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Assessment of ambient air diesel particulates in fire departments using different exposure metrics: Pilot study

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1. Introduction

Firefighters are exposed to many different toxins over the course of their job. While the epidemiological literature on firefighters is sparse, studies have reported a statistically significant, positive exposure-response relationship between firefighting and the risks of lung cancer and leukemia [1–3]. Previous studies have examined fire departments for exposures to polybrominated diphenyl ethers using dust samples from vacuum cleaner bags [4], or to polycyclic aromatic hydrocarbons using airborne samples [5,6]. However, few have focused on exposures to diesel particulate matter (DPM) or, if they have, have limited their focus to the engine bay [7]. Mass concentrations of DPM have been evaluated in other industries [8], sometimes using various surrogates such as particle fractions [9]. Yet the properties, associated particle fraction number, and mass concentration of DPM in relation to the characteristics of a fire department have not been well quantified, especially across different areas of small, rural fire departments.

DPM is a mixture of various components, but mainly consists of a carbonaceous core (elemental carbon [EC]) and adsorbed organic compounds (organic carbon [OC]) [10]. OC also includes non-diesel sources such as emissions from cooking or building heating systems [11], but EC is the main component (50%–85%) of DPM. As the main component, and due to several of its characteristics, EC has been widely used as a surrogate measure of DPM exposure [10,11]. Specifically, EC is generated proportionally to DPM, is relatively free of interference, and is more sensitive than OC, thus facilitating the detection of DPM concentrations [12–14]. When measuring particulate concentrations, the size of the particle becomes important because it determines which area of the respiratory system is penetrated, from the trachea to the alveolar regions of the lung. Particles that are less than 2.5 μm in aerodynamic diameter (Dae) tend to be deposited deep in the lung, as far as the alveolar region. In terms of particle size, DPM is less than 0.1 μm in aerodynamic diameter (Dae). Although DPM does aggregate and form larger particles, the larger particles are still smaller than 1.0 μm [8,15,16]. Debia et al. [17] have reported that the majority of particles in DPM are within the respirable fraction (< 4 μm in Dae) and most are nanoparticles (< 100 nm in Dae). Nanoparticles in DPM comprise < 10% of the particle mass, but > 90% of the number of particles [13,18]. Thus, nanoparticles have a larger surface area per gram mass than fine and coarse particles. Approximately 80%–95% of DPM mass consists of fine-sized particles (< 2.5 μm) [13].

The International Agency for Research on Cancer (IARC) has classified diesel engine exhaust as a group 1 human carcinogen, based on evidence that exposure is associated with an increased risk of lung cancer [19]. Investigations spanning three decades have examined the adverse health effects due to DPM, which include airway inflammation, rectal cancer, pulmonary function decline, and irritation of the eyes [20,21]. Experimental studies have also confirmed that extracts of particles from diesel engines are capable of inducing tumors and airway and lung parenchymal inflammation in animals [7,22]. In the meta-analysis of data from three occupational epidemiological studies, Vermeulen [23] concluded that lifetime diesel exposure accounted for a substantial number of excess lung cancer deaths.

Although the scientific community has begun to understand the carcinogenic respiratory effects of exposure to DPM in fire departments, few specific bodies or organizations are investigating or regulating that exposure. Currently, there is no Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL), National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL), or American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) specified for DPM. However, since it has been widely used as a surrogate for evaluating exposures to DPM, some state-level agencies have set limits for EC. For example, the California Environmental Protection Agency (EPA) has set the recommendation level for EC TWA to 20 μg/m^3 [24]. In fact, the ACGIH proposed a TLV of 20 μg/m^3 for EC in the 2001 Notice of Intended Changes, but the TLV was withdrawn in 2003. The most recent updated version has removed any mention of the ACGIH TLV for EC [10].

One organization that has addressed exhaust emissions is the

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National Fire Protection Association (NFPA). According to NFPA (2018) [25], *The fire department shall prevent exposure to fire fighters and contamination of living and sleeping areas to exhaust emissions* (NFPA 1500.10.1.5). This safety standard implies that negative air pressure should be maintained in an engine bay and positive air pressure in the living quarters, including the kitchen, dormitory, office, etc. For example, operating an HVAC in the living quarters helps decrease potential exposure to DPM because the air flows from the living quarters (positive air pressure) to the bay (negative air pressure) [9]. However, in one study, the dormitory had negative air pressure. Consequently, a higher level of TC, but not EC, was found in the dormitory than in the engine bay. Thus, negative air pressure may or may not be a contributing factor to DPM exposure [11].

The aim of this study is to characterize DPM concentrations, a mixture of mainly EC and OC, in the ambient air of selected areas of small, rural fire departments using integrated measurements and direct reading-based measurements. The integrated measures quantify EC and OC mass concentrations. In contrast, the direct reading-based measures include the number of particles and the mass concentrations from 10 nm to 10 μm. This pilot study will help us assess the feasibility of a larger epidemiological exposure assessment in the fire departments.

2. Methods

2.1. Population sample

For the purpose of the larger epidemiological exposure assessment, the research team has partnered with the Green River Firefighters Association (GRFA) on several studies. The GRFA includes firefighters that staff 70 municipal fire departments, which comprise 10% of all Kentucky fire departments, in eight counties in northwestern Kentucky. At the bimonthly meeting of the GRFA, we described the specific goals of this study for the purpose of recruiting fire departments. Additionally, the GRFA officers advertised the study on social media to reach firefighters who did not attend the meetings and to more broadly connect with local fire departments. Once a pool of tentative fire departments was established, we accessed data from the Kentucky Fire Commission database to determine the volume of runs and number of personnel for each potential department over the most recent three-year span (2014–2017). The incident frequency of runs and the number of firefighters at the fire department guided us in selecting a sample. A higher incident frequency means that diesel-powered fire apparatus, including firetrucks, are run more often, which results in higher concentrations of DPM. Similarly, a higher number of firefighters, in particular career (paid) firefighters, may indicate more runs for a fire department. Based on this information, a total of five fire departments were chosen for the assessment of possible exposure sources, focusing on DPM. At least one week before conducting the sampling, we discussed the study logistics (sampling schedule, locations, and processes) with the chief of each selected fire department as well as the firefighter instructors.

2.2. Strategy for assessment of possible exposure sources

Prior to conducting the sampling, we referred to our previous survey of the firefighter cohort in this region and consulted the fire chiefs to select sampling areas consistent with the areas in which firefighters spend most of their time. Based on the responses, we considered five areas (engine bay, kitchen/dining area, dormitory, office/training room, TV lounge/locker) for the sampling strategy. Firefighters spend the most time in the engine bay, which has a potentially high level of DPM because it usually houses the diesel-powered fire apparatus. They also stay in the kitchen/dining area as well as the dormitory during their 8- or 24-h work shifts in fire departments. The scope of this study was to assess possible exposure sources of DPM at the fire departments; therefore, we performed area (not personal) sampling to capture airborne DPM in selected areas at each fire department. We differentiated our sampling strategy on the basis of type of fire department, such as career versus volunteer, although most were career.

2.3. Sampling instruments – integrated DPM

The integrated instrument used to collect EC and OC samples consisted of a 37 mm quartz fiber filter, held in a 3-piece 37 mm cassette, with an air sampling pump (Apex Pro pump, Casella Inc., Amherst, NH). The pumps were calibrated with a primary flow device (DryCal Defender 530, Mesa Labs Inc., Lakewood, CO) and operated at 3.0 lpm so that the collected mass of EC and OC would be greater than the limit of detection for the method. Unlike the dusty trade industry, heavy loadings of carbonate were not expected in the fire departments. Thus, the DPM was collected without a size-selective sampler such as an impactor or cyclone [10]. The duration of the sampling at each area was approximately 6–8 h per sample. For the fire departments with 24-h work shifts, the integrated DPM were collected in three consecutive samples, starting from the morning shift (~8 h TWA [time weighted average]). Namely, the sampling period was equivalent to the shift length of firefighters at these two departments (fire department IDs [FDID] B and C). FDID D and E inevitably had fewer samples recorded due to the schedule; however, the sampling period was equivalent to that of FDID A, which has an 8-h work shift. One or two blank samples (approximately 15% of the DPM samples) were also collected per fire department for quality control. The collected samples were sent to a laboratory accredited according to the American Industrial Hygiene Association Laboratory Accreditation Program. The samples were analyzed using a thermal optical procedure for determining the EC and OC content, as specified by NIOSH Method 5040 Diesel Particulate Matter (as Elemental Carbon) [10]. As stated previously, EC is considered a better indicator of DPM than TC. However, the EC concentrations in the majority of the samples ($n = 37$; 88%) fell below the LOD, which would result in a highly misleading estimate of the EC level. Only seven samples had EC concentrations above the LOD. Therefore, instead of substituting the EC concentration in the majority of the samples, total carbon (TC) was chosen to represent the integrated concentration in this study. Each value less than the limit of detection was replaced with the value $\mathrm{LOD}/\sqrt{2}$ [26,27]. All analyses were completed using SAS 9.4 (SAS Institute, Cary, NC).

