



Evaluation of combustion products in air from electric and internal combustion engine vehicles during full-scale fire experiments

Richard M. Kesler^{a,ib,*}, Nathaniel Sauer^a, Adam Barowy^a, Chandler Probert^a, Danielle L. Neumann^b, Alexander C. Mayer^c, Micah Niemeier-Walsh^c, Kenneth W. Fent^c, Heather M. Stapleton^d, Gavin P. Horn^a

^a Fire Safety Research Institute, UL Research Institutes, Columbia, MD, 21045, USA

^b Enterprise Sustainability, UL Solutions, Brea, CA, 92821, USA

^c Division of Field Studies and Engineering, National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention, Cincinnati, OH, 45226, USA

^d Nicholas School of Environment, Duke University, Durham, NC, 27708, USA

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ABSTRACT

The combustion of vehicles generates fire effluent that may contain compounds that pose unique health hazards. This study evaluated the composition of products of combustion that may present chronic health concerns from electric vehicles (EVs) and internal combustion engine vehicles (ICEVs). Six EVs and three ICEVs were ignited with a 30 kW burner and allowed to burn until all combustible components of the entire vehicle were consumed. Active and passive air samplers were deployed 3.0 m in front of and 4.5 m behind the vehicle's bumpers, and in the smoke plume 8.7 m above the vehicle. Combustion gases were sampled for volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), heavy metals, acid gases, per- and polyfluoroalkyl substances (PFAS), and inhalable particulates. EVs and ICEVs burned for similar durations, though EVs took longer to initially catch fire with this particular ignition method. Acid gases, VOCs, PFAS, PAHs, and inhalable particulates in the smoke showed minor differences between the vehicle types, though fluoride particulate was notably greater in the EV fires. Greater amounts of heavy metals (specifically nickel, manganese, cobalt, and lithium) were detected in the EV fire effluent relative to the ICEVs. Both EV and ICEV fires produce combustion products that could present health hazards to responders or bystanders.

1. Introduction

The health hazards associated with electric vehicle (EV) fires, including the airborne chemical contamination produced by the combustion of lithium-ion (Li-ion) batteries, are not well understood. Previous research has examined the chemical hazards associated with the combustion of internal combustion engine vehicles (ICEV) [1] and characterized the products of combustion associated with Li-ion batteries alone [2]. A limited number of experiments have examined Li-ion EVs in a controlled laboratory environment [3], thus further investigation is necessary. The prevalence of EVs has increased dramatically over the last several years. In 2021, EVs accounted for 9% of new vehicle sales globally and in 2022 that increased to 14%. In 2022, the number of EVs on the road surpassed 26 million [4]. It has been estimated that by 2035, EVs will represent 10%–42% of vehicles on the road in the United States [5].

It has been well documented that exposure to products of combustion presents a carcinogenic hazard for firefighters. In 2022, the International Agency for Research on Cancer (IARC) classified the occupation of firefighting as a Group 1 carcinogen, indicating that it is “carcinogenic to humans” based on sufficient evidence of bladder cancer and mesothelioma in firefighters [6]. Firefighters’ exposures to carcinogens may include sources such as building materials, chemicals in fire suppression agents, flame retardants, diesel exhaust, and products of combustion [6].

A robust and growing body of literature has focused on products of combustion from structural firefighting [7–10] and training fires [11–15]. Concentrations of polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) are often reported in these studies and compared to occupational exposure limits to characterize firefighters’ exposures. Previous studies have deployed active air samplers [9,

* Corresponding author.

E-mail address: richard.kesler@ul.org (R.M. Kesler).

URL: <https://fsri.org> (R.M. Kesler).

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12,16,17], while others have utilized passive silicone wristbands [18–20] or dog-tag style samplers [21], to collect air contamination measurements in fire service populations. Regardless of the sample collection method, these studies consistently report firefighter exposures that exceed applicable occupational exposure limits.

There is substantially less research focused on the products of combustion from ICEV fires and even less data related to EV fires. Teixeira et al. [1] provided a review of studies that have examined the products of combustion emitted from vehicle fires [22–25] and measured firefighters' exposures when responding to these fires [26–30]. Previous research has characterized the temperatures and combustion gases in the interior of ICEVs during a fire to understand the risk to a passenger [22]. They found that firefighters may be exposed to several contaminants including particulate matter, carbon monoxide, VOCs, and PAHs during ICEV fires. Lönnemark and Blomqvist [23] quantified airborne compounds generated during full-scale vehicle burns and analyzed run-off water post fire suppression. They found that air contained VOCs, PAHs, acid gases, polychlorinated dibenzo-p-dioxins (PCDDs), and dibenzofurans (PCDFs), while run-off water contained several organic compounds and metals.

Fent et al. completed a National Institute for Occupational Safety and Health (NIOSH) Health Hazard Evaluation [31], and published their study results [26] on whole gas (VOCs) and personal air (PAHs, aldehydes, isocyanates, carbon monoxide (CO)) samples during the suppression of ICEV fires. The predicted 95th percentile of the personal breathing zone exposure distributions from this study were above short-term exposure limits for formaldehyde and acrolein [26]. Some studies have also analyzed particulate emissions from vehicle fires and found that particulate concentrations may exceed background levels by several orders of magnitude [27–29]. Caban-Martinez et al. [30] utilized multi-gas meters during real-world responses to vehicles (and other fires) and reported elevated personal air concentrations of VOCs and other gases.

Premnath et al. [2] examined the particle emission from batteries using four lithium iron phosphate and one nickel manganese cobalt oxide modules. Thermal runaway was initiated by nail-penetration and over-charging. They found that resulting hydrogen fluoride (HF) and formaldehyde emissions exceeded immediately dangerous to life or health (IDLH) limits after over-charging and combusting. Additional research by Premnath et al. [32] evaluated particulate emissions from battery cells in thermal runaway at different states of charge (SOC). They found high levels of particle emissions after single-cell failures, with the highest levels of emissions at higher SOC.

