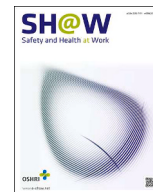




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Original article

Real-Time Assessment of Black Carbon Peaks Among Workers Exposed to Diesel Engine Exhaust Emissions



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ABSTRACT

Background: Workers are commonly exposed to diesel engine exhaust (DEE) from diesel-powered engines and vehicles (DEVs), which contain harmful particulates such as black carbon (BC). This study aimed to characterize the peak BC exposures of workers operating or working near DEVs.

Methods: BC levels were recorded every minute from workers driving or working near DEVs using a portable aethalometer and were categorized by job type and activity. Peak BC levels were characterized using the occupational exposure limits for DEE (measured as elemental carbon) of 10 $\mu\text{g}/\text{m}^3$ and 50 $\mu\text{g}/\text{m}^3$ as cut-off values.

Results: Forklift operators, garbage collectors, and machine operators showed peak BC exposure levels surpassing 20 $\mu\text{g}/\text{m}^3$, with average levels above 10 $\mu\text{g}/\text{m}^3$. Despite their short exposure durations (<1 hour), these peaks contributed significantly (>60%) to the daily average BC exposure. The daily contribution rate of peak exposures above 10 $\mu\text{g}/\text{m}^3$ to the average daily BC exposure often exceeded 50%. The ratio of peak levels above 10 $\mu\text{g}/\text{m}^3$ and 50 $\mu\text{g}/\text{m}^3$ to the arithmetic mean was negatively correlated with exposure duration, the proportion of exposure duration, and the daily contribution of peak levels.

Conclusion: Drivers of diesel-engine vehicles often experienced significant spikes in BC exposure, highlighting the need for real-time monitoring, which is recommended as a best-practice approach to identify and mitigate short-term peak exposures.

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1. Introduction

Diesel-powered engines and vehicles (DEVs) are widely used in transport and power generation, mainly to power heavy-duty vehicles. Workers can be exposed to diesel engine exhaust (DEE)

from a variety of direct sources, including on-road vehicles, off-road machinery, trains, and stationary equipment such as generators and cranes [1], as well as by spending time in the vicinity of DEVs. The particulate phase of DEE contains elemental carbon (EC), organic compounds, sulphates, nitrates, metals and other

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trace elements. Black carbon (BC) and EC are commonly used as surrogates for DEE [2]. EC typically accounts for 60–80% of the particulate matter in diesel engine exhaust emissions, while BC, which is closely related to EC, accounts for around 70–90% [3,4].

Exposure to BC has been linked to several health problems, including cardiovascular and respiratory diseases and cancer [5]. Peak exposures to BC can lead to acute health effects, including respiratory problems such as asthma exacerbation and decreased lung function. In addition, high levels of exposure can increase the risk of cardiovascular problems such as heart attack and stroke [6]. Assessment strategies based on time-weighted average (TWA) alone may not always be sensitive enough to identify specific short-term exposures to DEE during tasks such as running intermittent engines or working near them. An aethalometer is a valuable tool for monitoring BC and assessing exposure peaks. The data from the aethalometer can help with the study of public health, climate change, visibility, stationary source emissions, vehicle and engine emissions, and more [7–9]. Jeong and Park used personal aethalometers to characterize the peak concentrations of BC encountered by elementary school children by analyzing their time-activity patterns and the locations in which they stayed [10–12].

In our previous study, we characterized BC peak exposures by comparing concentrations above and below key statistical thresholds, including the arithmetic mean (AM), geometric mean (GM), and the 95th percentile [3]. In the present study, we expand upon that work by using a set of newly developed variables specifically designed to capture peak exposure patterns more precisely. The primary objectives are to characterize BC peak exposures among workers who operate or work near DEVs, and to analyze how these peak exposures vary by job type and specific work activities.

2. Materials and methods

2.1. Brief description of work related to exposure to DEE

In a previous study [3], we described processes, tasks, and jobs from six industries using diesel-powered vehicles or equipment classified according to the Korean Standard Industrial Classification (KSIC) codes. The sub-classes are indicated by a five-digit coding system that classifies companies based on their business activities. These industries include specific jobs, such as waste management, including jobs like garbage collectors and truck drivers, and delivery and toll-road jobs. The type of job and a brief description of the tasks or work performed, categorized by industry with five-digit codes, are provided in the result tables.

2.2. BC exposure assessment strategy

Our BC exposure assessment methods are described in our previous study [3]. BC concentrations were monitored for the duration of time spent in the workplace at a pump flow rate of 100 mL/min. A total of 71,987 BC measurements taken every minute from 106 workers were classified in industry type, job, and activity using a portable micro-aethalometer (Model AE51, Aeth Labs, USA) and assessed for BC peak exposure. This device, weighing 280 g, was worn in the breathing zone, within approximately 30 cm in front of the worker's face, to continuously record BC levels during different work environments and activities.

Each worker was primarily monitored over a full work shift, typically 6–8 hours, yielding approximately 360–480 measurements per worker, although a few workers had shifts that were not fully covered. Workers wearing the BC monitor were instructed to record their time-specific tasks and locations in a time-activity diary (TAD) prior to sampling. Immediately after each monitoring session, BC data were downloaded and compared with the

diary entries during post-shift interviews to minimize recall bias and data-handling errors. When unusual peak exposures were detected, additional clarification was obtained through interviews, and task or location information was corrected if necessary. These procedures were implemented to enhance the reliability of real-time BC monitoring data in relation to workers' activities and locations.

Prior to sampling, the precision of four micro-aethalometers was evaluated through an inter-comparison. All devices were co-located for 1 hour under controlled laboratory conditions, away from windows and combustion sources, at a pump rate of 150 mL/min. In addition, BC concentrations were monitored for 24 hours in an underground parking facility under real-world conditions. Both assessments demonstrated high consistency, with all devices showing strong correlations ($r > 0.96$).