2.4. Sampling instruments – direct-reading particulate matter

The particle concentrations and size distribution were measured and analyzed using particle spectrometers (NanoScan SMPS Nanoparticle Sizer 3910, TSI Inc., Shoreview, MN; Optical Particle Sizer [OPS] 3330, TSI Inc., Shoreview, MN) and a photometer (DustTrak DRX 8533, TSI Inc., Shoreview, MN). The NanoScan SMPS, a scanning mobility particle size distribution monitor, has 13 channels ranging from 10 to 420 nm. The flow rate of the inlet is 0.75 L per minute (lpm) and the flow rate for the sample is 0.25 lpm. The second spectrometer, OPS, has 16 channels that can measure 0.3–10 μm at 1.0 lpm. Therefore, the two instruments can be used to measure particle number concentrations ranging from 10 nm to 10 μm in Dae. The DustTrak DRX, which uses both light-scattering and single particle detection methods, measures size-based mass fraction concentrations for PM1, PM2.5, PM4, PM10, and total particulate matter simultaneously. The flow rate for the DRX was set at 3.0 lpm. The direct-reading instruments used a 1-min data-logging interval to monitor DPM levels after an annual calibration by the manufacturer. After the high correlation coefficients of the size-based mass fractions were examined by fire department (ranges: 0.848–0.999, p-values < 0.0001), PM10 was compared with the OPS measurements at 10 μm to identify parallel sizes. PM10 was chosen for the comparison because PM10 particles are considered thoracic [28], having a greater likelihood than larger particles to gain access to the lower respiratory tract. PM10 particles can be further categorized as coarse ($< 10\,\mu m$), fine ($< 2.5\,\mu m$), and nano- or ultrafine (< 100 nm) [29].

The direct-reading instruments were set up with the integrated instruments, thus the same sampling duration applied. To be consistent across fire departments, the direct-reading instruments were placed near the center of the engine bay or in the primary engine bay in the event of multiple bays (FDID C). If necessary, the sampling sites were chosen to prevent any disturbances from the main path of the firefighters or fire vehicles. In addition to compiling an observational record of when the fire trucks went in or out of the engine bay, the researcher asked the firefighters to run the diesel-generating fire apparatus so that the pattern of DPM in ambient air could be viewed in real-time.

2.5. Industrial hygiene survey

For the purpose of better understanding other factors contributing to DPM levels, an industrial hygiene survey was taken. Based on the survey, we characterized each fire department by layout (e.g., is the engine bay next to the kitchen/dining area or the dorm?); number of windows/doors in each area; size of area; type of ventilation; age of fire truck; existence of emission control system; and back-in or pull-through design in the engine bay [9]. Table 1 presents the characteristics of each fire department. Table 2 specifically lists the characteristics of the diesel-powered fire apparatus, which have the highest potential for generating DPM, in each fire department.

3. Results

3.1. Sampling results

A total of 51 air samples were collected. Of these samples, two samples were voided due to a manufacturing error (no filter was placed on the cassette) and seven samples were blanks used for quality control. Thus, 42 samples provided the data for analysis. To better understand the level of DPM in the ambient air, we monitored the integrated measurement in each of the selected areas. Results indicate that all EC samples in the dormitory and TV/locker room fell below the limit of detection level of 0.9 µg/m^3. Only seven EC samples had concentrations above the limit of detection (ranges: 3.0–6.7 µg/m^3). Five of those samples were from an engine bay. One was from a kitchen and one from an office, both of which are adjacent to the bay in FDID A. The ratio of EC to TC per sample ranges from 0.02 to 0.26, whereas the ratio of OC to TC per sample ranges from 0.73 to 1.00, which implies that OC is the predominant component, as opposed to EC. Furthermore, for $> 70\%$ samples (30 out of 42), the ratio was 1.00, which means that the sample was 100% OC.

The mean of TC concentration, with a 95% confidence limit (CI), is shown in Fig. 1 by fire department and by area. The Tukey's Studentized Range Tests for TC between fire departments and between areas were used to determine the statistical differences (p-values $<$ 0.05). The difference between the mean of TC concentration in FDID A and the other fire departments, except for FDID D, is statistically significant. A wide range of 95% CI was observed in FDID E, which indicates more variability, as opposed to the rest of the fire departments that presented a narrow 95% CI. This difference may occur due to the limited number of samples, which led to lower statistical power. Thus, the analysis was not nested for area within the fire department and vice versa. Surprisingly, the highest mean of TC concentration was from an office at 28.6 µg/m^3 (95% CI: 17–56), but was not statistically significant from the rest of the areas (p-value > 0.05). The next higher means of TC concentrations were from a kitchen at 24.6 µg/m^3 (95% CI: 9.6–57), an engine bay at 19.6 µg/m^3 (95% CI: 4–53), and an office.

One of the firefighters' daily tasks is to conduct visual and operating checks on all fire vehicles in the bay while idling for 5–10 min. For the purpose of identifying DPM patterns in the ambient air when the apparatus is idling, we incorporated the idling events and actual runs corresponding to EMS calls. Those events were used to plot the PM10 concentrations in the engine bay by elapsed time. For instance, in FDID A the highest PM10 concentration occurred at approximately 4000 s elapsed time (7:24–7:29) (Fig. 2). At that time, five fire vehicles were idling (cranking) for the regular check. All vehicles remained in the engine bay, but the middle front and back garage doors were open. FDID C has a weekly schedule for checking all maintenance equipment, including fire vehicles, thus no idling occurred except for the actual runs on that day. On the other hand, FDID E had no runs on that day as well as no daily inspection, so we asked them to simulate idling the fire apparatus. The highest PM10 concentration occurred at approximately 25,000 s elapsed time (14:43–15:25). Although the firefighters moved the apparatus outside of the bay, our results indicate that the idling has a great impact on the PM10 concentration because the diesel exhaust emissions can drift back into the fire department.

As mentioned before, the purpose of this pilot study is to assess the feasibility of a future epidemiological exposure assessment. As firefighters work less often at a fixed location (e.g., the fire department), correctly characterizing the exposures reduces the misclassifications that can occur in exposure modeling. Thus, we monitored PM10 for 24 h at two fire departments. Fig. 3, which plots PM10 levels by time of day, shows that PM10 levels are greater in the morning. According to the FDID B emergency service call volume in 2017, 58.77% of calls are made from 7:00–17:00, 23.04% calls from 17:00–22:00, and 18.19% calls from 22:00–7:00, which corresponds to the pattern of DPM by time and run. Although we were not able to collect the actual number of calls by time from other fire departments, a high volume of calls in the

Table 1
Fire department characteristics.

Characteristics	A	B	C	D	E
Department Type	Mixed	Career	Career	Mixed	Career
Est. Average # Runs/Month[a]	86	559	122	23	211
# Career Firefighters	7	30	15	6	24
# Volunteer Firefighters	33	0	0	15	0
Shift Length (Hours)	8	24	24	24	24
Firefighters/Shift	4 (8:00–16:00) 1 (16:00–24:00) 1 (24:00–8:00)	10 (7:00–7:00)	5 (6:00–6:00)	2 (8:00–8:00)	8 (8:00–8:00)
Age of building (year estd)	25 yrs (1993)	45 yrs (c 1973)	43 yrs (c 1975)	42 yrs (c 1976)	51 yrs (c 1967)
Bay Type	Pull-Through	Back-In	Back-In	Pull-Through	Back-In
# of Station Stories	2 Stories	1 Story	1 Story	2 Stories	1 Story
Est. Bay Volume (ft^3)	108,000	76,500	37,800 (Bay1) 22,800 (Bay2)	86,400	40,860
# of Bay Gates	6	5	4 Bay 1 2 Bay 2	4	5
Total Gate Surface Area (ft^2)	1014	980	784 (B1) 392 (B2)	672	980
Ventilation	HVAC/Fans	HVAC/Fans	HVAC/Fans	Exhaust	Exhaust

[a] Average number of runs for each fire department is based on the month (March) when the sampling was conducted as well as the annual average runs for 2014–2016 in the Kentucky fire commission database (records for the most recent 3 years).

Table 2
Diesel-power fire apparatus in each fire department.