Few research efforts have examined the combustion products of full scale electric vehicle fires. Hynynen et al. [3] examined three EVs, two ICEVs, and a single EV with the battery system removed. They found elevated concentrations of HF, nickel, cobalt, lithium, and manganese during EV fires relative to what was released during ICEV fires. Further research has examined differences between ICEV and EV fires and found elevated HF emissions [33]. Szmytko et al. [34] placed firefighting protective turnout gear near a car battery in a steel container and reported that the surface accumulation of PAHs, formaldehyde, lithium, cobalt, and several other compounds were above their detection limits. Overall, a comprehensive exposure assessment is needed to evaluate the combustion byproducts released during EV and ICEV fires. This information may be used by firefighters and other emergency responders so they can make informed decisions about the use of personal protective equipment (PPE) during fire incidents involving these vehicles.

This study sought to examine the composition and magnitude of chemical contaminants with known chronic human health concerns produced during vehicle fires. Specifically, the objective of this study was to characterize the airborne chemicals produced during EV fires and provide context by comparing these contaminants to those produced during ICEV fires. It was hypothesized that fires in EVs would produce amounts of heavy metals (e.g. lithium, cobalt, magnesium, nickel) and acid gases (especially HF) greater than what would be released during ICEV fires, though it was expected that both types of vehicles would produce high levels of airborne chemical contaminants that may have human health and environmental impacts.

2. Methods

Full-scale experiments involving both EVs and ICEVs were completed at an indoor large-fire laboratory. This manuscript focuses on the characterization of health hazard related products of combustion and air contamination in both the vapor and particulate phase, using both active and passive sampling methodologies. The data reported here are part of a larger study examining vehicle fires. The thermal characterization of the fires will be reported elsewhere.

Vehicles were positioned near the center of the lab, which measured approximately 33 m by 33 m. The fire lab contains a movable ceiling, which was positioned 9.1 m above ground level (volume of 9,900 m³). The vehicles were placed inside of a metal pan, that was situated on a large metal frame. The platform raised the vehicle approximately 39 cm above the lab floor. Plate sensor arrays, utilized for characterizing heat transfer from the fire, were placed on the driver and passenger side of the vehicle, approximately 2.7 m from the center line [35]. A large welding curtain was placed above the vehicle, 15 cm below the ceiling, to gather combustion products for sampling (Fig. 1). Fire effluent traveled from the vehicle, up within the welding curtain, reached the movable ceiling and spread along the movable ceiling. Effluent moved around the edges of the movable ceiling, then was removed from the lab via exhaust ducting in the center of the room at a rate of 28.3 m³/s throughout the experiments. All effluent passed through a regenerative thermal oxidizer prior to release to the environment. Two burner designs were used for vehicle ignition. A premixed burner was used for ICEV2 and ICEV3 while all other vehicles were ignited using a 30 cm by 30 cm by 8 cm tall diffusion style propane burner. The burner was placed under the battery in the EVs and under the engine bay on the ICEVs, representing a common location for a fire to start in the respective vehicle types. EV6 was an exception, where the burner was placed under the front of the vehicle. Gas flow to the burner was regulated to produce an output of 30 kW. The burner was shut off when flaming of the vehicle was observed indicating the fire had transitioned to the vehicle. For the first EV experiment (EV1), the burner output was increased after 60 min by 5 kW every 5 min until reaching a maximum output of 45 kW.

2.1. Vehicle descriptions

In total, nine vehicle experiments were conducted on commercially-available vehicles purchased by the Fire Safety Research Institute (FSRI), part of UL Research Institutes. The selected vehicles represent a multi-manufacturer cross-section of some of the most popular ICEVs and EVs in use in the United States. The vehicles range in class from compact to mid-size. Vehicles were filled with gasoline or charged to maximum capacity. The windows in each car were set to their lowest positions and vehicles turned to the "ON" position prior to the experiment starting. Gasoline engines were off. Coolant was removed from the traction battery packs of EVs with bottom-cooled battery packs (EV5 and EV6) after observations from the EV1 experiment that this battery pack construction significantly interfered with initiating thermal runaway with a burner. Removed coolant was placed in a pan beneath the vehicle for inclusion in the fire to account for its combustion contributions. All other vehicle systems and components remained intact. Full specifications including the year, curb weight, and fuel or battery capacity are noted in Table 1. Laboratory conditions were controlled throughout the tests, and tests were conducted in blocks. An initial ICEV vehicle was tested (ICEV1), followed by six EVs (EV1–EV6), then the final two ICEVs (ICEV2 and ICEV3). All test apparatus and the immediate lab area were cleaned before each block and between each test.



Fig. 1. Top: Overview of the experiment setup. Sampling stations were located in front of the vehicle, behind the vehicle, and above the vehicle near the ceiling. Left, bottom: exposure sampling boxes with personal air pumps where sampling media were connected to ceramic ports that extended 1.5 cm outside of the sampling box. Center, bottom: Test stands were positioned 3.0 m from the front bumper (as shown) and 4.5 m from the rear bumper of the vehicle (not visible). Right, bottom: Passive silicone samplers were placed at each sampling position.

Table 1

Specifications of internal combustion engine and electric vehicles utilized in testing.

Designation	Year	Curb weight (kg)	Battery pack charge (kWh) or fuel capacity (L)
EV1	2021	1631	65 kWh
EV2	2019	1595	40 kWh
EV3	2019	1448	28 kWh
EV4	2022	1825	82 kWh
EV5	2022	2256	91 kWh
EV6 ^a	2020	1689	65 kWh
ICEV1 ^a	2020	1318	50 L (Gasoline)
ICEV2 ^a	2020	1318	50 L (Gasoline)
ICEV3	2019	1536	55 L (Gasoline)

^a EV6, ICEV1, and ICEV2 were the same make and model of vehicles but with different propulsion systems.

2.2. Sampling methods

This study utilized two distinct methodologies to evaluate health hazard related products of combustion from vehicle fires that were present in the air, including (1) active sampling with area air sampling pumps for gas, vapor, and/or particulate characterization, and (2) passive sampling with silicone samplers. Field blanks were collected and handled in the same manner as all other samples, and all blank samples were below the respective minimum detection limit. Additional data collected included the time to events during the fire development, notably the time from ignition of the gas burner to (1) the first visible smoke from the vehicle, (2) the first visible flame from the vehicle, and (3) the conclusion of flaming combustion.

