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Characteristics of Respirable Elemental Carbon (EC) Exposures of Household Waste Collectors

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ABSTRACT

The objectives of this study to characterize exposure to respirable elemental carbon (EC), organic carbon (OC) and total carbon (TC) in relation to waste-handling activities and vehicle characteristics among workers who collect household wastes, and to examine the relationships among EC, OC and TC. A total of 72 household waste collectors were selected for exposure assessment over a full workday and most (70 of 72) exposures were collected from diesel emissions that underwent catalytic after-treatment by diesel particulate filters (DPFs). The exposure assessments were conducted from June through September 2014. Airborne EC and OC from the breathing zone were collected on pre-fired quartz filters and quantified using the thermal optical reflectance method. The average EC exposure level of the household waste collectors was 7.2 µg m^{-3} with a range of 2.0-30.4 µg m^{-3}. A significant relationship between EC and TC exposure levels was observed (logTC = 0.38 × logEC + 3.22, $p < 0.0001$, adjusted $R^2 = 0.23$). EC level (µg m^{-3}), truck age (< 10 year-old vs. ≥ 10 year-old), type of waste collection job (collector vs. driver), current smoking status (yes vs. no) and month were found to significantly influence the level of TC exposure (n = 70, adjusted $R^2 = 0.56$, $p < 0.0001$). The average exposure to EC of household waste collectors can be categorized into the relatively low exposure group when compared to other DE exposure jobs. TC was not a best surrogate for DE exposure in household waste collection environments because it was affected by other OC interferences that were not generated from diesel engines.

Keywords: House waste collector; Carbon exposure; Elemental carbon; Organic carbon; Respirable carbon.

INTRODUCTION

Household waste refers to daily household life- or activity-derived mixed-waste streams that typically require some form of pre-processing or sorting before they can be properly disposed. Workers handling household wastes out of doors can be exposed to not only microorganisms and toxins generated from the household wastes they handle, but also to vehicle exhaust fumes (Poulsen *et al.*, 1995). Workers collect, transfer and transport municipal waste work on heavily trafficked roads, particularly in large cities. Household wastes are generally collected using a variety of types of vehicles, including diesel-powered vehicles. Workers using diesel vehicles for collection of household waste can be directly exposed to diesel engine exhaust emissions (DE) because they spend more time in the area around the engine tailpipe while collecting household waste.

The carcinogenicity of DE has been elevated by the International Agency for Research on Cancer from Group 2A (probably carcinogenic to humans) to Group 1 (carcinogenic to humans) (IARC, 2012). DE is a complex mixture of gases and particulates. The particulate fraction in DE is mainly comprises highly agglomerated solid carbonaceous material and adsorbed volatile organic compounds, as well as small amounts of sulfate, nitrate, metals, and other trace elements (Kittelson, 1998; USEPA, 2002). Solid carbon is formed during combustion in locally rich regions (Kittelson, 1998). Organic vapors and gases are derived from oil, unburned fuel and products of combustion. As the mixture issues from the engine, it cools and the hotter-boiling organic

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materials condense onto particles (Groves and Cain, 2000). Chemical constituents (carbonaceous particles, organics and ions) of particle fraction can vary depending on the type of after-treatment device, driving mode, fuels, etc. (Kittelson *et al.*, 2006; Biswas *et al.*, 2009; Feng *et al.*, 2014). In particular, after-treatment devices significantly reduce mass emission rate including solid carbon, but can increase solubility of organic carbon, ions such as ammonium and sulfate though variable based on the type of after treatment (Biswas *et al.*, 2009).

Carbonaceous particles are frequently divided into two categories: elemental (or black carbon (BC)) carbon (EC) and organic carbon (OC). A lot of field studies have been conducted to assess workers' exposure to diesel particulate matter (DPM) by measuring EC and OC in various occupations; mines, tunnel constructions, bus/truck repair garages, locomotive workshops, bus/truck drivers, railroad crews, etc. (Seshagiri and Burton, 2003; Ramachandran *et al.*, 2005; Davis *et al.*, 2007; Coble *et al.*, 2010; Hewett and Bullock, 2014). The EC and OC results can be summed to provide a total carbon (TC) figure. EC is formed by incomplete combustion via pyrolysis of hydrocarbons, and its major sources are the burning of biomass and fossil fuels (Janssen *et al.*, 2011). In Korea, burning of fossil fuels including vehicle exhaust contribute about three-fold the burning of biomass to the ambient $PM_{2.5}$ levels (Lee *et al.*, 2009).

Few studies have assessed exposures to DE generated during household waste collection. Recently, we reported exposures of household waste collection workers to DPM using various DPM indicators and found major exposure determinants (Lee *et al.*, 2015). The objectives of this study are to to characterize exposure to respirable EC, OC and TC in relation to waste-handling activities and vehicle characteristics among waste collection workers and to examine the relationships among EC, OC and TC. After that, we evaluated whether TC is a representative surrogate for DE exposure in household waste collecting environment as recommended by MSHA. This is the second article of the research project on the occupational exposure to DE of household waste workers in Korea. The exposure dataset used in the previous article was utilized for different characterization of DPM exposures (Lee *et al.*, 2015)

METHOD

Brief Description of Household Waste Collection

In Korea, household waste is required to be separated into food waste and several types of recyclable wastes, such as plastic, glass bottles, and paper, and deposited at a fixed collection point. Source-sorted recyclable waste is a purer fraction of domestic waste, e.g., glass, newspapers, cardboard, aluminum cans. The source-separated biodegradable domestic waste fraction is supposed to be contained in degradable plastic bags and gathered by waste collectors. Recyclable and biodegradable wastes from households are collected separately at designated points on specific dates, loaded into vehicles, transported to another nearby point and finally transferred to the final destination for further treatment by household waste collectors (Park *et al.*, 2011). Trucks burning diesel fuel are the most commonly used vehicles for the collection of wastes from large apartment complexes. The distance between the collection points within an apartment complex is generally very short and requires only a few minutes of travel. We studied waste collection work using diesel-powered trucks. Other waste collection processes using gasoline vehicles or motorcycles were excluded. Potential exposure during sorting at the material processing plant at disposal sites (incinerator or landfill) was also excluded. All exhaust tailpipes of the trucks surveyed were located under and toward the rear of the trucks. Since the workers spend their time a lot at the rear of the trucks, this feature can increase workers' exposure to DE (Lee *et al.*, 2015).