Characteristics	A	B	C	D	E
Total # of Diesel Engines	7	3	3	4	3
Pump	4	1	3	3	2
Ladder	1	1	0	0	1
Rescue	2	1	0	1	0
Peak Total Horsepower (hp)	2693	1350	1260	1540	1265
Peak Total Torque (ft-lb)	7390	4000	3860	4295	3770
Total Engine Displacement (L)	56.7	31.5	30.8	36.3	30.3
Average Engine Age (Ranges)	12.57 (2–27)	9.33 (2–15)	10.33 (5–14)	15 (11–24)	14.33 (8–22)

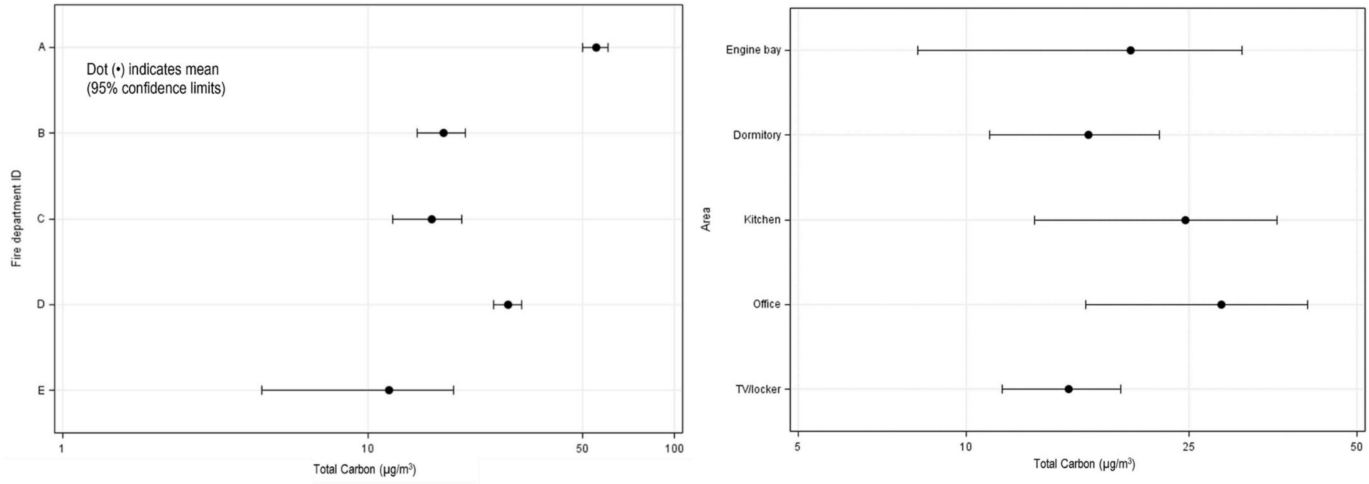

Fig. 1. Total carbon concentration (μg/m^3) by fire department (Left) and by sampled area (Right).

morning is common in small, rural fire departments.

Fig. 4 shows the distribution of particle sizes in the engine bay by fire department. FDID A has an order of magnitude higher distribution than the other FDIDs. The distribution presents monodispersed particles, which have the most size ranges at 100–1000 nm. The peak size was found between 205.4 and 374 nm. Almost no particles were observed with a size greater than 2500 nm, which suggests that the particles in the engine bay have a greater likelihood to be fine or nanoparticles. This result corresponds to the size ranges obtained from the diesel engine exhaust. To determine a relationship between the metrics (number versus mass) of different size-based particle levels, the Pearson correlation coefficients (R) were tested. As shown in Fig. 5 (left), FDID A showed a high number concentration, displaying the same result as in Fig. 4. Thus, R is plotted in Fig. 5 (right) for all data points except those

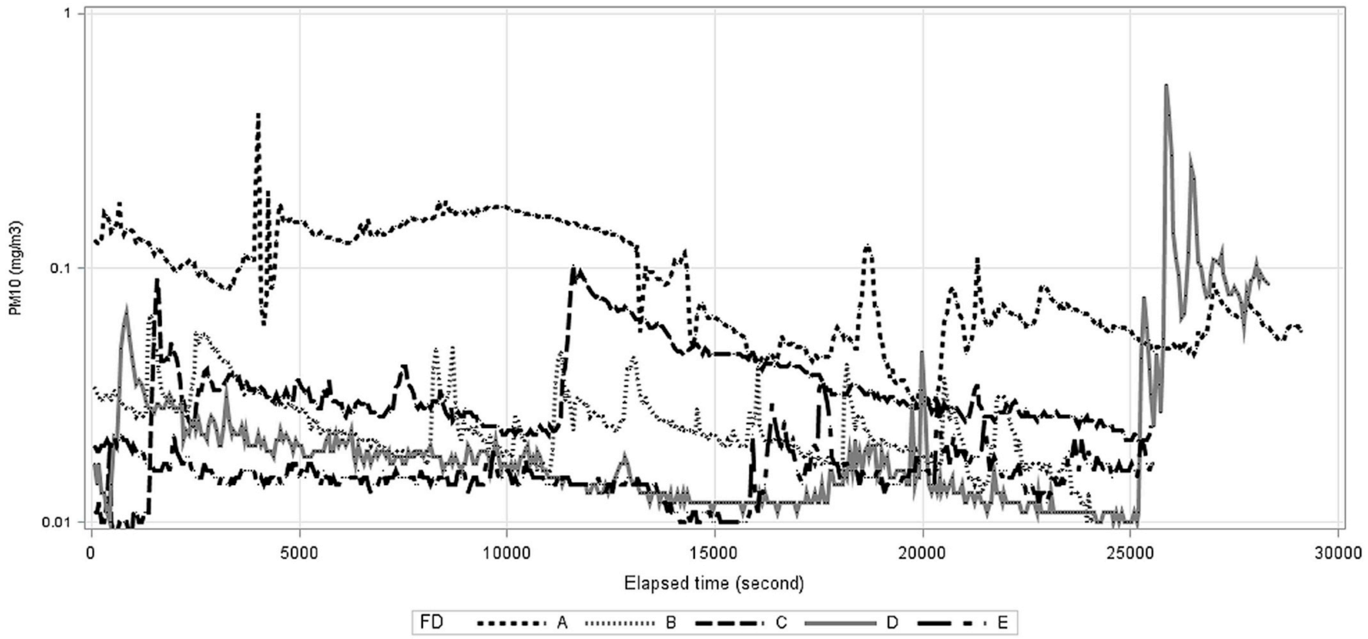

Fig. 2. PM10 concentration (mg/m^3) as a function of elapsed time (seconds) in engine bay across all fire departments.

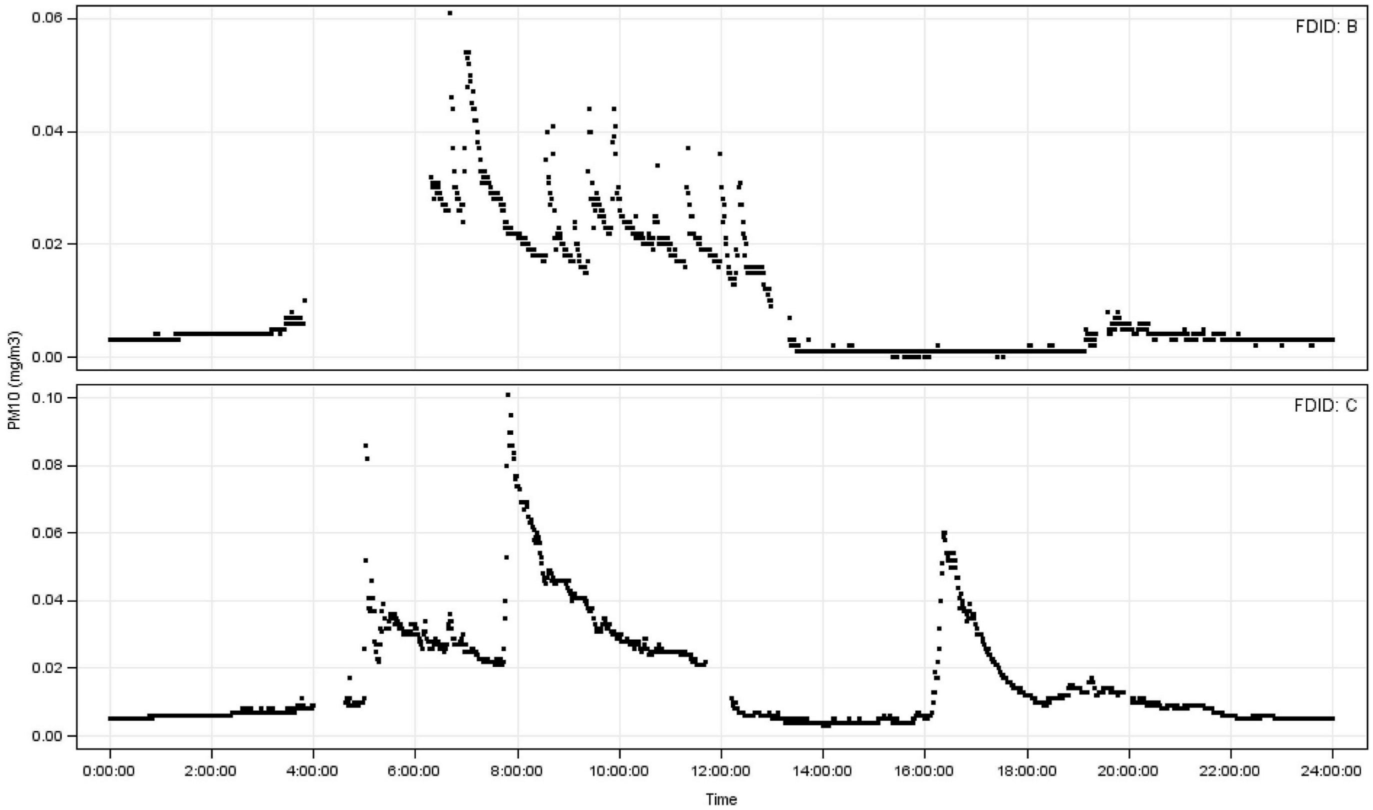

Fig. 3. Example of real-time PM10 measurements over 24 h.

