D and long haul areas are small areas inside trucks in which drivers stay during their driving. Thus the concentrations of EC and OC at those areas are easily affected by traffic situations and drivers' personal habits such as smoking and window opening or closure. Even though the windows of the trucks or tractors were closed due to the severe weather conditions, significant amount of air pollutants such as diesel emissions could be transferred into the vehicles. The EC and OC concentrations at long haul areas were lower than those at the P&D areas. That is because of the different environment between them. The P&D driving frequently meets local traffic jams in the city areas which are not diluted or dispersed quickly. Thus P&D drivers might easily experience high concentrations of particulate including EC and OC. However, long haul drivers more frequently meet rural areas which are easily diluted and disperse particulate matter as compared to that of P&D driving. However, long haul driving also can meet traffic jams on local roads and highways and thus these situations significantly increase EC concentrations at long haul areas.

The lowest concentrations of EC and OC were identified in the offices and the yard areas. EC is usually considered as an indicator of diesel engine exhaust emissions (Groves and Cain, 2000). The lowest concentrations of EC at the offices are probably because the offices are located relatively far away from the diesel emission sources. However, the office are located near the dock areas which have higher particulate sources because of the exhaust emissions

from forklift using LPG fuel and the frequent mobility of the forklifts to load and unload cargos inside dock areas. The particulate matter including OC produced from the dock areas can be significantly transferred into the offices through the frequent openings of the doors. Even though the yard was selected as an upwind background area within the company K, the yard area could be affected by the exhaust emissions from the diesel engines, mostly trucks, passing through the roads near or within the company. Therefore, the ambient EC concentrations at the yard might be higher than those at the offices.

Fig. 4 represents the EC fraction to the total carbon (EC plus OC) concentrations measured during the winter at workplace areas of trucking companies in Michigan, USA. The highest EC ratio of the total carbon was observed in the shop areas. Even though EC and primary OC often have common sources, EC is predominantly emitted from combustion sources (Park et al., 2002). Since EC is well known as an indicator of diesel emissions, the high EC fraction of the total carbonaceous particulates means a high contribution from the diesel engine exhaust emissions. There was no big difference surprisingly among the ratios of EC to the total carbon among dock, yard, and P&D areas. The authors expected that the ratios among them would be quite different because of different area or microenvironment characteristics. For example, dock area has significant sources from LPG combustion indoor and yard has the ambient environment at upwind (background) areas. Also, P&D areas have in-vehicle microenvironments which are easily affected by diesel emissions, traffic emissions and conditions, and drivers' behaviors like smoking and window opening status as mentioned above. Therefore, the further measurement and analysis on the ratios of EC to the total carbon among different environments should be done to investigate a proper cause of this phenomenon. The lowest EC fraction was identified in the office areas followed by the long haul areas. This means that the offices might have very low EC contribution to the total carbon or relatively low EC and high OC concentrations to the total particulates because they might be located a relatively long distance from diesel emission sources.

3.3 Personal Exposure to PM_{2.5}

Fig. 5 compares personal exposure concentrations of the workers to PM_{2.5} and area concentrations of PM_{2.5} during the winter sampling period of the investigated trucking company. In general, the workers' personal exposure concentrations to PM_{2.5} were usually much higher than the corresponding area concentrations (Figs. 2 and 5). The high personal exposure to PM_{2.5} might be related to frequent mobility of the workers at the investigated areas and thus the workers might frequently experience the high concentration zones within their work areas. However, the area concentrations were collected from the arbitrarily selected areas without moving during the sampling periods and might represent air concentrations near the sampling zones. Also, various activities of the workers, such as smoking, loading and unloading, repairing, fueling, cleaning, and maintenance, could significantly increase the personal exposure concentrations to PM_{2.5}. For example, smoking of the workers significantly increased the personal exposure concentrations to PM_{2.5} as compared to the personal exposure of the non-smoking workers to PM_{2.5} or the corresponding area concentrations (Fig. 5).