2.3. Operational definition of BC peak exposure

As the term 'peak exposure' is used inconsistently in exposure assessment literature and lacks a universally accepted scientific definition [13–15], it is applied here as an operational concept. In this study, peak exposure denotes short-term, high-concentration excursions, which are of concern because brief, high-intensity exposures may overwhelm normal defense and detoxification mechanisms, triggering acute inflammatory responses or oxidative stress [16,17], as demonstrated in controlled exposure studies of DEE and combustion aerosols. Accordingly, peak exposure is defined as one-minute BC measurements exceeding reference values of 10 or 50 $\mu\text{g}/\text{m}^3$, derived from EC-based occupational exposure limits adopted or recommended in several EU member states. While no OEL has been set specifically for BC, the European Union has introduced a legally binding OEL of 50 $\mu\text{g}/\text{m}^3$ for EC as a substitute for diesel engine exhaust that has been in effect since 2023. Some member states, such as the Health Council of the Netherlands and Denmark, have adopted stricter health-based limits of 10 $\mu\text{g}/\text{m}^3$. Consistent with previous studies that have used OELs as cut-points to characterize peak exposures, this definition reflects the temporal resolution of the aethalometer and does not represent a toxicologically defined rise-and-fall peak event [18,19]. Several previous studies have also adopted OELs as cut-points for defining peak exposures [13,14]. On the basis of both the OELs for DEE measured as EC, the two cut-off values of 10 $\mu\text{g}/\text{m}^3$ ($C_{\text{peak}10}$) and 50 $\mu\text{g}/\text{m}^3$ ($C_{\text{peak}50}$) were chosen to characterize BC peak exposure levels. Cut-off values for EC were applied as reference values to characterize short-term, high-concentration excursions in one-minute BC measurements. These thresholds were used for the purposes of exposure characterization and reflect the long-term exposure standards set by regulators, rather than health-based criteria for minute-scale exposures associated with acute or transient adverse health effects in humans. The following variables were also used to characterize BC peak exposures (Fig. 1).

- Average of BC AMs monitored during daily working time
- Average of 95th percentile BC levels monitored during daily working time
- Average of maximum BC levels monitored during daily working time
- Average of BC exposure levels ($\mu\text{g}/\text{m}^3$, E) above 10 $\mu\text{g}/\text{m}^3$ and 50 $\mu\text{g}/\text{m}^3$; $E_{\text{peak}10}$ and $E_{\text{peak}50}$
- The duration of exposure (hours, T) above 10 $\mu\text{g}/\text{m}^3$ and above 50 $\mu\text{g}/\text{m}^3$; $T_{\text{peak}10}$ and $T_{\text{peak}50}$
- The percentage (%), P_T of $T_{\text{peak}10}$ and $T_{\text{peak}50}$ within the total exposure duration; $P_{T_{\text{peak}10}}$ and $P_{T_{\text{peak}50}}$
- The ratio (R) of the peak exposure levels ($E_{\text{peak}10}$ and $E_{\text{peak}50}$) to the average daily exposure levels; $R_{\text{peak}10}$ and $R_{\text{peak}50}$

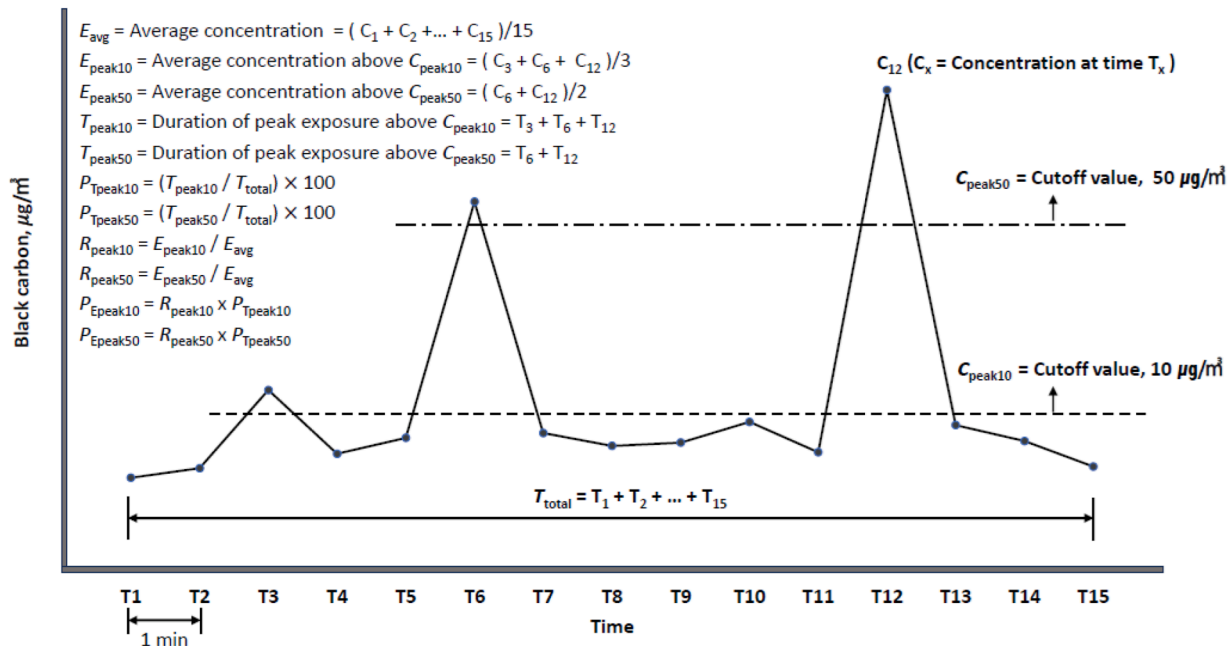


Fig. 1. Conceptual diagram of the variables used to characterize peak exposure to black carbon (BC) recorded every one minute during the working day.

- The percentage contribution (%), P_E) of the peak exposure levels (E_{peak10} and E_{peak50}) to the average daily exposure levels; $P_{Epeak10}$ and $P_{Epeak50}$.

