보건학박사 학위논문

Occupational Exposure to Diesel Engine Exhaust in Municipal Household Waste Workers

환경미화원의 디젤엔진 배출물질 대리인자에 대한 노출 평가

2016년 2월

서울대학교 대학원

보건학과 환경보건학 전공

이 경 희

환경미화원의 디젤엔진배출물질 대리인자에 대한 노출 평가

지도교수 윤 충 식

이 논문을 보건학 박사학위논문으로 제출함

2015년 9월

서울대학교 대학원

보건학과 (환경보건학전공)

이 경 희

이 경 희 의 박사학위 논문을 인준함

2015년 12월

위 원 장 ______ 이 승 묵 ______ (인)

부 위 원 장 ______ 이 기 영 ______ (인)

위 원 ______ 김 성 균 ______ (인)

위 원 ______ 박 동 욱 ______ (인)

위 원 ______ 윤 충 식 ______ (인)

Occupational Exposure to Diesel Engine Exhaust in Municipal Household Waste Workers

Advised by **Professor Chungsik Yoon**

A Dissertation Submitted in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Philosophy in Public Health

To the Faculty of the Gradu,ate School of Public Health
at **Seoul National University**
by **Kyonghui Lee**

Data approved: December, 2015

ABSTRACT

Occupational Exposure to Diesel Engine Exhaust in Municipal Household Waste Workers

Kyonghui Lee

Department of Public Health (Environmental Health)

Graduate School of Public Health

Seoul National University

Objectives: The purposes of this study were as follows: 1) to assess the occupational exposure of municipal household waste (MHW) workers to diesel engine exhaust (DE) using a range of surrogates including elemental carbon (EC), organic carbon (OC), total carbon (TC), black carbon (BC), fine particulate matter ($PM_{2.5}$), and nitrogen dioxide (NO_2); 2) to determine appropriate surrogates for DE for MHW workers; and 3) to identify the main exposure determinants that influence personal exposure to DE at the task level, as well as using Time Weighted Average (TWA).

Methods: A total of 72 workers from five MHW collection companies were assessed over seven days in total between June 26 and September 18, 2014. During the field sampling period, 72 respirable EC/OC/TC, 17 BC, 21 $PM_{2.5}$ and 70 NO_2 samples were collected. EC/OC/TC samples were quantified using the thermal optical transmittance

method. BC and $PM_{2.5}$ were measured using real-time monitors, an aethalometer, and a laser photometer. NO_2 samples were taken using passive filter badges and were analyzed with a spectrophotometer. For task-based exposure assessment, 1,969 BC and 1,983 $PM_{2.5}$ measurements (1-min data) collected from nine workers were categorized into six specific tasks based on time activity information. Resultantly, 259 BC task samples and 261 $PM_{2.5}$ task samples were obtained for assessment. All results were statistically analyzed for occupational and environmental variables in order to identify exposure determinants for DE.

Results: The geometric means (GM) of EC, OC, TC, BC, $PM_{2.5}$ and NO_2 were 4.8, 39.6, 44.8, 9.1, 62.0 μg/m^3, and 105.3 μg/m^3, respectively. In comparison with other occupations, the EC levels found for the MHW collectors (GM=5.6 μg/m^3) were similar or slightly higher than those for truck drivers (GM=1.1−4.0 μg/m^3), railroad crews (GM=1.4–5.6 μg/m^3), mechanics in truck repair garages (GM=3.2–5.9 μg/m^3) and in locomotive workshops (GM=2.6–3.2 μg/m^3), and surface workers at mining facilities (GM=1–4 μg/m^3). The EC levels for MHW truck drivers (GM=3.8 μg/m^3) were comparable to those of local truck drivers (GM=1.2–4.0 μg/m^3) and long-haul truck drivers (GM=1.1−3.8 μg/m^3). On the other hand, all of their exposures proved much lower compared to those of mining workers (GM=62−85 μg/m^3). NO_2 exposure levels for MHW workers showed similar comparison results with those for EC levels.

Among the five surrogates for diesel particulate matter (DPM: EC, OC. TC, BC and $PM_{2.5}$), EC measurements showed consistent and relevant exposure patterns against various exposure factors, such as job title (collector > driver), European engine emission standards (Euro 3 truck > Euro 4 truck), distance from the rear of the truck to the engine tailpipe (longer > shorter), age of truck (older > younger), average driving speed (slow > fast), number of containers collected (more > less), and others. More importantly, EC was not affected by worker smoking, ambient dust, weather, and malodors from food waste, as opposed to OC, TC, BC and $PM_{2.5}$. This indicates that EC is the most appropriate surrogate for DPM exposure among MHW workers.

NO_2 measurements were also consistent and predictable according to various occupational and environmental factors such as job title (collector > driver), Euro engine standard (Euro 3 truck > Euro 4 truck), engine size (bigger > smaller), driving distance (longer > shorter), location (urban area > suburban area), weight of collected waste (more > less). Like EC, NO_2 was unaffected by worker smoking habit, ambient dust, and malodors from waste. Furthermore, NO_2 was significantly correlated with EC levels, indicating a consistent association between both surrogates ($r=0.339$, $p=0.002$). This suggests that NO_2 can be used as an alternative surrogate for EC to assess MHW workers using Euro 3–4 standards trucks.

Task-based exposure assessment identified the task of collection < 2 m (GM of BC=9.4 $\mu g/m^3$) as the highest-exposure task in MHW collection work. For collectors, the task of collection < 2 m was the task that contributed most to TWA exposure with a contribution rate of 56.6%. The task of riding in the cabin (driving) was the greatest contributor (76.4%) for drivers. Between BC and $PM_{2.5}$, BC was the better surrogate for DPM for real-time measurements. BC was less affected by smoking or weather than was

$PM_{2.5}$. We also found how well task-based exposure assessment refined exposure characterization at the task level with a small number of subjects. In addition, the task-based method was more effective for assessing repetitive work composed of multiple tasks with significantly different exposure levels.

Based on the multiple regression model, worker's job title, European engine emission standard of the truck and average driving speed were the most influential factors in determining EC exposures. For NO_2 exposure levels, worker's job title, engine size, and driving distance were the main exposure determinants. The BC levels of the highest exposure task, collection < 2 m, were mainly affected by job title and Euro engine emission standard of the truck. In summary, job title and the Euro engine emission standard of the truck were the most important factors to predict EC and BC exposure levels.

Conclusion: This study assessed the exposure of MHW workers to DE using parallel samples of six surrogates: EC, OC, TC, BC, $PM_{2.5}$ and NO_2. The levels of exposure to DE were slightly higher than those found among mechanics in both truck repair garages and locomotive workshops, truck drivers, railroad crews and surface workers at mining facilities. In particular, the MHW workers were exposed to higher levels of DE when they remained near the tailpipe of truck (the task of collection < 2 m) indicating that the primary source of DE for MHW workers is the trash truck. A worker's job title and the European engine emission standard of the truck were the most influential factors for exposure to DE. Among the six surrogates, EC was the most appropriate surrogate for DPM exposure because it showed less interference compared to the other surrogates and demonstrated the most relevant exposure pattern for occupational and environmental factors. NO_2 levels also can be used as an alternative surrogate for EC as well as DE among MHW workers using Euro 3–4 standard trucks, since it was significantly correlated with EC levels and showed consistent and predictable exposure patterns for occupational and environmental factors.

Key words: diesel engine exhaust, diesel particulate matter, municipal household waste, waste collection, elemental carbon, black carbon, $PM_{2.5}$, nitrogen dioxide

Student Number: 2008-31061

Table of Contents

List of Tables

List of Figures

1. Introduction

1.1. Diesel Engine Exhaust

Since the diesel engine was first patented by Rudolf Diesel in 1892, they have been used primarily in heavy-duty trucks, buses, railroad locomotives, and marine vessels, as well as in a variety of off-road heavy equipment. Their advantages over other internal combustion engines include greater power, longer working life, better fuel economy, and less required maintenance (U.S.DoE, 2003; U.S.EPA, 2002).

In Korea, the number of diesel-fueled vehicles has increased by 44% from 57,220,000 in 2008 to 82,310,000 in 2012. Data indicate that diesel-powered vehicles accounted for 36.72% of the total vehicles in use in 2012 (MOLIT, 2012). In addition, diesel fuel was the single most-used petroleum product in Korea: out of the 312,603 barrels of petroleum products consumed in 2011, diesel (134,157 barrels) made up the largest share, followed by gasoline (69,574 barrels), bunker-C (51,505 barrels), kerosene (25,430 barrels), and bunker-A (2,213 barrels).

1.1.1. Health Effects

With the increased use of diesel engines, the health concerns associated with environmental exposure to diesel engine exhaust (DE) have increased. A consistent causal relationship between DE exposure and lung cancer has been found in numerous epidemiologic studies (Cal.EPA, 1998; Lloyd and Cackette, 2001). Recently, the International Agency for Research on Cancer (IARC) reclassified DE as “carcinogenic to humans (Group 1)”. This decision was based on a U.S. National Cancer Institute (NCI) and National Institute for Occupational Safety and Health (NIOSH) study that showed exposure-response relationships between respirable elemental carbon (EC) exposure and lung cancer mortality in underground miners: workers with higher exposures to DE demonstrated three to five times greater mortality rates for lung cancer compared to those with the lowest exposures (Attfield *et al.*, 2012; Silverman *et al.*, 2012). The IARC also noted a positive association (on limited evidence) with an increased risk of bladder cancer (Group 1) (IARC, 2012).

Although there is only limited information on the health effects of acute high exposure, it has been reported that acute exposure to DE can cause eye and mucus membrane irritation, respiratory symptoms including coughing and phlegm, light-headedness, nausea, dizziness, etc. Evidence for immunologic effect, including increased allergenic response and asthma-like symptoms, has been obtained from epidemiologic studies based on self-reported data and from animal studies as well (Ciccone *et al.*, 1998; Diaz-Sanchez *et al.*, 1999; Duhme *et al.*, 1996; Takano *et al.*, 1998). However, the immunologic effect is neither as consistent nor strong as that of lung cancer. Additional research is needed to identify the mechanisms of cellular or tissue responses.

There is a wide range of epidemiologic studies consistently indicating a positive association between fine particulate air pollution and daily mortality (Birch, 2003). Fine particulate pollution mainly originates from vehicle combustion sources, primarily diesel engines. Pope et al. estimated that diesel exhaust pollution accounted for 3,566 annual deaths in California (Pope III *et al.*, 1995). The California EPA projected that 2400 premature deaths were related with air pollution from port-related movement of goods in 2005, at a cost of U.S. \$19 billion (Cal.EPA, 2006). A handful of human studies have failed to show any significant cardiovascular or lung function changes in workers over a work shift or following short-term exposure to DE (e.g. 2-hr exposure at a concentration of 200 $\mu g/m^3$ or 1-hr exposure at 300 $\mu g/m^3$) (Nightingale *et al.*, 2000; Salvi *et al.*, 1999; Salvi *et al.*, 2000). However, a number of epidemiological studies have reported that fine particles are associated with increased hospital admissions due to respiratory or cardiovascular disease (Burnett *et al.*, 1995; Schwartz, 1994; Schwartz and Morris, 1995).

1.1.2. Composition

DE is a complex mixture of gaseous and particle-phase emissions comprised of hundreds of constituents (IPCS, 1996; U.S.EPA, 2002). The most abundant of these components are listed in Table 1-1. Gaseous components of DE include carbon dioxide, oxygen, nitrogen, water vapor, nitrogen compounds, carbon monoxide, sulfur compounds, and low-molecular-weight hydrocarbons (C_1–C_{10}) and their derivatives (Ris, 2007). Among low-molecular-weight hydrocarbons, light-weight carbonyls make up the largest fraction and acetaldehyde, formaldehyde, and acetone account for the next largest fraction. Alkanes (< C_{10}) and cycloalkanes are smaller fraction of gaseous components (Lloyd and Cackette, 2001; Schauer *et al.*, 1998).

The particulate fractions are defined as diesel particulate matter (DPM). DPM is comprised of respirable particles with a mean aerodynamic diameter of about 0.2 µm, and 80–95% of those are fine particles < 2.5 µm. Ultrafine particles (< 0.1 µm) with a mean particle aerodynamic diameter of 0.02 μm account for only 1–20% of the diesel particle mass but make up 50–90% of the total number of particles (Kittelson, 1998; U.S.EPA, 2002).

DPM consists of a center core of elemental carbon (EC), which has attached organic compounds comprised of hydrocarbon molecules as well as small amounts of sulfate, nitrate, and other elements. The organic compounds are defined as organic carbon (OC) and may comprise 19–43% of the DPM, while the EC content may comprise 50–75% of the DPM (U.S.EPA, 2002). DPM is formed by physical processes such as nucleation, coagulation, condensation, and adsorption while the diesel exhaust cools and is diluted with ambient air. The core EC particles are formed out of primary spherical particles sized about 10 to 80 nm, and organic and sulfur compounds with other chemicals are adsorbed to the core carbon. Particles with organic compounds are agglomerated and grow into larger particulates with a graphite-like structure.

The composition and generation of DE varies depending on the age of the diesel engine, the type of engine, fuel characteristics, speed, motor load, ambient air temperature and relative humidity, driving cycle, and after-treatment devices (Clark *et al.*, 2002; Schuetzle and Frazier, 1986). For example, lowering the sulfur content of the fuel reduces sulfur dioxide and particulate sulfur emissions. As of 2006, almost all of the diesel fuel available in Europe and North America is ultra-low sulfur diesel (ULSD, < 50 parts per million sulfur) and most diesel fuel sold in Korea is now also ULSD.

Table 1-1. Classes of compounds in diesel exhaust

Gaseous Phase		Particle phase	
Heterocyclics, hydrocarbons (C_1–C_{10}) and derivatives:		Heterocyclics, hydrocarbons (C_{14}–C_{35}) and PAHs derivatives:	
Acids,	Cycloalkanes	Acids	Cycloalkanes
Aldehydes,	Cycloakenes	Alcohols	Esters
Alkanoic acids	Dicarbonyls	Alkanoic acids	Halogenated cmpds.
n-Alkanes	Ethyne	n-Alkanes	Ketones
n-Alkenes	Halogenated cmpds.	Anhydrides	Nitrated cmpds.
Anhydrides	Ketones	Aromatic acids	Sulfonates
Aromatic acids	Nitrated cmpds.		Quinones
	Sulfonates		
	Quinones		
Acrolein		Elemental carbon	
Ammonia		Inorganic sulfates and nitrates	
Carbon dioxide, carbon monoxide		Metals	
Benzene		Water	
1,3-Butadiene			
Formaldehyde			
Formic acid			
Hydrogen cyanide, hydrogen sulfide			
Methane, methanol			
Nitric and nitrous acids			
Nitrogen dioxide, nitrogen oxide, nitrous oxide			
Sulfur dioxide			
Toluene			
Water			

Sources: U.S.EPA, Health assessment document for diesel engine exhaust, 2002, which summarized the works of Mauderly(1992), Schuetzle and Frazier (1986), Carey (1987), Zaebst et al. (1988), McDonald (1997) and Schauer et al.(1999).

1.1.3. Surrogates for DE Exposure

Since DE is a mixture of various components, several surrogates have been used to determine workers' exposure to DE. For particle-phase compounds in DE, EC, OC, total carbon (TC, EC+OC), black carbon (BC) and fine particulate matter ($PM_{2.5}$) are used to evaluate DPM exposures (Groves and Cain, 2000; Liukonen *et al.*, 2002; Verma *et al.*, 1999). To evaluate exposure to gaseous-phase DE, poly-nuclear aromatic hydrocarbons (PAHs), nitrogen dioxide (NO_2), nitrogen monoxide (NO), sulfur dioxide (SO_2) and carbon monoxide (CO) have all been measured.

The definition and characteristics of reprisentative surrogates for DE are as follows:

- EC: Carbon generated from pyrolysis. EC in its pure form contains only carbon atoms, but as it exists in combustion particulate matter, it is likely to include some hydrogen atoms.
- OC: Carbon- and hydrogen-containing molecules adsorbed onto agglomerated EC particles. Emitted in DE as the result of un-combusted diesel fuel and engine lubrication oil, OC compounds can also contain oxygen, nitrogen, and sulfur, as well as other elements in small quantities.
- TC: Sum of EC and OC.
- BC: Black aerosol, soot, or carbonaceous aerosol. BC was defined as an aerosol that absorbs light and is evaluated by measuring light-absorbing carbon.
- $PM_{2.5}$: Particulate matter less than 2.5 μm in aerodynamic diameter.
- NOx and NO_2: Diesel engines generate much more nitrogen oxides (NOx, NO and NO^2) than do gasoline-fueled engines because of their manner of combustion. In recent years, NO_2 fractions among NOx have increased because after-treatment devices oxidize NO to NO_2 (Czerwinski *et al.*, 2012; Feng *et al.*, 2014; U.S.EPA, 2008b).

- PAHs: Various types of PAHs (e.g. fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene) are all generated from diesel engines. PAH emissions from diesel trucks are weighted toward lower molecular-weight PAHs, whereas gasoline engine exhaust shows a greater abundance of higher molecular-weight PAHs (Miguel *et al*., 1998; Rogge *et al*., 1993).

1.2. Occupational Exposure to DE

Kauppinen et al. estimated that approximately 3 million workers were exposed to DE in 15 countries in the European Union from 1990 through 1993 (Kauppinen *et al.*, 2000). CARcinogen EXposure (CAREX) Canada estimated that 4.6% of all Canadian workers (781,000 workers) were exposed to DE in 2006, and this proportion was lower than the 17% rate among Australians. In Korea, the Occupational Safety and Health Research Institute (OSHRI) reported that the average number of workers exposed to DE rose from 261,825 in 1993 to 443,421 in 2012 (OSHRI, 2014).

A substantial number of studies have evaluated DE exposure in various occupations, such as truck/bus drivers, garage mechanics, railroad repair and locomotive crews, heavy equipment operators, underground miners, firefighters, and airport baggage workers, among others. However, few studies have assessed exposure to DE emissions for municipal household waste (MHW) workers. It is estimated that approximately 15,000 MHW workers are occupationally exposed to DE during the collection of MHW in Korea. In addition, a few workers have developed lung cancer in recent years potentially due to their exposure to DE (unpublished data from the Occupational Lung Disease Institute, Korea).

Table 1-2. Occupational exposure levels to diesel exhaust: elemental carbon, particulates and nitrogen dioxide (µg/m^3)

Occupational groups		Agent	N	AM	SD	GM	GSD	Location	Reference
Drivers	Truck drivers, local	EC_S	576	–	–	1.2	2.8	US	(Davis *et al.*, 2007)
	Truck drivers, local	EC_I	–	–	–	4	–	US	(Liukonen *et al.*, 2002)
	Truck drivers, long haul	EC_S	349	–	–	1.1	2.3	US	(Davis *et al.*, 2007)
	Truck drivers, long haul	EC_I	–	–	–	3.8	–	US	(Liukonen *et al.*, 2002)
	Bus drivers	EC_S	39	–	–	1.4	3.3	US	(Ramachandran *et al.*, 2005)
	Bus and truck drivers	PM_s	20	–	–	14	1.6	Sweden	(Lewne *et al.*, 2007)
	Truck drivers, local	PM_R	545	–	–	20	2.1	US	(Davis *et al.*, 2007)
	Truck drivers, long haul	PM_R	334	–	–	23	2.5	US	(Davis *et al.*, 2007)
	Bus drivers	PM_R	5	–	–	580	1.5	Estonia	(Boffetta *et al.*, 2002)
	Bus drivers	NO_2	42	60	18	–	–	Sweden	(Lewné *et al.*, 2006)
	Taxi drivers	NO_2	39	48	12	–	–	Sweden	(Lewné *et al.*, 2006)
	Taxi drivers (diesel)	NO_2	8	74	10.7	–	–	Korea	(Son *et al.*, 2004)
	Patrol cars	NO_2	50	78	83.3	–	–	US	(Riediker *et al.*, 2003)
Mechanics	Garage mechanics	EC_S	35	–	–	3.2	1.7	US	(Ramachandran *et al.*, 2005)
	Truck mechanics	EC_I	40	–	–	5.9	3.1	Canada	(Seshagiri and Burton, 2003)
	Locomotive workshop	EC_I	40	–	–	2.6	3.2	Canada	(Seshagiri and Burton, 2003)
	Railway Mechanics	EC_R	28	–	–	3.2	2.4	Canada	(Verma *et al.*, 2003)
	Railway, Rolling equipment	PM_R	55	–	–	203	1.9	UK	(Groves and Cain, 2000)

Occupational groups		Agent	N	AM	SD	GM	GSD	Location	Reference
	Bus Garage workers	NO_2	4	179	–	–	–	Sweden	(Lewné *et al.*, 2011)
	Garage workers-diesel	NO_2	16	93	–	–	–	Sweden	(Lewné *et al.*, 2011)
	Turnaround all yards	NO_2	18	190	–	–	–	Canada	(Verma *et al.*, 1999)
Railroad crews	Lead locomotives	EC	156	–	–	1.4	3.2	US	(Hewett and Bullock, 2014)
	Trailing locomotives	EC	22	–	–	5.6	3.4	US	(Hewett and Bullock, 2014)
	Train driver	EC_R	23	–	–	2.3	2	Canada	(Verma *et al.*, 2003)
	Lead locomotives (without preceding stacks)	EC_I	33	–	–	2.5	1.5	US	(Liukonen *et al.*, 2002)
	Driver, assistant	PM_R	17	–	–	797	1.5	Russia	(Boffetta *et al.*, 2002)
	Locomotives	NO_2	234	–	–	56	3.8	US	(Hewett and Bullock, 2014)
Mining surface workers	Limestone facility	EC_R	33	–	–	4	2.2	US	(Coble *et al.*, 2010)
	Potash facility	EC_R	61	–	–	1	3.9	US	(Coble *et al.*, 2010)
	Production/Maintenance (coal)	PM_R	68	–	–	651	1.6-2.3	Czeh R.	(Scheepers *et al.*, 2002)
	Train drivers	NO_2	12	978	–	–	–	Germany	(Dahmann *et al.*, 2009)
	Diesel engine drivers	NO_2	12	395	–	–	–	Germany	(Dahmann *et al.*, 2009)
	Surface workers (limestone)	NO_2	34	–	–	19	2	US	(Coble *et al.*, 2010)
	Surface workers (Trona)	NO_2	48	–	–	56	3.1	US	(Coble *et al.*, 2010)
	Tunnel construction workers	NO_2	6	–	–	316	–	Sweden	(Lewné *et al.*, 2011)
Underground	Production (non metal)	EC_R	6(a)	–	–	85	3.5	UK	(Leeming *et al.*, 2004)[R]

Occupational groups		Agent	N	AM	SD	GM	GSD	Location	Reference
	Production	EC_I	12	538	512	–	–	US	(Burgess *et al.*, 2007)
	Mining, NS (coal)	EC_R	7(a)	–	–	62	1.5	UK	(Leeming *et al.*, 2004)[R]
	Production (coal)	PM_S	24(a)	635	110-270	–	–	US	(Watts *et al.*, 1992)
	Mining, NS (metal)	PM_S	30(a)	1600	1020	–	–	US	(NIOSH, 1992)
	Production (non metal)	PM_R	305	–	–	1610	–	Germany	(Dahmann *et al.*, 2007)
	Production (metal)	NO_2	29	376	–	–	–	Sweden	(Ädelroth *et al.*, 2006)
	Production (metal)	NO_2	54(a)	2823	0.9	–	–	US	(NIOSH, 1992)
Fire fighters		EC_I	16(a)	–	–	1.5	–	US	(Roegner *et al.*, 2002)
Ramp attendants		EC_S	34	–	–	1.1	1.8	US	(Ramachandran *et al.*, 2005)
Airport	Baggage and screening	EC_I	72	1.1	5.4	–	–	US	(NIOSH, 2005)
	Baggage and screening	NO_2	40	–	–	226	0.07	US	(NIOSH, 2005)

(a): area sample
[am]: arithmetic mean
[sd]: standard deviation
[R]: Cited from the article of "Pronk, A., Coble, J. and Stewart, P. A. Occupational exposure to diesel engine exhaust: A literature review (Pronk *et al.*, 2009)".
Abbreviations: GM: geometric mean; GSD: geometric standard deviation; EC_S: submicron elemental carbon; EC_R: respirable elemental carbon; EC_I: inhalable elemental carbon; PM_S: submicron particulate matter; PM_R: respirable particulate matter; NO_2: nitrogen dioxide

1.3. Hypothesis

Four hypotheses were tested in this study. The first hypothesis is that MHW collection workers are exposed to a substantial amount of DE that may exceed both the applicable occupational exposure limit and background ambient levels. The second is that there will be correlations among surrogates for DE: EC, OC, TC, BC, and $PM_{2.5}$. Thirdly, NO_2 could be an alternative surrogate for DE for newer diesel engines which come equipped with after-treatment devices. The final hypothesis is that the exposure levels of MHW workers to DE would be different based on the tasks and various occupational and environmental factors.

1.4. Objectives and Study Design

The overall objectives of this study were as follows:

1) To assess the occupational exposure of MHW workers to DE using various surrogates such as EC, OC, TC, BC, $PM_{2.5}$ and NO_2.

2) To determine appropriate surrogates for DE for MHW workers.

3) To identify the main exposure determinants that influence personal exposure to DE task levels as well as Time Weighted Average (TWA).

To achieve these aims, three approaches were used. Figure 1-1 shows an outline of the study. Firstly, in Chapter 2, exposure assessment for particle-phase DE was performed by measuring EC, OC, TC, BC and $PM_{2.5}$. Secondly, NO_2 exposures were examined as a surrogate of gaseous-phase DE, and whether NO_2 can be used as a surrogate for DE was evaluated. In the third topic, task-based exposure assessment was conducted using real-time measurements of BC and $PM_{2.5}$ to evaluate the exposures of MHW workers to DE at the task level.

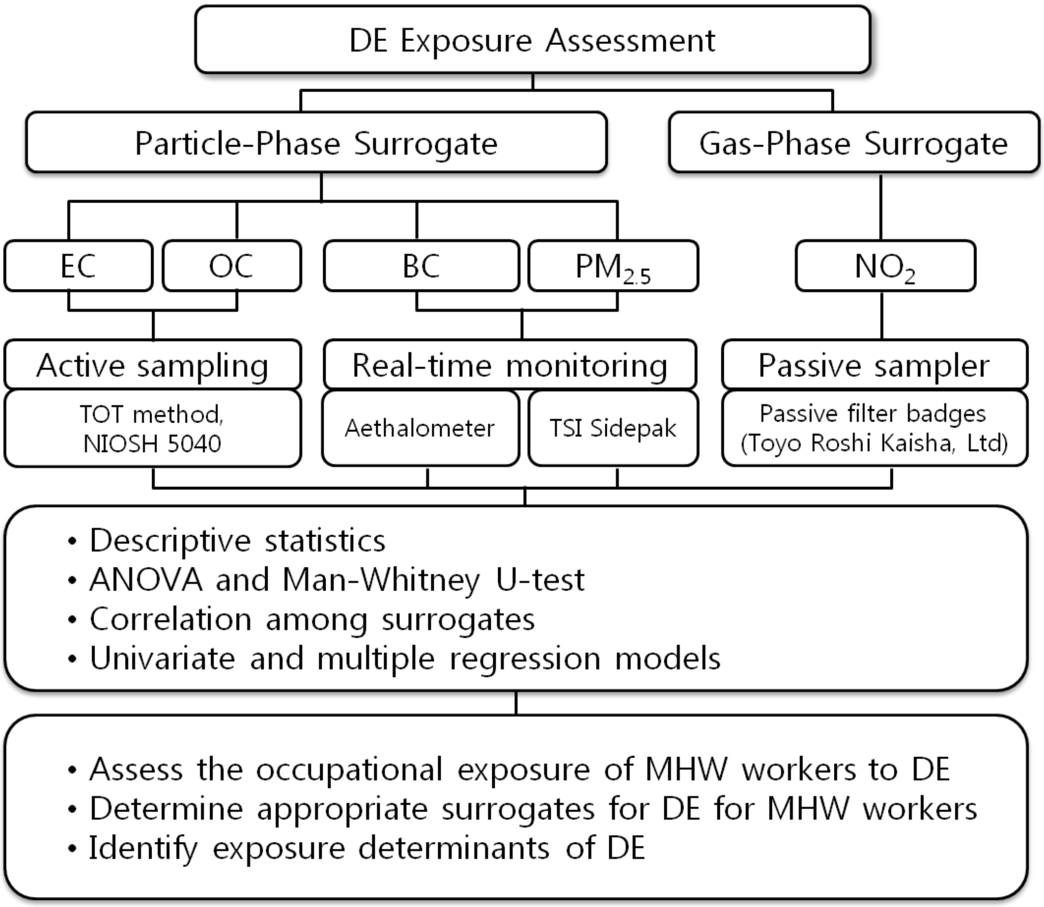

Figure 1-1. Study design.