In particular, a smoking office worker's exposure concentration to PM_{2.5} was 9 times as high as the area concentration of his work office. Also, the smoking hostler showed the highest personal exposure concentration to PM_{2.5} in this study. The severely high exposure concentrations were linked to his habit of smoking with a small opening in a narrow tractor space, and his tractor driving easily exposed him to diesel engine exhaust emissions (DEEEs) during his work. The workers at shop areas were exposed to higher PM_{2.5} concentrations than the workers at the dock areas. That is because the workers of the shop areas were significantly exposed to higher concentrations of DEEEs such as EC when compared to the workers at the dock areas. The personal exposure concentrations of non-smoking dock workers to PM_{2.5} were

much less than those of non-smoking shop workers. LPG fuel was combusted for forklifts used in the dock areas, while diesel fuel was combusted for tractors repaired, fuelled, and cleaned in the shop areas. Therefore, the lower exposure of the non-smoking dock workers to PM_{2.5} particulates is consistent with the known advantages of LPG as a low-emission fuel.

3.4 Personal Exposure to EC and OC

Figs. 6a and 6b represent the workers' exposure concentrations (8h TWA) to EC and OC during the winter sampling period of the investigated trucking company. In particular, the particulate EC contribution, ranging from 1 to 10% based on average values, in the PM_{2.5} personal exposure was very low as compared to that (50%) of an EC personal exposure study of transport users (Adams et al., 2002). The personal TWA EC and OC exposure concentrations were approximately 6.9% and 62.4% of the personal TWA PM_{2.5} concentrations, respectively, in the whole areas. In general, the workers' personal exposure concentrations to EC and OC were usually much higher than the corresponding area concentrations, except the EC exposure in the shop areas (Figs. 6a and 6b). The reasons of this high personal exposure to EC and OC as compared to their area concentrations might be quite similar to those of the high personal exposure to PM_{2.5} as discussed in the previous section. That is because the personal exposure to the total carbon (EC + OC) became approximately 71.3% of the personal exposure to PM_{2.5}, in a total.

The highest personal exposure to EC was observed in the shop areas among the investigated areas of the trucking company during the winter, while the lowest one was identified in the dock areas. The personal exposure fraction to EC was 1.9% of the personal exposure to PM_{2.5} in the dock areas and it was a quite lower value than the average fraction in the whole areas, 6.9%. However, the personal exposure fraction to EC was 13.5% of the personal exposure to PM_{2.5} in the shop areas and it was a quite high value as compared the average fraction in the whole areas. The personal exposure fractions to OC of the personal exposure to PM_{2.5} in the dock and shop areas were 60.2% and 61.6%, respectively, which are similar to the average fraction in the whole areas, 62.4%.

The forklifts operated in the dock areas use LPG fuel and thus the dock areas might not have significant diesel engine exhaust emissions. However, the tractors which were repaired, fueled, maintained, and cleaned in the shop areas used diesel as a fuel and thus the shop areas might have significant DEEEs. According to a DEEE study of Groves and Cain (2000), the personal exposure to EC might be a good indicator of the personal exposure to DEEEs. The personal exposure to EC of the non-smoking workers in the shop areas was slightly higher than or quite similar to that of the smoking workers (Fig. 6a). This trend was also identified in a comparison of the personal exposure to EC of the smoking and non-smoking workers in the dock areas. These facts indicate that the smoking activities do not significantly contribute to the personal exposure to EC (Hildemann et al., 1991), but the diesel exhaust mainly contributes to the personal exposure to EC.

Fig. 6b compares the personal exposure to OC of the smoking and non-smoking workers during their work activities during the investigated winter period in the trucking company. The personal exposure patterns to OC were quite different from those to EC, but they were very similar to those to PM_{2.5}. The smokers' exposure to OC was much greater than the non-smokers' exposure to OC. Also, the exposure concentrations to OC of the workers who might not significantly experience the DEEEs during their work were significant. For example, the personal exposure to OC of the dock workers was quite comparable with that of the shop workers. In addition, the personal exposure of the smoking hostler and the worker in the office to OC was very high as compared to that of the non-smoking workers in other areas of the trucking company. This indicates that the smoking activities can significantly contribute to increasing the personal exposure to OC. There was a large variation in the personal exposure

of the smokers to OC. This might be due to the different smoking environment and habit among the smokers. Thus different degree of combustion or burning of cigarettes and materials could affect the OC concentrations resulting in the various exposure patterns to OC.