Exposure Assessment Strategy

The study was performed in four areas within Goyang City and Seoul, Korea from June to September. A total of 72 household waste collectors from four waste collecting companies were selected for assessment of EC exposure over a full workday of waste collection. Airborne EC from the breathing zone was consecutively collected on pre-fired quartz filters (Pallflex Tissuquartz 2500QAT-UP, Pall Life sciences, USA) equipped with respirable sampler (personal environmental monitor (PEM), Cat No 761–203, SKC Inc., USA), then analyzed for OC and EC using the thermal optical transmittance (TOT) method (# 5040) recommended by the National Institute for Occupational Safety and Health (NIOSH). The detailed sampling and analytical method was described elsewhere (Lee *et al.*, 2015). Field blank filters were analyzed for each batch of samples and the sample results corrected appropriately. The entire period of waste collection was monitored, which lasted longer than 6 hours and varied according to work characteristics and the size of the service area covered, etc. All EC, OC and TC results reported here are representative of eight-hour time weighted exposures. The ratio of OC and EC concentrations was calculated in order to examine the source of their generation during waste collection

Data Analysis

A number of characteristics related to job, household waste collected and vehicle (independent variables) that may influence airborne EC and TC during waste handling were investigated. Vehicle driving characteristics including average vehicle speed (km hr^{-1}), vehicle idle duration (minutes) and distance driven (km) were examined in order to associate the level of exposure. Qualitative job and vehicle characteristics were also selected and categorized into groups assumed to have distinct exposure characteristics as follows:

- Month (June, July and September)
- Job title (driver vs. collector). Drivers, who do in fact often help with collection, were classified into a driver group
- Type of household waste collected was categorized (food vs. solid)
- Truck vehicle age (< 10 years old vs. ≥ 10)
- Truck vehicle load volume (< 5 ton vs. ≥ 5 ton)
- Status of diesel particulate filter (DPF) (originally installed vs. retrofit or no filter. Two vehicles with no DPF were grouped into the retrofit category (n = 30) due to their

small number (n = 2).

The distributions of EC, OC and TC were found to be skewed. To improve our statistical models, all exposure levels were log-transformed. Analysis of variance (ANOVA) was used to compare EC, OC and TC exposure levels among categories of qualitative variables. Chi-square (X^2) test was also employed to associate the dichotomized EC exposure level group (< 10 µg m^{-3} vs. ≥ 10 µg m^{-3}) with categories related to job, household waste collected and vehicle characteristics described above. Stepwise multiple regression analysis was employed in order to identify factors that significantly affect airborne TC levels. EC dichotomized at 10 µg m^{-3} and several variables related to job, household waste collected and vehicle characteristics were examined as independent factors. All variables with *P*-values < 0.25 were finally included in the multiple regression analysis. Categories serving as a reference group for comparison with other groups were given a value of zero. Descriptive statistics, correlation, ANOVA and multivariate regressions were carried out using STATA Version 11.0 software (Stata Corp, College Station, TX, USA).

RESULTS

Exposure to EC, OC and TC

The EC, OC and TC exposure levels of collectors were found to be significantly higher than those of drivers (Fig. 1). The average EC exposure level of the household waste collectors was 7.2 µg m^{-3}, with a range of 2.0–30.4 µg m^{-3}. Month, the type of waste-handling job, vehicle age, status of DPF and vehicle load volume were found to influence TC exposure level at *P*-values < 0.25. EC and OC exposure levels from vehicles with originally-installed DPFs were slightly lower than those for vehicles with a DPF retrofitted or uninstalled (Table 1). In contrast, average vehicle speed, vehicle idle duration and distance driven were not associated with TC exposure level at P-values < 0.25 (results not shown). Characteristics of job, vehicle and waste handled for workers who were exposed to relatively high EC levels (> 10 µg m^{-3}, n = 8) were further examined. Nineteen percent (19%) of collectors (n = 42) was found to be exposed to greater than EC 10 µg m^{-3}. The highest EC level (30.4 µg m^{-3}) was assessed among collectors who used 11-year-old vehicles with retrofitted DPFs. Most of the high EC exposure levels were from collectors, solid waste and older vehicles (Table 2). Characteristics of job and vehicle were found to be significantly associated with dichotomized EC exposure level (< 10 µg m^{-3} vs. ≥ 10 µg m^{-3}). Collectors (p = 0.023) and older diesel vehicles (p = 0.021) were found to be significantly distributed in the higher EC exposure group (≥ 10 µg m^{-3}).

Relationship between OC, EC and TC

The average of the OC/EC ratios was found to be 9.7, showing a large variation with a range of 1.4–26.1 (Table 3). They appear to be similar regardless of the categories by characteristics of job, vehicle and waste handled. However, the high EC exposure worker group (≥ 10 µg m^{-3}) showed a low average OC/EC ratio (3.7) and little variation (range = 1.4–5.7) compared to the low EC exposure group (< 10 µg m^{-3}) (n = 64, mean = 10.5, range = 2.8–26.1) (Fig. 2). A significant relationship between EC and TC exposure levels was observed (logTC = 0.38 × logEC + 3.22, p < 0.0001, adjusted R^2 = 0.23) (Fig. 3). Multiple regression analysis indicated that EC exposure level, truck age (< 10 year-old vs. ≥ 10 year-old), month and current smoking status (yes vs. no) significantly influenced the level of TC exposure, explaining 56% of the observed variation in TC exposure level (n = 70, p < 0.0001) (Table 4).