2. Occupational Exposure to Diesel Particulate Matter in Municipal Household Waste Workers

This chapter was published in PLoS ONE on 6 August 2015.

2.1. Introduction

Diesel engines are the primary power sources for heavy-duty trucks, rail-road locomotives, marine vessels and a variety of off-road heavy equipment used in agriculture, construction and mining because they have a longer life, greater power, better fuel economy and require less maintenance compared to gasoline engines (U.S.EPA, 2002). In Korea, the number of diesel fueled vehicles has increased by 44% from 57,220,000 in 2008 to 82,310,000 in 2012. Data indicate that diesel powered vehicles accounted for 36.72% of the total vehicles used in 2012 (MOLIT, 2012).

Despite the advantages of diesel engines, they generate pollutants that are characterized as diesel engine exhaust (DE) (IPCS, 1996; U.S.EPA, 2002). DE is a complex mixture of gaseous and particle-phase emissions. Gaseous components of DE include carbon dioxide, oxygen, nitrogen, water vapor, carbon monoxide, nitrogen compounds, sulfur compounds, and numerous low-molecular-weight hydrocarbons. The particulate fractions are defined as diesel particulate matter (DPM). DPM is comprised of respirable particles of which 80–95% are fine particles <2.5 μm (Kittelson, 1998; U.S.EPA, 2002). DPM consists of a center core of elemental carbon (EC), which has attached organic compounds comprised of carbon and hydrogen molecules as well as small amounts of sulfate, nitrate, and other elements. The organic compounds are defined as organic carbon (OC) and may comprise 19–43% of the DPM, while the EC content may comprise 50–75% of the DPM (U.S.EPA, 2002). The composition and generation of DE varies depending on the age of the diesel engine, type of engine, fuel characteristics, driving cycle, and whether the exhaust is filtered (Clark *et al.*, 2002; Schuetzle and Frazier, 1986).

Recently, the International Agency for Research on Cancer (IARC) reclassified DE as “carcinogenic to humans (Group 1)” based on sufficient evidence that exposure is associated with an increased risk for lung cancer (Attfield *et al.*, 2012; IARC, 2012). The decision was based on a U.S. National Cancer Institute (NCI) and National Institute for Occupational Safety and Health (NIOSH) study that showed exposure-response relationships between respirable elemental carbon exposures and lung cancer mortality in underground miners (Attfield *et al.*, 2012; Silverman *et al.*, 2012). The IARC also noted a positive association (limited evidence) with an increased risk of bladder cancer (Group 1) (IARC, 2012).

Besides the adverse health effects of DE, DPM reduces atmospheric visibility and is known as the second leading contributor to global warming after carbon dioxide (Ramanathan and Carmichael, 2008). Airborne particulate matter reduces the amount of solar radiation affecting the Earth. The black carbon (BC) of DPM also absorbs visible solar radiation in the atmosphere. According to Jacobson, the magnitude of the direct radiative forcing from BC itself exceeds that due to methane, suggesting that BC controls may be more beneficial than methane controls in terms of preventing warming (Jacobson, 2001).

With the increased use of diesel engines, concern about occupational exposure to DE is also increasing. Kauppinen et al. estimated that approximately 3 million workers were exposed to DE in 15 countries of the European Union from 1990 through 1993 (Kauppinen *et al.*, 2000). The Occupational Safety and Health Research Institute (OSHRI) of Korea reported that the average number of workers exposed to DE rose from 261,000 in 1993 to 443,000 in 2012 (OSHRI, 2014).

Numerous studies have evaluated DPM exposure in various occupations, such as railroad repair and locomotive crews, truck and bus drivers, truck/bus garage mechanics, fire fighters, heavy equipment operators, underground miners, and tunnel construction workers. However, few studies have assessed exposure to DE emissions for municipal household waste (MHW) workers. In Korea, MHW workers are occupationally exposed to DE because the trash trucks have diesel-fueled engines and workers generally operate at the rear of the trucks where the tailpipes are located.

It has been reported that MHW workers are potentially exposed to musculoskeletal injury, bioaerosols, infectious materials, temperature extremes, diesel exhaust, and particulate matter (Lavoie *et al.*, 2006; Poulsen *et al.*, 1995). Previous studies on waste handlers have mainly focused on accident and occupational disease prevalence rates, exposures to bioaerosols and the association of bioaerosol exposure to health. Park et al. assessed the size characteristics of particulate matter and the effects of the type of waste-handling activity on the levels of PM during waste collection and sorting. However, the PM samples were not based on the personal exposures during a shift, and the measurements were not specific for DPM (Park *et al.*, 2013).

Since DPM is a mixture of various components, EC, OC, total carbon (TC, EC+OC), BC and fine particulate matter ($PM_{2.5}$) can be used to determine DPM exposures (Groves and Cain, 2000; Liukonen *et al.*, 2002; Verma *et al.*, 1999). Among these, EC is known as the preferred surrogate of DPM because it is generated proportionally to DPM, relatively free of interferences (unlike OC), and can be measured at low concentrations (Liukonen *et al.*, 2002; Seshagiri and Burton, 2003; Verma *et al.*, 1999). BC (black aerosol, soot, carbonaceous aerosol) is often used interchangeably with EC, but the term was defined by measuring light-absorbing carbon. EC and BC are comparable but slightly different in thermal, optical, and chemical characteristics.

The purposes of this study were to determine the following: 1) the exposure of MHW workers to diesel particulate matter (DPM) using EC, OC, TC, BC and $PM_{2.5}$ as surrogates; 2) the correlations among these surrogates; 3) the appropriate surrogate for DPM; and 4) factors that influence personal exposure to DPM.

2.2. Materials and Methods

2.2.1. Exposure Group Selection and Task Description

Five Korean MHW collecting companies, three in Goyang and two in Seoul agreed to participate in this study. Goyang is a medium-sized (267.31 km^2) suburban city near Seoul with a population of 1 million. Seoul is a metropolitan city with 10 million residents.

In Korea, MHW is classified into three types: solid waste, food waste, and recyclable materials such as plastic, paper, cans, clothes and bottles. All of the companies collect all three types of MHW. Workers who collect recyclable waste were excluded from this study because the recyclable waste trucks use LPG (liquefied petroleum gas). Only MHW workers who use diesel-powered trucks were included in this study. Trucks that collected solid waste went either to their respective incineration plants or to interim collection points such as landfills 2–5 times per day, depending on their route and pick-up locations. The food waste trucks went to their recycling plant several times a day.

A MHW collection truck is manned by 1–2 collectors and a driver. Collectors retrieve the MHW and dump it into the rear compartment of the truck. All of the trucks are equipped with a GPS (Global Positioning System) system, and hydrodynamic presses and have semi-automated systems to lift the trash bins or containers to dump the trash into the trucks. Collectors usually stay in the rear of the truck to dump the trash and to operate the press and lifting mechanisms. All of the exhaust tailpipes of the trash trucks are positioned under and toward the rear of the trucks and the rear of the truck is where workers have the greatest risk of exposure to DE (Fig. 1). Drivers stayed inside the trucks for more than 6 hours unless they needed to assist the collectors. Drivers would help if there were only one

(a)

(b)

Figure 2-1. Photographs of municipal household waste-collecting activities: (a) Riding on the rear of a truck, (b) Collecting MHW with samplers mounted.

2.2.2. Sampling Strategy

Field sampling was conducted over a period of 7 days between 26 June and 18 September 2014. The sampling locations, dates, number of samples collected and waste type are listed in Table 2-1. Seventy-two EC/OC/TC, 17 BC, and 21 $PM_{2.5}$ personal samples were collected from 72 MHW workers. Prior to each sampling date, workers and managerial staff were briefed on the plan, purpose, and method of the sampling, and the majority of the workers agreed to participate. Because of the limited number of available instruments for BC and $PM_{2.5}$ sampling, just one to two trucks and their workers were selected for comparative sampling of EC/OC/TC, BC and $PM_{2.5}$ during the meeting. To minimize possible sampling bias, we selected the most representative ones after discussing the workload, manning, collection route and locations with the company manager and workers.

On the sampling day, all workers who volunteered for sampling wore an EC/OC/TC sampler. The workers who had previously been selected for comparative sampling additionally wore BC and $PM_{2.5}$ samplers, as shown in Figure 2-1. The sampling was performed during the entire workday. Work schedules differed among the companies and between the two cities. The workday also varied depending on the route and the amount of MHW collected. Typically, a workday and sampling period ranged from 400 to 500 minutes. Since MHW collection is physically demanding, we were unable to collect repeat samples from the same worker. After the sampling was completed, all workers answered a short questionnaire about their employment history, number of service years and smoking habits.

Table 2-1. Summary of study companies, work hours, waste type and number of workers sampled

City	Company	Sampling date	Work hour	Type of waste	No of Truck Surveyed	Payload capacity (ton)	No of workers sampled					
							EC/OC/TC		BC		$PM_{2.5}$	
							Clt[a]	Drv[b]	Clt	Drv	Clt	Drv
Goyang	A	6/26/2014	04:00-13:00	Solid	4	5	8	4	2	1	2	1
	B	7/1/2014	04:00-13:00	Solid	3	5	6	3	1	1	1	1
				Food	2	5	2	1	–	–	–	–
		7/2/2014	04:00-13:00	Solid	2	5	4	2	1	1	1	1
				Food	3	5	2	3	–	–	–	–
		7/11/2014	04:00-13:00	Solid	4	5	5	4	1	1	–	1
				Food	1	5	1	1	–	–	–	–
	C	7/10/2014	04:00-13:00	Solid	3	5	5	3	1	1	2	2
				Food	2	5	2	2	–	–	–	–
Seoul	D	9/16/2014	20:00-0500	Solid	3	2.2-2.5	4	3	3	1	3	2
				Food	1	2.2	–	1	–	–	–	–
	E	9/18/2014	20:00-04:00	Solid	2	1.7-2.4	2	2	1	1	2	2
				Food	1	2.5	1	1	–	–	–	–
Total					31		42	30	10	7	11	10

[a] Collector
[b] Driver
Abbreviations: EC: elemental carbon; OC: organic carbon; TC: total carbon; BC: black carbon; $PM_{2.5}$: fine particulate matter.

2.2.3. Sampling and Analysis

All samples were collected in the breathing zone of the collectors and drivers. EC/OC/TC samples were collected on 37-mm diameter, pre-fired quartz filters (Pallflex® Tissuquartz™ 2500QAT-UP, Pall Life sciences, USA) mounted on a personal environmental monitor (PEMs, Cat No 761–203, SKC Inc., USA) using a personal sampling pump (MSA Escort ELF pump, Mine Safety Appliance Co., USA). Pumps were pre- and post-calibrated using a DryCal DC-Lite primary flow meter (DCL-H, Bios International Co., USA). According to the PEM manufacturer's instructions, the pump flow rate was set at 2 L/min. At this rate, PEM samplers have a 50% cut-off point for particulates with an aerodynamic diameter of 2.5 μm. Field blanks were collected daily at the measurement sites and were handled identically to the personal samples. All samples were sent for analysis to the laboratory of the Occupational Lung Diseases Institute, Korea Worker's Compensation and Welfare Service. This is the only laboratory in Korea that analyzes EC/OC/TC samples using NIOSH method 5040. The laboratory participates in the American Industrial Hygiene Association (AIHA) Proficiency Analytical Testing (PAT) program. 1.5 cm^2 of the quartz filter was punched out and analyzed using an OCEC carbon aerosol analyzer (Sunset Laboratory Inc., USA). The limit of detection (LOD) was 0.2 μg per cm^2 filter for both EC and OC. All sample measurements for this study exceeded the detection limit.

BC was measured using an aethalometer (microAeth model AE51, Magee Scientific, USA). This instrument measures the intensity of light (880 nm wavelength) transmitted through a T60 Teflon coated glass fiber and reports BC concentrations in ng/m^3. The default manufacture's specific attenuation coefficient of 16.6 m^2/g was used. The air sampling rate was set at 0.15 L/min to enhance the sensitivity per the manufacturer's manual. Real-time measurements were recorded every minute.

The $PM_{2.5}$ concentrations were measured using a real-time laser photometer (SidePak™ Model AM510, TSI Inc., USA). The SidePak has a built-in $PM_{2.5}$ μm impactor. The instrument was set to an airflow rate of 1.7 L/min. All SidePaks used had been calibrated by the manufacturer within the recommended one year interval. Real-time readings were collected every minute. The measured PM levels were corrected using the gravimetric calibration factor, which was determined by collecting parallel samples on PVC filters (37-mm, pore size 5.0 μm, SKC, Inc., USA) mounted on the PEM samplers. Detailed experimental procedures for the determination of the calibration factor are presented in the S1 file.

2.2.4. Ambient Background Levels

Ambient concentrations of EC, OC, TC, BC and $PM_{2.5}$ for the field sampling date were obtained from the air pollution monitoring stations in Goyang and Seoul. The data were taken from the database of Air Quality Information of Seoul metropolitan area and GyeongGi-Do in November 2014. Monitoring stations are located on the roofs of 3–4 story buildings in residential areas and near main streets. The monitoring station data used in our study were located where the MHW workers made their collections. However, if there was no monitoring station near the collection site, then the data from the closest station were used for the background values.

The Air Quality Information monitors use a semi-continuous OCEC field instrument (Sunset Laboratory Inc., USA) for EC/OC/TC, and aethalometer (model AE22, Magee Scientific Company, USA) for BC. $PM_{2.5}$ concentrations were measured by a ß-ray absorption method using a continuous particulate analyzer (SPM 613-D, Kimoto, Japan). All measurements were collected at hourly intervals and the mean concentrations were calculated from the sampling period.

2.2.5. Statistical Analysis

Probability plots of EC/OC/TC, BC and $PM_{2.5}$ data were right-skewed and a Kolmogorov-Smirnov analysis of the data indicated that the measurements would be best described by a lognormal distribution. All time-weighted average (TWA) data were natural-log-transformed for statistical analysis, and the geometric mean and geometric standard deviation were used for the mean and standard deviation in the descriptive statistics. Since the Although real-time measurements were made for the $PM_{2.5}$ and BC monitors, only TWA values were used in this study. The real-time measurements will be described in later article. The descriptive statistics (geometric mean, geometric standard deviation, minimum and maximum) were calculated. A Pearson's correlation analysis was performed to assess the relationships among the log-transformed concentrations of each DPM surrogate.

All EC/OC/TC, BC and $PM_{2.5}$ results were classified using occupational and environmental variables. An analysis of variance (ANOVA) and t-test were used for EC/OC/TC samples to evaluate the variability within and between the categories of occupational and environmental variables and to compare average levels among categories of occupational and environmental variables. Since the number of samples for BC and $PM_{2.5}$ were small, non-parametric method (Man-Whitney U test) was used to compare average levels among categories of variables.

Multiple regression analysis was performed to identify the main exposure determinants for EC and OC. Categorical variables with p-value <0.05 in the ANOVA test were included in a multiple regression analysis. In addition, continuous variables were examined using univariate analysis, and all significant variables with p-value<0.05 entered into a multiple regression analysis. A multiple linear regression model with the backward elimination method was used. For the final models, differences were considered significant at p<0.05. Model diagnostics were performed with plots of residuals against predicted values and using standardized normal probability plots. Statistics analysis was performed using SPSS 20.0 software (IBM, Armonk, NY).

Categorical variables used for statistical analysis are as follow.

- Job title (collector vs. driver). Drivers, who often helped with collection, were classified into a driver group.
- Waste type (solid vs. food)
- Diesel engine emission standard (Euro 3 vs. Euro 4). The information on the Euro engine standard of each truck was obtained from the manufacture based on the model of each truck.
- Age of the vehicle (<10-yr vs. ≥10-yr). The number of samples was dichotomized at 10-yr.
- Truck payload capacity (≤ 2.5 ton vs. 5 ton). This information was obtained from vehicle registration card of each truck. All trucks surveyed were two types of truck size, ≤ 2.5 ton and 5 ton.

- Diesel particulate filter (factory-installed vs. retrofitted). Surveyor obtained this information from the MHW company during the pre-survey and confirmed during the sampling.
- Location (suburban vs. urban). Based on the GPS information, surveyor coded the location where the worker mainly collected MHW. If the worker worked both areas, longer stayed area was selected.
- City (Goyang vs. Seoul)
- Number of collected truck containers (1–2 vs. 3–4). Surveyor obtained this information from the company after the sampling.
- Worker smoking habits (smoker vs. non-smoker). This information was obtained from the questionnaire that each worker filled out after sampling.

Continuous variables are as follow.

- Driving distance (km). This information was obtained from the GPS information.
- Average driving speed (km/h). This information was obtained from the GPS information.
- Truck age (y)
- Engine size (L)
- Percentage of slow driving (<20 km/h) during the sampling period. This information was obtained from the GPS information.
- Weight of collected waste (ton). Surveyor obtained this information from the company after the sampling.

2.3. Results

A total of 72 EC/OC/TC, 17 BC and 21 $PM_{2.5}$ measurements were made during MHW collections of solid and food waste. Table 2-2 shows the TWA values for EC, OC, TC, BC and $PM_{2.5}$ for each company. None of the EC, OC and TC measurements were below substance analytical LODs. All measurements were higher than the ambient background levels. The average ratio of exposure level to background level for EC, OC, TC, BC and $PM_{2.5}$ was 4.1, 12.7, 9.8, 2.0 and 4.4, respectively. Ambient background levels for each day of sampling are listed in Table 2-3.

Filter samples of EC TWAs ranged from 1.7 to 29.0 $\mu g/m^3$ with a geometric mean of 4.8 $\mu g/m^3$ and the OC TWAs ranged from 13.5 to 107.8 $\mu g/m^3$ with a mean of 39.6 $\mu g/m^3$. Real-time measurements for BC had TWAs that ranged from 6.0 to 19.6 $\mu g/m^3$ with a mean of 9.1 $\mu g/m^3$. The real-time measurement TWAs for $PM_{2.5}$ ranged from 27 to 240 $\mu g/m^3$ with a mean of 62 $\mu g/m^3$.

Table 2-2. Exposure levels (μg/㎥) of EC, OC, TC, BC and $PM_{2.5}$ by company

City	Company	Sampling date	N[a]	EC GM (GSD) Range	OC GM (GSD) Range	TC GM (GSD) Range	N[b]	BC GM (GSD) Range	N[c]	$PM_{2.5}$ GM (GSD) Range
Goyang	A	6/26/2014	12	5.8 (2.2) 2.3-29.0	56.1 (1.3) 33.3-97.8	63.1 (1.4) 35.7-115.0	3	9.7 (1.1) 8.4-11.0	3	125.0 (1.4) 98-188
	B	7/1, 2 &11/2014	34	4.8 (1.7) 2.4-22.3	44.5 (1.5) 20.6-107.8	48.9 (1.5) 23.3-112.2	6	9.4 (1.5) 6.3-19.6	5	102.7 (1.9) 54-240
	C	7/10/2014	12	4.1 (1. 3) 2.4-6.4	29.2 (1.4) 19.4-52.3	33.4 (1.4) 22.9-58.5	2	7.2 (1.2) 6.5-8.0	4	49.9 (1.5) 33-78
	Subtotal		58	4.8 (1.7) 2.3-29.0	42.8 (1.5) 19.4-107.8	47.6 (1.5) 22.9-115.0	11	9.0 (1.4) 6.3-19.6	11	84.8 (1.8) 33-240
Seoul	D	9/16/2014	8	3.4 (1.5) 1.7-5.2	34.9 (1.5) 22.3-69.5	38.7 (1.5) 24.0-72.2	4	7.5 (1.2) 6.1-9.2	5	36.8 (1.1) 33-44
	E	9/18/2014	6	7.1 (1.7) 3.5-14.2	22.5 (1.6) 13.5-53.7	30.1 (1.6) 17.0-63.2	2	13.9 (1.0) 13.6-14.2	4	46.7 (1.6) 27-71
	Subtotal		14	4.7 (1.8) 1.7-14.2	28.9 (1.6) 13.5-69.5	34.8 (1.5) 17.0-72.2	6	9.2 (1.4) 6.1-14.2	9	40.9 (1.4) 27-71
Total Samples			72	4.8 (1.7) 1.7-29.0	39.6 (1.6) 13.5-107.8	44.8 (1.5) 17.0-115.0	17	9.1 (1.4) 6.0-19.6	21	62.0 (1.9) 27-240

[a] Number of workers sampled for EC/OC/TC.
[b] Number of workers sampled for BC.
[c] Number of workers sampled for $PM_{2.5}$.
Abbreviations: EC: elemental carbon; OC: organic carbon; TC: total carbon; BC: black carbon; $PM_{2.5}$: fine particulate matter; GM: geometric mean; GSD: geometric standard deviation.

Table 2-3. Ambient background levels for each sampling period

City	Date	Sampling Time	EC ($\mu g/m^3$)	OC ($\mu g/m^3$)	TC ($\mu g/m^3$)	BC ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)
Goyang	6/26/2014	04:00-13:00	1.1	2.0	3.1	5.4	18.7
	7/1/2014	04:00-13:00	1.1	3.7	4.8	5.8	19.3
	7/2/2014	04:00-13:00	2.3	5.3	7.6	6.7	38.0
	7/10/2014	04:00-13:00	1.3	3.5	4.8	5.7	14.0
	7/11/2014	04:00-13:00	2.2	5.0	7.2	5.7	25.2
Seoul	9/16/2014	21:00-05:00	1.4	4.1	5.5	3.3	17.1
	9/18/2014	21:00-04:00	3.0	4.9	7.9	4.0	10.0

Abbreviations: EC: elemental carbon; OC: organic carbon; TC: total carbon; BC: black carbon; $PM_{2.5}$: fine particulate matter.

Table 2-4 presents the exposure levels to EC of other occupational groups. Compared with other occupations, the MHW collectors (GM=5.6 μg/m^3) were exposed to slightly higher levels than mechanics of truck repair garages (GM=3.2–5.9 μg/m^3), mechanics of locomotive workshops (GM=2.6–3.2 μg/m^3), truck drivers (GM=1.1–4.0 μg/m^3), railroad crews (GM=1.4–5.6 μg/m^3), and surface workers at mining facilities (GM= 1–4 μg/m^3) (Coble *et al.*, 2010; Davis *et al.*, 2007; Hewett and Bullock, 2014; Liukonen *et al.*, 2002; NIOSH, 1999; Ramachandran *et al.*, 2005; Seshagiri and Burton, 2003; Verma *et al.*, 2003). The exposures of MHW truck drivers (GM=3.8 μg/m^3) were comparable to local truck drivers (GM=1.2–4.0 μg/m^3) and long-haul truck drivers (GM=1.1–3.8 μg/m^3).

Table 2-4. Exposure levels (μg/m^3) to EC for different occupational groups

Occupational groups		Agent	N	GM	GSD	Location	Reference
Drivers	Truck drivers, local	EC_S	576	1.2	2.8	U.S.	(Davis *et al.*, 2007)
	Truck drivers, local	EC_I	–	4.0	–	US	(Liukonen *et al.*, 2002)
	Truck drivers, long haul	EC_S	349	1.1	2.3	US	(Davis *et al.*, 2007)
	Truck drivers, long haul	EC_I	–	3.8	–	US	(Liukonen *et al.*, 2002)
	Bus drivers	EC_S	39	1.4	3.3	US	(Ramachandran *et al.*, 2005)
Ramp attendants		EC_S	34	1.1	1.8	US	(Ramachandran *et al.*, 2005)
Mechanics	Garage mechanics	EC_S	35	3.2	1.7	US	(Ramachandran *et al.*, 2005)
	Truck mechanics	EC_I	40	5.9	3.1	Canada	(Seshagiri and Burton, 2003)
	Locomotive workshop worker	EC_I	40	2.6	3.2	Canada	(Seshagiri and Burton, 2003)
	Railway Mechanics	EC_R	28	3.2	2.4	Canada	(Verma *et al.*, 2003)
Railroad crews	Lead locomotives	EC	156	1.4	3.2	US	(Hewett and Bullock, 2014)
	Trailing locomotives	EC	22	5.6	3.4	US	(Hewett and Bullock, 2014)
	Train driver	EC_R	23	2.3	2.0	Canada	(Verma *et al.*, 2003)
	Lead locomotives (without preceding stacks)	EC_I	33	2.5	1.5	US	(Liukonen *et al.*, 2002)
Fire fighters		EC_I	16(a)	1.5	–	US	(Roegner *et al.*, 2002)
		EC_I	12	<LOQ 16(max)	–	US	(NIOSH, 1999)
Mining surface workers	Limestone facility	EC_R	33	4	2.2	US	(Coble *et al.*, 2010)
	Potash facility	EC_R	61	1	3.9	US	(Coble *et al.*, 2010)
MHW workers	Trash truck drivers	$EC_{2.5}$	42	5.6	1.8	Korea	Current study
	Trash collectors	$EC_{2.5}$	30	3.8	1.5	Korea	Current study

(a): area sample
Abbreviations: GM: geometric mean; GSD: geometric standard deviation; EC_S: submicron elemental carbon; EC_R: respirable elemental carbon; EC_I: inhalable elemental carbon; $EC_{2.5}$: elemental carbon, <2.5 μm in aerodynamic diameter; LOQ: limit of quantification; MHW: municipal household waste.

2.3.1. Relationships between DPM concentrations and various exposure factors

Table 2-5 presents a comparison of the EC, OC, TC, BC and $PM_{2.5}$ concentrations among occupational and environmental categories. The mean EC (N=42, 5.6 μg/m^3), OC (44.2 μg/m^3), and TC (50.1 μg/m^3) for MHW collectors were significantly higher than those for drivers (EC, N=30, 3.8 μg/m^3, p=0.003; OC, 34.1 μg/m^3, p=0.015; TC, 38.3 μg/m^3, p=0.008). This indicates that the job title significantly influenced personal exposure levels of EC, OC and TC. Similarly, the mean BC (N=10, 10.1 μg/m^3) and $PM_{2.5}$ (N=11, 68.6 μg/m^3) for the collectors were slightly higher than those of the drivers (BC, N=7, 7.8 μg/m^3 and $PM_{2.5}$, N=10, 55.6 μg/m^3), albeit not significantly so.