2.4. Data analysis

All BC measurements taken during the working day were downloaded immediately after work was completed to reduce data-handling errors. A refined dataset of 71,987 observations was used to analyze BC peak exposure levels for workers operating or working near DEVs. All one-minute BC measurements were individually coded and linked to specific workers, job types, and discrete work tasks using detailed TAD. The aforementioned peak exposure variables were defined for each working day and worker based on two cut-off values ($10 \mu\text{g}/\text{m}^3$ and $50 \mu\text{g}/\text{m}^3$), and subsequently categorized by type of job and work activity to identify activity-related patterns. To evaluate the relationships among the peak exposure metrics, pairwise correlations were calculated at the daily level for each worker. Because the distributions of peak exposure variables were highly skewed and deviated from normality, Spearman's rank correlation coefficient was applied as a robust nonparametric measure of association. The statistical significance of correlations was examined using two-sided p-values. Descriptive statistics, boxplots, and correlation analyses were performed using R software (version 4.4.1; R Foundation for Statistical Computing, Vienna, Austria), providing detailed insights into the characteristics of BC peak exposures.

3. Results

The averages of the AM, 95th percentile, and maximum BC during working hours were found to be typically high for tasks such as toll collection, refuse collection and dumping, forklift operation, and machine operation near forklifts indoors (Table 1). Forklift operators, workers engaged in waste collection and dumping, and machine operators working near DEVs had BC exposure levels of E_{peak10} above $20 \mu\text{g}/\text{m}^3$, indicating a high

contribution rate ($P_{Epeak10} > 60\%$) to the daily average BC exposure level despite short exposure times above the BC peak exposure levels of $10 \mu\text{g}/\text{m}^3$ (<1 hour) (Table 2). All jobs had high average BC exposure levels, with AM above the peak threshold of $50 \mu\text{g}/\text{m}^3$ (E_{peak50}), and in particular, automobile assemblers and toll collectors showed values exceeding $80 \mu\text{g}/\text{m}^3$, despite very short exposure times (< a few minutes) (Table 3), when compared to the average daily exposure levels (Table 1). Some activities, such as forklift-related activities, forklift operation, driving inside refuse collection vehicles, and gantry crane operation, were found not to involve exposures exceeding $50 \mu\text{g}/\text{m}^3$, while all types of jobs and activities were found to involve exposure to more than $10 \mu\text{g}/\text{m}^3$ (Table 2, Table 3 and Fig. 2). The distributions of all BC exposure levels, as well as peak exposure levels averaging over $10 \mu\text{g}/\text{m}^3$ and $50 \mu\text{g}/\text{m}^3$, were found to be similar for workers operating or working near DEVs. The distribution of the daily contribution rate (P_{Epeak} , %) of peak exposures above $10 \mu\text{g}/\text{m}^3$ to the average daily BC exposure was found to be higher than that of $50 \mu\text{g}/\text{m}^3$. This rate was highest for diesel drivers or operators (Supplement 1). The correlations between variables related to BC peak exposures above $10 \mu\text{g}/\text{m}^3$ (Table 4) and $50 \mu\text{g}/\text{m}^3$ (Table 5) were mostly significant. In particular, the ratio of peak levels above $10 \mu\text{g}/\text{m}^3$ and $50 \mu\text{g}/\text{m}^3$ to the AM (designated R_{peak10} and R_{peak50}) was found to be negatively correlated with exposure duration, the proportion of exposure duration and the daily contribution of peak levels above the two cut-points. Examples of BC exposure patterns for garbage collectors (top) and forklift operators (bottom), monitored at one-minute intervals throughout the working day, clearly showed peak BC exposure patterns associated with specific activities (Supplement 2).

4. Discussion

This study assessed BC peak exposure using real-time BC exposure data for workers operating DEVs or working near DEVs across different job roles and work activities. The various characteristics, requirements and applications of peak DEE exposure assessment using real-time BC exposure data are discussed here.