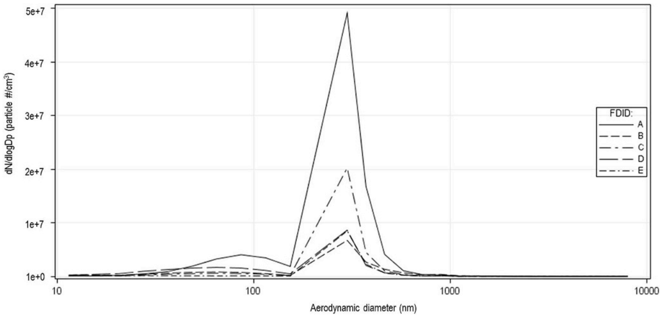

Fig. 4. Normalized particle number of concentration as a function of size-distribution by fire department.

enclosed in the dashed circle. Both R plots indicate a statistically high correlation ($p < 0.0001$) between the particle number and mass (0.782 on the left and 0.797 on the right in Fig. 5, respectively).

3.2. Industrial hygiene survey results

While the number of fire departments in this study was not large enough to establish a strong correlation between concentration level and any specific feature of a department, we examined the characteristics of each site for potential factors affecting those levels. Several of those characteristics are reported below.

3.2.1. Type of department

The fire departments with mixed personnel, career and volunteer (FDIDs A and D), exhibited higher DPM levels than the three career departments, despite their drastically lower frequency of runs (Table 1). This difference could be attributed to less manpower available for maintenance, less funding for vehicle maintenance and emissions control equipment, lower safety training standards, or older surplus apparatus. It is also worth noting that FDIDs A and D feature the greatest engine weight in the study, in terms of horsepower and displacement. The weight is due to the high number of engines at FDID A and the possession of Tanker 661, a semi-tractor unit that is one of the largest single vehicles in the study, by FDID D. Therefore, some of the elevated exposures at FDIDs A and D could be attributed to the greater weight of the equipment there rather than to any lapse in safety or maintenance standards on the part of the personnel.

3.2.2. Frequency of runs/calls

At each of the fire departments in this study, the firefighters noted that a majority of emergency calls (e.g., 77.74% at FDID B from the National Fire Incident Reporting System [NFIRS]) are rescue-, EMS-, or traffic-related. The percentage of calls that are fire-related is only 4.28%, with cooking as the leading cause. Similarly, at FDID E, 70% of calls are medically related or life threatening. As the majority of calls to a fire department are emergencies, they usually result in the deployment of rescue or squad vehicles rather than large ladder or pump trucks. At FDIDs A and D, the rescue vehicles are modified super-duty pickup trucks with diesel-powered engines, while FDIDs B, C, and E possess rescue vehicles that were modified from lighter, gasoline-powered vehicles. If rescue vehicles are the most frequently used apparatus, FDIDs A and D could more frequently use heavy diesel-powered equipment despite their much lower overall number of emergency calls.

3.2.3. Age of structural buildings and fire apparatus

The average age of the structural buildings of the five fire departments in our study is over 40 years old. Furthermore, the departments, which are not designated for modern fire apparatus, especially diesel-powered fire vehicles, have never been remodeled. Only 25% (5 out of 20) of the fire vehicles in this study were manufactured after 2010. In fact, the average age of the fire vehicles from the five fire departments ranges from 9.3 to 15 years old.

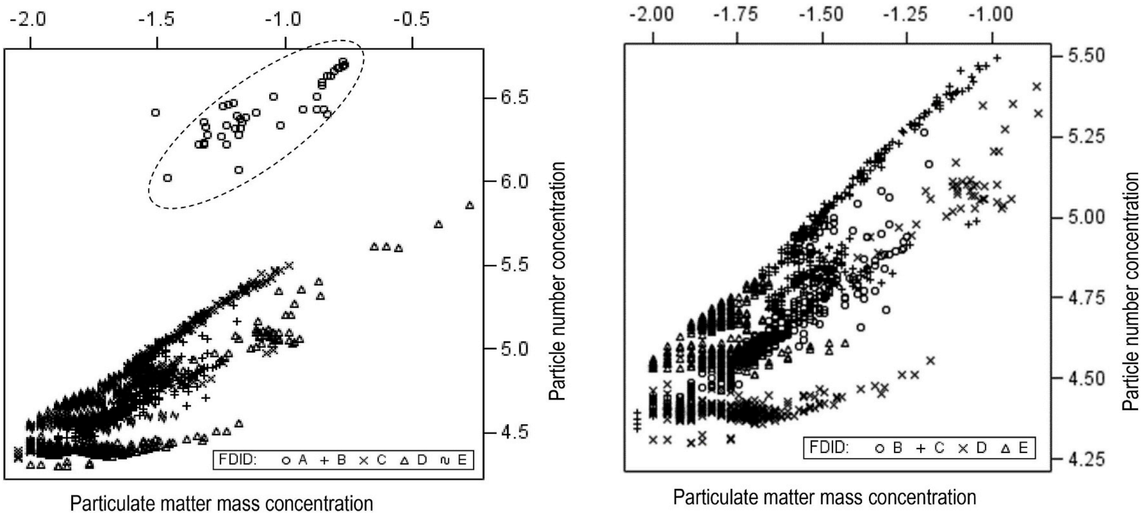

Fig. 5. Correlation between PM10 mass concentration and number concentration.

3.2.4. *Type of engine bay doors*

All engine bay garage doors were sectional operating doors that swing up. In addition, there are two types of engine bay, either pull-through or back-in. FDIDs A and D have a pull-through and the remaining FDIDs have a back-in bay (Table 1). For a back-in bay, fire trucks park in reverse so that they can respond as fast as possible to the next call. Thus, potential exposures to DPM in back-in bays are likely to be greater than pull-through bays when there are more runs, more fire vehicles, or more vehicles without exhaust systems. However, work practice seems to have a greater impact on the level of DPM than bay type. For instance, although FDID E has a back-in bay, all of the gates were open all the time, no matter whether the apparatus was idling. On the other hand, FDID A has a pull-through bay with three front and three back gates, respectively, but we observed that only one front gate and one back gate were open while the apparatus and fire vehicles were idling inside of the bay. In the rest of the fire departments, apparatus idled outside of the bay. This work practice likely causes high concentrations of DPM in FDID A. In FDID C, the main engine bay is pull-through, yet one side of the door is only used for authorized airport security personnel. As only one door is used, the pull-through design functions like a back-in bay. The annex engine bay in FDID C also has a back-in bay, which is uniquely set up (see Supplementary Fig. S3 – layout). Additionally, the physical disposition of equipment within a fire facility may be as important a factor in exposure as the type of equipment or the frequency with which it is used. For instance, FDID E operates three large diesel-powered engines, but only one of these was regularly parked inside the fire department's engine bay, while the others were parked outdoors on the grounds of the facility. In contrast, the remaining departments parked all vehicles, including diesel engines, indoors. If FDID E's vehicles are regularly kept outdoors, we would expect this fact to contribute to the low DPM levels at this facility.