Table 2-5. EC, OC, TC, BC and $PM_{2.5}$ levels (μg/㎥) according to occupational and working environment factors

		EC			OC		TC		BC			$PM_{2.5}$		
		N[a]	GM (GSD)	p-value[d]	GM (GSD)	p-value[d]	GM (GSD)	p-value[d]	N[b]	GM (GSD)	p-value[e]	N[c]	GM (GSD)	p-value[e]
Job title	Collector	42	5.6 (1.8)	**0.003**	44.2 (1.6)	**0.015**	50.1 (1.5)	**0.008**	10	10.1 (1.4)	0.070	11	68.6 (2.0)	0.349
	Driver	30	3.8 (1.5)		34.1 (1.5)		38.3 (1.5)		7	7.8 (1.3)		10	55.6 (1.8)	
Waste type	Solid	55	5.0 (1.8)	0.281	39.5 (1.5)	0.934	45.0 (1.5)	0.881	17	9.1 (1.4)	–	20	62.1 (1.9)	0.952
	Food	17	4.2 (1.5)		40.0 (1.7)		44.2 (1.7)		–	–		1	62.0 (–)	
Truck age	<10yrs	40	4.3 (1.7)	0.079	36.0 (1.6)	**0.041**	40.9 (1.5)	**0.046**	9	9.4 (1.4)	0.571	11	57.4 (1.9)	0.209
	≥10yrs	32	5.5 (1.7)		44.8 (1.5)		50.2 (1.5)		4	8.2 (1.3)		6	86.4 (1.6)	
Engine emission standard	Euro 3	41	5.6 (1.9)	**0.004**	45.0 (1.5)	**0.005**	50.8 (1.5)	**0.004**	6	9.4 (1.5)	1.000	6	96.2 (1.8)	0.066
	Euro 4	31	3.9 (1.5)		33.5 (1.6)		38.0 (1.5)		11	8.9 (1.3)		15	52.1 (1.7)	
Truck payload capacity	≤2.5ton	16	4.7 (1.7)	0.908	29.9 (1.6)	**0.004**	35.7 (1.5)	**0.016**	6	9.2 (1.4)	1.000	9	40.9 (1.4)	**0.006**
	5ton	56	4.8 (1.8)		43.0 (1.5)		47.8 (1.5)		11	9.0 (1.4)		12	84.8 (1.8)	
Diesel Particulate Filter[f]	Factory installed	40	4.3 (1.7)	0.213	36.0 (1.6)	0.107	40.9 (1.5)	0.117	13	9.4 (1.4)	0.624	17	57.4 (1.9)	0.237
	Retrofitted	30	5.5 (1.4)		45.3 (1.5)		50.8 (1.5)		4	8.2 (1.3)		4	86.4 (1.6)	
Distance to tailpipe[g]	<4m	33	6.3 (1.8)	**0.010**	44.2 (1.6)	0.996	50.7 (1.6)	0.759	7	10.3 (1.4)	0.548	7	66.8 (2.2)	0.329
	≥4m	9	3.6 (1.3)		44.2 (1.5)		48.2 (1.4)		3	9.5 (1.2)		4	71.9 (1.7)	
Location	Suburban Area	18	4.2 (1.4)	0.266	36.2 (1.5)	0.332	40.1 (1.5)	0.215	5	8.9 (1.2)	0.879	5	91.9 (1.5)	0.075
	Urban Area	54	5.0 (1.8)		40.9 (1.6)		46.4 (1.6)		12	9.2 (1.4)		16	54.9 (1.9)	
No of collected truck containers	1-2	40	4.1 (1.7)	**0.007**	40.2 (1.7)	0.790	44.6 (1.7)	0.935	9	8.4 (1.2)	0.673	10	79.3 (1.8)	0.051
	3-4	32	5.8 (1.7)		39.0 (1.4)		45.0 (1.4)		8	9.9 (1.5)		11	49.7 (1.8)	
Smoking [f]	Smoker	40	4.9 (1.8)	0.866	49.3 (1.4)	**<0.001**	54.5 (1.4)	**<0.001**	7	8.9(1.5)	0.626	12	68.7 (2.0)	0.374
	Non smoker	30	4.7 (1.7)		30.6 (1.5)		35.4 (1.5)		10	9.2 (1.3)		9	60.5 (1.8)	

[a] Number of workers sampled for EC/OC/TC; [b] Number of workers sampled for BC; [c] Number of workers sampled for $PM_{2.5}$.
[d] p-value of ANOVA test for EC/OC/TC concentrations.
[e] p-value of Man-Whitney U test for BC and $PM_{2.5}$ concentrations. Non-parametric test was performed due to the small number of samples.
[f] There are two missing values.
[g] Straight distance from the end of tailpipe to the back end of the truck, where MHW collectors mainly stay. Drivers are not included in this category.
Abbreviations: EC: elemental carbon; OC: organic carbon; TC: total carbon; BC: black carbon; $PM_{2.5}$: fine particulate matter; GM: geometric mean; GSD: geometric standard deviation.

All MHW trucks surveyed had manufacture dates after 2000. Their average age was 8.2 y and they met either the Euro 3 or 4 diesel engine emission standards. The ANOVA test results indicated that the Euro engine standard (Euro 3 vs. Euro 4) was a significant factor affecting personal exposure levels to EC, OC, and TC, whereas the statistical power was weak for $PM_{2.5}$ (p=0.066). The workers using Euro 3 Standard trucks were exposed to higher levels of EC (N=41, 5.6 µg/m^3, p=0.004), OC (45.0 µg/m^3, p=0.005), TC (50.8 µg/m^3, p=0.004) and $PM_{2.5}$ (N=6, 96.2 µg/m^3, p=0.066) than those working on the Euro 4 trucks (EC, N=31, 3.9 µg/m^3; OC, 33.5 µg/m^3; TC, 38.0 µg/m^3; $PM_{2.5}$, N=15, 52.1 µg/m^3). Those working on trucks with a payload capacity equal to 5 tons had significantly higher exposures to OC (29.9 vs. 43.0 µg/m^3, p=0.004), TC (35.7 vs. 47.8 µg/m^3, p=0.016) and $PM_{2.5}$ (40.9 vs. 84.8 µg/m^3, p=0.006) than those on trucks with a payload capacity of less than 2.5 tons. No such relationship was found for the EC and BC data.

All of the exhaust tailpipes of the MHW trucks were positioned under and toward the rear of the trucks. The distance from the tailpipe to the rear of the truck varied from 1.2 to 4.2 m, depending on the truck model. The newer trucks had greater distances between the tailpipe and the rear of the truck. The collectors working on trucks with greater distances (≥4 m) between the tailpipe and the rear of the truck had lower EC exposures than the collectors who worked on trucks that had tailpipes closer than 4m to the rear of the truck (6.3 vs. 3.6 µg/m^3, p=0.010). However, this relationship was not observed for OC, TC, BC and $PM_{2.5}$ measurements.

The number and quantity of waste of the collections was a significant factor for the DPM exposure levels. Workers who collected more containers (3–4 vs. 1–2) had significantly higher exposure levels to EC (5.8 vs. 4.1 $\mu g/m^3$, $p=0.007$), but there was no significant difference for OC, TC, BC and $PM_{2.5}$. The workers who smoked during the sampling period had mean exposures to OC (49.3 vs. 30.6 $\mu g/m^3$, $p<0.001$) and TC (54.5 vs. 35.4 $\mu g/m^3$, $p<0.001$) that were significantly higher than those of the non-smokers, but there was no significant difference in their exposures to EC, BC and $PM_{2.5}$.

Figure 2-2 shows plots of mean TC levels for job title, smoking habits and vehicle factors. The mean levels of TC for the collectors, smokers, workers on larger trucks, and on trucks meeting Euro Standard 3 were significantly higher than the levels of the drivers, non-smokers, workers on smaller trucks, and those working on trucks meeting Euro Standard 4. Figure 2-2 also shows the ratio of OC to EC at the end of each column, which ranged from 1.4 to 26.1, with a mean of 8.2. The mean ratio of OC to EC for smokers, workers on larger trucks, and workers on trucks that had greater distances between the tailpipe and rear of the truck was significantly higher than those for the other categories of workers. This indicates that the former workers were exposed to significantly higher fractions of OC compared to EC.

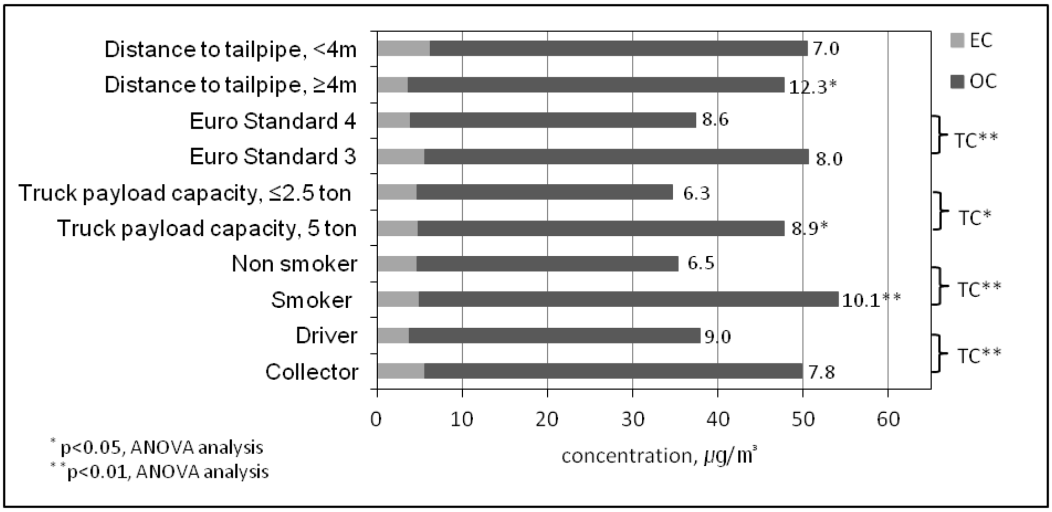

Figure 2-2. Geometric mean of TC and OC/EC according to job title, smoking habit, and type of truck. The geometric mean TC is presented as a bar chart. Each bar is the sum of EC (ivory bar) and OC (gray bar). The mean levels of TC for the collectors, smokers, workers on larger trucks and on trucks meeting Euro Standard 3 were significantly higher than those of the drivers, non-smokers, workers on smaller trucks, and those working on trucks meeting Euro Standard 4. The OC/EC is shown at the end of each bar. The OC/EC ratios for smokers, workers on larger trucks, and workers on trucks that had greater distances between the tailpipe and rear of the truck were significantly higher than those for the other categories of workers.

2.3.2. Correlations between DPM surrogates

The concentrations of EC were significantly correlated with the concentrations of OC, TC and BC, indicating a consistent pattern among representative DPM surrogates (Table 2-6). The Pearson correlation coefficients between EC levels and OC, TC, and BC were 0.325 ($p<0.01$), 0.468 ($p<0.001$), and 0.822 ($p<0.001$), respectively. $PM_{2.5}$ levels showed significant correlations with OC and TC, but not with EC and BC. Since TC is the sum of EC and OC, the significant correlation between $PM_{2.5}$ and TC is also related to the correlation between OC and $PM_{2.5}$.

Table 2-6. Correlation coefficients among levels of EC, OC, TC, BC and $PM_{2.5}$

	EC	OC	TC	BC	$PM_{2.5}$
EC	1.000				
OC	0.325*	1.000			
TC	0.468***	0.983***	1.000		
BC	0.822***	0.258	0.458**	1.000	
$PM_{2.5}$	0.283	0.650*	0.677***	0.319	1.000

* $p<0.01$ correlation is significant at the 0.01 level (one-tailed).
** $p<0.05$, correlation is significant at the 0.05 level (one-tailed).
*** $p<0.001$ correlation is significant at the 0.001 level (one-tailed).
Abbreviations: EC: elemental carbon; OC: organic carbon; TC: total carbon; BC: black carbon; $PM_{2.5}$: fine particulate matter.

2.3.3. Multiple linear regression analysis

Table 2-7 summarizes the results of the multiple linear regression analysis performed to identify exposure determinants affecting the levels of EC, OC and TC. The EC multiple regression model included seven variables related to the vehicle, worker activity, and environment. The factors included in the multiple regression analysis were selected after performing a univariate analysis using a significance level of 0.05. The univariate analysis results for EC levels were: job title (ß=0.387, p=0.003), Euro engine standard (ß=-0.376, p=0.004), truck age (ß=0.043, p=0.024), number of truck containers collected (ß=0.267, p=0.008), percentage of slow driving (< 20 km/h) during the sampling period (ß=2.146, p=0.014), average driving speed (ß=-0.038, p=0.024), and the ambient background level (ß=0.043, p=0.682). The background level was applied to adjust for the effects of ambient levels. Ambient values vary depending on the amount of traffic and the occasional Asian dust event (Kim, 2008; Kim and Kim, 2003). The variables were selected based on the backward elimination method for the multiple regression model. The final model to predict EC exposure levels included job title, Euro engine standard, and average driving speed (adjusted R^2=0.382, p<0.001).

Table 2-7. Multiple regression models to predict natural log-transformed EC (μg/m^3), OC (μg/m^3) and TC (μg/m^3) levels

Occupational and environmental factors		N	EC		OC		TC	
			Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
Intercept			2.576	<0.001	3.169	<0.001	4.573	<0.001
Truck model	Euro standard 3		Reference		Reference		Reference	
	Euro standard 4		-0.536	<0.001	-0.256	0.003	0.300	<0.001
Job title	Driver		Reference		Reference		Reference	
	Collector		0.408	0.001	0.205	0.014	-0.239	<0.001
Average driving speed (km/hr)			-0.055	<0.001	a	a	a	a
Smoking	Non-smoker		a	a	Reference		Reference	
	Smoker				0.460	<0.001	0.413	<0.001
Truck payload capacity (ton)			b	b	0.089	0.025	b	b
Ambient background level			0.109	0.262	-0.039	0.288	-0.021	0.382
Modeling Results	Adjusted R^2	72	0.382	<0.001	0.470	<0.001	0.413	<0.001

a: The variables were not included as candidate variables because they did not show significant results during the univariate regression.
b: The variables were removed to improve the model during the backward elimination.
Abbreviations: EC: elemental carbon; OC: organic carbon; TC: total carbon.

Six variables were included in the OC model: job title (ß=0.261, p=0.015), Euro engine standard (ß=-0.295, p=0.005), truck payload capacity (ß=0.140, p=0.004), smoking (ß=0.094, p<0.001), city (ß=-0.397, p=0.003), and ambient background level (ß=-0.063, p=0.198). The final model to predict the OC exposure level included smoking, Euro engine standard, job title and truck payload capacity (adjusted R^2=0.470, p<0.001).

For TC model, six variables were included: job title (ß=0.271, p=0.008), Euro engine standard (ß=-0.292, p=0.004), truck payload capacity (ß=0.110, p=0.018), smoking (ß=0.433, p<0.001), type of DPF (ß=0.214, p=0.041) and the ambient background level (ß=-0.037, p=0.239). The final model confirmed that smoking, Euro engine standard, and job title is main exposure determinants of TC levels (adjusted R^2=0.413, p<0.001).

2.4. Discussion

Our study determined the exposure levels of MHW workers to DPM by sampling and analyzing EC, OC, TC, BC and $PM_{2.5}$. All measurements were considerably higher than the ambient background levels; the mean ratio of exposure levels to background levels for EC, OC, TC, BC and $PM_{2.5}$ were 4.1, 12.7, 9.8, 2.0 and 4.4, respectively. Among the five surrogates, EC measurements showed consistent and reliable exposure patterns against various exposure factors, such as job title, European engine emission standard, distance from the rear of the truck to the engine tailpipe, age of truck, average driving speed, number of containers collected, etc. The concentrations of EC were significantly correlated with the concentrations of OC, TC and BC indicating a consistent pattern among representative DPM surrogates. The multiple regression model confirmed that job title, European engine emission standard and average driving speed were the most influential factors in determining EC exposures.

We assessed personal exposure levels to EC, OC, TC, BC and $PM_{2.5}$ for five MHW collection companies. However, there is no occupational exposure limit (OEL) for DPM recommended by standard occupational safety organizations for general industry workers. The existing OEL guidelines are all for underground miners. The Mine Safety and Health Administration (MSHA) recommends a Permissible Exposure Limit (PEL) of 160 $\mu g/m^3$ (measured as TC which is equivalent to 120 $\mu g/m^3$ for EC) while the Australia Department of Natural Resources and Mines (DNRM) recommends an exposure limit of 100 $\mu g/m^3$ (measured as EC) (DNRM, 2012; MSHA, 2001). The MSHA states that its

PEL was based on feasible control of emissions in mines and not on adverse health effects. American Conference of Governmental Industrial Hygienists (ACGIH) proposed a Notice of Intended Change (NIC) of the Threshold Limit Value (TLV) to 20 $\mu g/m^3$ expressed as EC in 2001, but withdrew the NIC in 2003 (ACGIH, 2001). Some local governments use a ACGIH guideline of 20 $\mu g/m^3$ for general industry (CHDS, 2002). This is the lowest OEL value recommended for general industry workers. In this study, three of 72 EC measurements (4.1%) exceeded the 20 $\mu g/m^3$ concentration and the 95th percentile of EC measurements was 22.0 $\mu g/m^3$ for MHW collectors and 10.0 $\mu g/m^3$ for drivers.

Comparisons of DPM levels should be carefully examined because of differences in sampling and analytical methods for the DPM surrogates. Several sampling and analysis methods have been used to measure EC concentrations and the results can significantly differ depending on the measurement technique (Birch and Cary, 1996; Chow *et al.*, 2001; Fung, 1990; Schauer, 2003). Therefore, we compared our results with the EC levels of other occupational groups measured using NIOSH method 5040 in Table 2-4. In summary, the exposure levels of MHW workers were markedly lower than those for underground miners and tunnel construction workers (Bakke *et al.*, 2001; Coble *et al.*, 2010). However, the MHW collectors were exposed to slightly higher levels than mechanics of truck garages and locomotive workshops, truck drivers, railroad crews, and surface workers at mining facilities. The exposures of MHW truck drivers were similar to local truck drivers and long-haul truck drivers.

Ambient background levels could be an important factor when comparing the exposure levels of MHW workers to those of other groups. MHW workers start their work either early in the morning or at night to avoid traffic congestion. Some of the sampling periods included travel during the morning rush hour. No Asian dust or yellow sand events, which can significantly affect the sampling results, occurred during the sampling dates. EC levels for the company "E" workers sampled recorded the highest level with a geometric mean of 7.1 $\mu g/m^3$. However, it should be noted that the ambient background level on 18 September 2014 when the company "E" workers were sampled was 3.0 $\mu g/m^3$. This is higher than those of the other sampling days. If the background level is subtracted from the EC concentrations of the company "E" workers, their exposure levels could be lower than those of the company "A" workers. The geometric mean of EC levels for the company "A" workers was 5.8 $\mu g/m^3$ and the background level on that day was 1.1 $\mu g/m^3$. Although this may indicate that the higher exposure levels of company "E" workers were caused by the higher ambient background level, it is obvious that MHW workers had occupational exposures to DPM that were much higher than ambient background levels based on the statistical analysis results ($p<0.001$).

BC levels showed high correlation with EC levels, but the mean BC level was about two fold the mean EC level. The ratio of BC/EC ranged from 1.18 to 3.08 with a mean of 1.99. Numerous inter-method and inter-location comparisons to determine EC and BC levels showed variations between EC and BC concentrations (Andreae and Gelencsér, 2006; Jeong *et al.*, 2004; Jeong *et al.*, 2008; Salako *et al.*, 2012; Yelverton *et al.*, 2014). Since BC measurements contain organic components that absorb light (e.g., brown carbon) in addition to EC, this may explain the differences between EC and BC (Andreae and Gelencsér, 2006; Yelverton *et al.*, 2014). An inter-comparison study of BC and EC levels reported that the slopes of co-located BC vs. EC measurements were 2.7 and 3.3 for two cities during the summer of 2002 (Jeong *et al.*, 2004). A study performed in Korea on seasonal variations in BC and EC levels in the atmosphere, reported ratios of BC/EC ranging from 0.98 to 1.38, showing the highest slope in the summer of 2007 (Jeong *et al.*, 2008). It has been reported that the optical attenuation coefficients to measure BC can differ depending on the size distribution and mixing state of the aerosols, chemical characteristics of light-absorbing species, and deposited mass per unit time (Ballach *et al.*, 2001; Bond *et al.*, 2006; Jeong *et al.*, 2004; Ng *et al.*, 2007). Since the aethalometer uses a specific attenuation coefficient of 16.6 m^2/g, BC measurements using aethalometer for EC require site-specific calibration because of the optical properties of the aerosol.

One-way ANOVA and univariate analyses showed that EC levels were significantly related with European engine standard of the truck, job title, average truck speed, distance from the rear of truck to tailpipe, age of truck, and workload (number of containers collected). Among these variables, the multiple regression model confirmed that the European engine standard, job title, and average truck speed played a key role in the measured EC levels. Although BC levels had the highest correlation with EC, BC levels did not show as significant a relationship or exposure pattern as the EC values. The aethalometer has been rarely used in the industrial hygiene field, but has been used frequently to monitor atmospheric DPM levels. This study indicates that further studies are required to evaluate the validity of BC measurements as a DPM surrogate for the occupational environment.

The average $PM_{2.5}$ level was 62 μg/m^3, ranging from 27 to 240 μg/m^3. These levels were 4.4-fold higher than the ambient background level and higher than the Korean Ministry of the Environment ambient air quality standard for $PM_{2.5}$ (24-h average=50 μg/m^3, annual average=25 μg/m^3) (KoreaMOE, 2013). Park et al. categorized MHW collection activities in Korea and reported $PM_{2.5}$ exposure levels during collection (73.29 μg/m^3), transfer (223.39 μg/m^3), sorting (61.57 μg/m^3) and transport (73.90 μg/m^3) (Park *et al.*, 2013). Since "transfer" and "sorting" activities are part of recyclable material collection, they were not included in the present study. Our $PM_{2.5}$ results were similar to those of the "collection" and "transport" activities in the study by Park et al.

Those workers using Euro standard 3 engines (p=0.037) and larger trucks (p=0.004) were exposed to higher $PM_{2.5}$ concentrations. Greater workload (p=0.086) and operating in suburban areas (p=0.109) also contributed to higher $PM_{2.5}$ concentrations without significance. However, EC levels did not differ based on truck size (p=0.908) and location (p=0.266). These results indicate that particulate matter may have originated from other sources besides MHW truck exhaust. Goyang is a medium-sized suburban city that has frequent foggy weather due to a lake, some unpaved roads, and an incineration plant within 6 km of the truck routes. These factors may have increased the $PM_{2.5}$ concentration in Goyang.

The exposures of the MHW workers had significantly higher OC/EC ratios than those reported in other studies, ranging from 1.4 to 26.1, with a mean of 8.2. It has been reported that the OC/EC ratio is generally <1 for diesel engines and >1 for gasoline engines (Pio *et al.*, 2011). In addition, it has been reported that OC interferences should be suspected if the EC/TC ratio is <0.35 (Birch, 2003; Sirianni *et al.*, 2003). Converting the EC/TC ratio of 0.35 to an OC/EC ratio, if the OC/EC ratio is >1.8, this indicates an additional possible source of OC. We employed a PEM sampler to exclude EC interference by larger particles. However, OC interferences caused by bioaerosols from food and solid waste and cigarette smoke could not be excluded on the basis of their particle size. The multiple regression model for OC confirmed that OC levels were most affected by the workers' smoking habits.

There is another possible explanation as to why our results showed much higher OC/EC ratios. It has been reported that the chemical composition of the filter and collected sample can influence the temperature at which EC is evolved during thermal-optical analysis (Lin and Friedlander, 1988). For example, biomass smoke contains inorganic components that catalyze oxidation of EC and result in lowering the oxidation temperature (Novakov and Corrigan, 1995). Wang et al. studied the effect of metal salts on the quantification of EC and OC in DPM and showed that metals in ambient aerosols reduced the oxidation temperature of EC and enhanced the charring of OC, and that the resulting EC/OC ratio was reduced by ~80%; i.e., the OC/EC ratio was increased by fourfold, depending on the metals and metal to carbon ratio (Wang *et al.*, 2010). Since MHW workers can be exposed to various trace metals that can be generated from dirt and solid and food wastes, this could explain the high OC/EC ratios and the possibility of underestimation of EC.

To elucidate why this study resulted in significantly higher OC/EC ratios, additional experiment was performed between 31 October and 3 November 2015. The results are presented in Appendix II. In summary, the mean OC/EC ratio of DE from the idling truck was 9.8 and the OC/EC ratio of malodor without diesel engine running was 9.5. This is the much higher OC/EC ratio than that of background level (2.4–5.9). On the other hand, the ratio of slow running truck was 6.5 and the ratio of a diesel van that does not have DPF was only 0.5. These results suggest that the higher OC/EC ratio in this study was caused by the driving condition of MHW trucks (mainly idling and slow driving) and malodor of waste. In addition, these indicate that OC and TC is not an appropriate surrogate of DE for MHW workers because OC and TC are significantly affected by malodor from waste.

Trash trucks manufactured after 2005 had an original factory-installed DPF and trucks manufactured before 2005 were retrofitted at commercial workshops, as required by Korean environmental regulations (KoreaMOE, 2003). There was no significant difference in EC, OC, TC, BC and $PM_{2.5}$ levels between factory installed and retrofitted filter systems. DPF is an important factor in the generation of DPM and worker exposure. According to the DPF manufacturer's specifications, the DPF installed on trucks can reduce DPM by 90% via catalyst reaction and exhaust filtering. This figure is based on the truck being driven for more than 20 minutes at speeds of at least 70 km/h or more.

However, the average driving speed for all the MHW trucks surveyed ranged from 11 to 30.2 km/h where the driving period over 70 km/h was less than 6 min/day. Therefore, the efficiency of the DPFs would be expected to be considerably lower than the manufacturer's claim.

Several limitations are associated with this study, and it might not be sufficiently representative of MHW collection. MHW collection varies according to the size and location of the routes, the trucks, emissions controls, local environmental conditions, waste management system, etc. The number of parallel samples collected was small due to the limited number of instruments for BC and $PM_{2.5}$,, and fewer BC and $PM_{2.5}$ samples were collected than EC and OC samples. The BC and $PM_{2.5}$ data showed some concentration differences depending on the job title and number of collected containers, but the results were not statistically significant. Additionally, this study may have missed some important factors. During a walk-through survey, we were informed that there could be considerable differences in seasonal and workday workload. MHW workers may collect more waste on Mondays, immediately after holidays, and during kimchi-making season (most Korean houses, restaurants and kimchi factories prepare kimchi for the winter in November using mainly Chinese cabbage and a large quantity of waste is generated during the trimming process). However, we did not sample during that time, hence our assessments may have underestimated worker exposure to DPM.

2.5. Conclusions

This is the first study to assess the exposure of MHW workers to DPM using five surrogates; EC, OC, TC, BC and $PM_{2.5}$. The exposure levels of the MHW collectors were slightly higher than those of mechanics in truck repair garages and locomotive workshops, truck drivers, railroad crews and surface workers at mining facilities. Among the five DPM surrogates sampled, EC was the most appropriate for determining MHW worker exposure. The source of EC for the MHW workers was mainly trash truck engines. The measurement of EC as a surrogate of DPM had less interference than OC, BC and $PM_{2.5}$, and yielded a consistent and relevant exposure pattern for the various exposure factors examined.

We also investigated various occupational, vehicle and environmental factors that could significantly affect DPM exposure levels. We found that the job title, the truck engine's European engine emission standard, and the average driving speed were the most important exposure factors for EC exposure. It should be noted that environmental regulations and auto/truck industry vehicle exhaust standards could reduce MHW worker exposure levels by increasing compliance. Therefore, the current study results should not be used to estimate past or future MHW worker exposure levels. Further study of MHW worker exposure to DPM should be conducted to include a wider range of occupational and environmental situations, and additional MHW collection procedures, daily and seasonal situations, and types of vehicle, and possibly different types of fuel.

3. Exposure Assessment for Diesel Engine Exhaust using NO_2 and EC in Municipal Household Waste Workers

3.1. Introduction

Municipal household waste (MHW) workers are exposed to various occupational health hazards such as bioaerosols, infectious materials, temperature extremes, ultra violet radiation, dusts, vehicle exhausts, noise, ergonomic concerns, etc (Lavoie *et al.*, 2006; Poulsen *et al.*, 1995). In Korea, MHW collection workers are occupationally exposed to diesel engine exhaust (DE), because most trash trucks are diesel-fueled vehicles and the workers spend their time at the rear of the trucks where the engine exhaust tailpipe is located (Lee *et al.*, 2015). However, few studies were conducted to determine MHW workers' exposures to DE emissions.

DE is a highly complex mixture of gaseous and particle-phase emissions. The gaseous components of DE contain carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx, nitrogen oxide (NO) + nitrogen dioxide (NO_2)), sulfur oxides, numerous hydrocarbons, etc (U.S.EPA, 2002). The particulate fractions are usually called diesel particulate matter (DPM). DPM consists of a center core of elemental carbon (EC) which has attached organic carbon (OC) comprised of hydrocarbons and small amounts of sulfate, nitrate, and other elements (U.S.EPA, 2002). In general, worker exposures to DPM have been assessed using several surrogates such as particulates, EC, total carbon (TC), black carbon (BC), etc.

In chapter 2, we addressed exposures of MHW workers' exposure to DPM based on EC, OC, TC, BC and fine particulate matter ($PM_{2.5}$) measurements (Lee *et al.*, 2015). All MHW workers had DPM exposures that were considerably higher than the ambient background levels. In comparison with other occupations, MHW collectors had higher exposure levels to EC (geometric mean (GM)= 5.6 $\mu g/m^3$) than those mechanics working in truck repair garages (GM=3.2–5.9 $\mu g/m^3$), mechanics working in locomotive workshops (GM=2.6–3.2 $\mu g/m^3$), truck drivers (GM=1.1–4.0 $\mu g/m^3$), railroad crews (GM=1.4–5.6 $\mu g/m^3$), and surface workers at mining facilities (GM=1–4 $\mu g/m^3$) (Coble *et al.*, 2010; Davis *et al.*, 2007; Hewett and Bullock, 2014; Liukonen *et al.*, 2002; NIOSH, 1999; Ramachandran *et al.*, 2005; Seshagiri and Burton, 2003; Verma *et al.*, 2003). We also identified that EC was the best quantifiable surrogate of DPM for MHW workers. We concluded that EC truly represented worker exposures and was little affected by interferences such as worker smoking habits or ambient dusts whereas OC and TC were influenced by those interferences.