Table 1
Distribution of BC exposure levels during the daily working time

Type of industry*	Type of job	Brief description of the job or task performed	Number of workers	Number of measurements		Exposure duration monitored per activity, hour		AM, µg/m ³		X95, µg/m ³		Max, µg/m ³	
				AM	Range	AM	Range	AM	Range	AM	Range	AM	Range
16,211	Forklift operator	Loading, moving, and unloading of panels and plywood	7	434	326-527	7.2	5.4-8.8	10.4	2.1-20.5	32.5	7.8-61.8	55.6	13.4-150.2
	Machinery operator	Operating plywood-making machines near forklift trucks	2	499	472-516	8.3	7.9-8.6	13.0	5.3-19.7	35.1	14.4-58.7	63.4	20.3-98.3
		Subtotal	9	446	326-527	7.4	5.4-8.8	10.8	2.1-20.5	33.0	7.8-61.8	57.0	13.4-150.2
17,211	Forklift operator	Cafeteria [†]	21	12	7-17	0.2	0.1-0.3	5.0	0.8-30.3	7.4	1.2-39.1	7.8	1.4-41.2
		Loading, moving, and unloading of paper boxes	23	311	154-426	5.2	2.6-7.1	15.3	2.1-37.6	34.0	5.0-115.2	67.8	6.2-178.1
		Indoor task other than forklift operation	4	90	19-168	1.5	0.3-2.8	4.1	3.3-5.2	7.2	5.0-8.9	9.1	5.1-11.1
		Office [†]	3	165	61-223	2.8	1.0-3.7	5.5	2.8-8.2	12.3	6.1-17.4	24.5	9.4-39.0
		Outdoor task other than forklift operating	2	62	8-115	1.0	0.1-1.9	4.8	2.0-7.6	7.6	4.6-10.6	10.6	9.9-11.4
		Rest [†]	20	36	5-96	0.6	0.1-1.6	4.0	0.8-9.3	7.2	1.5-18.0	8.9	2.2-18.7
		Subtotal	73	125	5-426	2.1	0.1-7.1	7.9	0.8-37.6	15.9	1.2-115.2	27.8	1.4-178.1
30,121	Automobile assembler	Assembling and moving manufactured diesel vehicles	14	262	94-447	4.4	1.6-7.4	6.7	3.3-13.4	15.6	9.1-32.0	54.5	12.9-164.7
		Inspection of assembled diesel vehicles	20	300	51-468	5.0	0.8-7.8	4.9	2.3-8.5	12.7	3.2-32.3	46.7	6.6-168.9
		Subtotal	34	284	51-468	4.7	0.8-7.8	5.6	2.3-13.4	13.9	3.2-32.3	49.9	6.6-168.9
38,110	Garbage collector	Collection of household waste, loading onto trucks	8	305	131-537	5.1	2.2-8.9	10.5	7.7-19.3	33.0	18.7-69.4	106.3	24.8-256.2
		Driving inside the truck	6	39	21-51	0.7	0.3-0.8	7.1	5.8-7.9	15.9	11.6-21.1	22.7	17.4-26.3
		Riding on a step at the back of the truck to approach a collection point	5	48	25-75	0.8	0.4-1.2	9.9	6.6-12.8	24.5	13.6-34.9	41.8	25.8-63.8
	Garbage truck driver	Subtotal	19	154	21-537	2.6	0.3-8.9	9.3	5.8-19.3	25.3	11.6-69.4	62.9	17.4-256.2
		Driving inside the truck	6	360	144-586	6.0	2.4-9.8	6.9	3.8-10.4	16.0	9.2-22.5	49.3	19.6-66.4
		Helping garbage collectors collect waste	4	50	36-65	0.8	0.6-1.1	10.8	5.0-15.7	37.6	13.3-94.1	51.4	15.9-138.0
		Subtotal	10	236	36-586	3.9	0.6-9.8	8.5	3.8-15.7	24.6	9.2-94.1	50.1	15.9-138.0
49,401	Delivery	Door-to-door delivery of various types of parcels	15	438	129-682	7.3	2.1-11.4	3.9	1.1-7.9	12.1	3.9-22.3	40.9	9.5-118.2
		Tasks other than delivery	8	52	5-271	0.9	0.1-4.5	3.8	0.5-11.6	8.2	0.5-22.3	15.6	1.1-73.1
		Subtotal	23	345	5-682	5.7	0.1-11.4	3.9	0.5-11.6	11.2	0.5-22.3	34.7	1.1-118.2
52,914	Toll collector	Collecting toll payments from drivers at expressway toll booths.	3	364	326-383	6.1	5.4-6.4	9.5	8.4-11.3	22.1	17.6-27.6	130.9	53.5-197.7
50,201	Crane operator	Gantry crane operation in the yard	2	554	528-613	9.2	8.8-10.2	2.2	1.3-4.6	9.2	2.2-22.3	18.9	8.2-31.2
		Diesel tractor in operation in the yard	4	467	458-473	7.8	7.6-7.9	6.4	4.5-9.0	20.4	15.0-27.3	46.6	39.8-57.1
		Transfer crane operating	2	537	529-545	8.9	8.8-9.1	2.0	1.4-2.7	5.2	3.9-6.1	35.7	14.1-77.0
		Subtotal	8	519	458-613	8.7	7.6-10.2	3.6	1.3-9.0	11.6	2.2-27.3	33.7	8.2-77.0
	Total		106	71,987	5-682	4.7	0.1-11.4	7.0	0.5-37.6	18.0	0.5-115.2	42.0	1.1-256.2

* Type of industry = 16,211: Manufacture of veneer sheets, plywood, and similar laminated wood boards, 17,211: Manufacture of corrugated paper, 30,121: Manufacture of passenger motor vehicles, 38,110: Non-hazardous waste collection, 49,401: Courier activities, 52,914: Operation of roads and related facilities, 50,201: Inland passenger and freight water transport.

[†] located in other rooms of the same building.

Table 2
Characteristics of peak BC levels above 10 µg/m³ by type of industry, job, and activity