Sampling occurred at three locations around the vehicle. Two positions represented the approximate location and breathing height of a typical person relative to the vehicle (Fig. 1). There were no firefighting interventions or suppression operations in these experiments; thus, these positions were chosen to serve as a representative baseline for characterization of potential contamination levels for first responders operating near the vehicle. Sampling stations were positioned 3.0 m from the front bumper and 4.5 m from the rear bumper of the vehicle, aligned with the vehicle's longitudinal plane. Passive samplers were located 1.4 m above the base of the vehicle. Active samplers were located 1.3 m above the base of the vehicle. The third location was above the front of the vehicle, 30 cm outside of the smoke curtain, 31 cm below the ceiling of the fire lab (8.7 m above the base of the vehicle) to sample from the smoke plume as the effluent traversed the movable ceiling, while keeping the sampling equipment protected from radiant heat and elevated temperatures.

2.2.1. Active sampling - Gas and particulate characterization

Area air samples were collected with battery powered sampling pumps to allow for characterization of several products of combustion with known health concerns. These same methods and protocols have been used by Fent et al. [13,26,36] and Horn et al. [15,17], which enables more straightforward comparison to exposure conditions that may be experienced on the residential fireground and in live-fire training scenarios. Area gas sampling methodologies, including the sampling media, flow rates, and the analytical method utilized for analysis are presented in Table 2. Combustion products were analyzed for VOCs, aldehydes, acid gases, and metals. VOCs targeted in this study included benzene, toluene, ethyl benzene, xylenes, and styrene (BTEXS) and 1,3 butadiene. IARC classifies benzene and 1,3-butadiene as carcinogenic to humans (Group 1) and styrene as probably carcinogenic to humans (Group 2A). Specific aldehydes included acetaldehyde, acrolein (Group 2A), and formaldehyde (Group 1) which can also produce pulmonary and cardiovascular effects. Acid gases included sulfur dioxide (SO₂), hydrogen cyanide (HCN), hydrogen chloride (HCl), and hydrogen fluoride (HF). Particulate fluoride was also analyzed as there is significant concern in the fire service about fluoride compounds, specifically related to EV fires. Metal analysis was targeted for chromium, cobalt (Group 2A), copper, lead (Group 2B), lithium, manganese, aluminum, nickel (Group 2B), antimony, arsenic (Group 1), and cadmium (Group 1). Combustion gases were also analyzed for PAHs (IARC Classifications are noted in Supplemental Table A.6). PAH sampling data reported here only include those samples from the ground level as the PAH pumps in the plume faulted due to sample overloading resulting in low reliability of the plume data.

Sampling media were located in test stands 3.0 m in front of the car and 4.5 m behind the rear of the car, as well as near the ceiling above the vehicle. Sampling pumps were situated within a steel enclosure, with shielding and insulation protecting the enclosure from elevated temperatures and radiant heat during the experiment. Silicone tubing connected the pumps and media directly to 7.5 cm ceramic tubing which was ported through the enclosure. Sampler inlet tubing was parallel to the ground so that the openings were facing the vehicle at

the 3.0 m and 4.5 m locations (Fig. 1). Sampler inlet tubing was vertical in the plume such that the openings were facing the ceiling so that they could sample from the plume as effluent flowed along the movable ceiling. Sampling pumps (GilAir-Plus, Sensidyne, St Petersburg, FL) were calibrated to within 5% of the target flow rate outlined in Table 2. All post-fire calibration of the pumps resulted in variations less than 5% of the pre-experiment flow rate except for 4 of 243 pumps (all in the plume) that differed by 5%–10% of the pre-experiment value. All media were stored pre- and post-sampling following the analytical method described in Table 2. Samples were stored on-site in a refrigerator or freezer and shipped on ice to an analytical laboratory under chain of custody. All sampling media and tubing were thoroughly cleaned between tests.

Stainless steel Institute of Occupational Medicine (IOM) samplers (SKC 225-76A, Eighty Four, PA, USA) connected to SKC XR5000 pumps, operated at 2 L/min, were deployed at each sampling area to measure inhalable particulate up to 100 µm in aerodynamic diameter. IOM samplers were oriented vertically such that the opening was perpendicular to the ground and deployed at 116 cm above the base of the vehicle, 3.0 m from the front of the vehicle and 4.5 m from the rear of the vehicle, and were placed in the plume above the vehicle. The IOM samplers were fitted with 25 mm quartz fiber filters (SKC 225-1825, Eighty Four, PA, USA). Generally, polytetrafluoroethylene (PTFE) or polyvinyl chloride (PVC) sampling media are preferred for this type of sampling; however, quartz fiber was selected because the elevated temperatures (above 200 °C) would not allow use of the traditional media for these analyses. Samples were analyzed gravimetrically using NIOSH Method 0500.

2.2.2. Passive sampling - Silicone samplers

Passive sampling was performed utilizing commercially available silicone wristband samplers (24hourwristbands.com, Houston, TX, USA). Silicone samplers have been used in numerous other studies examining chemical exposure in fireground environments due to their simplicity and ease of deployment [19–21,37,38].

The silicone samplers were pre-cleaned following standard practices as used in previous studies [39], then placed in an airtight metal tin and sealed in a protective pouch until field deployment. At the time of deployment, immediately prior to ignition of the vehicle, silicone samplers were secured to the test stand using steel wire and positioned such that the sampler avoided any contact with the stand (Fig. 1). Following the experiment, silicone samplers were collected and returned to the airtight tin, and then sealed in the pouch. Samplers were stored in a refrigerator after the experiment, then shipped on ice to the research laboratory at Duke University. Once at the laboratory, they were stored at −20 °C until analysis. Field blanks (undeployed samplers) were shipped back and forth with the samples for quality assurance and quality control purposes.

Extraction of target analytes followed previously published methodologies [39–42]. Samplers were sectioned into two ~0.7 g segments. One segment was spiked with isotopically labeled internal standards and extracted with 50:50 hexane:acetone for semi-volatile organic compound measurements. The second piece was spiked with isotopically labeled standards and extracted using methanol for per- and polyfluoroalkyl substances quantification. Extracts were concentrated with purified nitrogen. The hexane-acetone extracts were concentrated and brought back up in 1.0 mL of hexane and a second set of isotopically-labeled standards were added prior to analysis via gas chromatography-high resolution mass spectrometry (GC-HRMS) for PAHs. The methanol extract was concentrated to 0.5 mL and then 0.5 mL of LC-MS grade water was added, along with isotopically-labeled recovery standards, prior to analysis via liquid chromatography-tandem mass spectrometry (LC-MS/MS) for a suite of 37 different PFASs using the method reported in Proctor et al. [42]. Specific focus was placed on the 16 PAHs designated as High Priority Pollutants by the US Environmental Protection Agency (EPA) [43]. The 16 priority PAHs,

Table 2
Area gas sample collection and analysis methods.