MHW workers are also exposed to various gaseous constituents of DE but few studies have assessed personal exposure to DE gases. Gases like CO, NOx and poly aromatic hydrocarbons (PAHs) have been measured to assess exposures to DE gases. Among them, NOx has been frequently used as a representative surrogate because diesel engines generate much more NOx than gasoline-fueled engines. In recent years, NO_2 is becoming a significant concern of DE because after-treatment devices for DE control can generate more NO_2 fractions among NOx due to the oxidation of NO (Czerwinski *et al.*, 2012; Feng *et al.*, 2014; U.S.EPA, 2008b). According to DEFRA (Department for Environment, Food & Rural Affairs, UK) report, NO_2 from diesel-fueled vehicles has increased overall from 10–15% for Euro 3 Standard vehicles to an average of almost 30% for newer Euro 4 or 5 vehicles. Besides, it was found that diesel engines emit more NOx as the engine power has increased for Euro 3 to Euro 5 vehicles (Carslaw and Rhys-Tyler, 2013a). The use of low sulfur fuels has also contributed to the increase of NO_2 emission (Czerwinski *et al.*, 2012).

NO_2 has higher toxicity than NO. Since NO_2 can increase the risk of respiratory disease by irritating deep lung tissue, several countries and standard occupational safety organizations have lowered the occupational exposure limit (OEL) for NO_2 (ACGIH, 2012; U.S.EPA, 2008a). Since 2004, the Dutch have used an OEL of 0.2 ppm (376 $\mu g/m^3$) for an 8-hr TWA and 0.5 ppm for a short term exposure limit (STEL) (HCN, 2004). To protect workers with asthma, ACGIH in 2012 lowered the TWA –TLV from 3 ppm to 0.2 ppm and eliminated the previous STEL of 5 ppm. The European Scientific Committee on Occupational Exposure Limits (SCOEL) recommends a TWA of 0.5 ppm with a STEL of 1 ppm (SCOEL, 2014).

NO_2 can be measured using passive monitors or a direct-reading instrument. Compared to measurements of the other components of DE such as PAHs and EC, the measurement of NO_2 is easier and requires a less complicated lab procedure. EC has been used as a preferred surrogate of DE exposure. NO_2 can be a good surrogate of exposure because it is an increased exhaust component of diesel-fueled engines, it has a low OEL and it is relatively easy to measure.

The objective of this study was to characterize MHW workers' exposure to NO_2, and determine factors that influence personal exposure to NO_2. We also evaluated NO_2 whether it can be used as an alternative surrogate of DE for MHW workers. This was done by comparing exposure profiles on occupational and environmental factors and determining correlation between NO_2 and EC. The EC data reported in chapter 2 was utilized for this chapter to compare NO_2 and EC exposures as possible values to determine DE exposure.

3.2. Materials and Methods

3.2.1. Subjects and Sampling Strategy

Five Korean MHW collecting companies, three in Goyang and two in Seoul participated in this study. Field sampling was conducted for 7 days between 26 June and 18 September 2014. Detailed information on how study subjects were selected, how sampling was performed, and how MHW workers performed their job tasks were described in chapter 2. The sampling locations, dates, number of samples collected and the waste type are listed in Table 3-1. Each worker who volunteered for sampling wore an NO_2 passive filter badge and an EC sampler during a full workday. Work schedules and work days varied depending on the company, city, collection route and the amount of MHW collected each day. Typically, a workday and sampling period ranged from 400 to 500 minutes. After each day's sampling, the worker completed a short questionnaire about his employment history, number of service years and smoking habit.

3.2.2. Sampling and Analysis

All samples were collected in the breathing zones of the waste collectors and drivers. NO_2 samples were taken using passive filter badges (Toyo Roshi Kaisha, Ltd). These samplers absorb NO_2 on a cellulose fiber filter coated with a triethanolamine solution. Field blanks were prepared at the measurement sites every sampling day. The field blanks were handled the same as the personal samples. For analysis, a color agent is added to the filter and the absorbance of the diazo coupling of NO_2 and NEDA (N-(1-

Napthyl)-ethylenediamine dihydrochloride) in the color reagent is measured spectro-photometrically at 540 nm (Shimadzu UV-VIS Spectrophotometer, model UV-1201, Shimadzu Co., Japan). The limit of detection is 66 ppb-hr. The detailed analytical method and sampling and analysis errors were reported previously (Yanagisawa and Nishimura, 1982).

Respirable EC samples were collected on 37 mm diameter, pre-fired quartz filters (Pallflex® Tissuquartz™ 2500QAT-UP, Pall Life sciences, USA) mounted in personal environmental monitors (PEMs, Cat No 761-203, SKC Inc., USA). PEMs were connected to air sampling pumps and were analyzed using NIOSH method 4050. The detailed analytical method was described in chapter 2.

3.2.3. Ambient Background Levels

Ambient concentrations of NO_2 were collected from the database of AIR Quality Information of Seoul metropolitan and Gyeonggi-do. This database also had EC air sampling data. The database and air pollution monitoring stations are the same ones where the EC data in the previous chapter. NO_2 concentrations at the monitoring stations were measured using a spectrophotometer (NA 623, Kimoto Electric Co., Japan). All measurements were collected at hourly intervals and averaged over the personal sampling periods.

Table 3-1. Summary of study companies, work hours, waste type and number of samples

City	Company	Sampling date	Work hour	Type of waste	No of Truck Surveyed	Payload capacity (ton)	No of samples	
							Collector	Driver
Goyang	A	6/26/2014	04:00-13:00	Solid	4	5	7	3
	B	7/1/2014	04:00-13:00	Solid	3	5	6	3
				Food	2	5	2	1
		7/2/2014	04:00-13:00	Solid	2	5	4	2
				Food	3	5	2	3
		7/11/2014	04:00-13:00	Solid	4	5	4	4
				Food	1	5	1	1
	C	7/10/2014	04:00-13:00	Solid	3	5	5	3
				Food	2	5	2	2
Seoul	D	9/16/2014	20:00-05:00	Solid	3	2.2-2.5	4	3
				Food	1	2.2	–	1
	E	9/18/2014	20:00-04:00	Solid	2	1.7-2.4	2	2
				Food	1	2.6	1	1
Total					31		40	29

3.2.4. Statistical Analysis

Basically, same statistical analysis that was performed in chapter 2 was repeated to analyze NO_2 data. According to Kolmogorov-Smirnov analysis and probability plots, NO_2 data distribution was best described by a lognormal distribution similar to the EC data. Therefore, all the time-weighted average (TWA) data were natural-log-transformed for statistical analysis in this study. Descriptive statistics were presented using GM, geometric standard deviation (GSD), minimum and maximum. Exposure assessment statistics were also calculated using exceedance fraction of working OELs and the 95th percentile. A Pearson's correlation analysis was performed to assess the associations among the log-transformed concentrations of each sample.

All NO_2 and EC results were classified using occupational and environmental variables. An analysis of variance (ANOVA) and t-test were used to evaluate the variability within and among categories of occupational and environmental variables and to compare average levels between categories of those variables.

Multiple linear regression analysis was performed to identify main exposure determinants for NO_2 and EC. Categorical variables with p-values <0.05 of ANOVA analysis were included in a multiple regression analysis. For continuous variables, univariate analysis was performed and significant variables with p-value<0.05 entered into the multiple regression analysis. A multiple linear regression model was used with the backward elimination method. For the final model, differences were considered significant at $p<0.05$. Model diagnostics were carried out with plots of residuals against predicted values and using standardized normal probability plots. Statistics analysis was carried out using the SPSS 20.0 program (IBM, Armonk, NY).

Categorical variables used for statistical analysis are as follow.

- Job title (collector vs. driver). Drivers, who often helped with collection, were classified into a driver group.
- Waste type (solid vs. food)
- Diesel engine emission standard (Euro 3 vs. Euro 4). The information on the Euro engine standard of each truck was obtained from the manufacture based on the model of each truck.
- Age of the vehicle (<10-yr vs. ≥10-yr). The number of samples was dichotomized at 10-yr.
- Diesel particulate filter (factory-installed vs. retrofitted). Surveyor obtained this information from the company during the pre-survey and confirmed during the sampling.
- Location (suburban vs. urban). Based on the GPS information, surveyor coded the location where the worker mainly collected MHW. If the worker worked both areas, longer stayed area was selected.
- City (Goyang vs. Seoul)
- Number of collected truck containers (1–2 vs. 3–4). Surveyor obtained this information from the company after the sampling.
- Worker smoking habits (smoker vs. non-smoker). This information was obtained from the questionnaire that each worker filled out after sampling.

Continuous variables are as follow.

- Driving distance (km). This information was obtained from the GPS information.

- Average driving speed (km/h). This information was obtained from the GPS information.
- Truck age (y)
- Engine size (L). This information was obtained from vehicle registration card of each truck.
- Percentage of slow driving (<20 km/h) during the sampling period. This information was obtained from the GPS information.
- Weight of collected waste (ton). Surveyor obtained this information from the company after the sampling.

3.3. Results

A total of 69 NO_2 and 72 EC measurements were taken while MHW workers collected solid and food wastes. However, 3 EC measurements were excluded in this chapter because of missing NO_2 data. TWA values for NO_2 and EC for each company are presented in Table 3-2. NO_2 concentrations ranged from 40.7 to 248.6 μg/m^3 with GM of 105.3 μg/m^3. EC concentrations ranged from 1.7 to 29.0 μg/m^3 with GM of 4.9 μg/m^3. None of the measurements exceeded the OEL of 376 μg/m^3.

All NO_2 and EC measurements were above the ambient background level as well as the analytical LOD. On average, the NO_2 concentrations were 4.1-fold higher than the background concentration. Exposure levels for trash collectors and drivers were 4.9 and 3.0-fold higher than the ambient background levels. In turn, the EC concentrations were 4.0-fold higher. The background levels during each sampling period are presented in Table 3-3.

Table 3-4 presents the exposure levels to NO_2 of other occupational groups with our study results. The trash collectors (GM=126.9 μg/m^3) had higher exposures than bus (arithmetic mean (AM)=60 μg/m^3), taxi (AM=4–74 μg/m^3), lorry drivers (AM=56 μg/m^3), railroad crews (AM=56 μg/m^3) and surface workers at mining facilities (AM=19–56 μg/m^3) (Coble *et al.*, 2010; Lewné *et al.*, 2006; Lewné *et al.*, 2011; Riediker *et al.*, 2003; Son *et al.*, 2004). On the other hand, trash collectors had similar or lower exposures than garage workers (GM=93–179 μg/m^3) and locomotive mechanics (AM=190 μg/m^3) (Hewett and Bullock, 2014; Lewné *et al.*, 2011; Verma *et al.*, 1999). In addition, their exposure levels were much lower exposures than those of mining workers (Dahmann *et al.*, 2009). The exposure levels of trash truck drivers (GM=81.3 $\mu g/m^3$) were slightly higher than bus, taxi and lorry drivers, but lower than garage workers (Lewné *et al.*, 2006; Lewné *et al.*, 2011).

Table 3-2. Personal exposure levels of NO_2, and EC by Company

City	Company	Sampling date	N	NO_2 (μg/m^3)		EC (μg/m^3)	
				GM (GSD)	Range	GM (GSD)	Range
Goyang	A	6/26/2014	10	103.6 (1.4)	55.6-190.1	6.2 (2.3)	2.3-29.0
	B	7/1, 2&11/2014	33	125.4 (1.4)	61.0-248.6	4.9 (1.7)	2.6-22.3
	C	7/10/2014	12	70.1 (1.5)	40.7-117.7	4.1 (1.3)	2.4-6.4
	Subtotal		55	106.7 (1.5)	40.7-248.6	4.9 (1.8)	2.4-29.0
Seoul	D	9/16/2014	8	93.5 (1.4)	54.7-148.2	3.4 (1.5)	1.7-5.2
	E	9/18/2014	6	109.3 (1.3)	68.9-149.5	7.1 (1.7)	3.5-14.2
	Subtotal		14	100.0 (1.3)	54.7-149.5	4.7 (1.8)	1.7-14.2
Total Samples			69	105.3 (1.5)	40.7-248.6	4.9 (1.8)	1.7-29.0

Abbreviations: NO_2: nitrogen dioxide; EC: elemental carbon; GM: geometric mean; GSD: geometric standard deviation.

Table 3-3. Ambient background levels for each sampling period

City	Date	Day	Sample Time	NO_2 ($\mu g/m^3$)	EC ($\mu g/m^3$)
Goyang	6/26/2014	Thursday	04:00-13:00	24.6	1.1
	7/1/2014	Tuesday	04:00-13:00	27.5	1.1
	7/2/2014	Wednesday	04:00-13:00	35.9	2.3
	7/10/2014	Thursday	04:00-13:00	14.4	1.3
	7/11/2014	Friday	04:00-13:00	25.9	2.2
Seoul	9/16/2014	Tuesday	21:00-05:00	55.4	1.4
	9/18/2014	Thursday	21:00-04:00	50.3	3.0

Abbreviations: NO_2: nitrogen dioxide; EC: elemental carbon.

Table 3-4. Occupational exposure levels to NO_2 ($\mu g/m^3$) for different occupational groups

Occupational groups		N	AM	SD	Location	Reference
Drivers	Bus and lorry drivers	6	56^{gm}	–	Sweden	(Lewné *et al.*, 2011)
	Bus drivers	42	60	18	Sweden	(Lewné *et al.*, 2006)
	Taxi drivers	39	48	12	Sweden	(Lewné *et al.*, 2006)
	Taxi drivers (diesel)	8	74	10.7	Korea	(Son *et al.*, 2004)
	Patrol cars	50	78	83.3	US	(Riediker *et al.*, 2003)
Mechanics	Busg workers	4	179^{gm}	–	Sweden	(Lewné *et al.*, 2011)
	Garage workers-diesel	16	93^{gm}	–	Sweden	(Lewné *et al.*, 2011)
	Turnaround all yards	18	190	–	Canada	(Verma *et al.*, 1999)
Railroad crews	Locomotives	234	56^{gm}	3.8^{gsd}	US	(Hewett and Bullock, 2014)
Tunnel construction workers		6	316	–	Sweden	(Lewné *et al.*, 2011)
Mining	Train drivers	12	978	–	Germany	(Dahmann *et al.*, 2009)
	Diesel engine drivers	12	395	–	Germany	(Dahmann *et al.*, 2009)
	Surface workers (limestone)	34	19^{gm}	2.0^{gsd}	US	(Coble *et al.*, 2010)
	Surface workers (Trona)	48	56^{gm}	3.1^{gsd}	US	(Coble *et al.*, 2010)
MHW workers	Trash truck drivers	29	81.3^{gm}	1.4^{gsd}	Korea	Current study
	Trash collectors	40	126.9^{gm}	1.4^{gsd}	Korea	Current study

^{gm}: geometric mean
^{gsd}: geometric standard deviation.
Abbreviations: AM: arithmetic mean; SD: standard deviation; MHW: municipal household waste.

3.3.1. Various exposure factors and relationships between NO_2 and EC concentrations

A t-test and ANOVA analysis were performed to compare the average levels of NO_2 and EC among various occupational and environmental categories. The comparison results are presented in the Table 3-5. The geometric means of NO_2 for the collectors (126.9 vs. 81.3 µg/m^3, p=0.003), workers on trucks meeting Euro 3 Standard (113.6 vs. 94.1 µg/m^3, p=0.048) and workers in urban areas (110.9 vs. 88.5 µg/m^3, p=0.042) were significantly higher than the means of the drivers, workers on trucks meeting the Euro 4 Standard and workers in suburban areas. However, there were no significant differences on the NO_2 means in the categories of waste type, age of the truck, diesel particulate filters (DPF), distances between the tailpipe and rear of the truck, number of collected containers and smoking habits. The workers on vehicles with larger engines had higher levels of NO_2 exposure than the workers on smaller engine vehicle. Although the difference between the groups by engine size (<4 L vs. ≥4 L) was not significant (90.0 vs. 110.4 µg/m^3, p=0.065), univariate analysis using continuous variables showed significant result (ß=0.092, p=0.023).

Table 3-5. NO_2 and EC levels according to occupational and environmental factors

Factor		N	NO_2 (μg/㎥)		EC (μg/㎥)	
			GM (GSD)	p-value[a]	GM (GSD)	p-value[a]
Job title	Trash Collector	40	126.9 (1.4)	**0.003**	5.8 (1.8)	**0.007**
	Driver	29	81.3 (1.4)		3.8 (1.5)	
Waste type	Solid	52	105.6 (1.5)	0.904	5.1 (1.8)	0.231
	Food	17	104.2 (1.4)		4.2 (1.5)	
Truck age	<10yrs	19	102.6 (1.4)	0.562	4.4 (1.6)	0.115
	≥10yrs	29	108.4 (1.4)		5.5 (1.8)	
Truck model	Euro standard 3	41	113.6 (1.5)	**0.048**	5.6 (1.9)	**0.007**
	Euro standard 4	28	94.1 (1.4)		3.9 (1.5)	
Engine size	< 4 L	16	90.0 (1.5)	0.065	4.7 (1.7)	0.819
	≥ 4 L	53	110.4 (1.5)		4.9 (1.8)	
Diesel Particulate Filter[b]	Factory installed	37	102.6 (1.5)	0.193	4.4 (1.7)	0.119
	Retrofitted	30	115.3 (1.3)		5.5 (1.7)	
Distance to tailpipe[c]	< 4 m	33	129.3 (1.4)	0.458	6.3 (1.8)	**0.021**
	≥ 4 m	7	116.5 (1.4)		3.7 (1.3)	
Location	Suburban Area	16	88.5 (1.6)	**0.042**	4.2 (1.4)	0.258
	Urban Area	53	110.9 (1.4)		5.1 (1.8)	
No of collected truck containers	1-2	37	102.1 (1.4)	0.483	4.2 (1.7)	**0.012**
	3-4	32	109.1 (1.5)		5.8 (1.7)	
Smoking[b]	Smoker	38	104.9 (1.6)	0.893	5.0 (1.8)	0.692
	Non smoker	29	106.3 (1.4)		4.7 (1.7)	

[a] p-value of ANOVA test for NO_2 and EC concentrations.
[b] There are two missing values.
[c] Straight distance from the end of tailpipe to the back end of the truck, where MHW collectors mainly stay. Drivers are not included in this category.
Abbreviations: NO_2: nitrogen dioxide; EC: elemental carbon; GM: geometric mean; GSD: geometric standard deviation.

The EC means for the collectors (5.8 vs. 3.8 µg/m^3, p=0.007), and workers on trucks meeting Euro 3 Standard (5.6 vs. 3.9 µg/m^3, p=0.007) were significantly higher than the means of the drivers and workers on trucks meeting the Euro 4 Standard. However, unlike NO_2 results, EC exposure levels were significantly different by the distances between the tailpipe and rear of the truck (6.3 vs. 3.7 µg/m^3, p=0.021) and the number of collected containers (5.8 vs. 4.2 µg/m^3, p=0.012). These two factors are significant factors that could greatly effect on personal exposures to DE. In summary, job title and trucks (Euro engine standards) are significant exposure factors that affect personal exposures to NO_2, and EC.

The NO_2 levels were significantly correlated with EC levels indicating a consistent association pattern between both surrogates (Figure 3-1). The Pearson correlation coefficients between the levels of NO_2 and EC were 0.339 (p=0.002) for all workers, 0.258 (p=0.052) for workers on Euro 3 Standard trucks and 0.371 (p=0.026) for workers on Euro 4 Standard trucks.

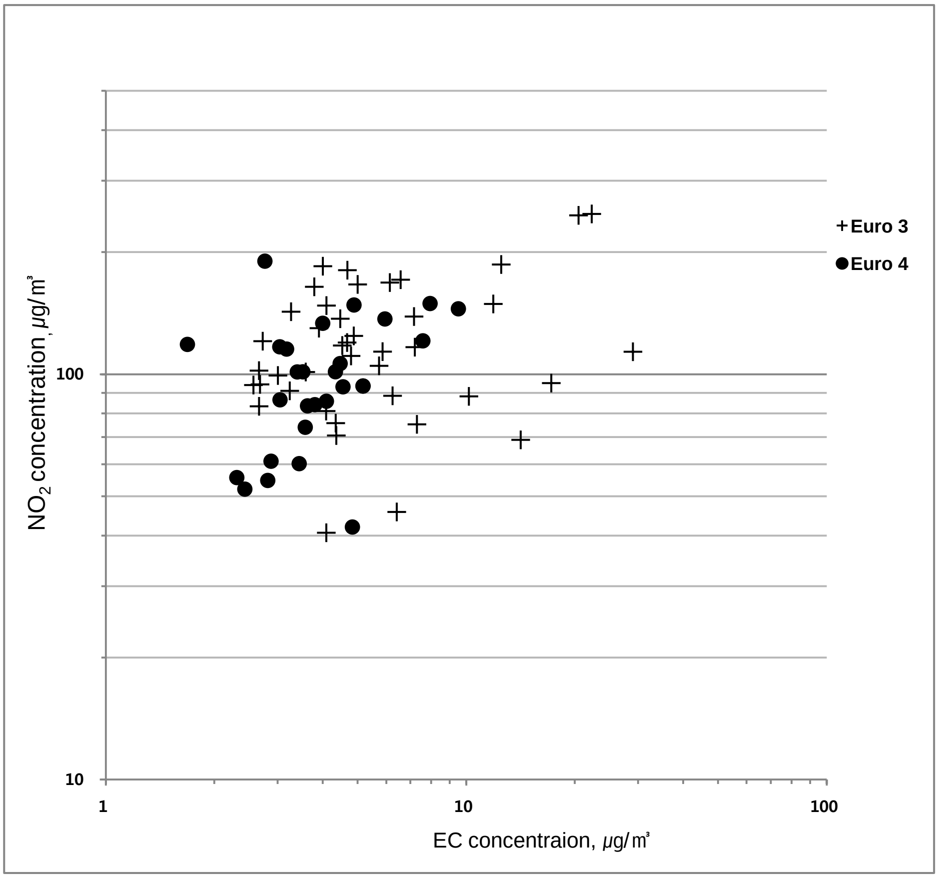

Figure 3-1. Correlation between nitrogen dioxide (NO_2) and elemental carbon (EC) concentrations. Scatter chart shows the concentrations of workers on Euro 3 and 4 standards trucks. The Pearson correlation coefficients between the levels of NO_2 and EC were 0.339 (p=0.002) for all workers, 0.258 (p=0.052) for workers on Euro 3 Standard trucks and 0.371 (p=0.026) for workers on Euro 4 Standard trucks.

3.3.2. Multiple linear regression analysis

Multiple linear regression analysis was performed to identify the main exposure factors that influence the levels of NO_2 exposure. Table 3-6 summarizes the multiple linear regression model for NO_2 and EC. The NO_2 model included seven variables after performing a univariate analysis using a p-value <0.05. The univariate analysis results of the factors with p<0.05 were: job title (ß=0.449, p<0.001), trucks (Euro engine standards) (ß= -0.188, p=0.044), engine size (ß=0.092, p=0.023), weight of collected waste (ß=0.043, p<0.001), driving distance (ß=-0.010, p<0.001), location (ß=0.219, p=0.039), and the ambient background level (ß=0.005, p=0.164). The ambient background level was included in the model to adjust its effect. Finally, the exposure determinants for NO_2 levels consisted of job title, engine size, driving distance and ambient background level (adjusted R^2=0.729, p<0.001).

For the EC model, the job title, Euro engine standard, and average driving speed were the factors determined to predict EC exposure levels (adjusted R^2=0.405, p<0.001) (Lee *et al*., 2015). These results indicate that EC exposure levels are mainly affected by Euro engine standard and job title while NO_2 levels are affected by job title and engine size.

Table 3-6. Multiple regression models to predict natural log-transformed NO_2 (μg/m^3) and EC (μg/m^3) levels

Occupational and environmental factors		N	NO_2 level			EC level		
			Coefficient	Standard error	p-value	Coefficient	Standard error	p-value
Intercept			2.143	0.275	<0.001	2.708	0.341	<0.001
Job title	Driver		Reference			Reference		
	Collector		0.430	0.056	<0.001	0.405	0.124	0.002
Engine size (L)			0.151	0.035	<0.001	b	b	b
Driving distance (km)			0.011	0.002	<0.001	b	b	b
Truck model	Euro standard 3		a	a	a	Reference		
	Euro standard 4					-0.585	0.134	<0.001
Average driving speed (km/h)			a	a	a	-0.060	0.014	<0.001
Ambient background level			0.021	0.003	<0.001	0.209	0.171	0.229[c]
Modeling Results	Adjusted R^2	69	0.729	0.203	<0.001	0.405	0.433	<0.001

[a] The variables were removed to improve the model during the backward elimination.
[b] The variables were not included as candidate variables because they did not show significant results during the univariate regression.
[c] Although p-value is above the significance level, the variable was included to adjust the effect of ambient background levels.
Abbreviations: NO_2: nitrogen dioxide; EC: elemental carbon.

3.3.3. Comparison of exposure assessment statistics

Table 3-7 contains the exposure assessment statistics for NO_2 and EC exposures by company and job title. For NO_2 exposures, none of the measurements exceeded the American Conference of Government Industrial Hygienists (ACGIH) Threshold Limit Value (TLV)-TWA of 376 $\mu g/m^3$ (=0.2 ppm) and the 95th percentile of 218.6 $\mu g/m^3$ for 40 collectors and 135.6 $\mu g/m^3$ for 29 drivers. These levels are much lower than the TLV-TWA.

For EC exposures, three of 69 EC measurements exceeded the applicable OEL of 20 $\mu g/m^3$ (California guideline). The 95th percentile of the probability distribution function of natural log-transformed EC data was 15.1 $\mu g/m^3$ for all collectors and 7.9 $\mu g/m^3$ for all drivers. These levels are lower than the OEL. However, the 95th percentile of the probability distribution function for the collectors of company "A" was 34.7 $\mu g/m^3$ that was above the OEL of 20 $\mu g/m^3$. The exceedance fraction of the distribution function that exceeds the OEL was also calculated as 14.3%. This indicates that the collectors of company "A" were exposed to hazardous level of EC during their waste collection work and corrective action (e.g., check of diesel engine and DPF) is recommended to reduce their exposure to EC.

Table 3-7. Comparison of exposure assessment statistics for NO_2 (μg/m^3) and EC (μg/m^3) exposures by company and job title

Company	SEG	N	NO_2			EC		
			GM (GSD)	95th percentile[a]	%>OEL (376 μg/m³)[bc]	GM (GSD)	95th percentile[a]	%>OEL (20 μg/m³)[bc]
A	Collector	7	125.2 (1.3)	181.5	<0.001	7.3 (2.6)	34.7	14.3
	Driver	3	66.6 (1.2)	86.6	<0.001	4.2 (1.8)	10.8	0.3
B	Collector	19	153.5 (1.3)	232.1	0.004	6.1 (1.7)	15.3	1.7
	Driver	13	95.2 (1.2)	130.1	0	3.6 (1.3)	5.6	0
C	Collector	7	84.0 (1.4)	139.6	0	4.2 (1.2)	6.0	0
	Driver	5	54.3 (1.4)	91.4	0	4.0 (1.4)	7.2	0
D	Collector	4	106.5 (1.2)	153.5	0	4.4 (1.3)	6.9	0
	Driver	4	82.0 (1.4)	137.9	0	2.6 (1.4)	4.4	0
E	Collector	3	130.0 (1.2)	185.4	0	6.4 (1.7)	15.4	1.6
	Driver	3	91.9 (1.3)	146.0	0	7.9 (1.8)	20.1	5.1
Total	Collector	40	126.9 (1.4)	218.6	0.05	5.8 (1.8)	15.1	1.7
	Driver	29	81.3 (1.4)	135.6	0	3.8 (1.5)	7.9	0.008

[a] 95th percentile of the probability distribution function of natural log-transformed NO_2 and EC data.
[b] Exceedance fraction: the proportion (%) of the probability distribution function that exceeds the OEL. Natural log-transformed NO_2 and EC data were used.
[c] OEL: 376 μg/m^3 (ACGIH TLV-TWA) for NO_2 and 20 μg/m^3 (California guideline) for EC was used as OELs
Abbreviations: NO_2: nitrogen dioxide; EC: elemental carbon; GM: geometric mean; GSD: geometric standard deviation; OEL: occupational exposure limit.