3.2.5. *Exhaust removal practices/systems*

Finally, we observed that firefighters were concerned about preventing any exposure to DPM. For instance, in FDID D, the dispatchers' office was located right by the engine bay. When the door was opened, they could smell the diesel exhaust fumes from the fire vehicles, so they temporarily wrapped the door with duct tape. Similarly, in FDID B, the door to the dormitory was sealed airtight with weather stripping and purposely not used, as it directly faced the engine bay. Only one of the fire departments, FDID E, currently operated an exhaust removal system; therefore, the efficacy of such a system in reducing DPM levels is difficult to assess from this study. FDID E installed two diesel exhaust extraction systems for the engine they actively use, which may have significantly reduced the DPM levels. The system is a tailpipe exhaust hose (exhaust extractor), which acts as a local exhaust ventilation (LEV) control for diesel emissions from the truck. Two other fire departments (FDIDs B and D) had exhaust systems as well, but neither was currently operating. Furthermore, the systems were installed in different positions. In FDID B, the system was installed underneath the floor; in FDID D, the diesel exhaust system was overhead. Ultimately, the disparity in DPM levels between the sites with functioning exhaust removal systems could be contributed to a general lack of efficacy in the system functions or to the aforementioned confounding factors present at each site. In terms of general exhaust ventilation (GEV), none of the fire departments except FDID E had a ventilation system or air filter changes for diesel-powered fire vehicles. At FDID B, even though there is an exhaust fan on the back wall and an exhaust system for diesel-powered fire vehicles, it was not operating (closed) according to the chief. In fact, during the walk-through survey, the firefighters at the station could not answer questions regarding the diesel emission control systems [30], emission tests [16], or DPM exhaust systems [9].

4. Discussion

Our results quantify the concentrations of airborne DPM, which were less likely to consist of EC, as measured using the integrated instrument in selected areas of the fire departments. Concurrently, a majority of the particles were either fine or nano-sized as measured using the direct-reading instruments in the engine bay. The concentration level of EC in airborne DPM was consistent with other recent findings at fire stations [11,31]. However, the EC level was lower than that found in other industries. For instance, the hydraulic fracturing industry found higher concentrations of EC (area sample average is 16.9 $\mu g/m^3$) during oil and gas extraction operations [32]. Although not directly comparable with the PM10 particle sizes from our study, other mass-based studies have examined concentration levels of PM2.5 particle sizes in fire stations [33,34]. Their results are also consistent with our concentrations of PM10, suggesting that living quarters and kitchens may contain particles due to the layout in particular, in which the areas adjoin the engine bay.

The fire departments in small, rural communities have different challenges than those in urban cities. Although there are less frequent runs/calls, resources are often outdated and limited. Another issue regarding the age of buildings, according to Shen et al. (2015), is that building materials from the early 1970s, such as PCB-contaminated materials, were subsequently banned. Thus, the concentration levels of chemicals (e.g., brominated diphenyl ethers, BED and polychlorinated biphenyls, PCB) in the materials and the age of a building are positively correlated. Another example of outdated or limited resources is the age of fire apparatus. The Environmental Protection Agency [35] has the authority to approve modifications to emission control systems on emergency vehicles, including fire trucks, by manufacturers. Diesel exhaust fluid has been required for diesel-powered vehicles since 2010. Diesel-powered vehicles are equipped with selective catalytic reduction systems, which are formulated to meet 2010 EPA regulations by reducing nitrogen oxide (NOx) emissions from diesel exhaust into nitrogen, water, and carbon dioxide. The emissions are then vented via the tailpipe. According to NFPA 1911, although not part of the requirement, fire apparatus more than 15 years old that have been properly maintained and that are still in serviceable condition should be placed on reserve status. In addition, NFPA 1911 suggests that apparatus that were not manufactured in compliance with the applicable NFPA fire apparatus standards or that are over 25 years old should be replaced [36].

Since small, rural fire departments have a lower number of runs/calls, firefighters spend more time at the department. Our previous survey of a cohort of firefighters in small, rural cities found that the average number of hours per week they spent at the department was 57.4. During that time, they spent 10 h per week running fire apparatus, such as maintaining fire vehicles and equipment. Correspondingly, the engine bay was the area in which they spent the most time while in the fire department. Anderson et al. [37] conducted a qualitative survey in which firefighters from > 80% of the fire departments were concerned about diesel exhaust exposures from the engine bays. To address their concerns, the firefighters started fire trucks at the last moment before leaving the department. Baldwin and Thomas [38] have reported that a fan exhaust at 600 cfm per vehicle may effectively remove diesel exhaust emissions from fire trucks. However, many of the fire departments in our study did not operate the exhaust fans that were available. Furthermore, the firefighters were not aware of basic information concerning emission or exhaust systems.

4.1. Limitations of the study

There are a number of limitations and circumstantial factors to consider. Due to the limited sampling methods, either integrated or direct reading-based measurements, we were able to characterize the EC/OC/TC and particle sizes independently. Namely, the EC/OC/TC mass concentrations were measured using the time-weighted average without any size specifications (or size ranges, e.g., PM10). Simultaneously, PM10 mass concentrations do not clearly reflect the ratio of EC/OC/TC on a direct-reading instrument. An additional limitation of the sampling process was that we were only able to set up the direct reading-based measurement in the engine bay. Although our sampling strategy was developed to capture the variability between and within fire departments and areas, we did not present this finding due to the lack of statistical power resulting from the small sample size. This preliminary study serves as a snapshot of our random monitoring at each fire department. Seasonal or weather-related variability cannot be ignored as the department's complement of engines is often parked outside of the engine bay in order to clear the bay for use as a recreational and social space. Thus, levels of DPM in the bay will likely be lower due to natural ventilation. Furthermore, we did not consider any confounding factors in this study. For instance, NFPA 1500 restricts smoking inside of a fire department; however, smoking fumes from outside may drift in, especially in the engine bay when the gates are open. Also, one of the fire departments is located right beside a major road, which has heavy diesel trucks frequently passing by. Therefore, the levels of DPM are likely higher in that fire department than the others. In addition, we did not record vehicle mileage and engine hours. As this study only measured DPM levels within the fire department, we did not consider potential exposures when traveling to and from the station, but the drive may represent another source of diesel exposure [7]. Finally, a closer investigation of the properties of exhaust removal systems may be warranted in future studies.

4.2. Patterns and questions

While our monitoring methodology allows us to conclude that elevated DPM levels are a matter of concern at fire department facilities, as well as suggests questions for further study, we cannot draw any firm conclusions on the causes of the elevated levels. Any firm evidentiary recommendations are precluded by the small number of departments and the sheer number of potential confounding factors discussed above. The results do, however, suggest patterns and questions for future investigation.

Namely, firefighters in low-traffic mixed fire departments may be at an elevated risk of respiratory health issues due to exposure in the department, despite the small number of fire suppression events they experience. The efficacy of exhaust removal systems may vary, but they are not in and of themselves a solution to workplace DPM exposure for fire departments. The age of fire apparatus might not be as large a factor in workplace respiratory exposure as is often thought, given the relatively pronounced age of the engines at FDID E, where the lowest DPM levels were recorded. The use of larger commercial vehicle classes as the base for fire apparatus may be a contributing factor to elevated DPM levels. Respiratory health risks in a fire department workplace are significant and do not all originate from direct smoke/debris inhalation during fire suppression, meaning that safety countermeasures implemented during fire suppression may not be enough to curtail long-term health risk.

In order to answer these questions and produce strong evidentiary recommendations for use by fire departments, further exposure studies should be carried out to build a larger cross-section of departments within the sample set. The additional samples will elevate the statistical power of any analysis and produce a greater likelihood of useful and life-saving policy recommendations. Real-time methods, such as those employed in this study, are an optimal choice for the additional studies due to their ability to produce immediate results without extensive lab work, and their ability to operate without constant supervision or user input.

Conflicts of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.firesaf.2019.04.005.

References

[1] R.D. Daniels, S. Bertke, M.M. Dahm, J.H. Yiin, T.L. Kubale, T.R. Hales, D. Baris, S.H. Zahm, J.J. Beaumont, K.M. Waters, L.E. Pinkerton, Exposure-response relationships for select cancer and non-cancer health outcomes in a cohort of US firefighters from San Francisco, Chicago and Philadelphia (1950-2009), Occup. Environ. Med. 0 (2015) 1–8, https://doi.org/10.1136/oemed-2014-102671.

[2] R.D. Daniels, T.L. Kubale, J.H. Yiin, M.M. Dahm, T.R. Hales, D. Baris, S.H. Zahm, J.J. Beaumont, K.M. Waters, L.E. Pinkerton, Mortality and cancer incidence in a

pooled cohort of US firefighters from San Francisco, Chicago and Philadelphia (1950-2009), Occup. Environ. Med. 71 (2014) 388–397, https://doi.org/10.1136/oemed-2013-101662.

[3] R.J. Tsai, S.E. Luckhaupt, P. Schumacher, R.D. Cress, D.M. Deapen, G.M. Calvert, Risk of cancer among firefighters in California, 1988-2007, Am. J. Ind. Med. 58 (2015) 715–729, https://doi.org/10.1002/ajim.22466.

[4] B. Shen, T.P. Whitehead, S. McNeel, F.R. Brown, J. Dhaliwal, R. Das, L. Israel, J.S. Park, M. Petreas, High levels of polybrominated diphenyl ethers in vacuum cleaner dust from California fire stations, Environ. Sci. Technol. 49 (2015) 4988–4994, https://doi.org/10.1021/es505463g.