Compound	Sampling media	Flow rate (L/min)	Analytical method
BTEXS	SKC 226-01	0.2	NIOSH 1501
Aldehydes	SKC 226-117	0.1	OSHA 52/OSHA 68
Metals	Mixed Cellulose Esters Membrane (MCE)	2.5	NIOSH 7303
SO ₂	SKC 225-9005	1.5	NIOSH 6004
HCN	SKC 225-710 & SKC 226-210	0.2	NIOSH 6010
HF	SKC 225-9031	2.0	NIOSH 7903 ^a
HCl	SKC 225-9032	0.2	NIOSH 7907
1,3-Butadiene	SKC 226-09	0.25	NIOSH 1024
PAHs	SKC 226-57	1.0	NIOSH 5528

^a Results were reported as the mass of hydrogen fluoride (HF) and fluoride particulate (F⁻).

their molecular mass, and IARC classification are listed in Supplemental Table A.6. In the protocol employed in this study benzo[b]fluoranthene, benzo[k]fluoranthene, and benzo[j]fluoranthene (which is not listed as a priority PAH) are reported as a single value for benzo[j,b,k]fluoranthene due to their co-elution in the GC-HRMS method. Total mass of PAHs (in ng/g of silicone material) were reported as the sum of the 16 PAHs, including the three benzo[j,b,k]fluoranthene isomers. The total mass of benzo[a]pyrene, an IARC Group 1 known carcinogen, is also reported.

For PAHs, chemical masses collected on the silicone samplers were used to estimate the air concentrations based on chemical uptake rates (R_s) reported in [44], to allow for comparison between active and passive sampling methodologies (Eq. (1)). Samplers had an average mass (M_{sampler}) of 4.48 ± 0.08 g and surface area (A_{sampler}) of 0.48 dm^2 . Time (T) was recorded as the time between ignition of the propane burner and the collection of the sampler at the conclusion of flaming combustion. The benzo[a]pyrene relative toxicity equivalence (BaP_{TEQ}) was computed by multiplying the calculated air concentration values by scaling factors based on the relative toxicity of each compound as described by Nisbet and LaGoy [45] (Eq. (2)).

$$C_{\text{air}} = \frac{C_{\text{sampler}} * M_{\text{sampler}}}{R_s * A_{\text{sampler}} * T} \quad (1)$$

$$\begin{aligned} BaP_{\text{TEQ}} = & 0.001 * ([Ace] + [Acy] + [Fla] + [Fl] + [Nap] + [Ph] + [Py]) \\ & + 0.01 * ([An] + [Ch] + [BghiP]) \\ & + 0.1 * ([BaA] + [BbF] + [BkF] + [IP]) \\ & + 1 * [BaP] \\ & + 5 * [DBA] \end{aligned} \quad (2)$$

PFAS analysis targeted 37 different PFASs. The majority of PFASs were below the minimum detection limit across all samples and locations, so data are only reported for perfluoropropionic acid (PFPrA) and trifluoroacetic acid (TFA) which were consistently above the minimum detection limit. PFPrA and TFA are reported as the mass collected per gram of sampler, as sampling rates are not validated for these short chain PFASs.

2.3. Analysis

For both active and passive sampling, some compounds were not detected above the minimum detection limit in several samples. In cases where a compound was frequently detected, the value of the minimum detection limit divided by the square root of two was used for censored data in figures [46]. Sampling time varied between the methodologies due to the time needed to stop pump sampling and collect the silicone samplers. Pumps were turned on and samplers were deployed just prior to ignition. Calculations of concentrations are based on the time from ignition of the burner until the pump was turned off or the sampler was collected. These times and the volumes collected are reported in the results for each compound. Due to the small number of tests for each condition (six EV fires and three ICEV fires), statistical

significance between the vehicle types was assessed using the non-parametric Mann-Whitney U test. The threshold for significance was set at $p = 0.05$. Statistical significance is noted when there were significant differences between the EV fires and ICEV fires. Throughout the results, the data are presented as the median and range by vehicle type and sampling location.

3. Results and discussion

3.1. Study timing

Nine vehicles were burned until flaming combustion had ceased and nearly all combustible materials were consumed. Fire development progressed similarly in each of the nine vehicles. Smoke typically developed from pyrolysis of the vehicle's undercarriage within several minutes of ignition of the burner (first smoke). The median time to first visible smoke was 0.7 min for the ICEVs and 2.3 min for the EVs. Median times to the first visible flames on the vehicles were 1.4 min for ICEVs and 37.0 min for the EVs. Median times from the initial flaming of the vehicles to the conclusion of flaming combustion were 69.8 min for the ICEVs and 65.5 min for the EVs (Table 3), though one experiment (ICEV1) was terminated while some localized smoldering was still present, and one experiment (EV4) was briefly cooled with water 34 min after thermal runaway started to control smoke, as the building's exhaust was being overwhelmed. Cooling was stopped after three minutes though flaming combustion continued.

Total experiment duration ranged from a median of 71.2 min in the ICEVs to 99.3 min in the EVs. The longer durations in the EVs were due to the longer time required to initiate flaming combustion of the vehicle. In the EVs, the ignition burner was placed under the battery case, the bottom of which was typically constructed of non-combustible materials. The thermal energy from the burner heated the protective case until the batteries were driven to thermal runaway, or until the battery case absorbed enough thermal energy that the nearby vehicle components ignited. In the ICEVs, the burner was placed under the engine bay, where rubber and plastic components ignited more quickly than the non-combustible battery case. When the time from first flame to conclusion of flaming combustion is considered, the time was consistent between vehicle types (69.8 min for the ICEVs and 65.5 min for the EVs).

Active and passive sampling times varied based on fire development and smoke conditions. Ignition of the gas burner was used as the start time for all sampling. Both active and passive samplers were turned off or removed from the environment as soon as combustion had concluded. The duration of data collection between ignition and pump off time (for active sampling) and ignition to sampler removal time (for passive sampling) are included in Supplemental Table A.7. The median time from ignition to pump off was 77.0 min for ICEVs and 112.0 min for EVs. Silicone sampler deployment times were slightly longer with median times of 83.0 min for ICEVs and 119.0 min for EVs. While the production of smoke from the vehicle typically began within 3 min of burner ignition, the intensity of smoke production increased dramatically after first flame. As such, the longer time between first smoke and first flame for the EV vehicles may have resulted in an underestimation of the potential exposure hazard relative to the ICEVs.