Fig. 7 represents the personal exposure fraction to EC to the total carbon (EC plus OC) exposure concentrations measured during the winter at workplace areas in the trucking company. The primary OC/EC ratios exceeding 2.0 have been used to indicate the presence of secondary organic aerosols (SOA) (Park et al., 2002; Hildemann et al., 1991; Turpin et al., 1990; Gray et al., 1986). The average OC/EC ratio in the personal exposure analysis was 23.7 which was similar to that (19.9) in the area concentration analysis. Therefore, there might be secondary sources of OC like combustion of fuels or wastes. The highest exposure ratio to EC of the total carbon exposure was observed in the shop areas. That is because the shop areas have the highest diesel engine exhaust emissions among the investigated areas. Fig. 7 also shows that smoking does not significantly contribute to the personal exposure to EC. The EC fractions at the office and dock areas that might not have significant diesel exhaust sources were quite low as compared to those at the shop areas.

3.5 Area concentrations vs Personal exposure concentrations

Table 3 represents a statistical analysis of area concentrations and personal exposure concentrations to EC, OC, and $PM_{2.5}$ during the winter sampling period in a trucking company. In general, the averaged values (mean, median, and geomean) of the personal exposure concentrations of the workers were much greater than those of the corresponding area concentrations (Adams et al., 2002). The highest difference between the area and personal exposure concentrations was in the $PM_{2.5}$ concentrations followed by the OC concentrations. In survey analysis of 252 workers responding to a survey mailed to all 526 employees at one of the terminals that our research groups visited in Atlanta, Georgia, the average fraction of current smokers was approximately 19%, ranging from 11% to 20% depending upon the job title. Thus the concentration difference between them might be mainly because the personal data contain the personal exposure of the smoking workers. The workers are moving around within their work areas during the personal samplings, while the area concentrations well represent particulate concentrations around the areas which were selected and fixed for the area samplings. Thus, the difference in the sampling methods might be a part of the difference between the area and personal exposure concentrations.

The identified total carbon concentrations were responsible for only 58 and 60% (based on geomean) of the area and personal exposure concentrations to $PM_{2.5}$, respectively (Table 3). This indicates that there is some very fine dust or semi-volatile material that is not included in carbon measurement but does contribute of the total measured $PM_{2.5}$. In particular, spatially constant secondary inorganic aerosol such as ammonium sulfates and ammonium nitrates can contribute equally to every $PM_{2.5}$ measurement made in a short period of sampling time.

Table 3 also indicates statistical variability of EC, OC and $PM_{2.5}$ concentrations. A change of atmospheric pressure between pre- and post-exposure weighing could affect the filter buoyancy in air resulting in change of the variability. This variability would be significant if the sample masses are small. Thus the variability of EC and OC, which has smaller masses as compared $PM_{2.5}$, would be larger than that of $PM_{2.5}$. In this study the filters were on-weighed in two sessions (and off-weighed in three sessions). The average change of atmospheric pressure between the on- and off-weighing was 4.3 mm Hg and 37 mm filters of $PM_{2.5}$ weighed about 100ug. Thus the variability of EC, OC and $PM_{2.5}$ by the effects of filter buoyancy in air between pre- and post-exposure weighing might not be large.