[5] M. Oliveira, K. Slezakova, M.J. Alves, A. Fernandes, J.P. Teixeira, C. Delerue-Matos, M. do C. Pereira, S. Morais, Polycyclic aromatic hydrocarbons at fire stations: firefighters' exposure monitoring and biomonitoring, and assessment of the contribution to total internal dose, J. Hazard Mater. 323 (2017) 184–194, https://doi.org/10.1016/j.jhazmat.2016.03.012.

[6] M. Oliveira, K. Slezakova, A. Fernandes, J.P. Teixeira, C. Delerue-Matos, M. do C. Pereira, S. Morais, Occupational exposure of firefighters to polycyclic aromatic hydrocarbons in non-fire work environments, Sci. Total Environ. 592 (2017) 277–287, https://doi.org/10.1016/j.scitotenv.2017.03.081.

[7] J.R. Froines, W.C. Hinds, R.M. Duffy, J. Edward, W. V Liu, Exposure of firefighters to diesel emissions in fire stations, Am. Ind. Hyg. Assoc. J. 48 (1987) 202–207, https://doi.org/10.1080/15298668791384634.

[8] A. Pronk, J. Coble, P.A. Stewart, Occupational exposure to diesel engine exhaust: a literature review, J. Expo. Sci. Environ. Epidemiol. 19 (2009) 443–457, https://doi.org/10.1038/jes.2009.21.

[9] NIOSH, Evaluation of diesel exhaust exposures at multiple fire stations in a city fire department, in: J. Couch, M.A. de Perio, K. Broadwater (Eds.), U.S. Department of Health and Human Services, Centers for Diesease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati, OH, 2016.

[10] NIOSH, NIOSH Manual of Analytical Methods (NMAM) 5040, fourth ed., NIOSH, 2016, pp. 1–5 Diesel particulate matter (as Elemental Carbon) http://www.cdc.gov/niosh/docs/2003-154/pdfs/5040.pdf.

[11] R.L. Payne, V.M. Alaves, R.R. Larson, D.K. Sleeth, An evaluation of diesel particulate matter in fire station vehicle garages and living quarters, J. Chem. Health Saf. 23 (2016) 26–31, https://doi.org/10.1016/j.jchas.2015.10.020.

[12] J.J. Sauvain, T. Vu Duc, M. Guillemin, Exposure to carcinogenic polycyclic aromatic compounds and health risk assessment for diesel-exhaust exposed workers, Int. Arch. Occup. Environ. Health 76 (2003) 443–455, https://doi.org/10.1007/s00420-003-0439-4.

[13] U.S. EPA, Health Assessment Document for Diesel Engine Exhaust, (2002) http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=29060#area.

[14] D.K. Verma, L. Shaw, J. Julian, K. Smolynec, C. Wood, D. Shaw, A comparison of sampling and analytical methods for assessing occupational exposure to diesel exhaust in a railroad work environment, Appl. Occup. Environ. Hyg 14 (1999) 701–714, https://doi.org/10.1080/104732299302332.

[15] M. Lewné, N. Plato, P. Gustavsson, Exposure to particles, elemental carbon and nitrogen dioxide in workers exposed to motor exhaust, Ann. Occup. Hyg. 51 (2007) 693–701, https://doi.org/10.1093/annhyg/mem046.

[16] G. Michalak, Diesel Emissions in Fire Stations, (2004).

[17] M. Debia, M.-C. Trachy-Bourget, C. Beaudry, E. Neesham-Grenon, S. Perron, C. Lapointe, Characterization of indoor diesel exhaust emissions from the parking garage of a school, Environ. Sci. Pollut. Res. (2016), https://doi.org/10.1007/s11356-016-8129-4.

[18] G. Ramachandran, D. Paulsen, W. Watts, D. Kittelson, Mass, surface area and number metrics in diesel occupational exposure assessment, J. Environ. Monit. 7 (2005) 728–735, https://doi.org/10.1039/b503854e.

[19] L. Benbrahim-Tallaa, R. Baan, Y. Grosse, B. Secretan-Lauby, F. El Ghissassi, V. Bouvard, N. Guha, D. Loomis, K. Straif, Carcinogenicity of diesel-engine and gasoline-engine exhausts and some Nitroarènes, Pollut. Atmos. (2012) 43–44, https://doi.org/10.1016/S1470-2045(12)70280-2.

[20] L. Kachuri, P.J. Villeneuve, M.-É. Parent, K.C. Johnson, S.A. Harris, Workplace exposure to diesel and gasoline engine exhausts and the risk of colorectal cancer in Canadian men, Environ. Health 15 (2016) 4, https://doi.org/10.1186/s12940-016-0088-1.

[21] A.J. Ghio, C.B. Smith, M.C. Madden, Diesel exhaust particles and airway inflammation, Curr. Opin. Pulm. Med. 18 (2012) 144–150, https://doi.org/10.1097/MCP.0b013e32834f0e2a.

[22] K. Yoshizaki, J. Brito, H.T. Moriya, A.C. Toledo, S. Ferzilan, A. Ligeiro de Oliveira, I.D. Machado, S. Farsky, L. Silva, M.A. Martins, P. Saldiva, T. Mauad, M. Macchione, Chronic exposure of diesel exhaust particles induces alveolar enlargement in mice, Respir. Res. 16 (2015) 18, https://doi.org/10.1186/s12931-015-0172-z.

[23] R. Vermeulen, D.T. Silverman, E. Garshick, J. Vlaanderen, L. Portengen, K. Steenland, Exposure-response estimates for diesel engine exhaust and lung cancer mortality based on data from three occupational cohorts, Environ. Health Perspect. 122 (2014) 172–177, https://doi.org/10.1289/ehp.1306880.

[24] California Department of Public Health, Hazard Evaluation System and Information Service - Diesel Engine Exhaust, (2002) Richmond, CA www.cdph.ca.gov/ohb.

[25] NFPA, National Fire Protection Association 1500, Standard on Fire Department Occupational Safety, Health, and Wellness Program, Quincy, MA, MA, 2018.

[26] R.W. Hornung, L.D. Reed, Estimation of average concentration in the presence of nondetectable values, Appl. Occup. Environ. Hyg 5 (1990) 46–51.

[27] K. Fent, B. Alexander, J. Roberts, S. Robertson, C. Toennis, D. Sammons, S. Bertke, S. Kerber, D. Smith, G. Horn, Contamination of firefighter personal protective equipment and skin and the effectiveness of decontamination procedures, J Occup Env. Hyg. Oct. 14 (2017) 801–814.

[28] International Organization for Standardization, Air Quality - Particle Size Fraction Definitions for Health-Related Sampling, ISO 7708, Geneva, Switzerland, 1995.

[29] S. Tarlo, P. Cullinan, B. Nemery, Occupational and Environmental Lung Diseases:Diseases from Work, Home, Outdoor and Other Exposures, John Wiley & Sons, Ltd., 2010.

[30] R. Avsec, Is Emission Control Disabling Fire Trucks? FireRescue1.com, 2013.

[31] R.C. Bott, K.M. Kirk, M.B. Logan, D.A. Reid, Diesel particulate matter and polycyclic aromatic hydrocarbons in fire stations, Environ. Sci. Process. Impacts. 19 (2017) 1320–1326, https://doi.org/10.1039/C7EM00291B.

[32] E.J. Esswein, M. Alexander-Scott, J. Snawder, M. Breitenstein, Measurement of area and personal breathing zone concentrations of diesel particulate matter (DPM) during oil and gas extraction operations, including hydraulic fracturing, J. Occup. Environ. Hyg. 15 (2018) 63–70, https://doi.org/10.1080/15459624.2017.1388512.

[33] E.H. Sparer, D.P. Prendergast, J.N. Apell, M.R. Bartzak, G.R. Wagner, G. Adamkiewicz, J.E. Hart, G. Sorensen, Assessment of ambient exposures firefighters encounter while at the fire station: an exploratory study, J. Occup. Environ. Med. 59 (2017) 1017–1023, https://doi.org/10.1097/JOM.0000000000001114.

[34] C.S. Baxter, J.D. Hoffman, M.J. Knipp, T. Reponen, E.N. Haynes, Exposure of firefighters to particulates and polycyclic aromatic hydrocarbons, J. Occup. Environ. Hyg. 11 (2014) D85–D91, https://doi.org/10.1080/15459624.2014.890286.

[35] EPA, Federal Register Vol. 77, No. 111, Part II Rules and Regulations, (2012).

[36] NFPA, National Fire Protection Association 1911, Standard for the Inspection, Maintenance, Testing, and Retirement of In-Service Emergency Vehicles, (2017) Quincy, MA.