Type of industry	Type of job	Brief description of the job or work done	Number of workers	Number of measurements above 10 µg/m ³		E_{peak10} , µg/m ³		T_{peak10} , hr		$P_{T\text{peak10}}$, %		R_{peak10}		$P_{E\text{peak10}}$, %	
				AM	Range	AM	Range	AM	Range	AM	Range	AM	Range	AM	Range
16,211	Forklift operator	Loading, moving, and unloading of panels and plywood	7	149	10-357	22.9	11.1-45.4	2.5	0.17-5.95	32.4	2.5-69.1	2.9	1.4-6.6	63.2	9.7-95.3
	Machinery operator	Operating plywood-making machines near forklift trucks	2	222	77-308	22.2	12.8-29.3	3.7	1.28-5.13	44.5	15.6-63.3	1.8	1.5-2.9	75.1	41.3-93.0
Subtotal			9	162	10-357	22.8	11.1-45.4	2.7	0.17-5.95	34.5	2.5-69.1	2.7	1.4-6.6	65.3	9.7-95.3
17,211	Forklift operator	Cafeteria	21	1	0-9	27.2	24.1-30.3	0.1	0.03-0.15	60	20.0-100.0	2.1	1.0-3.3	82.8	65.7-100.0
		Loading, moving, and unloading of paper boxes	23	163	0-378	21.7	13.2-55.2	2.8	0.07-6.30	54.9	1.2-97.2	1.7	1.0-3.4	69.3	4.0-99.8
		Indoor task other than forklift operation	4	1	0-3	11	11.0-11.0	0.03	0.02-0.05	1.3	0.6-1.9	2.4	2.1-2.6	2.8	1.6-4.1
		Office	3	19	0-39	15	13.0-16.9	0.5	0.28-0.65	22.7	17.5-27.9	2.2	2.1-2.3	49.0	40.3-57.8
		Outdoor task other than forklift operating	2	0	0-1	11.4	11.4-11.4	0.02	0.02-0.02	12.5	12.5-12.5	1.5	1.5-1.5	18.8	18.8-18.8
		Rest	20	4	0-45	13.5	10.9-17.6	0.2	0.02-0.75	16.8	2.9-46.9	2.3	1.6-3.2	32.0	8.4-79.6
		Subtotal	73	53	0-378	19.1	10.9-55.2	1.8	0.02-6.30	41.8	0.6-100.0	1.9	1.0-3.4	56.6	1.6-100.0
30,121	Automobile assembler	Assembling and moving manufactured diesel vehicles	14	34	5-120	17.8	11.8-41.3	0.6	0.08-2.00	15.8	2.4-39.4	3.1	1.6-7.2	34.4	12.8-66.2
		Inspection of assembled diesel vehicles	20	24	0-98	17.5	10.4-30.8	0.4	0.03-1.63	10	0.5-26.8	3.9	2.1-10.4	29.9	2.0-67.5
		Subtotal	34	28	0-120	17.6	10.4-41.3	0.5	0.03-2.00	12.5	0.5-39.4	3.5	1.6-10.4	31.9	2.0-67.5
38,110	Garbage collector	Collection of household waste, loading onto trucks	8	100	38-261	23	14.8-34.6	1.7	0.63-4.35	30.3	17.4-52.3	2.2	1.7-3.6	63.9	43.3-90.8
		Driving inside the truck	6	8	5-13	14.9	12.1-17.8	0.1	0.08-0.22	21	11.4-26.3	2.2	1.6-3.0	43.0	33.9-53.7
		Riding on a step at the back of the truck to approach a collection point	5	15	11-21	18.3	15.3-22.6	0.3	0.18-0.35	34.6	14.7-44.0	1.9	1.6-2.5	62.0	37.0-73.9
		Subtotal	19	49	5-261	19.2	12.1-34.6	0.8	0.08-4.35	28.5	11.4-52.3	2.1	1.6-3.6	56.8	33.9-90.8
	Garbage truck driver	Driving inside the truck	6	74	6-117	15.7	13.3-17.6	1.2	0.10-1.95	18.5	4.2-35.2	2.4	1.7-3.5	39.7	14.5-59.4
		Helping garbage collectors collect waste	4	19	6-32	27.4	12.7-66.9	0.3	0.10-0.53	34.4	16.7-56.1	2.4	1.3-4.3	64.4	42.6-79.2
		Subtotal	10	52	6-117	20.4	12.7-66.9	0.9	0.10-1.95	24.9	4.2-56.1	2.4	1.3-4.3	49.6	14.5-79.2
49,401	Delivery	Door-to-door delivery of various types of parcels	15	34	0-125	17	11.8-26.0	0.6	0.12-2.08	8.1	1.2-23.9	4.5	2.1-9.5	32.4	6.9-57.7
		Tasks other than delivery	8	6	0-42	15.1	11.5-21.4	0.2	0.03-0.70	19.4	3.5-57.1	3.2	1.2-5.6	43.4	11.8-69.7
Subtotal			23	27	0-125	16.7	11.5-26.0	0.5	0.03-2.08	9.7	1.2-57.1	4.3	1.2-9.5	34.0	6.9-69.7
52,914	Toll collector	Collecting toll payments from drivers at expressway toll booths.	3	107	68-154	18.5	14.6-21.7	1.8	1.13-2.57	28.9	20.9-40.2	2	1.7-2.5	54.7	44.6-67.8
50,201	Crane operator	Gantry crane operation in the yard	2	28	0-89	15.1	13.0-19.4	0.6	0.10-1.48	6.2	1.1-14.5	7	4.3-8.7	32.4	9.3-61.8
		Diesel tractor in operation in the yard	4	94	45-175	18.1	16.3-20.5	1.6	0.75-2.92	20.1	9.7-37.0	3.1	2.1-4.4	53.1	35.3-77.8
		Transfer crane operating	2	8	4-13	16.2	11.4-25.0	0.1	0.07-0.22	1.4	0.8-2.4	8.3	5.6-13.6	11.7	6.3-20.5
		Subtotal	8	43	0-175	16.6	11.4-25.0	0.8	0.07-2.92	9.5	0.8-37.0	6.1	2.1-13.6	32.4	6.3-77.8
Total			106	60	0-378	18.9	10.4-66.9	1.2	0.02-6.30	23.3	0.5-100.0	3.2	1.0-13.6	46.7	1.6-100.0

Table 3
 Characteristics of peak BC levels above 50 ug/m3 by type of industry, job, and activity