3.6 Worker and Shift-to-Shift Variability of Personal Exposure Concentration

Figs. 8a and 8b show worker and shift-to-shift variability of personal exposure concentration to $PM_{2.5}$ and total carbon. It was identified that there is a significant variation of exposure concentrations among workers and shifts. The worker variability indicates that work environment, job category, and personal habit such as smoking affect personal exposure concentrations of workers. The shift-to-shift variability might be due to different meteorological conditions, such as wind, sun light, and temperature, and different activity levels, such as the number of workers and freight amounts, among shifts. For example, the personal exposure during nighttime shift might be different from that during day time shift. Figs. 8a and 8b also show that concentration change trends of $PM_{2.5}$ and total carbon as a function of worker and shift-to-shift are quite similar. This indicates that $PM_{2.5}$ and total carbon might have common emission sources.

3.7 Correlation

Figs. 9a and 9b show that there are strong correlations between $PM_{2.5}$ and OC or between $PM_{2.5}$ and total carbon (EC+OC) area concentrations, respectively. However, the correlations between $PM_{2.5}$ and EC or between EC and OC area concentrations were not that significant. This means that OC is the main components of $PM_{2.5}$, and EC and OC may not have the common emission sources in this study.

Figs. 10a and 10b represent that the correlation coefficients between personal exposure to $PM_{2.5}$ and OC or between personal exposure to $PM_{2.5}$ and total carbon, respectively, are higher than those between their area concentrations. This means that the personal exposure to OC can well represent the personal exposure to $PM_{2.5}$ in the trucking company. There were no significant correlations between personal exposure to $PM_{2.5}$ and EC or between personal exposure to EC and OC.

3.8 Significance of the Exposure Data

This paper dealt with exposure data to EC, OC and $PM_{2.5}$ measured at two diesel trucking companies in a city during the specific sampling period of 6 days of the winter. The geometric concentrations (based on 12 hr-time weighted average values) of exposure to OC and $PM_{2.5}$ at workers' breathing zone during the sampling period were 29.4 and 47.8 $\mu g/m^3$, respectively, which significantly exceeded the annual standard of $PM_{2.5}$, 15 $\mu g/m^3$, specified in the national ambient air quality standards (NAAQSs) of USA. 13.8 and 27.6% of the personal exposure data to OC and $PM_{2.5}$, respectively, measured also exceeded the 24 hr standard, 65 $\mu g/m^3$, of the NAAQSs. Our team has investigated similar studies through the entire country including measurements at trucking companies in 36 different cities in USA. Currently, the exposure results to EC, OC and $PM_{2.5}$ discussed in this paper might not be significantly different from others. If many workers of the trucking companies are exposed to high concentrations of OC and $PM_{2.5}$ for long time periods, they may experience troubles or symptoms related to the high exposure of them. In particular, smokers of the exposed workers may have more adverse health effects than others.

4. Conclusions

In the analysis of the area concentrations and the personal exposure concentrations to fine particulate ($PM_{2.5}$), elemental carbon (EC), and organic carbon (OC) measured during the winter period in trucking companies, we reached the following conclusions.

The personal exposure concentrations to particulate matter were much greater than those of the area concentrations. The personal TWA EC and OC exposure concentrations were approximately 6.9% and 62.4% of the personal TWA $PM_{2.5}$ exposure concentrations,

respectively, in the whole areas. The area concentrations of PM_{2.5}, EC, and OC at a large terminal, which has busier activity levels, were higher than those at a small one. The area concentrations and personal exposure to PM_{2.5}, EC, and OC in the shop and P&D areas, which are highly affected by diesel engine exhaust emissions, were much higher than those in the docks, which are significantly affected by liquefied petroleum gas (LPG) engine exhaust emissions. Smoking significantly contributed to the worsening of the indoor air quality in the workplaces and the break rooms and thus increased the personal exposure to PM_{2.5} and OC. However, smoking may not significantly contribute to the personal exposure to EC. There were significant correlations between the PM_{2.5} and OC concentrations in both the area and personal exposure concentrations.

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Fig. 1.
Emission sources and worker exposures for the trucking industry.
(The emissions marked by smoke in the diagram are exaggerated.)

Fig. 2.
TWA area concentrations of PM_{2.5} during the winter at trucking companies in Detroit, USA.