DISCUSSION

We assessed not only EC, OC and TC exposure levels of workers who handled household wastes, but also the relationships among them based on characteristics of job, diesel vehicle and residential environment. Our EC exposure level for household waste collectors was found to be higher than that estimated for surface workers in mine industry during 1998–2001 (2–6 µg m^{-3}), and both of these are far lower than the EC levels of underground mine workers (40–384 µg m^{-3}) (Stewart *et al.*, 2010) and seven groups from the following workplaces or jobs: ambulance depots (31 µg m^{-3}, n = 3), RO-RO ferries (49 µg m^{-3}, n = 20), railway repair (21 µg m^{-3}, n = 64), vehicle testing (13 µg m^{-3}, n = 11), fork-lift trucks (122 µg m^{-3}, n = 27), bus garage and/or bus repair (39 µg m^{-3}, n = 53) and toll booths and tunnels (23 µg m^{-3}, n = 39) (Groves and Cain, 2000). EC exposure levels of household waste collectors were found to be lower than those (generally < 50 µg m^{-3}) of workers assessed as being in intermediate EC exposure job groups, such as mechanics in a shop, emergency workers in fire stations, distribution workers at a dock, and workers loading or unloading inside a ferry (Pronk *et al.*, 2009). Accordingly, the EC exposure level of household waste collectors can be assigned to the relatively low occupational exposure group those who generally perform jobs in areas separated from the source, such as drivers and train crew, or outdoors such as surface miners, parking attendants, vehicle testers, utility service workers, surface construction workers and airline ground personnel. Diesel engines are considered likely to be the only significant source of EC in workplaces with vehicles, instruments and equipment using diesel fuel such as mines, tunnels and other manufacturing industries(Pronk *et al.*, 2009) However, since workers who generally perform jobs in the outdoor atmospheric environment, including vehicle drivers, can be exposed to various carbonaceous sources such as industry, road traffic, biomass burning from restaurants and fossil fuel combustion, even if the major source is diesel vehicles, exposure sources vary according to the types of energy used in households.

The collection of household waste involves working with a vehicle that moves through traffic throughout the year. During the waste collection process, waste collectors stay around the engine tailpipe and frequently ride upon a step at the rear of the truck in order to facilitate exiting the vehicle at frequent stops for picking up household wastes, resulting in elevated exposure. Most collection points are within short distances of roads. In addition, workers dump

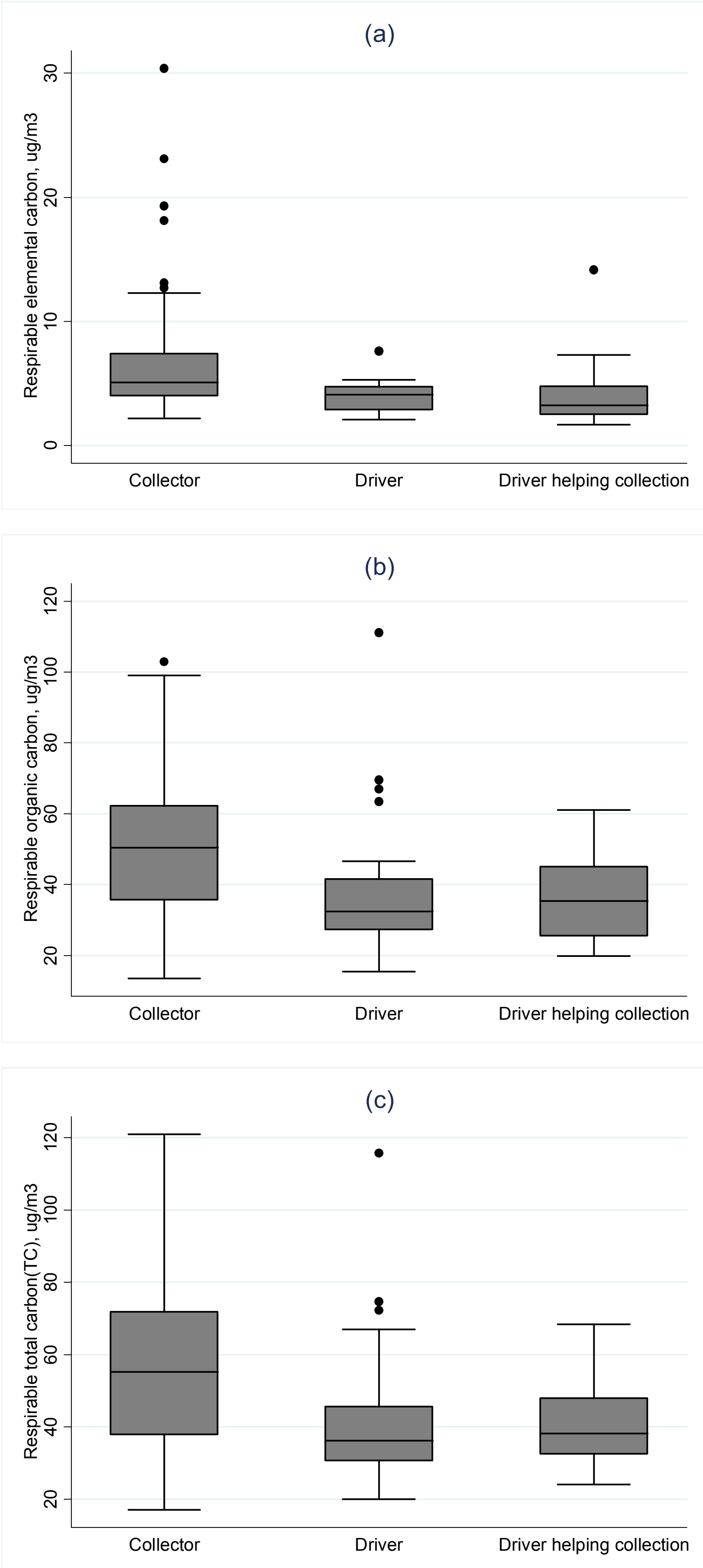

Fig. 1. (a) Respirable elemental (EC), (b) organic (OC) and (c) total carbon (TC) exposure level by type of household waste collecting job.

Table 1. Comparison of exposure levels of elemental carbon (EC) and organic carbon (OC) according to occupational and environmental variables.