3.4. Discussion

In this chapter, we determined NO_2 exposure levels of MHW workers and identified the main exposure determinants for NO_2. The NO_2 levels of MHW workers were mostly below 50% of the working OEL of 0.2 ppm (376 μg/m^3). None of the measurements exceeded the OEL. A limited number of studies have been performed to evaluate various occupational groups' exposure to NO_2 as a surrogate of DE and no study has assessed the MHW workers' exposure to NO_2 (see the Table 3-4). Nevertheless, comparison results of NO_2 levels of MHW workers with those of other occupations are similar with EC results. In the previous chapter, the trash collectors were exposed to slightly higher levels of EC than truck drivers, railroad crews, garage mechanics, locomotive workshop worker, and surface workers at mining facilities. The EC levels of trash truck drivers were similar or slightly higher than truck drivers.

Comparing the exposure levels to NO_2 of MHW workers with other studies done for other occupations, trash collectors and drivers had higher exposures than bus, taxi, and lorry drivers, railroad crews and surface workers at mining facilities. On the other hand, they had similar or lower exposures than mechanics and much lower than mining workers. In particular, the trash truck drivers usually open the windows while driving regardless of the season. They maneuver their trucks to place them close to the trash collection point. These activities result in DE gases intruding into the truck cabin and probably results in the higher exposures of trash truck drivers than bus, taxi and lorry drivers.

Although all measurements were markedly higher than the ambient background levels, ANOVA test results showed significant difference on NO_2 levels between workers operating in suburban and urban areas. This indicates that the background levels of NO_2 could affect the exposure levels of MHW workers. During the sampling period, the ambient background level in urban areas of Seoul averaged 52.9 $\mu g/m^3$ which was double of the background level in suburban Goyang city of 25.7 $\mu g/m^3$. For EC levels, workers in urban area had higher exposures than the workers in suburban area, but there was no significant difference between these groups observed. This can be attributed by insignificant difference between the average background levels of the cities (2.2 vs.1.6 $\mu g/m^3$).

ANOVA test and univariate analysis results indicated that NO_2 levels are consistent and predictable by various occupational, vehicular and environmental factors: job title (collectors > drivers), trucks (Euro 3 engine > Euro 4 engine), location (urban area > suburban area), engine size (larger > smaller), weight of collected waste (more > less), driving distance (longer > shorter), and the ambient background level (higher > lower). These results are not much different than the EC results investigated in the previous study.

A few variables showed different relationship with EC. For example, EC levels were significantly different based on the distances between the end of the tailpipe and rear of the truck (<4 m vs. ≥4 m). This was no so for the NO_2 exposure levels. This may be explained by the physical characteristics of the compounds (particulate vs. gas). Several studies reported that the concentration at a fixed point downwind from a tailpipe greatly varied and was influenced by the location of the tailpipe, tailpipe orientation, vehicle shape, wind direction, driving speed, exhaust exit velocity, etc (Chang *et al.*, 2009; Wang *et al.*, 2006). Nevertheless, it can be assumed that NO_2 gas has a higher dilution ratio because of different diffusion and Brownian motion mechanisms resulting in a different exposure profile for the MHW workers.

The multiple linear regression model determined that NO_2 levels were mainly affected by the job title, engine size and driving distance per day. While the EC regression model resulted in job title, trucks (Euro engine standards) and average driving speed as the most influential factors. In particular, personnel working on larger trucks were exposed to higher levels of NO_2 than those on smaller trucks, but the EC data did not show this relationship. It is well known that larger diesel engines without after-treatment device emit more NOx and EC (g/km) than smaller engines (Faiz *et al.*, 1996). Numerous dynamometer measurements showed that EC emissions have tremendously decreased with the installation of after-treatment devices, but total NOx emissions have not decreased as expected (Carslaw and Rhys-Tyler, 2013b; Czerwinski *et al.*, 2012; Feng *et al.*, 2014; Grice *et al.*, 2009; Karthikeyan *et al.*, 2013). Several studies reported that Euro 4–6 vehicles emitted higher fractions of NO_2 among NO_x than the Euro 3 class vehicles (Carslaw and Rhys-Tyler, 2013b; Grice *et al.*, 2009). Therefore, it was expected that Euro engine standards of the truck would not be a significant factor for NO_2 exposures unlike EC exposures. In this study, all the MHW trucks observed had DPF because Korean environmental regulations required their installation as of 2006

(KoreaMOE, 2003). Basically, NO_2 levels are more related to the engine size whereas EC levels are more associated with the Euro emission standards of the truck which focused on the reduction of particulate matter.

NO_2 concentrations were significantly correlated with the concentrations of EC resulting in a Pearson correlation coefficient of 0.339 (p=0.002). This figure indicates that personal NO_2 exposures are consistent with EC exposures. Worker exposures on Euro 4 trucks (coefficient=0.371) presented better correlation than workers using Euro 3 trucks (coefficient=0.258). All Euro 4 trucks had factory-installed DPFs and Euro 3 trucks had factory-installed and retrofitted DPFs. However, some of retrofitted DPFs showed a different relationship between NO_2 and EC resulting in lower correlation for Euro 3 trucks.

Samat et al. reported that the Spearman correlation coefficient of 0.65 between ambient NO_2 and EC concentrations in Steubenville, Ohio in 2006. They also discussed that the correlations can be significantly different between personal and ambient concentrations and vary depending on the locations, seasons and activities (Sarnat *et al.*, 2006). During the sampling period, the correlation coefficient between ambient NO_2 and EC levels was 0.432 ($p<0.001$) in our study.

Our study that assessed MHW workers' exposure to DE using NO_2 and EC, has a few limitations. The exposure levels to DE vary depending on the types of engine, types of emission control, fuels, the size locations of the routes, date, month, and the local environmental status, etc (Lee *et al.*, 2015). Our samples were collected during the use of

Euro 3–4 trucks and super ultra-low sulfur diesel. All trucks surveyed had a DPF that consisted of diesel oxidation catalyst (DOC) and catalyzed particulate filter (CPF). Since many factors can affect on MHW workers' exposures, our data and assessment is limited in representing the occupational exposures associated with MHW collection. In addition, the type of emission control should be carefully considered when using NO_2 as an surrogate of DE because the NO_2 fractions among NOx as well as total NOx emission can be different based on the type of emission control (Feng *et al.*, 2014; Liu *et al.*, 2012). Grice et al. expected that NO_2 emissions have increased due to an increase in road traffic in 2015 and may be followed by a decline in 2020 to 2004 levels (Grice *et al.*, 2009). This is based on a calculated emission inventory that shows a large reduction in NOx emissions but an increase in the NO_2 fractions of NOx. With these limitations, further study of MHW worker exposures should be conducted to include various types of emission controls, newer engines, and a wider range of occupational and environmental situations.

3.5. Conclusions

This study is the first study that assessed the MHW workers exposures to DE by measuring NO_2 and EC. We also evaluated NO_2 as a surrogate of DE by comparing the exposure profiles against various occupational and environmental factors and investigating correlation between NO_2 of EC. None of NO_2 measurements exceeded the ACGIH TLV-TWA and the 95th percentile of the probability distribution function of NO_2 was also lower than the TLV-TWA. In comparison with other occupations, the trash collectors and drivers had higher exposure to NO_2 than bus, taxi, lorry drivers, railroad crews and surface workers at mining facilities while their exposures were similar or lower than those of garage workers and locomotive mechanics.

Based on multiple regression model, Job title, the engine size, the driving distance and ambient background levels were the most influential exposure factors for NO_2 exposure. ANOVA and univariate analyses results indicated that NO_2 levels were consistent and predictable based on various occupational, vehicular and environmental factors and not affected by smoking. In addition, NO_2 concentrations were significantly correlated with the concentrations of EC indicating a consistent association pattern between both surrogates. These results suggest that NO_2 can be used as an alternative surrogate of EC as well as DE for MHW workers using Euro 3–4 emission standards trucks.

4. Characteristics of Task-Based Black Carbon and $PM_{2.5}$ Exposures in Municipal Household Waste Workers

4.1. Introduction

In Korea, municipal household waste (MHW) collection workers are occupationally exposed to diesel engine exhaust (DE) since the majority of trash vehicles are diesel-fueled trucks and workers frequently operate at the rear of the trucks where the tailpipes are located (Lee *et al.*, 2015). Furthermore, a few MHW workers have potentially developed lung cancer due to their exposure to DE (unpublished data from the Occupational Lung Disease Institute, Korea). In Chapter 2, we reported the full-shift time-weighted average (TWA) of MHW workers to diesel particulate matter (DPM) during waste collection work.

DPM is the particulate fractions of DE and a mixture of various components (U.S.EPA, 2002). DPM can be assessed using range of surrogates such as elemental carbon (EC), total carbon (TC, EC+ organic carbon (OC)), black carbon (BC) and fine particulate matter ($PM_{2.5}$) (Groves and Cain, 2000; Liukonen *et al.*, 2002; Lloyd and Cackette, 2001; Verma *et al.*, 1999). Among them, EC was found in Chapter 2 to be the most appropriate surrogate for DPM exposure among MHW workers. However, BC and $PM_{2.5}$ still have strengths for the evaluation of DPM exposures because they can be easily measured using real-time instruments.

Traditionally, $PM_{2.5}$ has been the typical surrogate for vehicle exhaust, and especially for DPM since it mainly consists of fine particles < 2.5 μm, including ultrafine particles (< 0.1 μm) (Kittelson, 1998; U.S.EPA, 2002). BC is also used as a surrogate for DPM. BC is known as black aerosol, soot, and carbonaceous aerosol, and it is produced through the incomplete combustion of biomass and fossil fuels. Since BC is a unique primary tracer for combustion emissions and it shows a better relationship with road traffic than does PM mass, it has been used in recent years to evaluate ambient air pollution stemming from traffic (Invernizzi *et al.*, 2011; Vanderstraeten *et al.*, 2011). In addition, BC can be more easily measured compared to other chemicals that require integrated media sampling (Lloyd and Cackette, 2001). Although BC is often used interchangeably with EC, BC is somewhat different from EC, which is measured by the thermal optical method (Jeong *et al.*, 2004). BC is defined by the measurement method, i.e., measuring light-absorbing carbon, so strictly speaking, BC is optical EC.

Since BC and $PM_{2.5}$ can be measured using direct-reading instruments, task-based exposure assessment can be applied to evaluate the exposures of MHW workers to DPM. When compared to the full-shift integrated sampling used to acquire TWAs, task-based sampling has several advantages; it can directly identify high exposure tasks, target control measures, evaluate short-term exposures in high risk tasks, and estimate TWA exposures in highly variable work procedures such as those involved in the construction industry or batch production, etc. (Benke *et al.*, 2000; Goldberg *et al.*, 1997; Hager, 1998; Seixas *et al.*, 2003; Virji *et al.*, 2008). The rapid development of direct-reading instruments has accelerated the use of the task-based sampling method in the industrial hygiene field (Ham *et al.*, 2012; Viegas *et al.*, 2015). In particular, the task-based method can be a useful tool for assessing repetitive work composed of multiple tasks with significantly different exposure levels. MHW collection work is comprised of several tasks: collection (pick up and dumping), transportation, transfer, sorting, and more (Park *et al.*, 2013). Therefore, task-based exposure assessment can be helpful for characterizing MHW workers' exposure at a more detailed level.

The objective of this study was to identify high exposure tasks based on real-time measurements and determine their relative contributions to TWA exposures during MHW collection work. We also compared BC and $PM_{2.5}$ levels to identify better surrogates for DPM in real-time monitoring. The main occupational and environmental factors that influence both the exposure levels of high exposure tasks and TWAs were also determined.

4.2. Materials and Methods

4.2.1. Sampling and Selection of Dataset

Five Korean MHW collection companies participated in this study. Field sampling was conducted on seven days falling between June and September 2014. Detailed information on the selection of subjects, sampling strategy, sampling method and equipment used were described in the second chapter (Lee *et al.*, 2015). During the field sampling, we selected one or two representative trucks and their assigned workers for task-based exposure assessment. As a result, five trucks and nine workers were selected for the task-based sampling.

During the sampling, trained industrial hygienists continually followed the selected truck and observed those workers who were wearing BC and $PM_{2.5}$ samplers. The industrial hygienists recorded time activities including tasks, task durations, work characteristics, locations, activities (smoking, break times) and environmental conditions on a standardized sampling sheet. They also obtained information on each truck: year manufactured, engine size, payload capacity, model, use of diesel particulate filter (DPF), Euro engine standard, location of tailpipe, and more. Along with this data, eight BC and nine $PM_{2.5}$ personal samples were collected as real-time measurements. The company, sampling date, information on the vehicle used and number of workers monitored for task-based assessment are listed in Table 4-1.

Table 4-1. Summary of companies, sampling date, characteristics of vehicle used and number of workers sampled for task-based exposure assessment

City	Company	Sampling date	Weather	Vehicle	Vehicle age (yr)	Engine size (L)	Distance from backside to tailpipe (m)	Truck model	Status of engine filter	No of workers sampled	
										Collector	Driver
Goyang	A	6/26/2014	Foggy	I	3	5.899	4.2	Euro 4	Factory installed	2	1
	B	7/1/2014	Foggy	II	11	6.606	2.2	Euro 3	Retrofitted	1	–
	C	7/10/2014	Clear	III	7	6.606	4	Euro 4	Factory installed	1	–
Seoul	D	9/16/2014	Clear	IV	5	3.933	2.2	Euro 4	Factory installed	1	1
		9/16/2014	Clear	V	5	3.933	2.2	Euro 4	Factory installed	1	1

4.2.2. Task Description and Categorization

A household waste collection truck is conventionally staffed by one or two collectors and a driver. The collectors gather the waste from the collection point for respective houses/apartment complexes/buildings, transport it to the truck, and dump it into the rear compartment. The distance between the truck and the collection points within a given housing area or apartment complex is generally small and requires only a few minutes of travel. All of the trucks surveyed were diesel-fueled and equipped with hydrodynamic presses and semi-automated lifting systems. Collectors remained at the rear of the truck to dump the trash and to operate the press mechanism. Drivers stayed inside the trucks unless they were required to assist the collectors. Drivers would often help if there were only one collector.

Since there is no standardized task definition for MHW collection, three tasks (collection, transportation and others) were defined by the researcher and divided into six categories: (1) collection < 2 m; (2) collection > 2 m; (3) riding on the rear step; (4) riding in the cabin; (5) MHW disposal; and (6) going on break. Although going on break was not a task per se, it was included for the purpose of comparison as a control. The collection task was subdivided into < 2 m and > 2 m based on the distance between the worker and the truck, since the level of exposure to DPM can differ with distance. During the collection < 2 m task, collectors dumped the waste into the rear compartment of the truck and operated the press mechanism. If they traveled more than two meters away from the truck while retrieving the waste from each collection point, it was classified as collection > 2 m. Collectors frequently rode on the rear step of the truck to facilitate brief transits to the next stop (see the Figure 2-1). During the MHW disposal task, workers remained at the incineration plant or interim collection area in order to dispose of the collected waste.

4.2.3. Data analysis

Real-time measurements of BC and $PM_{2.5}$ were recorded once per minute. In total, 1,969 BC and 1,983 $PM_{2.5}$ readings were collected from nine workers. To perform task-based exposure assessment, these minute readings were categorized by specific task based on the time activity information collected. BC and $PM_{2.5}$ concentrations for each task were averaged from the concentrations recorded in the associated minutes. During the task categorization, smoking data were excluded in order to mitigate confounding bias. One-minute duration tasks were also excluded following a review of time trend plots. Figure 4-1 presents one of these time trend plots. The data quality for one-minute tasks was insufficient due to the response-time lag in the instrument reading impacting brief tasks. In addition, the results of Durbin-Watson tests indicated that the data were positively auto-correlated if we included all one-minute tasks. Appendix III shows the results of the multiple regression model and Durbin-Watson test results with the inclusion and exclusion of one-minute task data. After the removal of one-minute task data, 259 BC and 261 $PM_{2.5}$ task data were obtained.

The probability plots of BC and $PM_{2.5}$ averages for each task were right-skewed. A Kolmogorov-Smirnov test indicated that natural-log-transformed BC data had a normal distribution. Although, $PM_{2.5}$ data were right-skewed, the natural-log-transformed $PM_{2.5}$ data showed a clear bimodal distribution that was separated by weather (foggy vs. clear). BC and $PM_{2.5}$ concentrations of tasks were natural-log-transformed for statistical analysis in this study. Descriptive statistics include arithmetic mean (AM), geometric mean (GM), geometric standard deviation (GSD) and data range.

All BC and $PM_{2.5}$ task data were classified using occupational and environmental variables. An analysis of variance (ANOVA) was performed to evaluate the variability within and among categories of occupational and environmental variables, and to compare BC and $PM_{2.5}$ levels between categories of those variables as well. We also calculated the relative contribution of specific task exposures to total exposure. This is a percentage rate of the sum of specific task exposures over TWA exposures. The value was calculated using the following formula:

$$\text{Relative contribution rate (\%) of specific task}$$
$$= \frac{\sum_{n=1}^{N}(BC_1 \times task\ duration_1 + \cdots BC_N \times task\ duration_N)}{TWA \times sampling\ time} \times 100$$

N= number of performances of a specific task

BCn = average BC concentration of each task

TWA = TWA of each worker during the sampling period

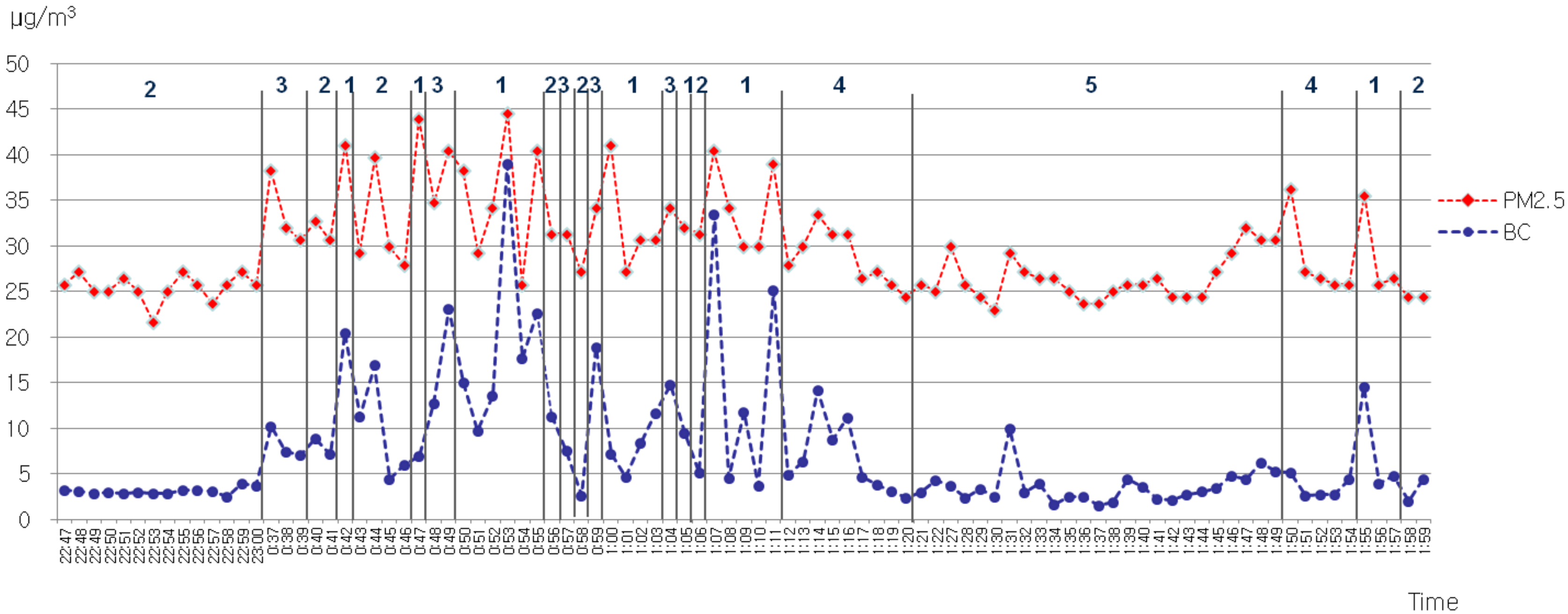

Figure 4-1. Example of time trend plot of 1-min readings of black carbon (BC) and fine particulates matter ($PM_{2.5}$). The line plots show concentration profiles over the monitored period. Tasks performed over minutes were marked above the plots based on the information of time activity diary. The numbers are: 1. collection < 2 m from the truck); 2. collection > 2 m from the truck); 3. riding on the rear step; 4. riding in the cabin; 5. MHW disposal (incineration plant, interim collection point); 6. break & meal.

Multiple linear regression analysis was performed to identify exposure determinants for BC level. To find key factors for BC exposure, an additional multiple regression analysis was performed for the task that was identified in the first multiple regression model as the one contributing most to BC exposures. Variables with p-values < 0.05 in the ANOVA test were included in a multiple regression analysis. Backward elimination using p-values > 0.10 to exclude variables was used for the multiple regression model. For the final model, differences were considered significant at $p < 0.10$. Model diagnostics were carried out with plots of residuals against predicted values and using standardized normal probability plots. It has been reported that real-time data are highly auto-correlated between samples due to brief sampling, and a few statistical models have been developed to handle real-time data in recent years (Entink *et al.*, 2011; Houseman *et al.*, 2002; Ott *et al.*, 1994). In this study, a Durbin-Watson test was employed to identify whether the data were auto-correlated. Statistical analysis was carried out using SPSS 20.0 software (IBM, Armonk, NY).

The categorical variables used for statistical analysis are as follow.

- Task ((1) collection < 2 m, (2) collection < 2 m, (3) riding on the rear step, (4) riding in the cabin, (5) MHW disposal, (6) going on break). Tasks were defined in 4.2.2. Task Description and Categorization.
- Job title (collector vs. driver). Drivers, who often helped with collection, were classified into a driver group.
- Diesel engine emissions standard (Euro 3 vs. Euro 4). Based on its model, the information on the Euro engine standard of each truck was obtained from the manufacturer.

- Age of the vehicle (<10 yr vs. ≥ 10 yr). This information was obtained from the vehicle registration card of each truck.
- Engine displacement (< 4 L vs. > 4 L). This information was obtained from the vehicle registration card of each truck.
- Diesel Particulate Filter (factory–installed vs. retrofitted). This information for each truck was obtained from the manufacturer based on the model.
- Location (street, residential area and other). Based on the time activity diary and GPS information, a surveyor coded the location.
- Weather (foggy vs. clear). Based on the time activity diary and historical weather records from the Korea Meteorological Administration, surveyor coded.

4.3. Results

A total of 259 BC and 261 $PM_{2.5}$ task data were created from real-time measurements on nine workers according to the categorization of the task performed. Table 4-2 presents descriptive statistics including GM, GSD, and concentration ranges for each worker. The sampling time listed in Table 4-2 is smaller than the full-shift sampling period applied in Chapter 2 since we excluded one-minute task data and certain measurements due to missed time activities or smoking events. Each worker's TWA was recalculated based on the sampling time listed in Table 4-2. Overall, task-based BC concentrations ranged from 1.7 to 28.2 $\mu g/m^3$ with a GM of 7.4 $\mu g/m^3$. $PM_{2.5}$ concentrations ranged from 21-198 $\mu g/m^3$ with a GM of 52.0 $\mu g/m^3$.

4.3.1. BC and $PM_{2.5}$ concentrations by task

Table 4-3 contains descriptive statistics, including number of samples, GM, GSD, and data ranges for each task. The task of collection < 2 m showed the highest BC concentration (GM=9.4 $\mu g/m^3$) and the MHW disposal task showed the lowest BC concentration (GM=5.0 $\mu g/m^3$) among the six task categories. Each task performance lasted from 2 to 40 minutes. A one-way ANOVA test showed that BC concentrations were not equal among tasks at a significant level ($p < 0.001$). For $PM_{2.5}$ concentrations, the task of going on break had the highest concentration among the tasks.

Table 4-2. Descriptive statistics of task-based samples and TWA for each worker

Company	Worker	Sampling date	Job title	Vehicle #	BC (㎍/㎥)				PM$_{2.5}$ (㎍/㎥)			
					TWA[a]	N[b]	GM (GSD)[c]	Range[d]	TWA	N	GM (GSD)	Range
A	#1	26 Jun 14	Collector	I	9.9	40	10.0 (1.5)	4.8–27.6	87.5	34	111.8 (1.2)	84–170
	#2	26 Jun 14	Collector	I	8.4	38	8.7 (1.4)	3.7–17.6	112.2	38	105.7 (1.2)	73–154
	#3	26 Jun 14	Driver	I	7.0	18	6.2 (1.5)	3.4–11.6	90.9	13	114.8 (1.1)	104–138
B	#4	2 Jul 14	Collector	II	12.6	25	10.6 (1.6)	3.9–20.5	146.2	25	140.1 (1.2)	93–198
C	#5	10 Jul 14	Collector	III	8.9	33	7.7 (1.9)	1.7–17.2	32.1	25	30.1 (1.4)	21–91
D	#6	16 Sep 14	Collector	IV	7.3	51	6.2 (1.9)	1.7–22.9	30.5	51	30.0 (1.2)	21–45
	#7	16 Sep 14	Driver	IV	–	–	–	–	25.7	21	25.9 (1.1)	24–31
	#8	16 Sep 14	Collector	V	6.8	33	7.1 (1.9)	2.2–28.2	28.1	33	29.3 (1.2)	22–38
	#9	16 Sep 14	Driver	V	3.9	21	3.8 (1.6)	2.0–10.0	27.8	21	28.1 (1.1)	23–35
	Total					259	7.4 (1.8)	1.7–28.2		261	52.0 (2.0)	21–198

[a] Real time-weighted average for the sampling period listed.
[b] Number of task-based samples..
[c] GM and GSD of BC concentrations of task-based samples.
[d] Range of BC concentrations for task-based samples.
Abbreviations: BC: black carbon; PM$_{2.5}$: fine particulate; TWA: time-weighted average; GM: geometric mean; GSD: geometric standard deviation.

Table 4-3. BC and $PM_{2.5}$ levels by tasks

Task/event		Task duration(min) mean (range)	BC (μg/㎥)					$PM_{2.5}$ (μg/㎥)				
			No of workers	N	GM (GSD)	Range	p-value[a]	No of workers	N	GM (GSD)	Range	p-value[a]
Collection	<2 m	4.5 (1-35)	7	100	9.1 (1.8)	1.7-28.2	**<0.001**	8	96	51.9 (2.0)	23-183	**0.030**
	>2 m	2.7 (1-40)	6	20	6.3 (1.9)	1.7-15.4		7	19	48.9 (2.0)	23-135	
Transportation	Riding on the rear step	2.3 (1-13)	6	48	7.5 (2.0)	2.1-27.6		7	44	46.5 (2.0)	21-153	
	Riding on the cabin	6.9 (1-24)	8	70	5.5 (1.8)	2.0-20.5		9	83	48.9 (2.1)	23-170	
MHW disposal[b]		7.3 (2-23)	4	12	5.0 (2.0)	2.2-19.1		5	12	42.5 (2.5)	21-198	
Break time		19.7 (2-38)	5	9	5.5 (1.8)	1.7-11.6		6	7	115.6 (1.3)	80-166	
Total		4.7 (1-40)	8	259	7.4 (1.8)	1.7-28.2		9	261	52.0 (2.0)	21-198	

N: Number of task-based samples
[a] One-way ANOVA test showed that BC and PM2.5 concentrations were not equal among tasks.
[b] Workers stayed at the incineration plant or interim collection point.
Abbreviations: BC: black carbon; $PM_{2.5}$: fine particulate; GM: geometric mean; GSD: geometric standard deviation.