Table 3

Event timing for each experiment. Time is reported as the time from ignition of the gas burner under the vehicle to the first indication of (1) smoke, (2) flaming, and (3) the end of flaming combustion before the experiment was terminated. Time from first flame to end of flaming combustion is also reported.

Vehicle	Ignition to first smoke (mins)	Ignition to first flame (mins)	Ignition to end of flaming combustion (mins)	First flame to end of flaming combustion (mins)
ICEV1	1.0	3.5	50 ^a	46.5 ^a
ICEV2	0.7	1.4	71.2	69.8
ICEV3	0.3	0.8	72.2	71.4
EV1	3.2	76.0	154.5	78.5
EV2	11.1	12.8	65.8	53.0
EV3	1.9	33.7	95.0	61.3
EV4	2.6	40.3	103.5 ^b	63.2 ^b
EV5	1.6	42.7	121.9	79.2
EV6	0.3	1.2	68.9	67.7

^a Experiment was terminated while localized smoldering was ongoing, prior to end of flaming combustion.

^b Cooling water was applied between 34 and 37 min after thermal runaway, though flaming combustion continued.

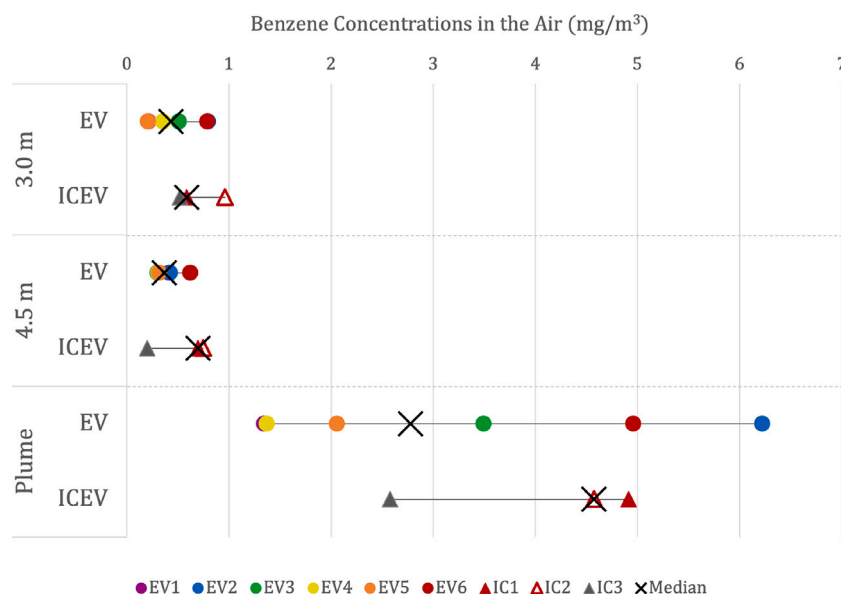


Fig. 2. Benzene concentrations in the air (mg/m^3) during electric vehicle (EV, $N = 6$) and internal combustion engine vehicle (ICEV, $N = 3$) fire experiments. X represents the median of each group, while bars extend to the minimum and maximum values. Censored data were imputed values as described in the methods. Markers of the same color (red) represent vehicles of the same model across propulsion systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Active sampling

3.2.1. VOCs and aldehydes

Gases were sampled for VOCs (i.e., benzene, toluene, ethylbenzene, xylenes, styrene, 1,3-butadiene, and aldehydes) at each sampling location. Concentrations of each compound are presented in Supplemental Table A.8. Ethylbenzene was detected in several EV samples across the three locations, but all ICEV samples were below the detection limit. Styrene and xylenes were detected in less than 10% of samples (detection limit $1.4 \mu\text{g}$) and thus are not reported. Styrene was only detected in the plume samples for the EVs but not in any ICEV samples. Xylenes were not detected at either ground-level sampling location but was present in the plume for several EV samples and one ICEV sample. Acetaldehyde and acrolein were detected in less than 10% of samples (detection limit $1.4 \mu\text{g}$) and thus are not reported.

Benzene concentrations were comparable between EV and ICEV fires at all sampling sites; however, the median benzene levels were greater during the ICEV fires (see Fig. 2 and Supplemental Table A.8). In the plume, benzene levels were greater for both vehicle types than near ground level, with ICEVs reaching a median of $4.57 \text{ mg}/\text{m}^3$, compared to $2.78 \text{ mg}/\text{m}^3$ for EVs. At the 3.0 and 4.5 m positions,

averaged concentrations were less than $1 \text{ mg}/\text{m}^3$ in the air. Fent et al. [31] reported benzene concentrations of 5.2 and $60 \text{ mg}/\text{m}^3$ for engine compartment and cabin fires, respectively, through the collection of a 1-liter Summa canister placed within the smoke over 30 s. The close positioning and short sampling time during the active combustion period are both likely contributors to the greater concentrations reported by Fent et al. Of note, Fent et al. also conducted area air sampling 7.6 m from the vehicles for the duration of the fires, and benzene was not detected in the majority (six out of nine) of the samples collected.

Benzene concentrations on the fireground are of particular concern because it is a known human carcinogen (IARC Group 1) and responders who are not directly involved in fire suppression may not wear respiratory protection. Additionally, benzene has been shown to readily breakthrough firefighter protective turnout gear [47]. Benzene concentrations reported here, even in the plume, are lower than personal air concentrations for firefighters during interior structural firefighting operations [36] and training fires [12] measured in previous studies. Fent et al. [36] reported median benzene concentrations of $128.7 \text{ mg}/\text{m}^3$ and $121.1 \text{ mg}/\text{m}^3$ for firefighters performing attack and search operations, respectively, during a controlled residential structure fire and Fent et al. [12] reported a range of median concentrations of 9.6 to $101.3 \text{ mg}/\text{m}^3$ during training fires. The range of benzene