Independent variables	N	EC, μg m^{-3}			OC, μg m^{-3}			TC, μg m^{-3}		
		Mean	S.E. [a]	95% C.I. [b]	Mean	S.E.	95% C.I.	Mean	S.E.	95% C.I.
Month										
June	12	8.5	2.4	3.3–13.0	62.3	5.1	51.0–73.0	70.8	6.9	55.7–86.0
July	46	5.5	0.6	4.3–6.6	44.2	2.9	38.4–49.0	49.0	3.1	42.8–55.0
September	14	5.5	0.9	3.5–7.3	32.5	4.6	22.6–42.0	38.0	4.6	28.1–47.0
p-value				0.307			0.0001			0.0003
Job type [c]										
Collector	42	7.2	0.9	5.3–9.0	49.6	3.1	43.4–55.8	56.2	3.6	49.0–63.4
Driver	30	4.3	0.4	3.4–5.2	38.4	3.7	30.9–45.9	42.5	3.7	34.8–50.1
p-value				0.003			0.011			0.006
Waste type [c]										
Food	17	4.7	0.6	3.5–6.0	46.0	5.7	33.9–58.1	50.0	5.9	37.6–62.4
Solid	55	6.4	0.7	4.9–7.8	44.6	2.7	39.3–50.0	50.6	3.1	44.5–56.8
p-value				0.256			0.981			0.796
Truck age, years old										
< 10	43	5.5	0.7	4.2–6.8	41.8	3.0	35.7–47.8	47.1	3.2	40.6–53.6
≥ 10	29	6.7	1.1	4.5–8.9	49.6	4.0	41.5–57.8	55.5	4.6	46.1–64.9
p-value				0.184			0.081			0.097
Vehicle load volume, ton [c]										
< 2.5	16	5.5	0.8	3.8–7.2	34.0	4.2	25.0–43.0	39.5	4.2	30.6–48.5
5	56	6.1	0.7	4.7–7.5	48.1	2.8	42.5–53.6		3.1	47.3–59.9
p-value				0.879			0.004			0.015
Status of vehicle engine filter [c]										
Originally installed	40	5.3	0.7	3.9–6.7	40.7	3.1	34.3–47.0	45.8	3.4	39.0–52.6
Retrofit	30	6.7	1.0	4.6–8.7	49.3	3.8	41.6–57.0	55.2	4.3	47.4–64.0
No filter	2	5.3	1.2	–9.4–19.9	38.3	8.0	–61.0–140.5	43.6	3.3	–74.0–161.0
p-value				0.171			0.083			0.028
Type of household serviced [c]										
Urban	54	6.3	0.8	4.8–7.8	45.4	2.9	39.6–51.1	51.3	3.2	44.8–57.8
Suburban	18	5.1	0.5	3.9–6.2	43.7	4.6	34.0–53.4	48.1	4.7	38.1–58.1
p-value				0.032			0.000			0.606
Total	72	6.0	0.6	4.8–7.1	44.9	2.4	40.1–49.8	50.5	2.7	45.1–55.7

[a] Standard error;
[b] Confidential interval;
[c] These categories were cited from "Occupational Exposure to Diesel Particulate Matter in Municipal Household Waste Workers" (Lee *et al.*, 2015).

trash bags into the rear compartment of the truck at a collection point without turning off the engine. Although the time-weighted exposure to EC of waste collectors is relatively low, the frequent peak exposure to EC over short periods of less than approximately one minute may be occurred. Therefore, real-time measurements would be another effective tool to evaluate the waste workers' peak exposures to DE in the future. EC exposure level, diesel vehicle age, month, job title and current smoking status were found to be significant factors influencing TC exposure level (Tables 1, 2 and 4). Our results indicated that diesel vehicle age and household waste collection characteristics including job title and smoking habits could be closely associated with exposure to DE including EC. Diesel vehicles from traffic other than waste collecting vehicles may contribute to the EC exposure of waste handling workers according to the characteristics of the surroundings of waste collection areas, such as the distance (m) of separation from waste collection, volume of traffic, the distance of the collection point from the traffic load, the time spent at waste collecting work, and other factors. The EC exposure levels of household waste collectors are found to be generally higher than measurements reported in the atmospheric environment where the general population may be exposed (He *et al.*, 2004).

We assumed that the major source of EC exposure among household waste collectors stemmed from diesel vehicles, even if there may be a minor contribution to EC exposure from traffic load. EC is often used as a tracer of primary OC because it is predominately emitted from combustion sources (Turpin and Huntzicker, 1991). OC in particles can be emitted from primary emission sources (primary OC), either anthropogenic or biogenic sources, and even from in-situ chemical reactions among primary gaseous OC species in the atmosphere (secondary OC) (Seinfield, 1986; Kim *et al.*, 2000; Ho *et al.*, 2002; Park *et al.*, 2002). OC is also generated by condensation processes in vehicle exhaust

Table 2. Characteristics of job, vehicle and household waste handled by workers exposed to higher than 10 µg m^{-3} of elemental carbon (EC).

Type of job	Type of city	Type of waste handled	Vehicle-born year	Vehicle age	Vehicle load volume, ton	Status of engine filter	Driving distance km	Collection time	% of idling in total drive time	% of slow driving (10 km hr^{-1}) in total drive time	Average Drive speed, km hr^{-1}	EC level µg m^{-3}
Collection	Goyang	Food	2003	11	5	Retrofitted	64	4:13 AM–11:46 AM	0.6	0.8	8.2	12.3
Collection	Goyang	Solid	2004	10	5	Retrofitted	76	3:59AM–12:11 PM	0.4	0.8	10.2	12.7
Collection	Goyang	Solid	2005	9	5	Originally installed	75	4:08 AM–11:53AM	0.5	0.8	10.4	13.1
Driver [a]	Seoul	Solid	2000	14	1.7	Retrofitted	48	9:21 PM–3:32 AM	0.3	0.8	8.5	14.2
Collection	Goyang	Solid	2003	11	5	Retrofitted	61	3:45AM–11:42 AM	0.5	0.9	8.82	18.1
Collection	Goyang	Solid	2005	9	5	Originally installed	78	4:07AM–11:14 AM	0.5	0.8	10.6	19.3
Collection	Goyang	Solid	2005	9	5	Originally installed	75	4:08 AM–11:53AM	0.5	0.8	10.4	23.1
Collection	Goyang	Solid	2003	11	5	Retrofitted	61	3:45AM–11:42 AM	0.5	0.9	8.82	30.4