We calculated the relative contribution of specific task exposures to personal TWA exposures. Figure 4-1 shows a comparison of the relative contribution of specific task exposures to BC TWA exposures between collectors and drivers. For collectors, the task of collection < 2 m was the greatest contributor to TWA exposures. On the other hand, the task of riding in the cabin, i.e., driving, was the task that contributed the most for drivers. There were distinct differences in exposure patterns based on job between collectors and drivers. Collectors' exposures mainly occurred while performing dumping behind the truck and riding on the rear step while moving. Drivers' exposures came mainly from driving.

4.3.2. BC and $PM_{2.5}$ concentrations according to various exposure factors

An ANOVA test was performed to compare the BC and $PM_{2.5}$ concentrations among various occupational and environmental categories. Table 4-4 presents the comparison results. The GM of BC for the collectors were significantly higher than that for the drivers (8.0 vs. 4.8 μg/m^3, $p < 0.001$). Workers on a Euro 3 truck, truck with a larger engine, truck with a retrofitted diesel particulate filter (DPF), and a truck with a greater distance between its tailpipe and the rear had significantly higher BC concentrations than did workers on a Euro 4 truck, truck with a smaller engine, truck with a factory-installed DPF, and truck with a shorter distance between its tailpipe and rear. In addition, there were differences in BC concentrations by location (street > residential area > other) and weather (foggy > clear).

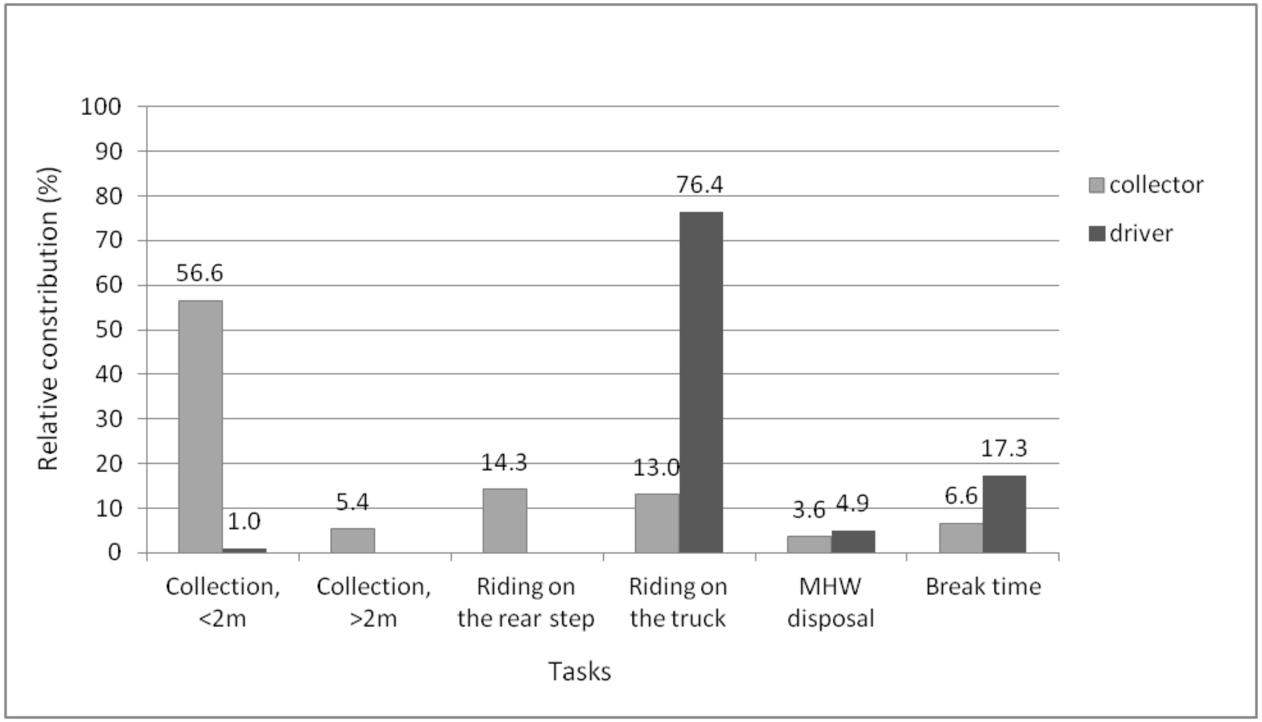

Figure 4-2. Comparison of relative contribution of each task to the Time-Weighted Average (TWA) exposures of black carbon (BC) between collector and driver

Table 4-4. BC and $PM_{2.5}$ levels according to occupational and working environment factors

Factor		BC (μg/㎥)					$PM_{2.5}$ (μg/㎥)				
		N	AM (SD)	GM (GSD)	Range	p-value	N	AM (SD)	GM (GSD)	Range	p-value
Job	Collector	220	9.3 (5.0)	8.0 (1.8)	1.7-28.2	<0.001	206	72.0 (47.8)	56.5 (2.0)	21-198	<0.001
	Driver	39	5.3 (2.6)	4.8(1.6)	2.0-11.6		55	48.0 (38.1)	38.0 (1.9)	23-138	
Truck age	<10 yrs	234	8.4 (4.8)	7.1 (1.8)	1.7-38.2	0.001	236	58.9 (40.9)	46.8 (1.9)	21-170	<0.001
	≥10 yrs	25	11.8 (5.2)	10.6 (1.6)	3.9-20.5		25	142.8 (28.1)	140.1 (1.2)	93-198	
Truck model	Euro 3	25	11.8 (5.2)	10.6 (1.6)	3.9-20.5	0.001	25	142.8 (28.1)	140.1 (1.2)	93-198	<0.001
	Euro 4	234	8.4 (4.8)	7.1 (1.8)	1.7-28.2		236	58.9 (40.9)	46.8 (1.9)	21-170	
Engine size	<4 L	105	7.3 (5.3)	5.9 (1.6)	1.7-28.2	<0.001	126	29.1 (4.8)	28.8 (1.2)	21-45	<0.001
	>4 L	154	9.7 (4.4)	8.7 (1.8)	1.7-27.6		135	102.3 (40.6)	90.2 (1.8)	21-198	
Diesel Particulate Filter	Factory installed	234	8.3 (4.8)	7.1 (1.8)	3.9-20.5	0.001	236	58.9 (40.9)	46.8 (1.2)	21-170	<0.001
	Retrofitted	25	11.8 (5.2)	10.6 (1.6)	1.7-28.2		25	142.8 (28.1)	140.1 (1.9)	93-198	
Distance to tailpipe [a]	<4 m	130	8.1 (5.6)	6.6 (1.9)	1.7-28.2	0.001	151	48.0 (44.1)	37.4 (1.8)	21-198	<0.001
	≥4 m	129	9.3 (4.1)	8.4 (1.6)	1.7-27.6		110	93.0 (37.2)	81.6 (1.8)	21-170	
Location	Street	96	8.5 (4.6)	7.5 (1.9)	2.2-27.6	<0.001	92	68.5 (41.7)	55.4 (1.9)	23-170	0.506
	Residential Area	131	9.4 (5.1)	6.3 (1.5)	2.0-28.2		138	66.3 (48.1)	50.8 (2.1)	21-183	
	Others [b]	32	6.3 (4.3)	7.4 (1.8)	1.7-19.1		31	65.5 (56.8)	47.5 (2.2)	21-198	
Weather	Foggy	121	9.9 (4.4)	9.0 (1.5)	1.7-27.6	<0.001	110	118.1 (24.4)	115.8 (1.2)	73-198	<0.001
	Clear	138	7.7 (5.2)	6.3 (1.9)	1.7-28.2		151	29.7 (8.2)	29.0 (1.2)	21-91	

S: No of workers
N: No of task-based samples
[a] Straight distance from the end of tailpipe to the rear of the truck where MHW collectors mainly stayed. Drivers were not included in this category.
[b] Workers stayed at the incineration plant or interim collection point.
Abbreviations: BC: black carbon; AM, arithmetic mean; SD, standard deviation, GM, geometric mean; GSD, geometric standard deviation.

The results of the comparison of $PM_{2.5}$ means among occupational and environmental categories were the same with the BC results described above. It is noteworthy that samples on foggy days had significantly higher task $PM_{2.5}$ levels than those from clear days.

4.3.3. Multiple linear regression analysis

Multiple linear regression analysis was performed to identify the main exposure determinants influencing BC concentrations. Table 4-5 summarizes the multiple linear regression model for BC concentrations. The variables included in the model were determined after performing an ANOVA test using a significance level of 0.05. The factors with $p < 0.05$ were: collection < 2 m, riding on the rear step, Euro engine emission standard, engine size, job title, weather, and location. The final model includes tasks (collection < 2 m and riding on the rear step), job title, Euro engine standard, weather, and location (adjusted R^2=0.263, $p < 0.001$). The Durbin-Watson test result indicated that there is no statistical evidence that the data are positively auto-correlated.

Additional multiple linear regression for the BC levels of the task collection < 2 m was performed to find key factors that influence the BC levels during the highest-exposure task. In conclusion, job title and Euro engine standard were the main exposure determinants for predicting BC exposure levels (adjusted R^2=0.110, $p < 0.001$). These are the same factors as those identified as exposure determinants for EC levels in Chapter 2.

Table 4-5. Multiple regression model to predict natural log-transformed BC levels of all tasks

Independent factors		BC level of all tasks			
		N	Coefficient	Standard error	p-value
Intercept			1.182	0.126	<0.001
Task	Riding in the cabin		Reference		
	Collection, < 2m		0.457	0.076	<0.001
	Riding on the rear step		0.266	0.084	0.002
Job title	Driver		Reference		
	Collector		0.250	0.102	0.015
Truck model	Euro Standard 4		Reference		
	Euro Standard 3		0.260	0.118	0.028
Weather	Clear		Reference		
	Foggy		0.262	0.065	<0.001
Area	Others[a]		Reference		
	Street		0.288	0.111	0.010
	Residential area		0.184	0.108	0.088
Modeling Results	Adjusted R^2	411	0.195	0.586	<0.001
	Durbin Watson d^a ($1.603<d<1.746$)		1.436		>0.01

[a] Workers stayed at the incineration plant, interim collection point, underground, etc.

[b] If the number of variables is seven ($k'=7$) when perform a Durbin Watson test, the lower and upper critical values ($d_{L,0.01}$ and $d_{U,0.01}$) are 1.603 and 1.746.

If $d< d_{L,0.01}$, there is statistical evidence that the error terms are positively auto-correlated.

If $d >d_{U,0.01}$, there is no statistical evidence that the error terms are positively auto-correlated.

If $d_{L,0.01}<d< d_{U,0.01}$, the test is inconclusive.

Abbreviation: BC: black carbon.

Table 4-6. Multiple regression model to predict natural log-transformed BC levels for the task of collection < 2 m

Independent factors		BC level for the ‘collection, < 2m’			
		N	Coefficient	Standard error	p-value
Intercept			1.374	0.450	0.003
Job title	Driver		Reference		
	Collector		0.850	0.267	0.002
Truck model	Euro Standard 4		Reference		
	Euro Standard 3		0.398	0.153	0.010
Modeling Results	Adjusted R^2	144	0.099	0.527	<0.001
	Durbin Watson d ($1.598<d<1.651$)		1.306		

[b] If the number of variables is seven (k'=2) when perform a Durbin Watson test, the lower and upper critical values ($d_{L,0.01}$ and $d_{U,0.01}$) are 1503 and 1.583.
If $d< d_{L,0.01}$, there is statistical evidence that the error terms are positively auto-correlated.
If $d >d_{U,0.01}$, there is no statistical evidence that the error terms are positively auto-correlated.
If $d_{L,0.01}<d< d_{U,0.01}$, the test is inconclusive.
Abbreviation: BC: black carbon.

4.4. Discussion

This study identified the high exposure tasks from among six tasks for MHW collection work and found the main exposure determinants for BC exposure using a task-based exposure assessment. We defined the six tasks for MHW collection work based on our observations and professional judgment. The task definitions are more detailed compared with Park et al.'s grouping of collection, transfer, transportation, and sorting (Park *et al.,* 2013). This study did not include transfer and sorting because our subjects did not perform those tasks (which are for the collection of recyclable material). Instead, we detailed collection and transportation to focus on exposures to and sources of DPM. Within that, we identified the tasks of collection < 2 m and riding on the rear step as high-exposure tasks. Consistent task definition is a critical component in applying a task-based procedure (Neitzel *et al.,* 2011; Virji *et al.*, 2009). However, it is frequently difficult to achieve consistency in task definitions because work procedures vary and the study purpose on which researchers focus is usually unique.

We described the weaknesses of BC and $PM_{2.5}$ measurements as surrogates for DPM in Chapter 2: they were affected by interference and the data showed relatively weak statistical significance during the ANOVA test (see Table 2-4). In that study, we used 17 BC and 21 $PM_{2.5}$ TWA data points to compare means among categories of occupational and environmental variables. In this study, we used eight BC and nine $PM_{2.5}$ real-time data sources from nine workers and made 259 BC and 261 $PM_{2.5}$ instances of task data using a task-based procedure. As a result, the statistical explanatory power of the ANOVA test was markedly increased, as seen in Table 4-4. In addition, the results were logically acceptable; e.g., collector > driver, Euro 3 truck > Euro 4 truck, greater engine size > lesser engine size, longer driving distance > shorter driving distance. This indicates how well task-based exposure assessment refines the exposure characterization at the task level.

The multiple linear regression model included high-exposure tasks, job title, European engine standard, weather and location as key factors in predicting BC levels. Another multiple regression model for BC levels from the task of collection < 2 m confirmed that European engine standard and job title played a key role in predicting BC levels. These exposure determinants match the results of the multiple regression model for EC levels presented in the second chapter. There, BC levels did not show a significant relationship due to the insufficient number of TWA samples. These results showed that task-based exposure assessment is effective, especially in assessing repetitive work with real-time data derived from multiple tasks.

We used SidePak aerosol monitors to measure $PM_{2.5}$ in this study. SidePak aerosol monitors measure aerosols such as dust, smoke, fumes, and mist using a laser diode sensor. Fog is a discernible mist that floats in air, and fog particles range in size from 1 to 10 μm (Hinds, 2012). This means that fog can be measured with a SidePak monitor installed with a $PM_{2.5}$ impactor. For this reason, workers number 1, 2, 3 and 4 who worked on a foggy day had considerably higher $PM_{2.5}$ concentrations (114.4 vs. 29.4 $\mu g/m^3$) compared with the other workers. The probability plot of $PM_{2.5}$ data had a distinctly bimodal distribution. All measured PM concentrations were corrected using the gravimetric calibration factor, which was determined by collecting side-by-side samples on PVC filters (see the Appendix I for detail). However, we collected gravimetric samples after field sampling rather than collecting on every sampling day in order to determine site-specific calibration factors. Resultantly, $PM_{2.5}$ data could not be compared with BC data because the weather conditions deeply affected the statistical analysis as a confounding factor.

While manually linking time activities with minute-by-minute data, we noticed that BC concentrations rose as high as 161 μg/m^3, with an average of 34.9 μg/m^3, during tobacco smoking. Furthermore, $PM_{2.5}$ concentrations rose as high as 3,208 μg/m^3, with an average of 453 μg/m^3. These levels are 4.8-fold the average BC level and 64 fold the average $PM_{2.5}$ level. Hence, we decided to exclude tobacco-smoking events from the task dataset. As reported in previous studies, $PM_{2.5}$ measurements using a SidePak are seriously affected by tobacco smoking and require the control of workers' smoking during DPM sampling (Dacunto *et al.*, 2013; Klepeis *et al.*, 2007). Although few studies have reported on the relationship between BC and tobacco smoking, based on our task-based real-time measurements, it is obvious that BC measurements using an aethalometer are affected by tobacco smoking.

With the removal of smoking events based upon the recorded time activities, the mean of task BC levels declined from 9.2 to 7.4 μg/m^3. This BC level is still higher than the comparable mean EC level of 4.8 μg/m^3. As described in Capter 2, BC measurements contain organic components that absorb visible light, such as brown carbon, resulting in a positive bias (Andreae and Gelencsér, 2006; Ng *et al.*, 2007; Yelverton *et al.*, 2014). In addition, a number of studies have recommended a site-specific calibration in BC monitoring because the optical attenuation coefficients for measuring BC can differ depending on the characteristics of aerosols (size, chemicals involved, and mixing state)

(Ballach *et al.*, 2001; Bond *et al.*, 2006; Jeong *et al.*, 2004; Lavanchy *et al.*, 1999; Ng *et al.*, 2007). Although, further study is required to evaluate the validity of BC measurements for more various occupational environments, BC measurements can be a useful surrogate for DPM as real-time data if field calibration is used.

This study has certain limitations. MHW collection work is composed of multiple tasks, and due to the nature of waste collecting work, task duration is sometimes very short, even less than one minute. Our trained industrial hygienists recorded tasks based on the minute, but they may have unknowingly made an erroneous categorization of a given task. For these reasons, our multiple linear regression model resulted in a relatively lower coefficient of model determination compared with the previous model.

4.5. Conclusions

Based on task-based exposure assessment, this study identified high-exposure tasks for MHW collection work, namely collection < 2 m and riding on the rear step. We found that job title and the European engine emission standard of the truck's engine were the most important exposure factors for BC during the task of collection < 2 m. These indicate that MHW workers' exposure to DPM is closely associated with the source of DPM, which is the diesel engine, i.e., engineering control of DPM at the engine is the most important factor for reducing workers' exposure.

Between BC and $PM_{2.5}$, BC was the better surrogate for DPM for real-time measurements. BC was less affected by interference and showed consistent and predictable exposure patterns for the various exposure factors examined, as EC showed before. We investigated how well task-based exposure assessment refines exposure characterization at the task level. In particular, the task-based method is more effective for assessing repetitive work composed of multiple tasks with significantly different exposure levels.

5. Summary and Conclusions

There are approximately 15,000 MHW collection workers in Korea, and the majority of them are considered to be occupationally exposed to DE. DE has been classified as "carcinogenic to humans (Group 1)" by the IARC. In recent years, some MHW workers in South Korea have possibly developed lung cancer due to their exposure to DE. Nevertheless, few studies have been conducted to determine MHW workers' exposures to DE.

In this study, we assessed the occupational exposure of MHW workers to DE using six surrogates for DE: elemental carbon (EC), organic carbon (OC), total carbon (TC), black carbon (BC), fine particulate matter ($PM_{2.5}$), and nitrogen dioxide (NO_2). We determined appropriate surrogates for DE from among these and identified the main exposure determinants that influence personal exposure to DE at the task level, as well as TWA exposures.

The geometric means of EC, OC, TC, BC, $PM_{2.5}$ and NO_2 were 4.8, 39.6, 44.8, 9.1, 62.0 $\mu g/m^3$, and 105.3 $\mu g/m^3$ respectively. These results were considerably higher than the ambient background levels: the average background levels of EC, OC, TC, BC, $PM_{2.5}$ and NO_2 for the sampling period were 1.5, 3.8, 5.3, 5.4, 16.1 and 28.4 $\mu g/m^3$, respectively. Converted to the average ratio of exposure level to background level, the ratios for EC, OC, TC, BC, $PM_{2.5}$ and NO_2 were 4.1, 12.7, 9.8, 2.0, 4.4, and 4.1, respectively. These results indicate that MHW collection workers are occupationally exposed to DE during their normal work.

When compared to other occupations, the exposure levels of the MHW collectors to DE were similar to or slightly higher than those of bus, taxi, and truck drivers; mechanics in truck repair garages and locomotive workshops; railroad crews; and surface workers at mining facilities. The exposures of MHW truck drivers were comparable to those of local truck drivers and long-haul truck drivers. On the other hand, all their exposure levels were much lower than those of mining workers.

ANOVA and univariate analyses were performed in order to determine which surrogates offered appropriate exposure profiles against various occupational exposure factors. EC, OC, TC and NO_2 measurements showed similar exposure patterns for job title (collector > driver), Euro engine standard (Euro 3 truck > Euro 4 truck), and age of truck (older > newer). However, EC measurements provided more consistent and relevant exposure profiles for the workload performed and sources of DE, such as number of containers collected (more > less), distance from the rear of the truck to the engine tailpipe (longer > shorter), average driving speed (slow > fast), etc. More importantly, EC was not affected by worker smoking habit, ambient dust, weather, and malodors from food waste, as were OC, TC, BC and $PM_{2.5}$. This indicates that EC is the most appropriate surrogate for DPM exposure among MHW workers.

NO_2 measurements also provided consistent and predictable exposure patterns by various occupational and environmental factors such as job title (collector > driver), Euro engine standard (Euro 3 truck > Euro 4 truck), engine size (larger > smaller), driving distance (longer > shorter), location (urban area > suburban area), and weight of collected waste (more > less). Like EC, NO_2 was not affected by worker smoking habit, ambient dust, and malodor from waste. Although NO_2 is one of the surrogates for gas-phase DE, it was significantly correlated with EC levels, indicating a consistent association between both surrogates ($r=0.339$, $p=0.002$). This suggests that NO_2 can be used as an alternative surrogate for EC when assessing MHW workers using Euro 3−4 standards trucks.

Based on the results of the multiple regression model, job title, the European engine standard of the truck, and average driving speed were the most influential factors in determining EC exposures. For NO_2 levels, job title, engine size, and driving distance were the most influential factors. On the other hand, OC and TC levels were mostly affected by worker's smoking habit, along with the variables of job title, European engine standard, and size of engine.

Task-based exposure assessment identified the task of collection < 2 m (GM=9.4 $\mu g/m^3$) as the highest-exposure task in MHW collection work. For the collectors, collection < 2 m was the task contributing most to the TWA exposures of BC, showing a contribution rate of 56.6%. For the drivers, the task of riding in the cabin (driving) was the task contributing most (76.4%) to their BC exposures.

Multiple regression analysis on the BC levels confirmed that the tasks of collection < 2 m and riding on the rear step, along with job title, the Euro engine standard of the truck, weather, and location, were all influential factors. For the BC levels during collection < 2 m, job title and the Euro engine standard of the truck were the most important factors. These are the same results as those identified as the main exposure determinants for EC levels as described above.

Between BC and $PM_{2.5}$, BC proved a better surrogate for DPM for real-time measurements. BC was less affected by interferences such as smoking or weather than was $PM_{2.5}$. We also investigated how well task-based exposure assessment refined the exposure characterization at the task level with a small number of subjects. In addition, the task-based method was more effective in assessing repetitive work composed of multiple tasks with significantly different exposure levels.

In conclusion, this study assessed the exposures of MHW workers to DE using parallel samples of six surrogates: EC, OC, TC, BC, $PM_{2.5}$ and NO_2. The workers were exposed to levels of DE substantially higher than ambient background levels. In particular, their exposure levels to DE increased when they stayed near its source (i.e., the tailpipe of the truck). Among various occupational and environmental factors, the workers' job title and the European engine standard of the truck were the most influential factors for exposure to DE. These indicate that engineering control that reduces the emission of DE from diesel engines is the most effective way to reduce workers' exposure.

Among the six surrogates, EC was the most appropriate surrogate for DE exposure among MHW workers. EC experienced less interference than did the other surrogates and showed the most relevant exposure pattern against various occupational and environmental factors. NO_2 also showed a consistent and predictable exposure pattern for occupational and environmental factors, although it was affected by the ambient background level. In addition, NO_2 was significantly correlated with EC levels. These indicate that NO_2 can be used as an alternative surrogate for EC as well as for DE for MHW workers using Euro 3–4 standard trucks. For real-time measurements, BC can be used to measure DE exposure if it is used with field calibration.

Lastly, it should be noted that environmental regulations and auto/truck industry vehicle exhaust standards have been continuously enforced, resulting in increased compliance. Accordingly, MHW worker exposure levels must have changed considerably apace with the development of diesel engines and after-treatment devices. Limited data from an additional experiment performed in 2015 showed that DE emissions from a truck with a DPF were only 10% of the emissions of one without a DPF, even though they were manufactured in the same year. According to local government regulations, since 2010 every MHW truck on the road in Korea has required a DPF. Therefore, the results of this current study should not be directly applied to estimate past exposure levels of MHW workers. To estimate their past exposures, another study using older trucks should be conducted to assess personal exposure. Dynamometer test results for various types of diesel engines, such as Euro 1-2 engine standard trucks or Euro 3 trucks without a diesel particulate filter, could be used.

Recently, some local governments in Korea have been transitioning their MHW trucks from diesel engines to LPG (liquefied petroleum gas) engines in an effort to reduce air pollution. In addition, local governments are setting more stringent compliance regulation for diesel engines. Hence, in the future workers' exposure to DE should differ from these current results, and the main pollutants of concern could shift as well. Further study of MHW worker exposure to DE should be conducted so as to include a wider range of occupational and environmental situations, more varied MHW collection procedures, daily and seasonal conditions, different types of vehicles, and possibly different types of fuel.

References

ACGIH (2001). Threshold limit values for chemical substances and physical agents and biological exposure indices, American Conference of Governmental Industrial Hygienists

ACGIH (2012). Nitrogen dioxide. Documentation of the threshold limit values and biological exposure indices, American Conference of Governmental Industrial Hygienists

Ädelroth, E., Hedlund, U., Blomberg, A., Helleday, R., Ledin, M., *et al.* (2006). Airway inflammation in iron ore miners exposed to dust and diesel exhaust. *European Respiratory Journal* 27(4): 714-719.

Andreae, M. and Gelencsér, A. (2006). Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols. *Atmospheric Chemistry and Physics* 6(10): 3131-3148.

Attfield, M. D., Schleiff, P. L., Lubin, J. H., Blair, A., Stewart, P. A., *et al.* (2012). The diesel exhaust in miners study: A cohort mortality study with emphasis on lung cancer. *Journal of the National Cancer Institute* 104(11): 869-883.

Bakke, B., Stewart, P., Ulvestad, B. and Eduard, W. (2001). Dust and gas exposure in tunnel construction work. *AIHAJ : a journal for the science of occupational and environmental health and safety* 62(4): 457-465.

Ballach, J., Hitzenberger, R., Schultz, E. and Jaeschke, W. (2001). Development of an improved optical transmission technique for black carbon (bc) analysis. *Atmospheric Environment* 35(12): 2089-2100.

Benke, G., Sim, M., Fritschi, L. and Aldred, G. (2000). Beyond the job exposure matrix (jem): The task exposure matrix (tem). *Annals of Occupational Hygiene* 44(6): 475-482.

Birch, M. E. (2003). Monitoring of diesel particulate exhaust in the workplace. *NIOSH Manual of Analytical Methods (NMAM)*: 2003-2154.

Birch, M. E. and Cary, R. A. (1996). Elemental carbon-based method for occupational monitoring of particulate diesel exhaust: Methodology and exposure issues. *The Analyst* 121(9): 1183-1190.

Boffetta, P., Cherrie, J., Hughson, G. and Pitard, A. (2002). Cancer risk from diesel emissions exposure in central and eastern europe: A feasibility study. *Institute HE*: 59-78.

Bond, T. C., Habib, G. and Bergstrom, R. W. (2006). Limitations in the enhancement of visible light absorption due to mixing state. *Journal of Geophysical Research: Atmospheres (1984–2012)* 111(D20).

Burgess, J. L., Fleming, J. E., Mulenga, E. M., Josyula, A., Hysong, T. A., *et al.* (2007). Acute changes in sputum il-10 following underground exposure to diesel exhaust. *Clinical Toxicology* 45(3): 255-260.

Burnett, R. T., Dales, R., Krewski, D., Vincent, R., Dann, T., *et al.* (1995). Associations between ambient particulate sulfate and admissions to ontario hospitals for cardiac and respiratory diseases. *American journal of epidemiology* 142(1): 15-22.

Cal.EPA (1998). Proposed identification of diesel exhaust as a toxic air contaminant: Health risk assessment for diesel exhaust-appendix iii, part b, California Environmental Protection Agency, Office of Environmental Health Hazard Assessment.

Cal.EPA (2006). Appendix a, quantification of the health impacts and economic valuation of air pollution from ports and good movement in california, California Environmental Protection Agency.

Carslaw, D. and Rhys-Tyler, G. (2013a). Remote sensing of NO_2 exhaust emissions from road vehicles. City of London Corporation, London Brough of Ealing on behalf of Defra.