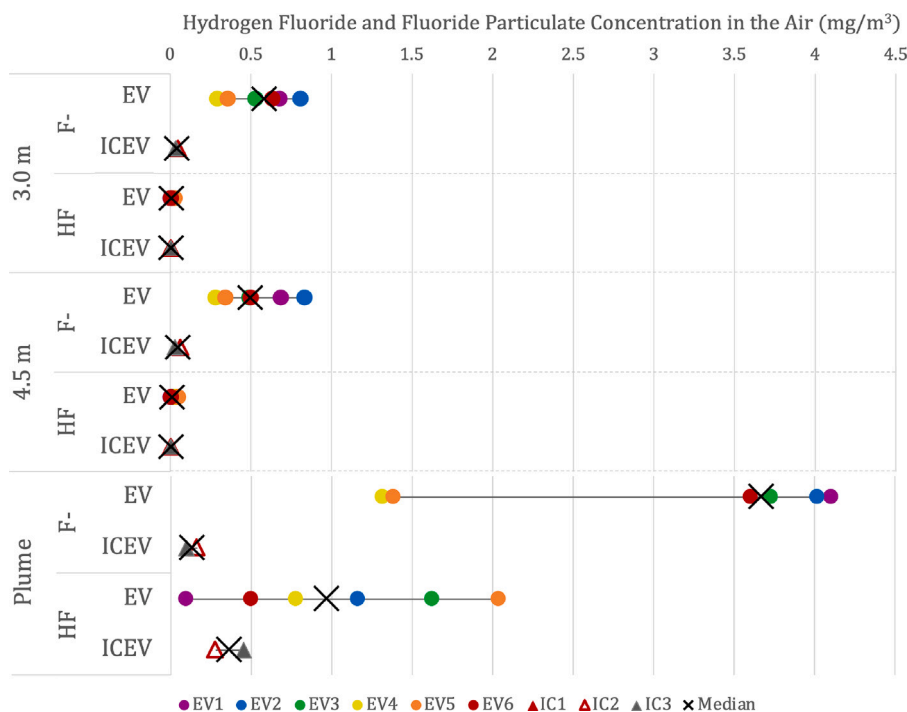


Fig. 3. Hydrogen fluoride (HF) and fluoride particulate (F⁻) concentrations in the air (mg/m³) during electric vehicle (EV, N = 6) and internal combustion engine vehicle (ICEV, N = 3) fire experiments. X represents the median of each group, while bars extend to the minimum and maximum values. Censored data were imputed values as described in the methods. Markers of the same color (red) represent vehicles of the same model across propulsion systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concentrations in the plume for both EV and ICEV fires overlaps with the range of concentrations measured during overhaul operations in the residential fire [36] but is greater than those experienced by wildland firefighters (0.04 mg/m³ [48]). Benzene concentrations at the ground level (3.0 m and 4.5 m locations) were the same order of magnitude, though had a narrower range, as the exterior instructor position next to a common firefighting training structure [17].

1,3-Butadiene and formaldehyde were generally present in lower concentrations than the BTEX compounds at the two ground level sampling locations. Greater concentrations of 1,3-butadiene and formaldehyde were present in the plume than at the ground level locations. Median concentrations of 1,3-butadiene were slightly greater in the plume than previously measured 1,3-butadiene concentrations measured during firefighting training, on the exterior of a common firefighting training structure [17], though there is substantial overlap in the ranges, depending on the fuel load used in the training environment.

Formaldehyde (IARC Group 1) was below the detection limit at the 4.5 m sampling location in both vehicle types but was detected at the 3.0 m sampling location in the EVs. Plume concentrations of formaldehyde had slightly greater median ranges than the mean concentrations reported by Fent et al. during vehicle fires, though the ranges overlap [26]. The plume concentrations of formaldehyde in this study had lower medians and ranges than those reported on the exterior of the fire behavior training structure in a previous study [17].

3.2.2. Acid gases

Sampling for acid gases included hydrogen cyanide (HCN), hydrogen chloride (HCl), sulfur dioxide (SO₂), and hydrogen fluoride (HF), as well as fluoride particulate (F⁻). Concentrations of each compound are reported in Supplemental Table A.9. HCN was detected in all but two samples (i.e., 3.0 m and 4.5 m during EV1). Median HCN levels were statistically greater in ICEVs compared to the EVs at the 3.0 m and 4.5 m sampling locations. HCN concentrations for both vehicle types at the ground level were lower than personal air concentrations previously measured on the exterior of a structure

fire. For example, Fent et al. [36] reported median HCN concentrations of 0.42 mg/m³ (0.379 ppm) for the command/pump operator position, 0.28 mg/m³ (0.249 ppm) during overhaul, and 18 mg/m³ (16.300 ppm, range 0.11 to 80.58 mg/m³) for exterior ventilation operations during a residential structure training fire. The HCN concentrations in the plume during vehicle fires more closely match the command/pump position and overhaul positions [36], though the duration of sampling by Fent et al. was considerably shorter (typically less than 20 min). The plume HCN concentrations in this study are also the same order of magnitude as shorter duration samples (approximately 7–30 min) collected from the interior of a training structure when using engineered wood products as the fuel (0.42–0.98 mg/m³ (0.376–0.899 ppm)), but are less than the interior concentrations when pallets and straw are the fuel source (0.67–2.48 mg/m³ (0.608–2.240 ppm)) [12].

HCl was below the detection limit at the 3.0 and 4.5 m locations in all EV experiments but was detected at the 3.0 m location in a single ICEV experiment. HCl was also detected in the plume for four of the EVs and all three ICEVs. The median HCl concentrations in the plume (2.18 mg/m³ for EVs, 0.13 mg/m³ for ICEVs) in this study were slightly lower than those inside a training structure (1.26–8.74 mg/m³, [12]). SO₂ was detected in all samples and had greater medians in the ICEVs than the EVs, though there is substantial overlap between the ranges.

HF was detected in about half of the EV samples at 3.0 and 4.5 m but was only detected in one ICEV sample at the ground level (3.0 m during ICEV1). HF was most abundant in the plume from EV fires (0.09–2.04 mg/m³). Fluoride particulate was detected in all samples (Fig. 3). Median concentrations of fluoride particulate were consistently greater by an order of magnitude in EVs than in ICEVs. In the plume, the fluoride particulate median for EVs was 30-fold the median in the ICEVs. Sampling media from ICEV1 was not submitted for fluoride particulate analysis (only for HF analysis) so those data were not available for statistical analysis, thus, the differences in fluoride particulate were not statistically significantly different. Additional assessments of fluoride particulate from ICEV fires could result in statistically significant differences.