[a] Driver helping collection.

systems. Organic compounds in the particles are attributed to unburned, pyrolyzed or partially oxidized fuel and lubricant oil and are transferred from the gas phase to the particulate phase by adsorption and condensation onto the existing particles or by nucleation of new particles as the exhaust cools (Ålander *et al.*, 2004). Several studies have related the OC/EC ratio to secondary organic particle formation (Gray *et al.*, 1986; Turpin and Huntzicker, 1991; Chow *et al.*, 1996). OC exposure can result from various sources other than diesel vehicles. Atmospheric EC is directly emitted, while OC can be both directly emitted and formed in the atmosphere through the low vapor pressure products of chemical reactions involving emissions of volatile organic compounds (VOCs) (Cao *et al.*, 2005).

Our results indicated a higher OC/EC ratio, despite the use of diesel vehicles (Table 3). The elevated OC/EC ratio found regardless of characteristics of job, vehicle and waste handled may be due to lower contributions from motor-vehicle exhaust during waste collection work. Our OC/EC ratio is much higher than values reported elsewhere of 2.7 for coal-combustion and 1.1 for motor vehicles (Watson *et al.*, 2001), or 9.0 for biomass burning (Cachier *et al.*, 1989; Cao *et al.*, 2005). In general, it has been reported that the OC/EC rate is less than 1 for diesel engines and more than 1 for gasoline engines. A primary OC/EC ratio of 2.2 was assumed to indicate the general direction of increasing secondary organic particle concentrations (Turpin and Huntzicker, 1991; Lin and Tai, 2001).

The OC/EC ratio calculated based upon the eight waste collectors who were found to be exposed to greater than 10 µg m^{-3} (mean = 3.7, range = 1.4–5.7) showed a much lower ratio than that (mean = 10.5, range = 2.8–26.1) for workers exposed to lower than 10 µg m^{-3} (Fig. 2), indicating higher contributions of EC exhausted from diesel vehicles. The diesel vehicles they used were found to be over 10 years of age and driven at slow speeds (< 11 km hr^{-4} average). Workers exposed to higher than 10 µg m^{-3} of EC (n = 6) were found to use diesel vehicles older than nine years, indicating a higher contribution of EC exposure.

Chow *et al.* (1993) and Kim *et al.* (1999) used a value of 2 for the OC/EC ratio to identify secondary aerosol formation. On the other hand, studies conducted on tunnels have shown a OC/EC ratio consistently lower than 1, in line with the prevalence of emissions from diesel vehicles. The OC/EC ratio is generally close to either "1" or "< 1" in occupational environments where diesel vehicles are the sole source of EC.

Household waste collectors working in the atmospheric environment are likely to show higher OC than EC due to various OC exposure sources. In particular, waste collectors may be exposed to high levels of OC over very brief periods when the lids of waste containers are opened, particularly if such containers hold source-separated biodegradable domestic waste. This exposure is greatest during warm months when both bacterial growth and VOC vapor pressures are highest (Poulsen *et al.*, 1995). Wilkins (1994) identified 92 different VOCs in the headspace of 11 waste trucks containing either biodegradable or mixed waste. The major compounds found included low concentrations of microbiological VOCs

Table 3. Ratio of organic carbon (OC)/elemental carbon (EC) according to occupational and vehicle characteristics.

Variable	EC < 10 μg m^{-3}				EC ≥ 10 μg m^{-3}				Total, μg m^{-3}			
	N	Mean	S.D. [a]	Range	N	Mean	S.D.	Range	N	Mean	S.D.	Range
Job type												
Collector	35	10.4	5.7	3.5–22.6	7	4.0	1.3	2.3–5.7	42	9.3	5.7	2.3–22.6
Drive + collection	9	11.6	3.1	8.1–16.1	1	1.4	N.A.[b]	N.A.	30	10.3	5.5	1.4–26.1
Driver	20	10.2	6.1	2.8–26.1	0							
Waste type												
Food	16	11.3	5.6	3.4–24.1	1	4.7		4.7–4.7	17	10.9	5.7	3.4–24.1
Solid	48	10.2	5.5	2.8–26.1	7	3.6	1.6	1.4–5.7	55	9.4	5.6	1.4–26.1
Truck age, year old												
< 10	22	10.9	6.5	2.8–24.1					22	10.9	6.5	2.8–24.1
≥ 10	42	10.3	5.0	5.1–26.1	8	3.7	1.6	1.4–5.7	50	9.2	5.2	1.4–26.1
Vehicle load volume, ton												
< 2.5	15	8.6	6.5	2.8–26.1	1	1.4	N.A.	N.A.	16	8.2	6.6	1.4–26.1
5	49	11.1	5.1	5.1–24.1	7	4.0	1.3	2.3–5.7	56	10.2	5.3	2.3–24.1
Status of DPF [c]												
Originally installed	37	10.5	6.2	2.8–26.1	3	3.4	1.2	2.3–4.7	40	10.0	6.3	2.3–26.1
Retrofit [d]	27	10.4	4.4	5.2–22.5	5	3.9	1.8	1.4–5.7	32	9.4	4.8	1.4–22.5
Type of household serviced												
Urban	47	10.8	5.8	2.8–26.1	7	3.6	1.6	1.4–5.7	54	9.9	6.0	1.4–26.1
Suburban	17	9.6	4.6	5.6–22.5	1	4.7		4.7–4.7	18	9.4	4.6	4.7–22.5
Total	64	10.5	5.5	2.8–26.1	8	3.7	1.6	1.4–5.7	72	9.7	5.6	1.4–26.1

[a] Standard deviation;
[b] Not applicable;
[c] Diesel particulate filter;
[d] Includes no filter (n = 2).