(3a) EC concentration

(3b) OC concentration

Fig. 3.
TWA area concentrations of EC and OC during the winter at trucking companies.

Fig. 4.
EC fraction to the total carbon (EC + OC) during the winter at areas of trucking companies.

*NS stands for non-smoking workers and S stands for smoking workers.

Fig. 5. Personal exposure to PM_{2.5} during the winter period at areas of a trucking company.

(6a) EC exposure

(6b) OC exposure.

*NS stands for non-smoking worker and S stands for smoking workers.

Fig. 6. Personal exposure concentration to EC and OC during the winter at areas of a trucking company.

*NS stands for non-smoking worker and S stands for smoking workers.

Fig. 7.
EC fraction to the total carbon exposure during the winter at areas of a trucking company.

(8a) PM_{2.5}

(8b) Total carbon (EC+OC)

Fig. 8. Worker and shift-to-shift variability of personal exposure concentration to PM_{2.5} and total carbon.

Fig. 9.

Correlations among $PM_{2.5}$, OC, EC, and total carbon (OC+EC) area concentrations.

Fig. 10. Correlations among personal exposure to $PM_{2.5}$, OC, EC, and total carbon (OC+EC).

Table 1

Description of major job categories, job duties, and job location.

Job Group	Job Duties	Job Location
Long haul driver	Operates heavy duty tractor-trailer trucks between cities	Highway truck cab
Pick-up/ Delivery (P&D) driver	Drive tractors and smaller single-bodied trucks either within cities or rural areas; pick-up and deliver cargo between terminal docks and consumers	In and out of truck cab
Dock worker	Load and unload cargo, may operate forklifts	Loading dock
P&D/Dock worker	Combination job: each day performs activities of either P&D driver or dock worker; combination job is more likely at smaller terminals	As noted above
Mechanic	Repair and maintain tractors; job may include fueling	Truck repair shop
Hostler	Drive tractor or yard tug (small, specialized tractor units that do not comply with emissions standards), moving trailers to and from the freight dock	Terminal yard
Clerks	Cashiers, dock clerks, dispatchers, customer service representatives, and others not regularly near diesel vehicles	Offices, occasionally dock

Table 2

Summary of facilities and the number of workers at the sampling sites in Detroit, Michigan.

Facility	Property(m ²)	Age(yr)	Size/Location	Break room	No smoking policy
K terminal	121,410	28	large/urban	dock, shop	not enforced
L terminal	36,360	8	small/less urban		enforced
Dock	Area(m ²)	Door no	Solid door	Opening	Heating
K dock	6,600	180	no	canvas seal	no
L dock	2,000	65	no	canvas seal	no
Shop	Area(m ²)	Door no	Repair bay no		
K shop	1,115	2 large	6		
L shop	300	2 large	2		
Worker	Dock	Long-haul	Pick up-delivery	Shop	Office
K terminal	119	58	61	13	71
L terminal	10	0	26	5	6

Table 3

Area (A) and personal (P) concentration statistics of elemental carbon (EC), organic carbon (OC), and fine particulate (PM_{2.5}) during the winter sampling period in a trucking company of Detroit, Michigan.

Concentration unit: ug/m³

	A-EC	P-EC	A-OC	P-OC	A-PM _{2.5}	P-PM _{2.5}
Sampling (n)	71	32	71	32	71	32
Median	0.627	0.987	10.027	22.229	20.670	41.119
Geomean	0.658	1.483	11.325	24.231	20.636	42.503
Mean	1.840	3.098	15.304	29.410	25.832	47.755
Std. Dev.	3.742	3.958	14.264	20.610	19.188	24.041
Std. Err.	0.450	0.723	1.717	3.763	2.310	4.389
95% Conf.	0.899	1.478	3.427	7.696	4.610	8.977
99% Conf.	1.194	1.992	4.551	10.373	6.122	12.099
Min	0.005	0.336	2.415	11.114	1.772	14.497
Max	18.919	14.025	82.933	83.661	110.464	110.577