Type of industry	Type of job	Brief description of the job or work done	Number of workers	Number of measurements above 50 µg/m ³		E _{peak50} , µg/m ³		T _{peak50} , hr		P _{Tpeak50} , %		R _{peak50}		P _{Epeak50} , %	
				AM	Range	AM	Range	AM	Range	AM	Range	AM	Range	AM	Range
16,211	Forklift operator	Loading, moving, and unloading of panels and plywood	7	10	0-38	58.7	53.4-67.7	0.31	0.02-0.63	4.5	0.2-11.4	4.4	2.9-8.7	20.6	0.9-65.3
	Machinery operator	Operating plywood-making machines near forklift trucks	2	11	0-37	62.3	55.7-68.0	0.25	0.02-0.62	2.9	0.2-7.3	5.6	3.3-12.7	10.8	2.6-24.2
	Subtotal		9	10	0-38	59.5	53.4-68.0	0.29	0.02-0.63	4.2	0.2-11.4	4.7	2.9-12.7	18.5	0.9-65.3
17,211	Forklift operator	Cafeteria	21	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Loading, moving, and unloading of paper boxes	23	11	0-68	66.7	53.8-84.8	0.41	0.02-1.13	9.8	0.3-29.2	2.9	1.8-4.4	23.0	1.2-75.5
		Indoor task other than forklift operation	4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Office	3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Outdoor task other than forklift operating	2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Rest	20	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Subtotal		73	3	0-68	66.7	53.8-84.8	0.41	0.02-1.13	9.8	0.3-29.2	2.9	1.8-4.4	23.0	1.2-75.5	
30,121	Automobile assembler	Assembling and moving manufactured diesel vehicles	14	1	0-4	81.2	50.1-164.7	0.03	0.02-0.07	1.4	0.2-3.8	11.2	5.3-28.5	10.0	1.9-24.7
		Inspection of assembled diesel vehicles	20	1	0-4	87.2	55.8-160.1	0.03	0.02-0.07	0.5	0.2-1.2	17.1	8.0-28.3	7.4	3.0-13.7
		Subtotal	34	1	0-4	84.5	50.1-164.7	0.03	0.02-0.07	0.9	0.2-3.8	14.4	5.3-28.5	8.6	1.9-24.7
38,110	Garbage collector	Collection of household waste, loading onto lorries	8	9	0-49	73.3	56.9-84.3	0.2	0.02-0.82	3.4	0.5-9.8	7.1	4.3-9.0	19.9	3.4-42.2
		Driving inside the truck	6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Riding on a step at the back of the truck to get close to a collection point	5	0	0-1	63.8	63.8-63.8	0.02	0.02-0.02	2.1	2.1-2.1	5.0	5.0-5.0	10.4	10.4-10.4
	Garbage truck driver	Subtotal	19	4	0-49	71.9	56.9-84.3	0.17	0.02-0.82	3.2	0.5-9.8	6.8	4.3-9.0	18.6	3.4-42.2
		Driving inside the truck	6	1	0-4	57	56.5-57.6	0.04	0.02-0.07	0.7	0.2-1.4	7.4	5.5-9.4	4.3	2.1-7.7
		Helping garbage collectors collect waste	4	1	0-5	93.4	93.4-93.4	0.08	0.08-0.08	11.6	11.6-11.6	5.9	5.9-5.9	69.1	69.1-69.1
Subtotal		10	1	0-5	66.1	56.5-93.4	0.05	0.02-0.08	3.4	0.2-11.6	7.0	5.5-9.4	20.5	2.1-69.1	
49,401	Delivery	Door-to-door delivery of various types of parcels	15	0	0-6	65.4	50.2-98.9	0.03	0.02-0.10	0.5	0.2-1.3	17.0	6.9-33.4	7.5	1.4-17.9
		Tasks other than delivery	8	0	0-1	63.7	54.3-73.1	0.02	0.02-0.02	0.5	0.4-0.5	12.6	11.1-14.1	5.6	5.2-5.9
		Subtotal	23	0	0-6	65.1	50.2-98.9	0.03	0.02-0.10	0.5	0.2-1.3	16.3	6.9-33.4	7.2	1.4-17.9
52,914	Toll collector	Collecting toll payments from drivers at expressway toll booths.	3	3	45,661	89.3	53.5-129.9	0.04	0.02-0.07	0.7	0.3-1.0	9.6	6.4-14.8	7.7	1.7-13.6
50,201	Crane operator	Gantry crane operation in the yard	2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Diesel tractor in operation in the yard	4	0	0-2	53.6	53.6-53.6	0.03	0.03-0.03	0.4	0.4-0.4	5.9	5.9-5.9	2.5	2.5-2.5
		Transfer crane operating	2	0	0-1	77	77.0-77.0	0.02	0.02-0.02	0.2	0.2-0.2	41.8	41.8-41.8	7.9	7.9-7.9
		Subtotal	8	0	0-2	65.3	53.6-77.0	0.02	0.02-0.03	0.3	0.2-0.4	23.9	5.9-41.8	5.2	2.5-7.9
Total			106	3	0-68	68.7	50.1-164.7	0.18	0.02-1.13	3.4	0.2-29.2	9.1	1.8-41.8	14.9	0.9-75.5

NA: no measurement detected above 50 µg/m³.

Firstly, job title and work activity were found to be associated with trends in workers' peak BC exposure (Tables 2 and 3). BC levels averaging above the peak exposure level ($10 \mu\text{g}/\text{m}^3$) were found to have a high contribution rate ($P_{E_{\text{peak}10}}$) to the daily average BC exposure level despite short exposure times above the BC peak exposure level (Tables 2 and 3). The ratios of peak levels above the two peak exposure levels to the AM were found to be negatively correlated with exposure duration, the proportion of exposure duration, and the daily contribution of peak levels (Tables 4 and 5). Operating DEVs or working near DEVs were found to contribute significantly to workers' peak daily exposure to BC. This was due to their proximity to DEV that emit high levels of BC during short-term tasks and activities. Engineering and administrative controls should be implemented for specific tasks or locations where peak exposures are identified. Predetermined BC peak exposure cut-points, such as $10 \mu\text{g}/\text{m}^3$ or $50 \mu\text{g}/\text{m}^3$, can be used as action levels to trigger engineering or administrative interventions aimed at reducing exposures associated with particular tasks, workplaces, or diesel-powered equipment.

Secondly, peak exposure to DEE is necessary to assess in order to investigate not only acute but also chronic health effects that may be caused by exposure. Peak exposure to DEE, including BC, can cause cardiovascular risks, such as an increased risk of heart attack and stroke, and aggravate respiratory diseases such as asthma and bronchitis [5,6]. In this context, the short-term BC excursions exceeding $50\text{--}100 \mu\text{g}/\text{m}^3$ observed in our study (Tables 2 and 3) may represent exposure patterns of potential relevance for acute cardiopulmonary effects, although health-based thresholds for minute-scale BC peaks have not yet been established. Controlled human exposure studies of DEE have demonstrated that brief, high-intensity exposures can induce acute cardiovascular responses, including endothelial dysfunction and arterial vasoconstriction, even over exposure durations of only a few hours [20]. The findings of this study indicate that the rate and intensity of exposure, as opposed to the mere cumulative dose,

Table 4

Correlation matrix showing the coefficients between certain variables associated with peak exposures exceeding BC $10 \mu\text{g}/\text{m}^3$