Carslaw, D. C. and Rhys-Tyler, G. (2013b). New insights from comprehensive on-road

measurements of no x, no 2 and nh 3 from vehicle emission remote sensing in london, uk. *Atmospheric Environment* 81: 339-347.
Chang, V. W.-C., Hildemann, L. M. and Chang, C.-h. (2009). Dilution rates for tailpipe emissions: Effects of vehicle shape, tailpipe position, and exhaust velocity. *Journal of the Air & Waste Management Association* 59(6): 715-724.
CHDS (2002). Health hazard advisory-diesel engine exhaust California Department of Health Services, Hazard Evaluation System and Information service, Oakland, California
Chow, J. C., Watson, J. G., Crow, D., Lowenthal, D. H. and Merrifield, T. (2001). Comparison of improve and niosh carbon measurements. *Aerosol Science and Technology* 34(1): 23-34.
Ciccone, G., Forastiere, F., Agabiti, N., Biggeri, A., Bisanti, L., *et al.* (1998). Road traffic and adverse respiratory effects in children. Sidria collaborative group. *Occupational and environmental medicine* 55(11): 771-778.
Clark, N. N., Kern, J. M., Atkinson, C. M. and Nine, R. D. (2002). Factors affecting heavy-duty diesel vehicle emissions. *Journal of the Air & Waste Management Association* 52(1): 84-94.
Coble, J. B., Stewart, P. A., Vermeulen, R., Yereb, D., Stanevich, R., *et al.* (2010). The diesel exhaust in miners study: Ii. Exposure monitoring surveys and development of exposure groups. *Annals of Occupational Hygiene*: meq024.
Czerwinski, J., Zimmerli, Y., Chiesura, C., Mayer, A. and D'Urbano, G. (2012). Influences on NO_2-emissions from dpf’s with passive regeneration. *Czasopismo Techniczne. Mechanika* 109(4-M): 3--21.
Dacunto, P. J., Cheng, K.-C., Acevedo-Bolton, V., Jiang, R.-T., Klepeis, N. E., *et al.* (2013). Real-time particle monitor calibration factors and pm 2.5 emission factors for multiple indoor sources. *Environmental Science: Processes & Impacts* 15(8): 1511-1519.
Dahmann, D., Monz, C. and Sönksen, H. (2007). Exposure assessment in german potash mining. *International archives of occupational and environmental health* 81(1): 95-107.
Dahmann, D., Morfeld, P., Monz, C., Noll, B. and Gast, F. (2009). Exposure assessment for nitrogen oxides and carbon monoxide in german hard coal mining. *International archives of occupational and environmental health* 82(10): 1267-1279.
Davis, M. E., Smith, T. J., Laden, F., Hart, J. E., Blicharz, A. P., *et al.* (2007). Driver exposure to combustion particles in the u.S. Trucking industry. *Journal of occupational and environmental hygiene* 4(11): 848-854.
Diaz-Sanchez, D., Garcia, M. P., Wang, M., Jyrala, M. and Saxon, A. (1999). Nasal challenge with diesel exhaust particles can induce sensitization to a neoallergen in the human mucosa. *Journal of Allergy and Clinical Immunology* 104(6): 1183-1188.
DNRM (2012). Shift adjustment of the guideline limit for diesel particulate matter. Safety bulletin no. 127., Australian Department of Natural Resources and Mines. Available: http://mines.industry.qld.gov.au/assets/safety-and-health/safety-bulletin-127.pdf.
Duhme, H., Weiland, S. K., Keil, U., Kraemer, B., Schmid, M., *et al.* (1996). The association between self-reported symptoms of asthma and allergic rhinitis and self-reported traffic density on street of residence in adolescents. *Epidemiology* 7(6): 578-582.
Entink, R. H. K., Fransman, W. and Brouwer, D. H. (2011). How to statistically analyze nano exposure measurement results: Using an arima time series approach. *Journal of Nanoparticle Research* 13(12): 6991-7004.
Faiz, A., Weaver, C. S. and Walsh, M. P. (1996). Air pollution from motor vehicles: Standards and technologies for controlling emissions, World Bank Publications.
Feng, X., Ge, Y., Ma, C., Tan, J., Yu, L., *et al.* (2014). Experimental study on the nitrogen dioxide and particulate matter emissions from diesel engine retrofitted with particulate oxidation catalyst. *The Science of the total environment* 472: 56-62.

Fung, K. (1990). Particulate carbon speciation by MnO_2 oxidation. *Aerosol science and technology* 12(1): 122-127.
Goldberg, M., Levin, S. M., Doucette, J. T. and Griffin, G. (1997). A task-based approach to assessing lead exposure among iron workers engaged in bridge rehabilitation. *American journal of industrial medicine* 31(3): 310-318.
Grice, S., Stedman, J., Kent, A., Hobson, M., Norris, J., *et al.* (2009). Recent trends and projections of primary NO_2 emissions in europe. *Atmospheric Environment* 43(13): 2154-2167.
Groves, J. and Cain, J. R. (2000). A survey of exposure to diesel engine exhaust emissions in the workplace. *The Annals of occupational hygiene* 44(6): 435-447.
Hager, L. D. (1998). Sound exposure profiling: A noise monitoring alternative. *American Industrial Hygiene Association* 59(6): 414-418.
Ham, S., Yoon, C., Lee, E., Lee, K., Park, D., *et al.* (2012). Task-based exposure assessment of nanoparticles in the workplace. *Journal of Nanoparticle Research* 14(9): 1-17.
HCN (2004). Nitrogen dioxide: Health-based recommended occupational exposure limit. Health Council of the Netherlands, Hague, Kingdom of The Netherlands.
Hewett, P. and Bullock, W. H. (2014). Rating locomotive crew diesel emission exposure profiles using statistics and bayesian decision analysis. *Journal of occupational and environmental hygiene* 11(10): 645-657.
Hinds, W. C. (2012). Aerosol technology: Properties, behavior, and measurement of airborne particles, John Wiley & Sons.
Houseman, E. A., Ryan, L., Levy, J. I. and Spengler, J. D. (2002). Autocorrelation in real-time continuous monitoring of microenvironments. *Journal of Applied Statistics* 29(6): 855-872.
IARC (2012). Iarc: Diesel engine exhaust carcinogenic. International Agency for Research on Cancer, Lyon, France.
Invernizzi, G., Ruprecht, A., Mazza, R., De Marco, C., Močnik, G., *et al.* (2011). Measurement of black carbon concentration as an indicator of air quality benefits of traffic restriction policies within the ecopass zone in milan, italy. *Atmospheric Environment* 45(21): 3522-3527.
IPCS (1996). Diesel fuel and exhaust emissions. Environmental health criteria 171, International Programme on Chemical Safety
Jacobson, M. Z. (2001). Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature* 409(6821): 695-697.
Jeong, C.-H., Hopke, P. K., Kim, E. and Lee, D.-W. (2004). The comparison between thermal-optical transmittance elemental carbon and aethalometer black carbon measured at multiple monitoring sites. *Atmospheric Environment* 38(31): 5193-5204.
Jeong, J. S., Kim, Y. J., Kim, M. J., Gu, J. H. and Kim, J. (2008). Intercomparision study between filter based optically measured bc and thermally measured ec. *Proceeding of the 46th Meeting of KOSAE*: 258-259.
Karthikeyan, S., Thomson, E. M., Kumarathasan, P., Guénette, J., Rosenblatt, D., *et al.* (2013). Nitrogen dioxide and ultrafine particles dominate the biological effects of inhaled diesel exhaust treated by a catalyzed diesel particulate filter. *Toxicological Sciences* 135(2): 437-450.
Kauppinen, T., Toikkanen, J., Pedersen, D., Young, R., Ahrens, W., *et al.* (2000). Occupational exposure to carcinogens in the european union. *Occupational and environmental medicine* 57(1): 10-18.
Kim, J. (2008). Transport routes and source regions of asian dust observed in korea during the past 40 years (1965–2004). *Atmospheric Environment* 42(19): 4778-4789.
Kim, K. H. and Kim, M. Y. (2003). The effects of asian dust on particulate matter fractionation in

seoul, korea during spring 2001. *Chemosphere* 51(8): 707-721.
Kittelson, D. B. (1998). Engines and nanoparticles: A review. *Journal of Aerosol Science* 29(5–6): 575-588.
Klepeis, N. E., Ott, W. R. and Switzer, P. (2007). Real–time measurement of outdoor tobacco smoke particles. *Journal of the Air & Waste Management Association* 57(5): 522-534.
KoreaMOE (2003). Special act on the improvement of air quality in seoul metropolitan area, Korea Ministry of Environment.
KoreaMOE (2013). Air quality standard, Korea Ministry of Environment.
Lavanchy, V., Gäggeler, H., Nyeki, S. and Baltensperger, U. (1999). Elemental carbon (ec) and black carbon (bc) measurements with a thermal method and an aethalometer at the high-alpine research station jungfraujoch. *Atmospheric Environment* 33(17): 2759-2769.
Lavoie, J., Dunkerley, C. J., Kosatsky, T. and Dufresne, A. (2006). Exposure to aerosolized bacteria and fungi among collectors of commercial, mixed residential, recyclable and compostable waste. *The Science of the total environment* 370(1): 23-28.
Lee, K.-H., Jung, H.-J., Park, D.-U., Ryu, S.-H., Kim, B., *et al.* (2015). Occupational exposure to diesel particulate matter in municipal household waste workers. *PloS one* 10(8): e0135229.
Lewné, M., Nise, G., Lind, M.-L. and Gustavsson, P. (2006). Exposure to particles and nitrogen dioxide among taxi, bus and lorry drivers. *International archives of occupational and environmental health* 79(3): 220-226.
Lewné, M., Plato, N., Bellander, T., Alderling, M. and Gustavsson, P. (2011). Occupational exposure to motor exhaust in stockholm, sweden—different grouping strategies using variability in no 2 to create homogenous groups. *International journal of hygiene and environmental health* 214(1): 47-52.
Lewne, M., Plato, N. and Gustavsson, P. (2007). Exposure to particles, elemental carbon and nitrogen dioxide in workers exposed to motor exhaust. *The Annals of occupational hygiene* 51(8): 693-701.
Lin, C. and Friedlander, S. K. (1988). A note on the use of glass fiber filters in the thermal analysis of carbon containing aerosols. *Atmospheric Environment (1967)* 22(3): 605-607.
Liu, Z., Ge, Y., Tan, J., He, C., Shah, A. N., *et al.* (2012). Impacts of continuously regenerating trap and particle oxidation catalyst on the NO_2 and particulate matter emissions emitted from diesel engine. *Journal of environmental sciences (China)* 24(4): 624-631.
Liukonen, L. R., Grogan, J. L. and Myers, W. (2002). Diesel particulate matter exposure to railroad train crews. *AIHA journal : a journal for the science of occupational and environmental health and safety* 63(5): 610-616.
Lloyd, A. C. and Cackette, T. A. (2001). Diesel engines: Environmental impact and control. *Journal of the Air & Waste Management Association* 51(6): 809-847.
Miguel, A. H., Kirchstetter, T. W., Harley, R. A. and Hering, S. V. (1998). On-road emissions of particulate polycyclic aromatic hydrocarbons and black carbon from gasoline and diesel vehicles. *Environmental science & technology* 32(4): 450-455.
MOLIT (2012). Registered motor vehicle statistics Ministry of Land Infrastructure and Transport of Korea
MSHA (2001). Diesel particulate matter exposure of underground metal and nonmetal miners, Mine Safety and Health Administration. 66: 5706-5910.
Neitzel, R., Daniell, W., Sheppard, L., Davies, H. and Seixas, N. (2011). Evaluation and comparison of three exposure assessment techniques. *Journal of occupational and environmental hygiene* 8(5): 310-323.
Ng, I. P., Ma, H., Kittelson, D. and Miller, A. (2007). Comparing measurements of carbon in diesel exhaust aerosols using the aethalometer, niosh method 5040, and smps, SAE Technical Paper.

Nightingale, J. A., Maggs, R., Cullinan, P., Donnelly, L. E., Rogers, D. F., *et al.* (2000). Airway inflammation after controlled exposure to diesel exhaust particulates. *American journal of respiratory and critical care medicine* 162(1): 161-166.

NIOSH (1992). Health hazard evaluation report 88-104-2207, asarco - troy unit mine, troy, montana. . Cincinnati, OH, National Institute for Occupational Safety and Health.

NIOSH (1999). Health hazard evaluation report 97-0304-2695, racine fire department, racine, wisconsin, National Inst. for Occupational Safety and Health, Cincinnati, OH (US).

NIOSH (2005). Health hazard evaluation report 2005-0091-2957, air contaminant and noise exposures among transportation security administration bagage screeners at four international airports. Cincinnati, OH, National Inst. for Occupational Safety and Health.

Novakov, T. and Corrigan, C. E. (1995). Thermal characterization of biomass smoke particles. *Microchimica Acta* 119(1-2): 157-166.

OSHRI (2014). Estimates of occupational exposure to diesel engine exhaust emissions in south korea, Korea Occupational Safety and Health Agency.

Ott, W., Switzer, P. and Willits, N. (1994). Carbon monoxide exposures inside an automobile traveling on an urban arterial highway. *Air & waste* 44(8): 1012-1018.

Park, D., Lee, K., Ryu, S., Kim, S., Yoon, C., *et al.* (2013). Characteristics of particulate matter generated while handling municipal household waste. *Journal of occupational health* 55(6): 503-510.

Pio, C., Cerqueira, M., Harrison, R. M., Nunes, T., Mirante, F., *et al.* (2011). Oc/ec ratio observations in europe: Re-thinking the approach for apportionment between primary and secondary organic carbon. *Atmospheric Environment* 45(34): 6121-6132.

Pope III, C. A., Thun, M. J., Namboodiri, M. M., Dockery, D. W., Evans, J. S., *et al.* (1995). Particulate air pollution as a predictor of mortality in a prospective study of us adults. *American journal of respiratory and critical care medicine* 151(3_pt_1): 669-674.

Poulsen, O. M., Breum, N. O., Ebbehøj, N., Hansen, Å. M., Ivens, U. I., *et al.* (1995). Collection of domestic waste. Review of occupational health problems and their possible causes. *Science of The Total Environment* 170(1–2): 1-19.

Pronk, A., Coble, J. and Stewart, P. A. (2009). Occupational exposure to diesel engine exhaust: A literature review. *Journal of exposure science and environmental epidemiology* 19(5): 443-457.

Ramachandran, G., Paulsen, D., Watts, W. and Kittelson, D. (2005). Mass, surface area and number metrics in diesel occupational exposure assessment. *Journal of Environmental Monitoring* 7(7): 728-735.

Ramanathan, V. and Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nature Geosci* 1(4): 221-227.

Riediker, M., Williams, R., Devlin, R., Griggs, T. and Bromberg, P. (2003). Exposure to particulate matter, volatile organic compounds, and other air pollutants inside patrol cars. *Environmental science & technology* 37(10): 2084-2093.

Ris, C. (2007). U.S. Epa health assessment for diesel engine exhaust: A review. *Inhalation toxicology* 19 Suppl 1: 229-239.

Roegner, K., Sieber, W. K. and Echt, A. (2002). Evaluation of diesel exhaust controls. *Applied occupational and environmental hygiene* 17(1): 1-7.

Rogge, W. F., Hildemann, L. M., Mazurek, M. A., Cass, G. R. and Simoneit, B. R. (1993). Sources of fine organic aerosol. 2. Noncatalyst and catalyst-equipped automobiles and heavy-duty diesel trucks. *Environmental science & technology* 27(4): 636-651.

Salako, G. O., Hopke, P. K., Cohen, D. D., Begum, B. A., Biswas, S. K., *et al.* (2012). Exploring the variation between ec and bc in a variety of locations. *Aerosol and Air Quality Research* 12(1): 1-7.

Salvi, S., Blomberg, A., Rudell, B., Kelly, F., Sandstrom, T., *et al.* (1999). Acute inflammatory responses in the airways and peripheral blood after short-term exposure to diesel exhaust in healthy human volunteers. *American journal of respiratory and critical care medicine* 159(3): 702-709.

Salvi, S. S., Nordenhall, C., Blomberg, A., Rudell, B., Pourazar, J., *et al.* (2000). Acute exposure to diesel exhaust increases il-8 and gro-α production in healthy human airways. *American journal of respiratory and critical care medicine* 161(2): 550-557.

Sarnat, S. E., Suh, H. H., Coull, B. A., Schwartz, J., Stone, P. H., *et al.* (2006). Ambient particulate air pollution and cardiac arrhythmia in a panel of older adults in steubenville, ohio. *Occupational and environmental medicine* 63(10): 700-706.

Schauer, J. J. (2003). Evaluation of elemental carbon as a marker for diesel particulate matter. *Journal of exposure analysis and environmental epidemiology* 13(6): 443-453.

Schauer, J. J., Kleeman, M. J., Cass, G. R. and Simoneit, B. R. (1998). Characterization and control of organic compounds emitted from air pollution sources. Final report, California Inst. of Tech., Dept. of Environmental Engineering Science, Pasadena, CA (United States); Oregon State Univ., Coll. of Oceanic and Atmospheric Sciences, Corvallis, OR (United States); California State Air Resources Board, Research Div., Sacramento, CA (United States).

Scheepers, P., Coggon, D., Knudsen, L. E., Anzion, R., Autrup, H., *et al.* (2002). Biomarkers for occupational diesel exhaust exposure monitoring (biomodem)—a study in underground mining. *Toxicology letters* 134(1): 305-317.

Schuetzle, D. and Frazier, J. A. (1986). Factors influencing the emission of vapor and particulate phase components from diesel engines. *Developments in toxicology and environmental science* 13: 41-63.

Schwartz, J. (1994). Air pollution and hospital admissions for the elderly in birmingham, alabama. *American journal of epidemiology* 139(6): 589-598.

Schwartz, J. and Morris, R. (1995). Air pollution and hospital admissions for cardiovascular disease in detroit, michigan. *American journal of epidemiology* 142(1): 23-35.

SCOEL (2014). Recommendation from the scientific committee on occupational exposure limits for nitrogen dioxide. In: Scoel/sum/53, The European Scientific Committee on Occupational Exposure Limits.

Seixas, N. S., Sheppard, L. and Neitzel, R. (2003). Comparison of task-based estimates with full-shift measurements of noise exposure. *AIHA Journal* 64(6): 823-829.

Seshagiri, B. and Burton, S. (2003). Occupational exposure to diesel exhaust in the canadian federal jurisdiction. *AIHAJ-American Industrial Hygiene Association* 64(3): 338-345.

Silverman, D. T., Samanic, C. M., Lubin, J. H., Blair, A. E., Stewart, P. A., *et al.* (2012). The diesel exhaust in miners study: A nested case-control study of lung cancer and diesel exhaust. *Journal of the National Cancer Institute* 104(11): 855-868.

Sirianni, G., Chemerynski, S., Cohen, H., Wheeler, R. and Borak, J. (2003). Sources of interference in field studies of diesel exhaust emissions. *Applied occupational and environmental hygiene* 18(8): 591-596.

Son, B., Yang, W., Breysse, P., Chung, T. and Lee, Y. (2004). Estimation of occupational and nonoccupational nitrogen dioxide exposure for korean taxi drivers using a microenvironmental model. *Environmental research* 94(3): 291-296.

Takano, H., Ichinose, T., Miyabara, Y., Shibuya, T., Lim, H.-B., *et al.* (1998). Inhalation of diesel exhaust enhances allergen-related eosinophil recruitment and airway hyperresponsiveness in mice. *Toxicology and applied pharmacology* 150(2): 328-337.

U.S.DoE (2003). Diesel engine, freedom car & vehicle technologies program, U.S. Department of Energy.

U.S.EPA (2002). Health assessment document for diesel engine exhaust. National Center for Environmental Assessment, U.S. Environmental Protection Agency.
U.S.EPA (2008a). Integrated science assessment for oxides of nitrogen-health criteria. Research Triangle Park, USA, National Center for Environmental Assessment-RTP Division Office of Research and Development US Environmental Protection Agency.
U.S.EPA (2008b). Integrated science assessment for oxides of nitrogen-health criteria, annexes. National Center for Environmental Assessment-RTP Division Office of Research and Development US Environmental Protection Agency, Research Triangle Park, USA.
Vanderstraeten, P., Forton, M., Brasseur, O. and Offer, Z. Y. (2011). Black carbon instead of particle mass concentration as an indicator for the traffic related particles in the brussels capital region. *Journal of Environmental Protection* 2(05): 525.
Verma, D. K., Finkelstein, M. M., Kurtz, L., Smolynec, K. and Eyre, S. (2003). Diesel exhaust exposure in the canadian railroad work environment. *Applied occupational and environmental hygiene* 18(1): 25-34.
Verma, D. K., Shaw, L., Julian, J., Smolynec, K., Wood, C., *et al.* (1999). A comparison of sampling and analytical methods for assessing occupational exposure to diesel exhaust in a railroad work environment. *Applied occupational and environmental hygiene* 14(10): 701-714.
Viegas, S., Santos, M. d., Faria, T., Almeida-Silva, M. and Viegas, C. (2015). Task-based occupational exposure assessment and particle number concentration: Two important data resources to perform risk assessment for occupational exposure to particles.
Virji, M. A., Woskie, S. R. and Pepper, L. D. (2008). Task-based lead exposures and work site characteristics of bridge surface preparation and painting contractors. *Journal of occupational and environmental hygiene* 6(2): 99-112.
Virji, M. A., Woskie, S. R., Waters, M., Brueck, S., Stancescu, D., *et al.* (2009). Agreement between task-based estimates of the full-shift noise exposure and the full-shift noise dosimetry. *Annals of occupational hygiene* 53(3): 201-214.
Wang, J. S., Chan, T. L., Cheung, C. S., Leung, C. W. and Hung, W. T. (2006). Three-dimensional pollutant concentration dispersion of a vehicular exhaust plume in the real atmosphere. *Atmospheric Environment* 40(3): 484-497.
Wang, Y., Chung, A. and Paulson, S. (2010). The effect of metal salts on quantification of elemental and organic carbon in diesel exhaust particles using thermal-optical evolved gas analysis. *Atmospheric Chemistry and Physics* 10(23): 11447-11457.
Watts, W., Cantrell, B., Ambs, J. and Rubow, K. (1992). Diesel exhaust aerosol levels in underground coal mines. Proceedings: Bureau of Mines Information and Technology Transfer Seminar. Bureau of Mines, Minneapolis, MN.
Yanagisawa, Y. and Nishimura, H. (1982). A badge-type personal sampler for measurement of personal exposure to NO_2 and NO in ambient air. *Environment International* 8(1–6): 235-242.
Yelverton, T. L., Hays, M. D., Gullett, B. K. and Linak, W. P. (2014). Black carbon measurements of flame-generated soot as determined by optical, thermal-optical, direct absorption, and laser incandescence methods. *Environmental Engineering Science* 31(4): 209-215.

Appendix I

Determination of the calibration factor for personal aerosol monitor.

The SidePak measurements were calibrated to the $PM_{2.5}$ concentration from the corresponding gravimetric measurements. We located a SidePak monitor and three reference samplers together at the gate of truck terminal where many diesel fueled vehicles were running and idling. The samplings were performed on 20 and 23 Jan 15.

The gravimetric $PM_{2.5}$ samples were collected on a polyvinyl chloride (PVC, diameter 37 mm, pore size 5.0 μm, SKC Inc., USA) filter mounted on $PM_{2.5}$ sampler (PEM, Cat No 761-203, SKC Inc., USA) using a portable high volume pump (SKC Inc., AirChek 52, USA). The pumps drew air through sampling inlets at 2.0 Lpm. Filters were stored in desiccators before and after sampling for at least 24 hours to equilibrate temperature and humidity. Each filter was also adapted to the antistatic equipment to protect it from static electricity. Pre– and post–weighing was performed using a microbalance (Mettler Toledo Inc., XP6 Automated-S, USA) with a sensitivity of 1μg in a weighing room where the temperature (20±5℃) and humidity (55±5%) were controlled. For each date, three field blank filters were subjected to the same experimental procedures and their average 'post-pre' weight was subtracted from each 'post–pre' weight of filter.

The SidePak measurements were recalculated using the average calibration factor for each measurement as follows. Table A. presents detail gravimetric analysis data and calibration factor calculated.

$$\text{Calibration factor} = \frac{\text{Gravimetric PM}_{2.5}\text{ concentration}}{\text{Time integrated SidePak concentration}}$$

Each SidePak measurement was multiplied by the calibration factor of 0.69 to estimate the true mass concentration.

Table. Reference gravimetric $PM_{2.5}$ concentrations and calculated calibration factor

Sampling date	Filter No.	Post-Pre weight (μg)	Sampling duration (min)	Sampling volume (m^3)	Gravimetric concentration (μg/m^3)	SidePak concentration (μg/m^3)	Calibration factor
20-Jan-15	PVC-101	76.7	374	0.791	80		
20-Jan-15	PVC-102	67	374	0.788	68		
20-Jan-15	PVC-103	51.7	265	0.555	68.9		
20-Jan-15	Average gravimetric $PM_{2.5}$ concentration				72.3	91	0.79
23-Jan-15	PVC-107	90.7	435	0.915	80.7		
23-Jan-15	PVC-108	83.3	435	0.916	72.6		
23-Jan-15	PVC-109	92.7	435	0.906	83.7		
23-Jan-15	Average gravimetric $PM_{2.5}$ concentration				79	134	0.59
Average Calibration Factor							0.69

Appendix II. Sources of organic carbon in assessing the occupational exposure of municipal household waste workers to diesel particulate matter

Abstract

Malodors from biodegradable waste and the movement condition of trash trucks (mainly idling and slow driving) positively influenced the higher fraction of organic carbon (OC). However, further study is required to clarify how many volatile hydrocarbons actually originate from malodors and from diesel engine exhaust.

Introduction

Recently, we reported on the occupational exposure of municipal household waste (MHW) workers to diesel particulate matter (DPM) by measuring elemental carbon (EC), organic carbon (OC), total carbon (TC), black carbon (BC) and fine particulate matter ($PM_{2.5}$).[1] During the analyses of EC, OC and TC data, we noticed that our study resulted in a significantly higher ratio of OC to EC concentrations for each worker. In general, the OC/EC ratio is less than 1 for diesel engines,[2] and it has been recommended to suspect OC interference if the OC/EC ratio surpasses 1.8.[3, 4] However, the OC/EC ratio of MHW workers in our study ranged from 1.4 to 26.1. Based on these results, we discussed that cigarette smoke and bioaerosols/malodors from waste could cause a higher fraction of OC to EC. Accordingly, the multiple regression model for OC levels confirmed workers' smoking habits to be the first exposure determinant.

Although we proposed potential OC interferences in that study, this was not fully explained based on reliable data. Therefore, we designed an additional experiment to identify the sources of OC in MHW work. The objective of this study was to identify sources of the higher OC fraction in assessing occupational exposure of MHW workers to DPM. First was the determination of whether malodors from waste are collected with ambient EC and OC onto the pre-fired quartz filter and analyzed as OC in the thermal-optical transmittance method. Second, it was determined whether diesel engine exhaust during the idling of MHW trucks contains a higher OC fraction to EC.

Methods

The experiment was performed with an MHW collection company located in Seoul on October 31 and November 3, 2015. Two vehicles were selected for the sampling: one was a diesel-powered MHW truck (6.6 L, Hyundai Motors, Mega-truck), and the other one was a diesel-powered SUV (2.8 L, Ssangyong motors, Rexton). The MHW truck was manufactured in 2004 and met Euro-3 emission standards. It had a retrofitted diesel particulate filter (DPF) as required by South Korean environmental regulations.[5] The SUV was manufactured in 2004 and did not have a DPF.

Seven sets of samples were collected: (1) sampling of malodors from food waste without the engine running; (2) sampling of diesel exhaust behind the tailpipe during idling of the MHW truck; (3) sampling of malodors after sampling #2; (4) sampling of diesel exhaust behind the tailpipe during running of the MHW truck engine (engine rpm: 1500–2000); (5) sampling of malodors after sampling #4; (6) sampling of diesel exhaust behind the tailpipe during idling of the SUV; (7) sampling of ambient air near a crosswalk. One to three samples were collected for each set and samples of the same set were collected side-by-side to minimize sampling bias. Malodor samples (e.g., from samplings #1, #3, and #5) were collected for several hours inside a food waste truck container without any running truck nearby. Tailpipe samples (e.g., samplings #2, #4, #6) were collected for a few minutes (3–5 minutes) because they were sampled from one foot away, immediately behind the tailpipe. The sampling durations for the tailpipe samples were decided after the measurement of PM2.5 and nitrogen dioxide levels as surrogate for DPM.