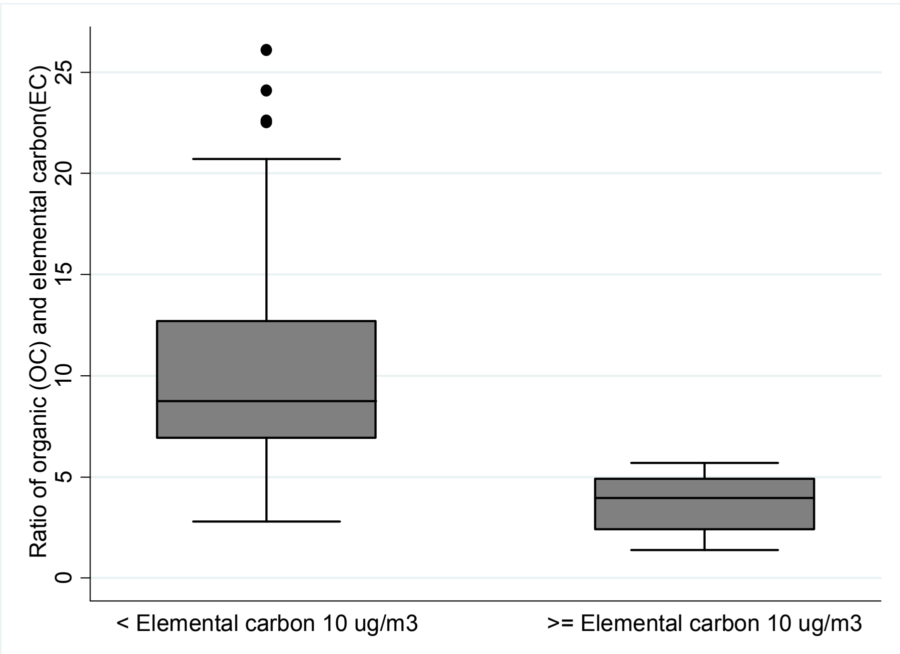

Fig. 2. Ratio of organic carbon (OC)/elemental carbon (EC) exposure level by dichotomized EC exposure level.

(alcohols, aldehydes, ketones, carboxylic acids, esters) and hydrocarbons. Total VOC concentration varied from 0.9 to 8.1 mg m^{-3} (Wilkins, 1994). To correct gaseous/semi-volatile organic compounds emitted from diesel engines as well as non-diesel engines, NIOSH recommended to use backup filter after the quartz fiber filter in tandem (Birch, 2003). However, our study did not apply backup filter and only collected field and media blanks to correct OC interferences. This procedure may overestimate the adsorbed OC to the quartz filter, resulting in higher OC/EC ratio (Birch, 2003).

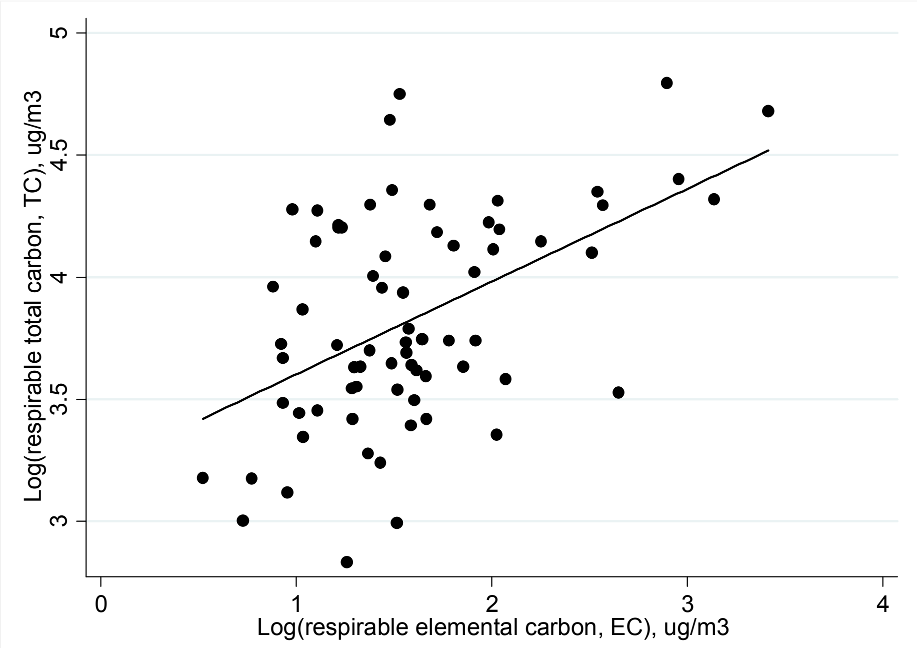

Fig. 3. Relationship between respirable total carbon (TC) and elemental carbon (EC).

Table 4. Multiple regression model to predict the level of exposure to total carbon (TC), μg m^{-3}.

Independent factor	Coefficient	S.E. [a]	p-value	95% C.I. [b]	
EC [c] μg m^{-3}	0.38	0.07	< 0.0001	0.23	0.52
Smoking					
Yes	1				
No	–0.38	0.09	< 0.0001	–0.56	–0.21
Truck age, year					
≥ 10	1				
< 10	–0.20	0.12	0.094	–0.43	0.03
Vehicle average speed, km hr^{-1}	0.07	0.03	0.008	0.02	0.13
Constant	2.88	0.29	< 0.0001	2.30	3.46

[a] Standard error;
[b] Confidential interval;
[c] Respirable elemental carbon.

Even use the backup filter, it is difficult to correct low volatile organic material such as cigarette smoke or bioaerosols from waste because they are collected primarily on the top quartz filter (Birch, 2003).