[37] D.A. Anderson, T.R. Harrison, F. Yang, J. Wendorf Muhamad, S.E. Morgan, Firefighter perceptions of cancer risk: results of a qualitative study, Am. J. Ind. Med. 60 (2017) 644–650, https://doi.org/10.1002/ajim.22726.

[38] B.Y.T.N. Baldwin, R. Thomas, Controlling Diesel Exhaust Exposure inside Firehouses, FireEngineering.com, 2011.

Hwang, J., Taylor, R., Cann, M.C., Golla, V., and Gilbert, W. (2019). Ambient Air Diesel Particulates in Fire Departments Using Different Exposure Metrics: Pilot Study. Fire Safety Journal, FISJ_2807 Supplemental Materials

Supplemental Layouts: Assessment of Ambient Air Diesel Particulates in Fire Departments Using Different Exposure Metrics: Pilot Study

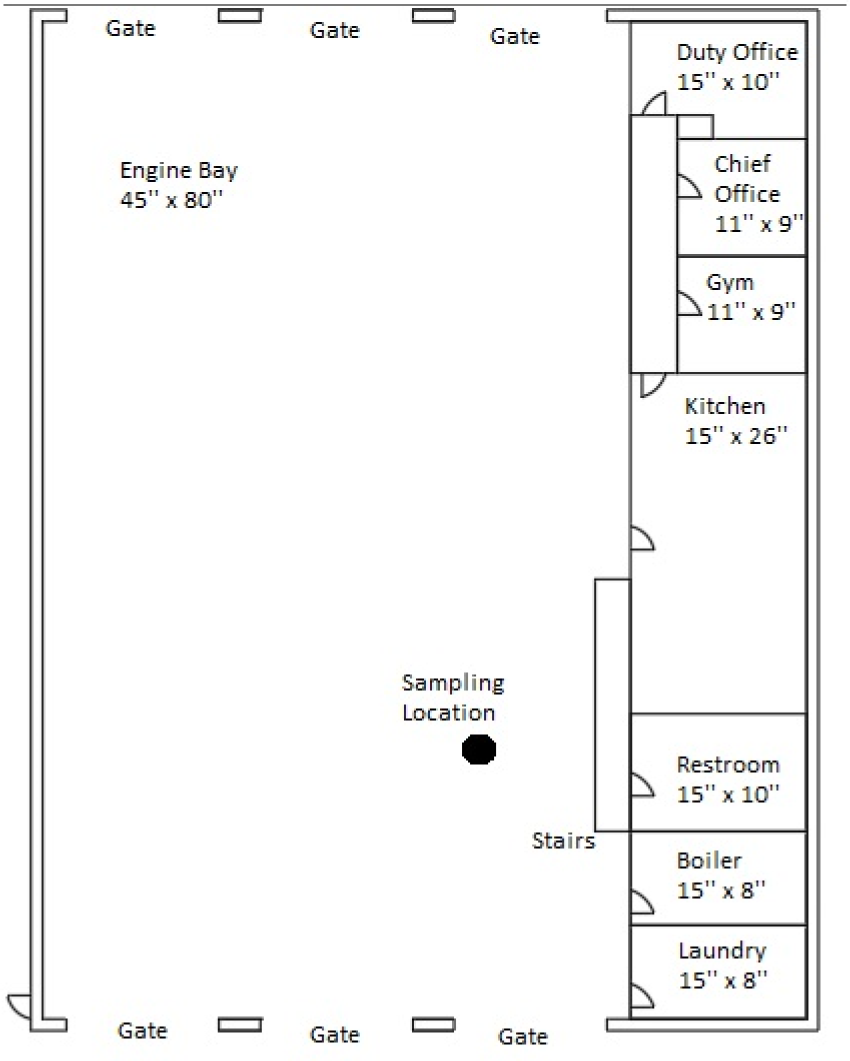
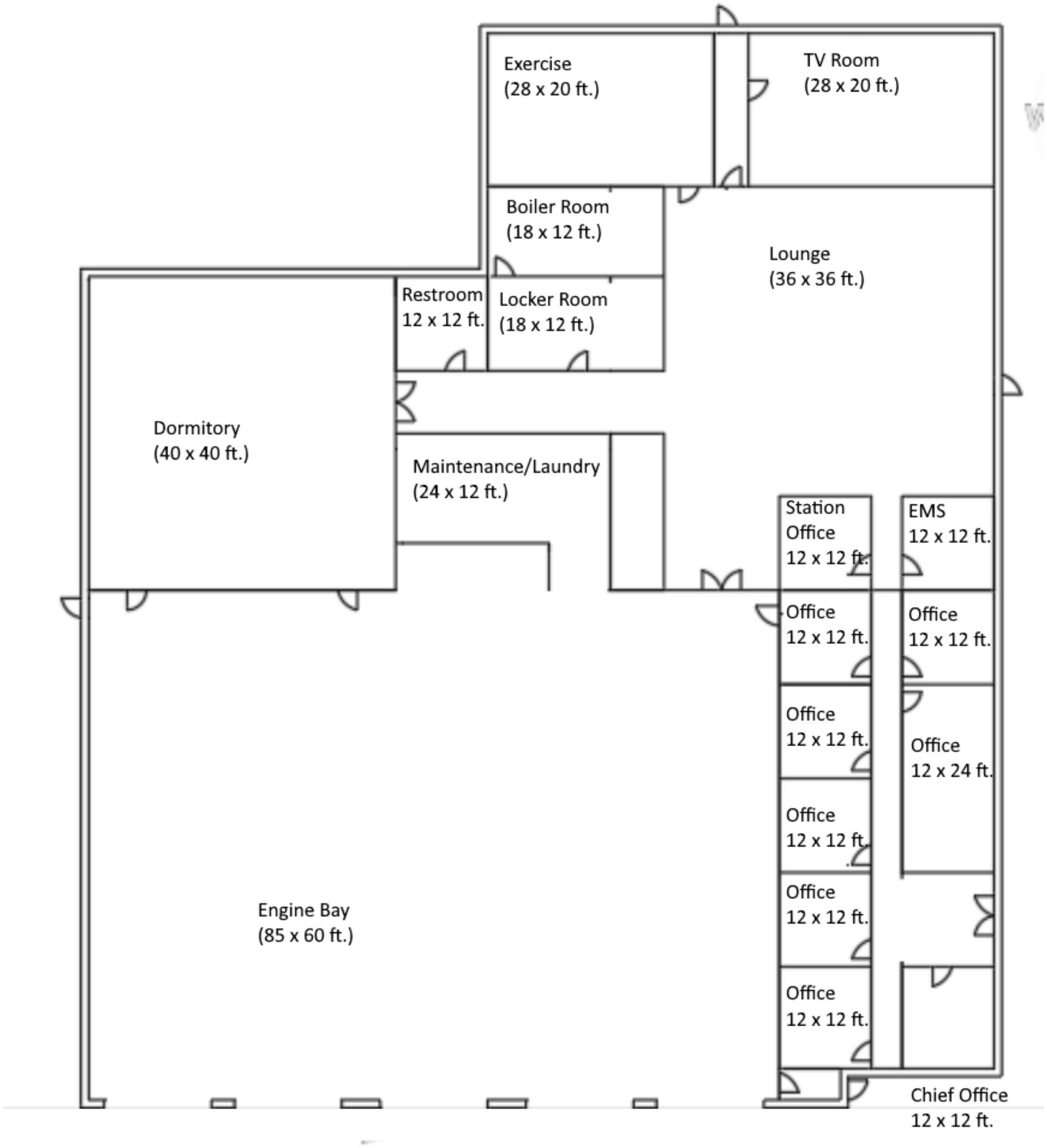