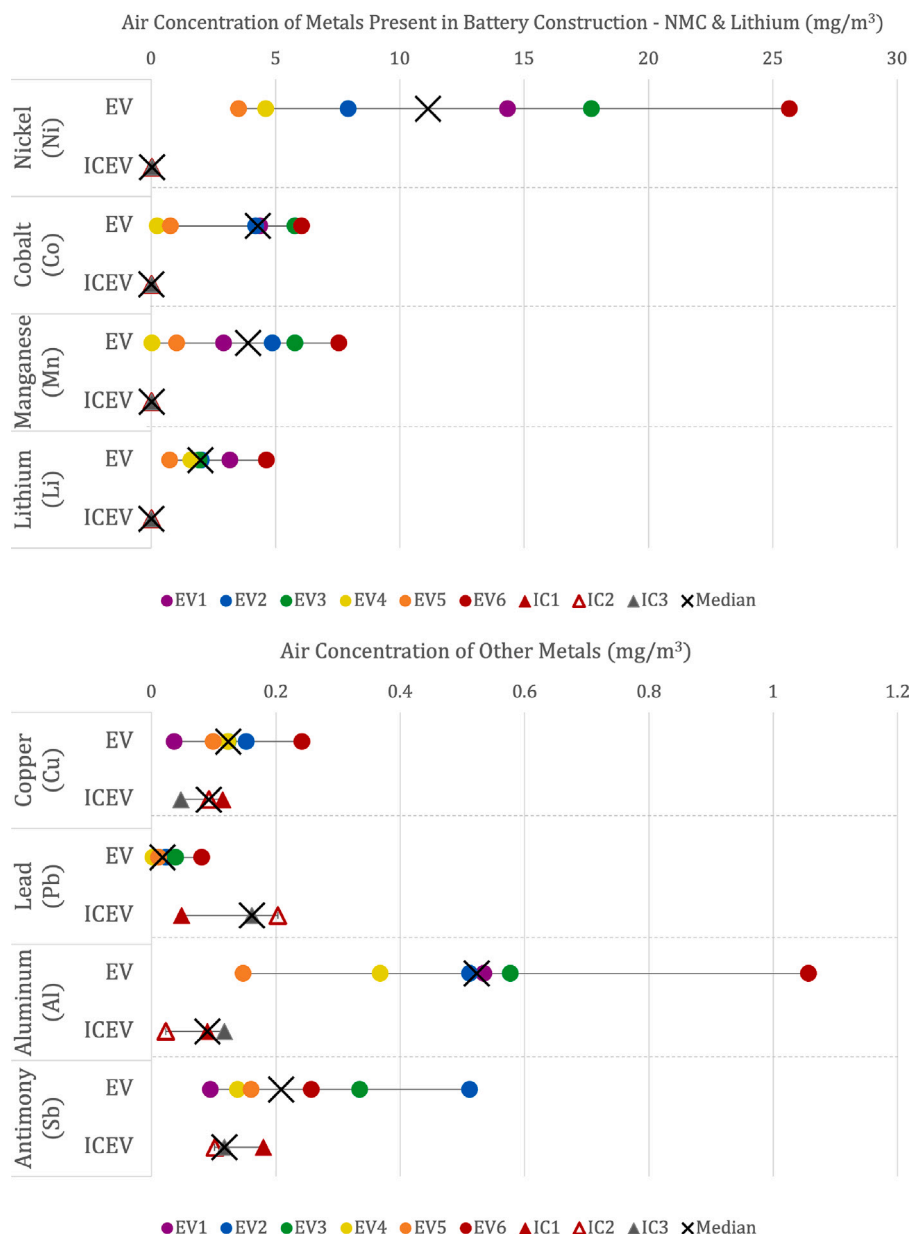


Fig. 4. Air concentration of metals involved in battery construction (top) and other metals present in the vehicles (bottom) sampled from the plume (mg/m³) during electric vehicle (EV, N = 6) and internal combustion engine vehicle (ICEV, N = 3) fire experiments. X represents the median of each group, while bars extend to the minimum and maximum values. Censored data were imputed values as described in the methods. Markers of the same color (red) represent vehicles of the same model across propulsion systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Larsson et al. [49] reported HF production of 20 to 200 mg/Wh in Li-ion battery fires. Based on these data, total HF production in the current study could range from 0.5 to 5.6 kg for the smallest battery pack to 1.8–18.2 kg for the largest battery pack. The current study was not able to measure the total volume of smoke production, so direct comparison is not feasible. Hynynen et al. found that among the gases examined, HF presented the largest difference between EV fires (120–859 g of HF) and ICEV fires (11–15 g of HF) [3]. In a study of vehicle fires in tunnels, Sturm et al. [50] reported HF values at various heights 16 m downstream of the fire. For EVs, HF concentrations ranged from 5.3 mg/m³ at the 1.6 m height to 38.4 mg/m³ at the 6.4 m height. HF values in the single ICEV were 0.7 mg/m³ at the 1.6 m height and 8.3 mg/m³ at the 6.4 m height. HF concentrations previously measured during active fire inside a live-fire training structure and residential training structure ranged from 1.03–3.84 mg/m³ to

0.19–2.06 mg/m³ [12,36]. Overall, results from these studies suggest that HF, as well as HCN and HCl, are likely to be present in fire effluent from a wide range of sources and have potential human exposure pathways [12,36]. Further, many studies only report vapor phase fluoride (HF), but our study found substantially greater concentrations of fluoride particulate (F⁻) during the EV fires. Additional assessments during other fire scenarios are needed to better understand potential fluoride particulate exposures and contamination.