It has been reported that EC can be regarded as a surrogate for DE level (Groves and Cain, 2000; Schauer, 2003; Noll *et al.*, 2015). The MSHA has promulgated rules to limit the exposure of underground metal/non-metal miners to diesel particulate matter (DPM) (MSHA, 2001, 2005). MSHA employed TC as a surrogate because it consistently represented over 80% of DPM (MSHA, 2005; Noll *et al.*, 2015). Strong correlations between TC and EC were reported in several underground coal (metal and nonmetal) mines in both the US (r = 0.99) and Australia (r = 0.96) (Noll *et al.*, 2015). It has been recommended that DPM exposures using EC as a surrogate can be measured in coal mines since diesel vehicles are the only source of EC and OC. However, there is interest in how well EC correlates to DPM in other occupational environments with a variety of OC sources, including waste collection. The proportion of EC in TC among household waste collectors ranged from 4% to 31%, which was far lower than that detected in underground mines (Kittelson, 1998). Our results found that the relationship between EC and TC (n = 72, adjusted $R^2 = 0.45$, $p < 0.0001$) was significant, although it is lower than that reported in underground mines. In multivariate analysis, EC remains the most significant factor influencing TC exposure level, along with smoking status and vehicle speed (km hr^{-1}). Generalizing factors that may influence either DE or EC exposure levels during household waste collection work are very difficult to specify because waste-collection characteristics and waste-manage ment systems (i.e., the types of waste handled, types of vehicle, the frequency of waste handling, the shifts worked, service time, the size of the areas serviced, and types of employment) may vary greatly among regions and countries. Furthermore, in a complex mixture such as diesel exhaust, it is difficult to identify a surrogate which would be representative of DE exposure as a whole. EC can be used as a surrogate for DE exposure in the work environment of household waste collectors where various TC and OC exposure sources other than EC are present.

CONCLUSIONS

When compared to other jobs such as workers in mines and tunnels, on ferries, etc., the average exposure to EC of household waste collectors can be categorized into the relatively low occupational exposure group. OC/EC ratios were generally higher than those reported in other occupational settings and atmospheric environments because of other OC interferences or lack of correction for gaseous emission absorption. TC exposure was found to be associated with EC exposure level, diesel vehicle age, month, job title and current smoking status. However, TC was not considered as a best surrogate for DE exposure in household waste collection environments because it was affected by other OC interferences that were not generated from diesel engines.

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REFERENCES

Ålander, T.J., Leskinen, A.P., Raunemaa, T.M. and Rantanen, L. (2004). Characterization of Diesel Particles: Effects of Fuel Reformulation, Exhaust Aftertreatment, and Engine Operation on Particle Carbon Composition and Volatility. *Environ. Sci. Technol.* 38: 2707–2714.

Birch, M.E. (2003). Monitoring of Diesel Particulate Exhaust in the Workplace. NIOSH Manual of Analytical Methods (NMAM), pp. 2003–2154.

Biswas, S., Verma, V., Schauer, J.J. and Sioutas, C. (2009). Chemical Speciation of Pm Emissions from Heavy-Duty Diesel Vehicles Equipped with Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR) Retrofits. *Atmos. Environ.* 43: 1917–1925.

Cachier, H., Brémond, M.P. and Buat-Ménard, P. (1989). Carbonaceous Aerosols from Different Tropical Biomass Burning Sources. *Nature* 340: 371–313.

Cao, J., Wu, F., Chow, J., Lee, S., Li, Y., Chen, S., An, Z., Fung, K., Watson, J. and Zhu, C. (2005). Characterization and Source Apportionment of Atmospheric Organic and Elemental Carbon during Fall and Winter of 2003 in Xi'an, China. *Atmos. Chem. Phys.* 5: 3127–3137.

Chow, J.C., Watson, J.G., Lowenthal, D.H., Solomon, P.A., Magliano, K.L., Ziman, S.D. and Richards, L.W. (1993). PM_{10} and $PM_{2.5}$ Compositions in California's San Joaquin Valley. *Aerosol Sci. Technol.* 18: 105–128.

Chow, J.C., Watson, J.G., Lu, Z., Lowenthal, D.H., Frazier, C.A., Solomon, P.A., Thuillier, R.H. and Magliano, K. (1996). Descriptive Analysis of $PM_{2.5}$ and PM_{10} at Regionally Representative Locations during SJVAQS/AUSPEX. *Atmos. Environ.* 30: 2079–2112.

Coble, J.B., Stewart, P.A., Vermeulen, R., Yereb, D., Stanevich, R., Blair, A., Silverman, D.T. and Attfield, M. (2010). The Diesel Exhaust in Miners Study: II. Exposure Monitoring Surveys and Development of Exposure Groups. *Ann. Occup. Hyg.* 54: 747–761.

Davis, M.E., Smith, T.J., Laden, F., Hart, J.E., Blicharz, A.P., Reaser, P. and Garshick, E. (2007). Driver Exposure to Combustion Particles in the U.S. Trucking Industry. *J. Occup. Environ. Hyg.* 4: 848–854.

Feng, X., Ge, Y., Ma, C., Tan, J., Yu, L., Li, J. and Wang, X. (2014). Experimental Study on the Nitrogen Dioxide and Particulate Matter Emissions from Diesel Engine Retrofitted with Particulate Oxidation Catalyst. *Sci. Total Environ.* 472: 56–62.

Gray, H.A., Cass, G.R., Huntzicker, J.J., Heyerdahl, E.K. and Rau, J.A. (1986). Characteristics of Atmospheric Organic and Elemental Carbon Particle Concentrations in Los Angeles. *Environ. Sci. Technol.* 20: 580–589.

Groves, J. and Cain, J.R. (2000). A Survey of Exposure to Diesel Engine Exhaust Emissions in the Workplace. *Ann. Occup. Hyg.* 44: 435–447.

He, Z., Kim, Y., Ogunjobi, K., Kim, J.E. and Ryu, S. (2004). Carbonaceous Aerosol Characteristics of $PM_{2.5}$ Particles in Northeastern Asia in Summer 2002. *Atmos. Environ.* 38: 1795–1800.

Hewett, P. and Bullock, W.H. (2014). Rating Locomotive Crew Diesel Emission Exposure Profiles Using Statistics and Bayesian Decision Analysis. *J. Occup. Environ. Hyg.* 11: 645–657.