The sampling and analysis procedures were same as in the previous study.[1] EC/OC/TC samples were collected on 37 mm diameter, pre-fired quartz filters (Pallflex Tissuquartz 2500QAT-UP, Pall Life sciences, USA) mounted on a personal environmental monitor (PEMs, Cat No 761–203, SKC Inc., USA) using a personal sampling pump (MSA Escort ELF pump, Mine Safety Appliance Co., USA). Pumps were pre- and post-calibrated using a DryCal DC-Lite primary flow meter (DCL-H, Bios International Co., USA). According to the PEM manufacturer's instructions, the pump flow rate was set at 2 L/min. At this rate, PEM samplers have a 50% cut-off point for particulates with an aerodynamic diameter of 2.5 μm. Field blanks were collected daily at the measurement sites and were handled identically to the area samples. All samples were analyzed using National Institute for Occupational Safety and Health (NIOSH) method 5040.

Results and Discussion

Table 1 shows the concentrations of EC, OC, and TC and the OC/EC ratio of each sampling set. The mean ratio of OC/EC for the samples of malodors without the diesel engine running (#1) was 9.5. On the other hand, the ratio of ambient air

(#7) was 5.9 near a crosswalk where multiple vehicles were running, stopping, idling, and starting. For reference, the mean ratio of ambient background levels during the period of the original field survey in 2014 was 2.4. Another reference sampling that was conducted at a highway toll booth for diesel trucks showed a ratio of 2.4. These results indicate that malodors from waste do positively affect OC concentrations, resulting in a higher OC/EC ratio.

The mean ratio for diesel exhaust from the idling truck (#2) was 9.8. The ratio for malodors plus idling truck exhaust (#3) was 9.6. This is similar with the ratios of samplings #1 and #2. The ratio for diesel exhaust from the running truck (#4) was 6.5 and the ratio for malodors plus running truck (#5) was 6.9. These results indicate that idling trucks generate a higher fraction of OC than do running trucks. According to a few studies, lower engine rpm with lower load (e.g., idling conditions) and high sulfur fuel resulted in higher OC/EC ratios.[6-8]

The OC/EC ratio for the SUV (#6) was 0.5, which was a typical value for a diesel engine without a DPF. The DPF installed on the trash truck had recently been replaced. A DPF is an important factor in the emission of DPM and worker exposure because per the DPF manufacturer's specifications it can reduce DPM by 90%. Hence, the EC levels of the SUV (3,413 $\mu g/m^3$) was about 10-fold that of trash truck (314 $\mu g/m^3$). However, it is not clear why the OC level of the trash truck (3,152 $\mu g/m^3$) was not lower, and in fact even much higher, than that of SUV (1,612 $\mu g/m^3$), whether this could be attributed to the use of a DPF or to excessive generation of gaseous organic compounds due to incomplete combustion. It has been reported that the OC/EC ratios of diesel engines with a DPF/particulate trap were much higher than that of a bus without one.[9, 10]

The particulate fractions of diesel exhaust consist of a center core of EC to which OC has attached. In general, OC is comprised of hydrocarbons (C_{14}–C_{35}), poly-nuclear aromatic hydrocarbons (PAHs), and their derivatives as well as small amounts of sulfate, nitrate, and other elements.[11] The odorous compounds emitted by food waste can vary depending on the related materials, temperature, ambient environment, etc. It has been reported that components of malodors from MHW include the following: S-compounds (e.g., hydrogen sulfide and methyl mercaptan), N-compounds (e.g., ammonia and trimethylamine), aromatics (toluene, benzene and naphthalene), alkanes (e.g., tetradecane and docosane), esters (e.g., dibutyl phthalate), and other compounds (e.g., decanal, phenol, and limonene).[12-14] The organic compounds of malodors are mostly volatile low molecular weight hydrocarbons (C_1-C_{10}), but also contain hydrocarbons of > C_{14} and sulfur and nitrogen compounds that can be adsorbed on a quartz filter and analyzed as OC.

Table 1. Concentrations of EC, OC, TC and OC/EC ratio of each sampling set

No	Type of sample	Sampling date	N	EC (μg/m^3)		OC (μg/m^3)		TC (μg/m^3)		OC/EC	
				Mean	Range	Mean	Range	Mean	Range	Mean	Range
1	Malodour (inside food waste truck container without truck running)	31-Oct-15	3	2.0	1.2–2.5	16.8	16.1–17.8	18.8	18.4–19.0	9.5	6.5–14.9
2	Idling of MHW truck[a]	31-Oct-15	2	314	291–337	3,152	1,830–4,475	3,466	2,120–4,812	9.8	6.3–13.3
3	Idling of MHW truck + Malodour	31-Oct-15	2	5	4.3–5.7	49.7	31.6–67.8	54.7	35.9–73.4	9.6	7.3–12.0
4	Running of MHW truck	31-Oct-15	3	350	278–408	2,214	1,929–2,360	2,564	2,293–2,768	6.5	5.3– 8.5
5	Running of MHW truck + Malodour	31-Oct-15	3	8.2	4.8–11.9	54.0	40.2–73.7	62.2	45.0–85.6	6.9	6.1–8.5
6	Idling of SUV[b] without DPF	03-Nov-15	1	3,413	–	1,621	–	5,034	–	0.5	–
7	Ambient background level, near a cross walk	03-Nov-15	3	3.4	3.2 - 3.6	20.0	17.5 - 24.7	23.4	21.0 - 28.0	5.9	4.8 - 7.6
Ref	Ambient background level during the original study[c]	Jun-Sep 2014	7	1.8	1.1 - 3.0	4.1	2.0 - 5.3	5.8	3.1 - 7.9	2.4	1.6 - 3.4
Ref	Toll booth for trucks	Sep 2014	3	6.0	5.7 - 6.3	14.5	10.0 - 19.4	20.4	15.6 - 25.7	2.4	1.8 - 3.1

[a] MHW truck: Hyundai Motors, Mega-truck, engine size (6.6 L), 2004

[b] SUV: Ssangyong motors, Rexton, engine size (2.8 L), 2004

Abbreviations: EC: elemental carbon; OC: organic carbon; TC: total carbon; MHW: municipal household waste; SUV: sports utility vehicle; DPF: diesel particulate filter

Adsorption of gas-phase organic compounds on the quartz filter (positive artefact) and the evaporation of particle-phase OC from the quartz filter (negative artefact) have been a concern for the monitoring of DPM in atmospheric air.[15-17] However, it is difficult to conclude which phenomena is the dominant artefact between adsorption and evaporation.[18-20] It may in fact vary according to atmospheric conditions, meteorological conditions, season, other contaminants (e.g., malodors), sampling procedure, etc.[16, 20] To minimize the positive artefact of OC, it was recommended to use a denuder or backup-filter behind the primary quartz filter in the atmospheric environment. However, such use of a denuder or backup filter to control positive artefact has not been commonly applied in the collection of breathing zone samples in the industrial hygiene field. In our study, we employed a PEM sampler to exclude EC interference from larger particles. However, OC interference caused by malodors from biodegradable waste, cigarette smoke or volatile organic gases could not be excluded.

In the previous study, we concluded that EC truly represented worker exposures and was little affected by interferences such as worker smoking habits or ambient dusts, whereas OC and TC were influenced by such interferences.[7] Subramanian et al. reported that ambient EC concentrations were not significantly affected by positive artefact.[16] According to them, there was no significant difference between EC concentrations from bare quartz and denuded quartz filter samples.

Conclusions

Based on the experiment results, it is clear that malodors from biodegradable waste interfere with the accurate quantification of OC because they contains gas-phase hydrocarbons (C_1-C_{10}) as well as > C_{14} hydrocarbons that can be analyzed as OC. In addition, idling and slow driving by the MHW truck may influence the higher fraction of OC. Further study is required to clarify how many volatile hydrocarbons originate from malodors and from diesel engine exhaust. In addition, a denuder or backup filter should have been employed to control the positive artefact by gas-phase organic compounds. Further validation testing is required to determine the appropriate correction of positive/negative artefacts for breathing zone samples in a wider range of occupational and environmental situations.

References

1. K.-H. Lee, H.-J. Jung, D.-U. Park, S.-H. Ryu, B. Kim, K.-C. Ha, S. Kim, G. Yi and C. Yoon,*Occupational Exposure to Diesel Particulate Matter in Municipal Household Waste Workers*, *PloS one*, 2015, **10**, e0135229.
2. C. Pio, M. Cerqueira, R. M. Harrison, T. Nunes, F. Mirante, C. Alves, C. Oliveira, A. S. de la Campa, B. Artinano and M. Matos,*OC/EC ratio observations in Europe: Re-thinking the approach for apportionment between primary and secondary organic carbon*, *Atmospheric Environment*, 2011, **45**, 6121-6132.
3. M. E. Birch,*Monitoring of diesel particulate exhaust in the workplace*, *NIOSH Manual of Analytical Methods (NMAM)*, 2003, 2003-2154.
4. G. Sirianni, S. Chemerynski, H. Cohen, R. Wheeler and J. Borak,*Sources of interference in field studies of diesel exhaust emissions*, *Applied occupational and environmental hygiene*, 2003, **18**, 591-596.
5. KoreaMOE, *Special act on the improvement of air quality in Seoul metropolitan area*,Korea Ministry of Environment, 2003.
6. J. Zhang, K. He, Y. Ge and X. Shi,*Influence of fuel sulfur on the characterization of PM 10 from a diesel engine*, *Fuel*, 2009, **88**, 504-510.
7. D. R. Cocker, S. D. Shah, K. C. Johnson, X. Zhu, J. W. Miller and J. M. Norbeck,*Development and application of a mobile laboratory for measuring emissions from diesel engines. 2. Sampling for toxics and particulate matter*, *Environmental science & technology*, 2004, **38**, 6809-6816.

8. S. D. Shah, D. R. Cocker, J. W. Miller and J. M. Norbeck,*Emission rates of particulate matter and elemental and organic carbon from in-use diesel engines*, *Environmental science & technology*, 2004, **38**, 2544-2550.
9. D. H. Lowenthal, B. Zielinska, J. C. Chow, J. G. Watson, M. Gautam, D. H. Ferguson, G. R. Neuroth and K. D. Stevens,*Characterization of heavy-duty diesel vehicle emissions*, *Atmospheric Environment*, 1994, **28**, 731-743.
10. S. Biswas, V. Verma, J. J. Schauer and C. Sioutas,*Chemical speciation of PM emissions from heavy-duty diesel vehicles equipped with diesel particulate filter (DPF) and selective catalytic reduction (SCR) retrofits*, *Atmospheric Environment*, 2009, **43**, 1917-1925.
11. U.S.EPA, *Health assessment document for diesel engine exhaust*,U.S. Environmental Protection Agency, 2002.
12. Y. Di, J. Liu, J. Liu, S. Liu and L. Yan,*Characteristic analysis for odor gas emitted from food waste anaerobic fermentation in the pretreatment workshop*, *Journal of the Air & Waste Management Association*, 2013, **63**, 1173-1181.
13. B. Song, J. Jung, S. Jung and G. Ji,*A Study of Odorous Compounds in the Foodwaste Treatment Processing*, *J. Korea Soc. Waste Manage*, 2004, **21**, 107-116.
14. I.-F. Mao, C.-J. Tsai, S.-H. Shen, T.-F. Lin, W.-K. Chen and M.-L. Chen,*Critical components of odors in evaluating the performance of food waste composting plants*, *Science of the Total Environment*, 2006, **370**, 323-329.
15. T. W. Kirchstetter, C. E. Corrigan and T. Novakov,*Laboratory and field investigation of the adsorption of gaseous organic compounds onto quartz filters*, *Atmospheric Environment*, 2001, **35**, 1663-1671.
16. R. Subramanian, A. Y. Khlystov, J. C. Cabada and A. L. Robinson,*Positive and negative artifacts in particulate organic carbon measurements with denuded and undenuded sampler configurations special issue of aerosol science and technology on findings from the fine particulate matter supersites program*, *Aerosol Science and Technology*, 2004, **38**, 27-48.
17. J. Noll and M. E. Birch,*Effects of sampling artifacts on occupational samples of diesel particulate matter*, *Environmental science & technology*, 2008, **42**, 5223-5228.
18. D. J. Eatough, D. A. Eatough, L. Lewis and E. A. Lewis,*Fine particulate chemical composition and light extinction at Canyonlands National Park using organic particulate material concentrations obtained with a multisystem, multichannel diffusion denuder sampler*, *Journal of Geophysical Research: Atmospheres (1984–2012)*, 1996, **101**, 19515-19531.
19. W. Cui, D. J. Eatough and N. L. Eatough,*Fine particulate organic material in the Los Angeles Basin-I: assessment of the high-volume Brigham Young University organic sampling system, BIG BOSS*, *Journal of the Air & Waste Management Association*, 1998, **48**, 1024-1037.
20. B. J. Turpin, J. J. Huntzicker and S. V. Hering,*Investigation of organic aerosol sampling artifacts in the Los Angeles Basin*, *Atmospheric Environment*, 1994, **28**, 3061-3071.

Appendix III. Comparison results between inclusion and exclusion of 1-min task data

Table 1. Multiple regression model to predict natural log-transformed BC levels of all tasks with/without 1-min task data

Independent factors		BC level of all tasks, with 1-min task data				BC level of all tasks, without 1-min task data			
		N	Coefficient	Standard error	p-value	N	Coefficient	Standard error	p-value
Intercept			1.182	0.126	<0.001		1.182	0.126	<0.001
Task	Riding in the cabin		Reference				Reference		
	Collection, < 2m		0.457	0.076	<0.001		0.370	0.083	0.000
	Riding on the rear step		0.266	0.084	0.002		0.248	0.101	0.015
Job title	Driver		Reference				Reference		
	Collector		0.250	0.102	0.015		0.158	0.090	0.082
Truck model	Euro Standard 4		Reference				Reference		
	Euro Standard 3		0.260	0.118	0.028		0.228	0.124	0.066
Weather	Clear		Reference				Reference		
	Foggy		0.262	0.065	<0.001		0.262	0.065	<0.001
Area	Others[a]		Reference				Reference		
	Street		0.288	0.111	0.010		0.273	0.103	0.008
	Residential area		0.184	0.108	0.088		0.254	0.101	0.012
Modeling results	Adjusted R^2	411	0.195	0.586	<0.001	259	0.263	0.499	<0.001
	Durbin Watson d[b] ($1.603<d<1.746$)		1.436		>0.01		1.959		<0.001

[a] Workers stayed at the incineration plant, interim collection point, underground, etc.

[b] If the number of variables is seven (k'=7) when perform a Durbin Watson test, the lower and upper critical values ($d_{L,0.01}$ and $d_{U,0.01}$) are 1.603 and 1.746.
If $d< d_{L,0.01}$, there is statistical evidence that the error terms are positively auto-correlated.
If $d >d_{U,0.01}$, there is no statistical evidence that the error terms are positively auto-correlated.
If $d_{L,0.01}<d< d_{U,0.01}$, the test is inconclusive.

Abbreviation: BC: black carbon.

Table 2. Multiple regression model to predict natural log-transformed BC levels for the ‘collection < 2m’ with/without 1-min task data

Independent factors		BC level for the ‘collection, < 2m’, with 1-min task data				BC level for the ‘collection, < 2m’, without 1-min task data			
		N	Coefficient	Standard error	p-value	N	Coefficient	Standard error	p-value
Intercept			1.374	0.450	0.003		1.374	0.450	0.003
Job title	Driver		Reference				Reference		
	Collector		0.850	0.267	0.002		0.558	0.230	0.017
Truck model	Euro Standard 4		Reference				Reference		
	Euro Standard 3		0.398	0.153	0.010		0.375	0.139	0.008
Modeling results	Adjusted R^2	144	0.099	0.527	<0.001	100	0.110	0.446	0.001
	Durbin Watson d^a ($1.5<d<1.6$)		1.306		>0.01		2.158		<0.01

[a] If the number of variables is two ($k'=2$) when perform a Durbin Watson test, the lower and upper critical values ($d_{L,0.01}$ and $d_{U,0.01}$) are 1.5 and 1.6.

If $d < d_{L,0.01}$, there is statistical evidence that the error terms are positively auto-correlated.

If $d > d_{U,0.01}$, there is no statistical evidence that the error terms are positively auto-correlated.

If $d_{L,0.01} < d < d_{U,0.01}$, the test is inconclusive.

Abbreviation: BC: black carbon.

Abbreviations

AIHA	American Industrial Hygiene Association
BC	Black Carbon
DE	Diesel Engine Exhaust
DPF	Diesel Particulate Filter
DPM	Diesel Particulate Matter
EC	Elemental Carbon
EPA	Environmental Protection Agency
GM	Geometric Mean
GSD	Geometric Standard Deviation
IARC	International Agency for Research on Cancer
NCI	U.S. National Cancer Institute
NIOSH	National Institute for Occupational Safety and Health
NO_2	Nitrogen Dioxide
OC	Organic Carbon
OEL	Occupational Exposure Limit
PAT	Proficiency Analytical Testing
$PM_{2.5}$	Fine particulate matter; particulate matter less than 2.5 micrometer in aerodynamic diameter
TC	Total Carbon
TLV	Threshold Limit Values established by American Conference of Governmental Industrial Hygienists

국문 초록

환경미화원의 디젤엔진 배출물질 대리인자에 대한 노출 평가

도시생활폐기물을 수거하는 환경미화원들은 높은 노동강도 외에도 바이오에어로졸(bioaerosol), 감염물질, 고온·한파, 중량물 취급 등의 다양한 작업환경 유해요인에 노출되고 있다. 특히, 국내에서는 대부분의 폐기물 수거차량이 디젤엔진을 사용하고 있어 엔진배기구 주변에서 쓰레기를 투척하는 폐기물 수거작업의 특성상 환경미화원들은 상당량의 디젤엔진 배출물질(diesel engine exhaust)에 노출될 것으로 예상된다. 그럼에도 국내는 물론 전 세계적으로 환경미화원의 디젤엔진 배출물질에 대한 노출평가 연구는 거의 없는 실정이다. 더우기 최근 국제 암 연구소(International Agency for Research on Cancer)에서는 디젤배출물질을 1급 발암물질로 상향조정하여 이에 대한 정확한 노출평가가 절실히 필요하다.

디젤엔진 배출물질은 수 백 가지의 가스상과 입자상물질의 혼합체로서 엔진 연소과정에서 발생하며, 그 중 입자상물질(diesel particulate matter)은 불완전연소과정에서 주로 발생한다. 입자상물질의 80–95 %는 입자의 직경이 2.5 μm 이하인 초미세먼지로 이루어져 있으며, 보통 핵을 이루는 원소탄소(elemental carbon, EC)와 거기에 붙어 있는 미량의 황산염, 질산염, 기타 잔류물질 등을

포함한 유기탄소(organic carbon, OC)로 구성돼 있다. 디젤엔진 배출물질의 발생량 및 그 구성비는 차량 종류, 연료의 특성, 운전 상태, 매연저감장치 등에 크게 영향을 받는다. 입자상물질은 단일물질이 아니므로 노출평가 대리인자로서 원소탄소, 유기탄소, 총탄소(total carbon, TC=EC+OC), 블랙카본, $PM_{2.5}$ (초미세먼지) 등이 주로 사용되고 있다.

가스상 물질 중 이산화질소(NO_2)는 폐 하부까지 침투·흡수되면서 독성작용을 일으켜 최근 작업환경기준이 크게 낮아졌다. 또한 매연저감장치를 설치한 차량의 배출가스에서 이산화질소 농도는 오히려 증가하는 걸로 보고돼 최근 대기오염물질의 측정지표로 재조명되고 있다. 더우기 이산화질소는 실시간 측정기기나 수동식시료채취기를 이용한 측정이 가능해 원소탄소, 유기탄소, 다핵방향족탄화수소 등의 대리인자들 보다 측정·분석이 용이한 장점이 있다.

이에 본 연구에서는 다양한 대리인자(원소탄소, 유기탄소, 총탄소, 블랙카본, $PM_{2.5}$, 이산화질소)를 생활폐기물 수거작업 중에 동시 측정해 환경미화원들의 디젤엔진 배출물질에 대한 노출수준을 평가하고, 대리인자들 간의 상관관계를 살펴보았다. 또한 직업환경적 요인에 의한 대리인자별 노출치의 차이를 비교분석하여 환경미화원의 노출을 가장 잘 대변하는 인자를 밝혀 내고자 하였다. 마지막으로, 직업환경적 요인에 의한 영향정도를 시간가중평균치와 작업기반(task-based) 노출농도를 분석하여 환경미화원의 디젤엔진 배출물질의 주요 노출인자(exposure determinant)를 결정하였다.

본 연구는 2014년 6월에서 9월 중 7일간 고양시와 서울에 소재한 5개 쓰

레기 수거업체에 근무하는 환경미화원들을 대상으로 디젤엔진 배출물질에 대한 노출평가를 실시하였다. 폐기물 수거원과 폐기물차량 운전수를 대상으로 작업자 호흡기 영역에서 원소카본/유기카본/총카본, 이산화질소, 블랙카본, $PM_{2.5}$ 시료를 포집하였다. 모든 측정대상 작업자가 1일 작업시간 동안 원소카본/유기카본/총카본과 이산화질소 시료채취기를 착용하였으며, 그 중 일부 작업자는 원소카본/유기카본/총카본, 이산화질소, 블랙카본, $PM_{2.5}$ 채취기를 모두 착용하였다. 원소카본/유기카본/총카본은 필터포집 후 열광학투과법(thermal optical transmittance method)으로 측정·분석하였고, 이산화질소는 수동식 시료채취기로 포집한 후 분광광도계를 이용해 분석하였다. 블랙카본과 $PM_{2.5}$는 실시간 측정기기를 이용해 1분 단위로 측정하였다.

노출조사 기간 동안 총 72명의 환경미화원들로부터 72개의 원소카본/유기카본/총카본, 70개의 이산화질소, 17개의 블랙카본, 21개의 $PM_{2.5}$ 샘플을 포집하였다. 환경미화원들의 원소카본, 유기카본, 총카본, 블랙카본, $PM_{2.5}$, 이산화질소의 시간가중평균치들의 기하평균은 각각 4.8, 39.6, 44.8, 9.1, 62.0, 105.3 $\mu g/m^3$로 나타났다. 이들 노출 농도는 대기환경 측정소의 대기 중 농도보다 2.0에서 12.7 배 높은 수준이었으며, 기존 다른 직업군들의 디젤엔진 배출물질 노출조사 결과와 비교해 보면, 원소카본의 경우 트럭정비사, 기차정비사, 트럭운전수, 철도승무원, 광산의 외부작업자들 보다 높고 광산 내의 작업자들보다는 낮은 수준으로 나타났다. 대리인자들 간의 상관관계는 유의하게 나타났으며, 원소카본의 경우 유기카본, 총카본, 블랙카본, 이산화질소와 유의한 양의상관

관계를 나타냈으며 그 중에서도 블랙카본과 가장 높은 상관관계를 나타냈다.

환경미화원의 직업·환경적 요인에 따른 디젤엔진 배출물질의 노출수준의 차이를 분석한 결과, 모든 배출물질에 대해 폐기물수거원이 운전수 보다, 배기가스 배출기준 유로-3 차량의 작업자들이 유로-4 차량의 작업자보다 높은 수준에 노출되는 것으로 나타났다. 특히 원소카본의 경우 작업자 노출량과 관계가 깊은 변수인 배기구와 차량후면(작업자위치)과의 거리가 짧을수록, 당일 수거한 차량의 수가 많을 수록 통계적으로 유의하게 높은 농도를 나타내 작업 연관성을 잘 대변하는 대리인자로 평가됐다. 또한 다른 입자상물질 대리인자들 보다 흡연이나 기타 유기물질, 일반먼지, 안개 미스트 등의 영향을 상대적으로 덜 받아 환경미화원의 노출평가를 위한 가장 유용한 디젤입자상물질의 대리인자로 밝혀졌다.

가스상물질의 대리인자인 이산화질소는 원소카본과 마찬가지로 수행업무, 차량의 유로기준에 따라 유의하게 다른 결과를 나타냈으며, 농촌지역에서 작업한 환경미화원이 도심의 미화원보다 낮은 농도를 나타내 상대적으로 주변환경 농도의 영향을 받는 것으로 나타났다.

다중선형회귀분석 결과 원소카본 농도에 영향을 미치는 노출인자는 직무(수거원 vs. 운전수), 차량의 유로기준(3 vs. 4) 및 주행속도로 나타났다. 한편 이산화질소 농도는 직무, 엔진 크기, 주행거리에 의해 유의하게 영향을 받는 것으로 나타났다. 기존의 연구와 마찬가지로 유로기준이 3에서 4로 엄격해지면서 원소카본의 농도는 현저하게 줄어들었으나 이산화질소의 농도는 차이가 나지

않아 엄격한 규제기준의 차량일수록 이산화질소가 작업자 노출의 주요지표가 될 수 있음을 알 수 있었다.

디젤 입자상물질의 대리인자 중 블랙카본과 $PM_{2.5}$는 실시간 측정 자료를 이용해 작업기반(Task-based) 노출평가를 실시하였다. 9명 환경미화원들의 블랙카본자료와 $PM_{2.5}$ 실시간 자료를 6개의 세부작업(task)으로 구분하여 총 259개의 블랙카본 작업기반 데이터와 261개의 $PM_{2.5}$ 작업기반 데이타를 얻었다.

세부작업은 2미터 이내 수거작업, 2미터 바깥 수거작업, 차에 매달린 탑승, 차량탑승, 폐기물처리(소각장/중간집하장), 휴식시간으로 구분지었다. 세부작업 중 2미터 이내 수거작업이 가장 높은 농도(9.4 $\mu g/m^3$)를 나타내 배기구 근처에서 작업하는 것이 가장 유해한 작업으로 나타났다. 수거원의 경우 ‘2미터 이내 수거작업’이 전체 노출량의 56.6 %를 기여하는 것으로, 운전수는 차량 내 운전이 전체노출량의 76.4 %를 기여하는 것으로 나타났다.

세부작업 별 블랙카본 농도에 대한 다중회귀분석 결과, 2미터 이내 수거작업, 차량 후면 매달리기, 직무, 차량의 유로기준, 작업장소 등이 유의한 노출인자로 밝혀졌다. 특히 세부작업 중 가장 유해한 작업으로 평가된 2미터 이내 수거작업의 블랙카본농도는 작업자 직무와 차량의 유로기준이 가장 큰 영향인자로 평가되었다. 즉, 차량의 배기가스 배출량과 작업자의 직무가 작업자의 블랙카본 노출 농도를 규정하는 것을 의미한다.

또한 작업기반 노출평가를 통해 고농도 작업이 전체포집시간으로 희석되는 시간가중평균치에 의한 노출평가보다 좀 더 정확하게 유해한 작업을 밝혀낼

수 있었으며, 좀 더 정밀하게 유해작업의 노출농도에 영향을 미치는 노출인자들을 알아낼 수 있었다.

본 연구는 최초로 환경미화원의 디젤엔진 배출물질에 대한 노출을 원소카본, 유기카본, 총카본, 블랙카본, $PM_{2.5}$, 이산화질소 등 다양한 대리인자를 이용해 평가한 연구이다. 결론적으로 환경미화원들은 일반 디젤엔진 관련 직종인 버스, 트럭, 택시, 기차 등의 운전수나 해당 차량의 정비사 보다는 높은 농도의 디젤엔진 배출물질에 노출되는 것으로 평가되었다. 특히, 쓰레기 투척 등을 위해 배기구 근처에 위치할 때 가장 높은 농도의 디젤배출물에 노출되었으며, 해당 작업을 수행할 때 작업자 노출 농도는 디젤엔진의 유로기준에 따른 배기가스 배출량과 작업자 직무에 의해 가장 큰 영향을 받았다. 또한 대리인자들 중 원소카본이 작업 중 노출정도를 가장 잘 대변하고 방해물질의 영향도 적게 받는 것으로 나타났으며, 블랙카본은 실시간 측정을 위해 유용한 디젤 대리인자로 평가되었다. 한편, 매연저감장치가 설치된 디젤 차량의 경우엔 이산화질소도 유용한 작업자 노출평가의 대리인자로 평가되었다.

주요어: 환경미화원, 디젤엔진배출물질, 원소카본, 유기카본, 총카본, 블랙카본, 이산화질소

학번: 2008-31061