	AM	$E_{\text{peak}10}, \mu\text{g}/\text{m}^3$	$T_{\text{peak}10}, \text{hr}$	$P_{T_{\text{peak}10}}, \%$	$R_{\text{peak}10}$	$P_{E_{\text{peak}10}}, \%$
AM	1.00		0.64**	0.93**	-0.88**	0.85**
$E_{\text{peak}10}, \mu\text{g}/\text{m}^3$	0.52	1.00	0.53**	0.48**	-0.13	0.67**
$T_{\text{peak}10}, \text{hr}$	0.64	0.53	1.00	0.72**	-0.50**	0.75**
$P_{T_{\text{peak}10}}, \%$	0.93	0.48	0.72	1.00	-0.85**	0.94**
$R_{\text{peak}10}$	-0.88	-0.13	-0.50	-0.85	1.00	-0.66**
$P_{E_{\text{peak}10}}, \%$	0.85	0.67	0.75	0.94	-0.66	1.00

Note that the Spearman correlation values remain the same on both the original scale and the log scale as they are calculated based on the ranks of the values. Statistical significance: ** <0.01.

may have a significant impact on the acute physiological responses to combustion aerosols. This observation lends support to the incorporation of peak DEE exposure in occupational health and safety assessments. Consequently, brief periods of elevated BC exposure should be identified and evaluated, even in cases where the time-weighted average concentrations are modest. Such peak exposures are likely to vary substantially by job and task, with

Table 5

Correlation matrix showing the coefficients between various variables associated with peak exposures exceeding BC $50 \mu\text{g}/\text{m}^3$

	AM	$E_{\text{peak}50}, \mu\text{g}/\text{m}^3$	$T_{\text{peak}50}, \text{hr}$	$P_{T_{\text{peak}50}}, \%$	$R_{\text{peak}50}$	$P_{E_{\text{peak}50}}, \%$
AM	1.00	0.02	0.74**	0.72**	-0.96**	0.37**
$E_{\text{peak}50}, \mu\text{g}/\text{m}^3$	0.02	1.00	0.08	0.19	0.22	0.42**
$T_{\text{peak}50}, \text{hr}$	0.74	0.08	1.00	0.93**	-0.70**	0.78**
$P_{T_{\text{peak}50}}, \%$	0.72	0.19	0.93	1.00	-0.66**	0.87**
$R_{\text{peak}50}$	-0.96	0.22	-0.70	-0.66	1.00	-0.25**
$P_{E_{\text{peak}50}}, \%$	0.37	0.42	0.78	0.87	-0.25	1.00

Statistical significance: ** <0.01; * <0.05.

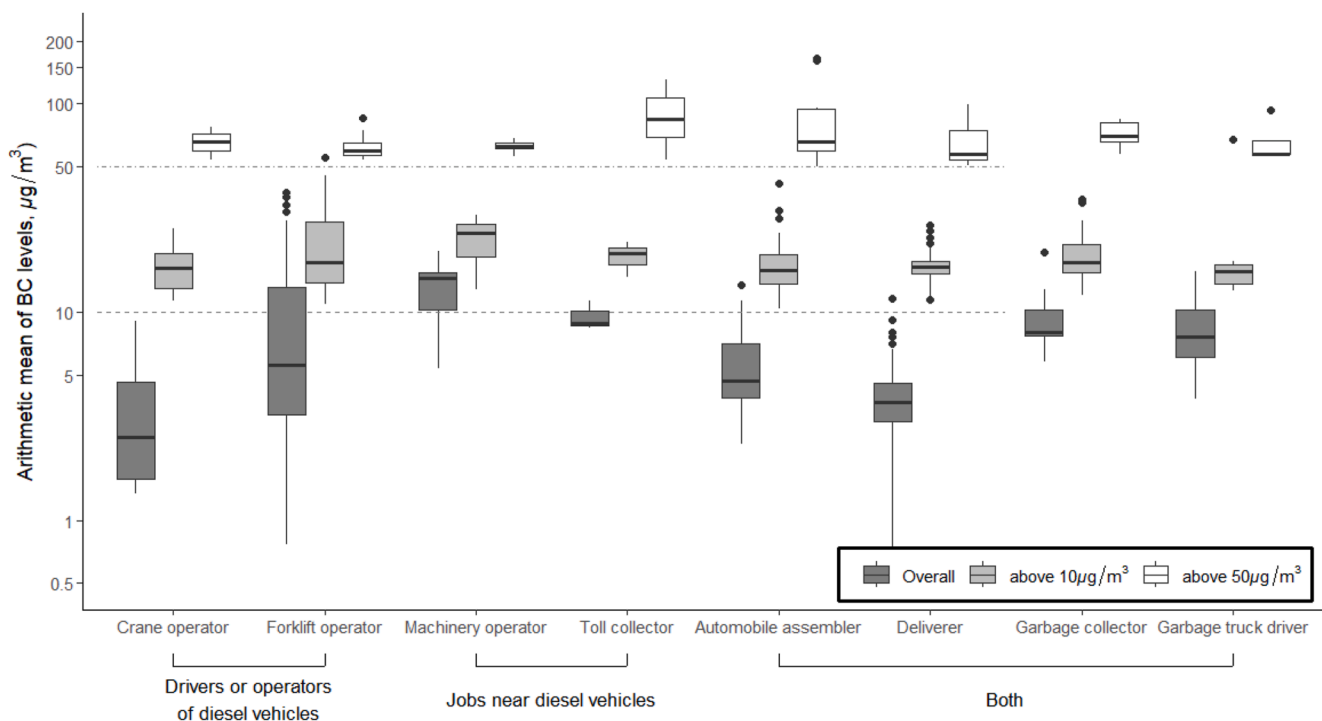


Fig. 2. Distributions of all BC exposure levels and peak exposure levels above $10 \mu\text{g}/\text{m}^3$ and $50 \mu\text{g}/\text{m}^3$, respectively, by job type (DEVs = diesel engine vehicles and machinery). The y-axis is presented on a logarithmic scale. Boxplots indicate the median (middle line), interquartile range (IQR, box), whiskers ($1.5 \times \text{IQR}$), and outliers (filled dots).

drivers and workers operating near DEVs experiencing intermittent but intense exposures, in contrast to production workers who tend to have more stable and predictable exposure profiles.