Ho, K., Lee, S., Jimmy, C.Y., Zou, S. and Fung, K. (2002). Carbonaceous Characteristics of Atmospheric Particulate Matter in Hong Kong. *Sci. Total Environ.* 300: 59–67.

IARC (2012). *Diesel and Gasoline Engine Exhausts and Some Nitrogenes*, International Agency for Research on Cancer, Lyon, France.

Janssen, N.A., Hoek, G., Simic-Lawson, M., Fischer, P., Van Bree, L., Ten Brink, H., Keuken, M., Atkinson, R.W., Anderson, H.R. and Brunekreef, B. (2011). Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM_{10} and $PM_{2.5}$. *Environ. Health Perspect.* 119: 1691–1699.

Kim, Y.P., Moon, K.C., Lee, J.H. and Baik, N.J. (1999). Concentrations of Carbonaceous Species in Particles at Seoul and Cheju in Korea. *Atmos. Environ.* 33: 2751–2758.

Kim, Y.P., Moon, K.C. and Lee, J.H. (2000). Organic and Elemental Carbon in Fine Particles at Kosan, Korea. *Atmos. Environ.* 34: 3309–3317.

Kittelson, D., Watts, W. and Johnson, J. (2006). On-Road and Laboratory Evaluation of Combustion Aerosols—Part 1: Summary of Diesel Engine Results. *J. Aerosol Sci.* 37: 913–930.

Kittelson, D.B. (1998). Engines and Nanoparticles: A Review. *J. Aerosol Sci.* 29: 575–588.

Lee, H.W., Lee, T.J. and Kim, D.S. (2009). Identifying Ambient $PM_{2.5}$ Sources and Estimating Their Contributions by Using PMF: Separation of Gasoline and Diesel Automobile Sources by Analyzing ECs and OCs. *J. Korean Soc. Atmos. Environ.* 25: 75–89.

Lee, K.H., Jung, H.J., Park, D.U., Ryu, S.H., Kim, B., Ha, K.C., Kim, S., Yi, G. and Yoon, C. (2015). Occupational Exposure to Diesel Particulate Matter in Municipal Household Waste Workers. *PLoS One* 10: e0135229.

Lin, J.J. and Tai, H.S. (2001). Concentrations and Distributions of Carbonaceous Species in Ambient Particles in Kaohsiung City, Taiwan. *Atmos. Environ.* 35: 2627–2636.

MSHA (2001). Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners; Final Rule. Mine Safety and Health Administration, Federal Register, Arlington.

MSHA (2005). Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners. Final Rules (30 CFR Part 57). Mine Safety and Health Administration, Federal Register, Arlington.

Noll, J., Gilles, S., Wu, H.W. and Rubinstein, E. (2015). The Relationship between Elemental Carbon and Diesel Particulate Matter in Underground Metal/Nonmetal Mines in the United States and Coal Mines in Australia. *J. Occup. Environ. Hyg.* 12: 205–211.

Novakov, T., Menon, S., Kirchstetter, T., Koch, D. and Hansen, J. (2005). Aerosol Organic Carbon to Black Carbon Ratios: Analysis of Published Data and Implications for Climate Forcing. *J. Geophys. Res.* 110: D21205.

Park, D.U., Ryu, S.H., Kim, S.B. and Yoon, C.S. (2011). An Assessment of Dust, Endotoxin, and Microorganism Exposure during Waste Collection and Sorting. *J. Air Waste Manage. Assoc.* 61: 461–468.

Park, S.S., Kim, Y.J. and Fung, K. (2002). $PM_{2.5}$ Carbon Measurements in Two Urban Areas: Seoul and Kwangju, Korea. *Atmos. Environ.* 36: 1287–1297.

Poulsen, O.M., Breum, N.O., Ebbehøj, N., Hansen, Å.M., Ivens, U.I., van Lelieveld, D., Malmros, P., Matthiasen, L., Nielsen, B.H. and Nielsen, E.M. (1995). Collection of Domestic Waste. Review of Occupational Health Problems and Their Possible Causes. *Sci. Total Environ.* 170: 1–19.

Pronk, A., Coble, J. and Stewart, P.A. (2009). Occupational Exposure to Diesel Engine Exhaust: A Literature Review. *J. Exposure Sci. Environ. Epidemiol.* 19: 443–457.

Ramachandran, G., Paulsen, D., Watts, W. and Kittelson, D. (2005). Mass, Surface Area and Number Metrics in Diesel Occupational Exposure Assessment. *J Environ. Monit*. 7: 728–735.

Schauer, J.J. (2003). Evaluation of Elemental Carbon as a Marker for Diesel Particulate Matter. *J. Exposure Sci. Environ. Epidemiol.* 13: 443–453.

Seinfield, J.H. (1986). *Atmospheric Chemistry and Physics of Air Pollution*, A Wiley-Interscience Publication.

Seshagiri, B. and Burton, S. (2003). Occupational Exposure to Diesel Exhaust in the Canadian Federal Jurisdiction. *AIHA J.* 64: 338–345.

Stewart, P.A., Coble, J.B., Vermeulen, R., Schleiff, P., Blair, A., Lubin, J., Attfield, M. and Silverman, D.T. (2010). The Diesel Exhaust in Miners Study: I. Overview of the Exposure Assessment Process. *Ann. Occup. Hyg.* 54: 728–746.

Turpin, B.J. and Huntzicker, J.J. (1991). Secondary Formation of Organic Aerosol in the Los Angeles Basin: A Descriptive Analysis of Organic and Elemental Carbon Concentrations. *Atmos. Environ.* 25: 207–215.

USEPA (2002). Health Assessment Document for Diesel Engine Exhaust, US Environmental Protection Agency, National Center for Environmental Assessment.

Watson, J.G., Chow, J.C. and Houck, J.E. (2001). $PM_{2.5}$ Chemical Source Profiles for Vehicle Exhaust, Vegetative Burning, Geological Material, and Coal Burning in Northwestern Colorado during 1995. *Chemosphere* 43: 1141–1151.

Wilkins, K. (1994). Volatile Organic Compounds from Household Waste. *Chemosphere* 29: 47–53.

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