Figure S1. Fire department A



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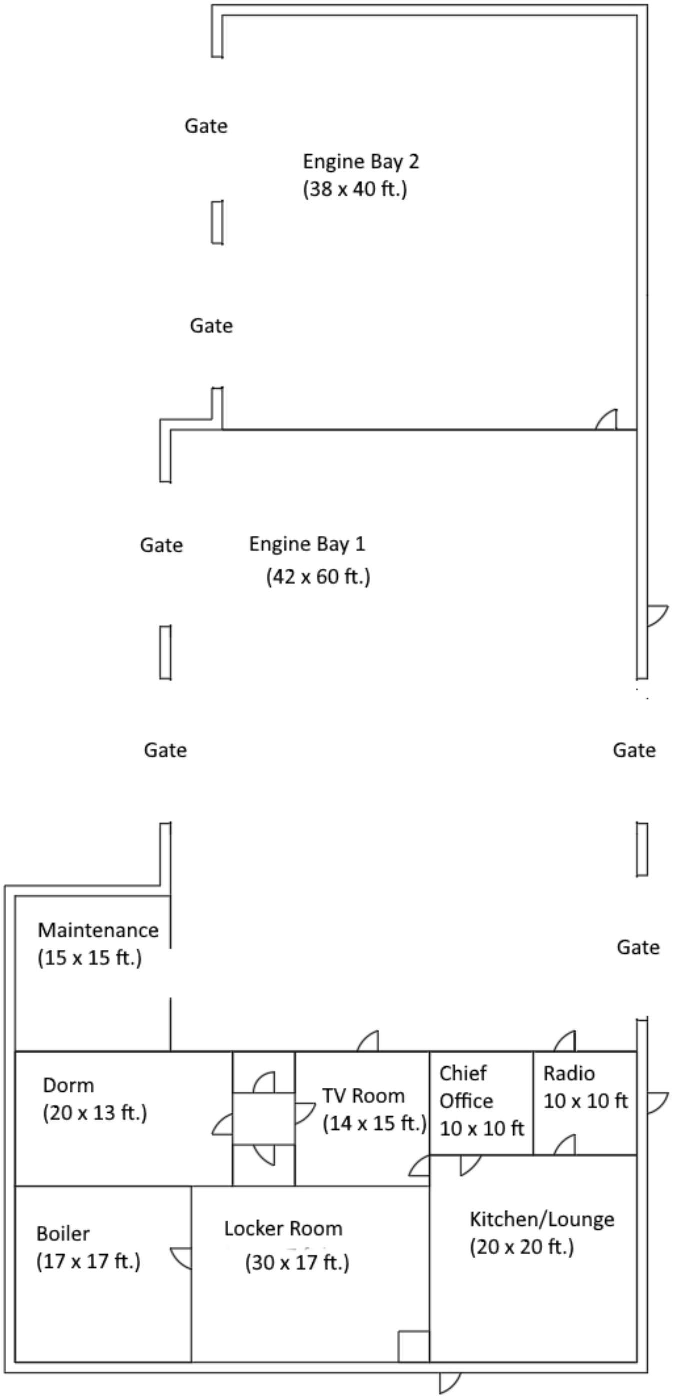

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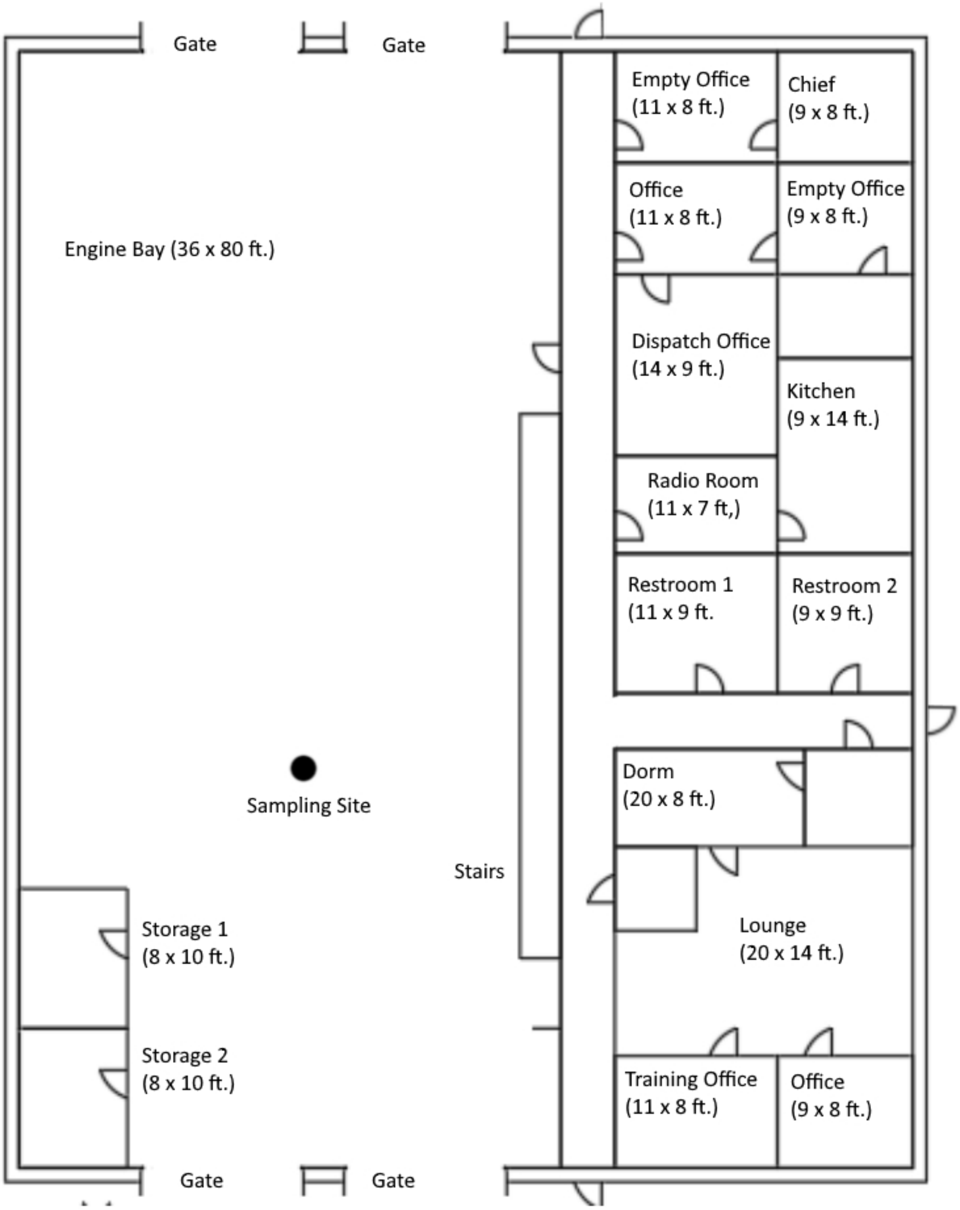

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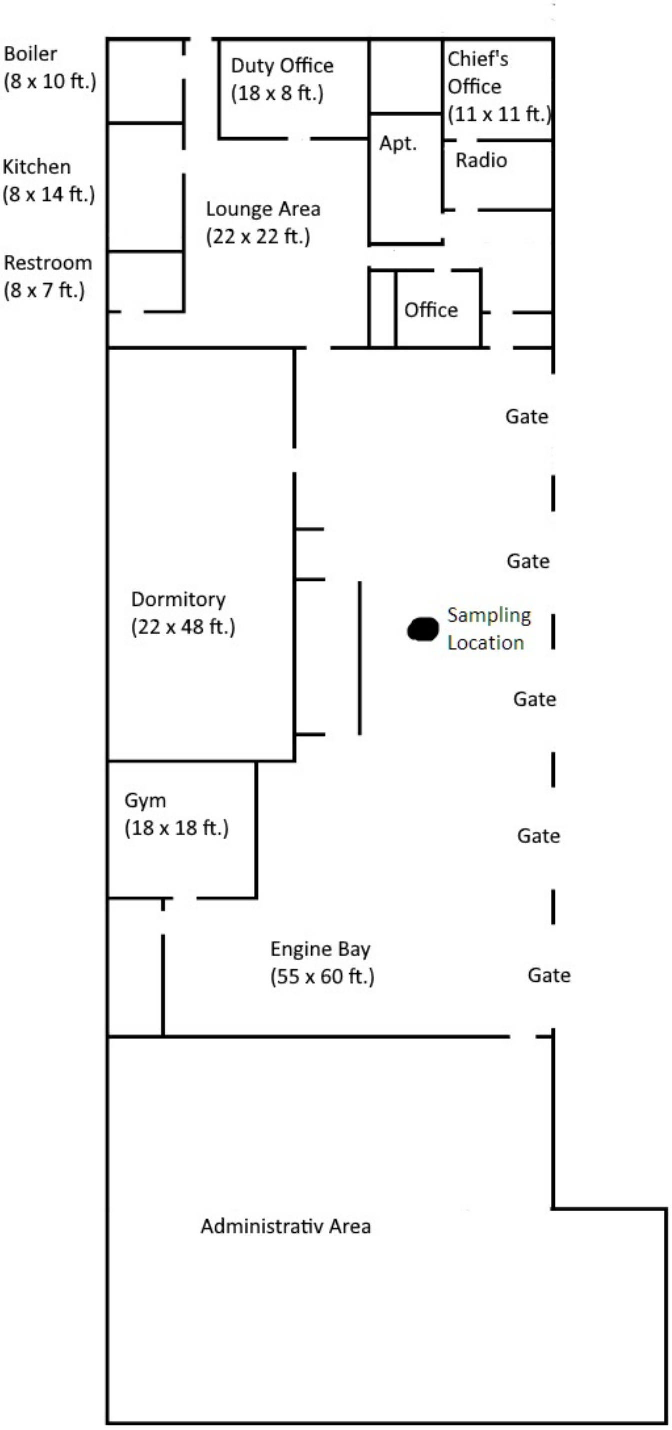

Figure S5. Fire department E