Thirdly, BC levels can be used as a surrogate for exposure to DEE, especially for peak exposure to DEE, in workplaces with DEVs. Motorized transport, particularly diesel vehicles, represents a significant source of BC exposure for workers [21]. EC is preferred to BC as a marker of diesel exhaust exposure since it is a major component of DEE and less common in gasoline engine emissions [22]. EC quantification based on filter media is not suitable for assessing peak exposures or identifying patterns of high exposure to DEE for brief periods. BC, a component of DEE, can be monitored in real time and is a practical and efficient method for assessing short-term exposure and emission trends, whereas EC is more suitable for long-term exposure studies. To assess peak exposures to BC, portable monitors and aethalometers can be used to measure personal and ambient BC concentrations [23,24].

Finally, our findings on peak exposures to BC have considerable potential applications in epidemiology and DEE exposure control strategies. The assessment of DEE exposures in different DEV drivers could shed light on the risks of cardiovascular and respiratory disease and lung cancer in epidemiological studies focusing on DEE peak exposure. Song et al. (2021) found in a meta-analysis of 37 studies that short-term exposure to BC and EC increased the risk of cardiovascular disease in the elderly by 1.6% per $1 \mu\text{g}/\text{m}^3$, while long-term exposure increased the risk by 6.8% [5]. Since peak exposure metrics are not consistently defined or utilized, they may be overlooked as an exposure metric in epidemiological studies where average or cumulative exposure metrics are used instead, potentially leading to bias in estimates of exposure-response associations [25]. To date, no epidemiological study has specifically investigated the health risks associated with either BC or DEE peak exposures. For example, based on our study results, qualitative peak exposure categories—such as workers with jobs that feature exposure to above either $20 \mu\text{g}/\text{m}^3$ or $50 \mu\text{g}/\text{m}^3$ (yes vs. no) for certain periods of time—can be used to investigate acute health effects due to peak exposure to DEE. Schnatter et al. (2012) found that peak benzene exposure, defined as at least one year's employment in jobs where exposure was likely to be $> 3 \text{ ppm}$ for 15–60 minutes at least weekly (yes vs. no), was associated with the risk of myelodysplastic syndrome [15]. For some carcinogens, disease processes may depend not only on cumulative dose but also on the dose rate and the maximum concentration reaching the target tissue. Such exposures can overwhelm metabolic or detoxification pathways that would otherwise eliminate or neutralize lower concentrations. In these cases, an appropriate exposure metric may be either the maximum concentration encountered (i.e., “peak” exposure) or the duration of time above a specified threshold [26,27].

A key limitation of this study is the lack of direct scientific evidence showing that exposure to black carbon (BC) concentrations of 10 or $50 \mu\text{g}/\text{m}^3$ over a period of one minute causes acute or transient adverse health effects in humans. The thresholds applied in this study were therefore derived from 8-hour time-weighted average occupational exposure limits for chronic risk management based on elemental carbon, and were used as reference values rather than health-based benchmarks for minute-scale exposures. Another limitation concerns the representativeness of the exposure assessment, as BC measurements in some occupations were based on a small sample size. Additionally, the study focused on a specific set of industries and diesel-powered vehicle operations, which may restrict the generalizability of the findings to other occupational groups or work environments. Variations in diesel emission characteristics, seasonal patterns, ventilation

conditions, specific work tasks and the size, age and usage of diesel-powered equipment were not fully captured, which may restrict the applicability of the results even further. Consequently, the findings may not be generalizable to workers with similar job titles employed in different work environments or operational conditions.

Despite these limitations, portable aethalometers were used to collect minute-by-minute BC data, enabling short-term peak exposures to be identified that are often obscured in conventional time-weighted average-based assessments. This linkage enabled the identification of task-specific exposure patterns, and representative cases were used to illustrate time- and activity-resolved BC exposure trends across work shifts (Supplement 2). The strength of this study lies in its integrated application of well-established peak-exposure metrics to high-resolution, real-time BC data, which is linked with detailed time-activity information. This approach allows task-specific short-term exposure patterns, which are often obscured in conventional TWA based assessments, to be characterized. It also provides a methodological basis for future investigations of the acute and chronic health effects associated with brief but intense exposure episodes. Our findings can also inform future research on both acute and chronic health risks potentially associated with brief but intense exposure episodes.

5. Conclusion

The exposure patterns to BC exhibited significant variation according to the nature of the job, with short-term high-concentration excursions above 10 and $50 \mu\text{g}/\text{m}^3$ occurring predominantly in tasks involving close proximity to DEV sources, such as forklift operators, garbage collectors, machine operators, and on-road mobile workers. These peak-dominated exposure profiles were not uniformly observed across all occupations, indicating that such patterns are characteristic of specific high-risk job functions and underscoring the necessity for task-targeted control strategies.

CRediT authorship contribution statement

Ju-Hyun Park: Visualization, Validation, Formal analysis, Data curation. **Sangjun Choi:** Visualization, Validation, Methodology, Data curation, Conceptualization. **Kyung Ehi Zoh:** Visualization, Resources, Methodology. **Seung Won Kim:** Writing – review & editing, Validation, Methodology. **Dong-Hee Koh:** Writing – review & editing, Validation, Methodology. **Won Kim:** Writing – review & editing, Validation, Methodology. **Dong-Uk Park:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Statement on the Use of AI Tools

Generative AI tools were used to rephrase sections of the manuscript for improved clarity during its preparation. However, the authors developed and validated all scientific content, interpretation of results and conclusions. The authors take full responsibility for the content and integrity of the work.

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Conflicts of interest

The authors have no competing interests to declare that are relevant to the content of this article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.shaw.2026.01.004>.

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