HF is a water-soluble weak acid, and fluoride particulate can produce hydrofluoric acid when it contacts water. This reaction could occur in the sweat of firefighters and first responders, resulting in an immediate dermal hazard. Skin damage from HF acid could also affect the permeability of the firefighters' skin, potentially impacting the uptake of contaminants through skin. HF is also an irritant to the

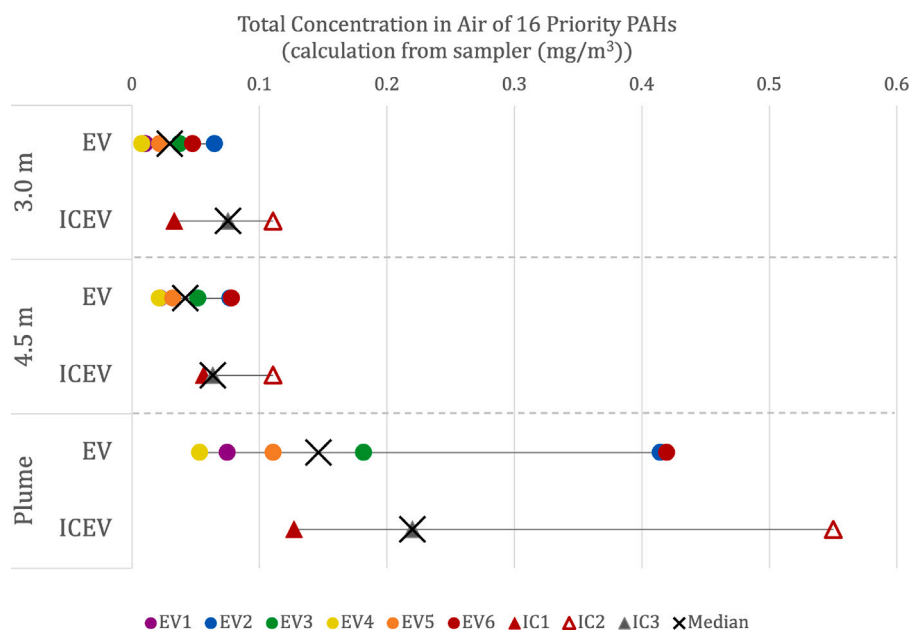


Fig. 5. Calculated air concentration of the sixteen priority polycyclic aromatic hydrocarbons (PAHs) ($\mu\text{g}/\text{m}^3$) from silicone samplers during electric vehicle (EV, $N = 6$) and internal combustion engine vehicle (ICEV, $N = 3$) fire experiments. X represents the median of each group, while bars extend to the minimum and maximum values. Censored data were imputed values as described in the methods. Markers of the same color (red) represent vehicles of the same model across propulsion systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mucus membranes and can cause severe irritation to the respiratory tract, potentially leading to pulmonary edema [51], emphasizing the need for respiratory protection for firefighters.

3.2.3. Metals

Fire effluent was sampled at each location for metals, including those commonly used in battery construction (nickel, manganese, cobalt, and lithium (Li-NMC)) and in other vehicle components (chromium, copper, lead, aluminum, antimony, arsenic, and cadmium). Metal concentrations are presented in Fig. 4 and tabular data are provided in Supplemental Table A.10. Both chromium and cadmium were not detected above the limit of detection in any samples ($<1.0 \mu\text{g}$ and $<0.5 \mu\text{g}$, respectively). Arsenic was detected in the plume for EV4 ($1.3 \mu\text{g}$) and EV5 ($1.4 \mu\text{g}$), though all other samples were below the detection limit ($<1.0 \mu\text{g}$). As anticipated, metals used in the construction of battery cells (nickel, manganese, cobalt, lithium) were present at statistically significantly greater levels in the EVs than in the ICEVs (Fig. 4, top), and were largely not detected in ICEV fire effluent. Median aluminum concentrations were statistically greater in EVs than ICEVs. Copper and antimony had greater median concentrations in EVs than the ICEVs, while lead had a greater median concentration in the ICEVs (Fig. 4, bottom), though these did not reach statistical significance.

Among the EVs, EV6 resulted in the highest concentration of most metals, while EV4 and EV5 generally had the lowest concentrations, despite EV4 and EV5 having the largest battery capacities. The composition and concentrations of metals measured in this study largely corroborate findings from previous studies. For example, H. Buston et al. [52] noted that cobalt, manganese, lithium and nickel were the primary metals found in commercially available Li-NMC cells. Sturm et al. [50] measured surface deposition of metals downstream from EVs (in mg/m^2), finding the highest levels of manganese and nickel, followed by much lower levels of aluminum, cobalt, and lithium. Hynynen et al. [3] also looked at particulate bound metals in the soot, finding the highest concentrations of nickel and manganese with lower levels of cobalt and lithium. Zinc was also detected, which was not measured in this study.

3.2.4. Inhalable particulate

Concentrations of total inhalable particulate, which encompasses particles up to $100 \mu\text{m}$ in aerodynamic diameter, varied by sampling location and vehicle type (Supplemental Table A.11). As anticipated, concentrations were highest in the plume; medians were similar between EVs and ICEVs at 50.1 and $51.6 \text{ mg}/\text{m}^3$, respectively, though concentrations from ICEV fires had a wider range. Inhalable particulate concentrations decreased as the sampling locations moved further away from the vehicles. Differences in median concentrations between vehicle types were also observed (ICEVs $>$ EVs), though these did not reach statistical significance.

3.2.5. PAHs

PAHs were sampled at the 3.0 m and 4.5 m . Total concentration of the 16 priority PAHs are reported in Table 4 and the concentrations of each compound are reported in Supplemental Tables A.12 and A.13. Personal air concentrations for total PAHs from firefighters performing attack and search operations in a controlled residential fire (7.46 – $78.20 \text{ mg}/\text{m}^3$ and 9.77 – $43.80 \text{ mg}/\text{m}^3$, respectively [36]) were greater than total concentrations in this study. Results from this study were slightly greater than the outside vent position in the previous study (median $0.096 \text{ mg}/\text{m}^3$, range 0.033 – $0.054 \text{ mg}/\text{m}^3$ [36]). The ranges of total concentration of the 16 priority PAHs from both types of vehicle fires were similar to those on the exterior of a firefighting training structure [17].

Median concentrations of individual PAHs tended to be greater in the EVs at 3.0 m , but greater in the ICEVs at 4.5 m , though generally ranges overlapped between the two locations. Chrysene and benzo[k]fluoranthene were statistically significantly higher in ICEV fires than EV fires at the 4.5 m sampling position. Naphthalene was found in the highest concentrations of the 16 priority PAHs, accounting for 56%–58% of the total mass collected. Two of the 16 priority PAHs were not detected in any samples (acenaphthene and dibenzo(a,h)anthracene). Additional PAH results, including comparison between active and passive sampling methodologies, are discussed later in the manuscript.

Table 4

Total concentration of 16 Priority PAHs in the air (mg/m^3) from active sampling during electric vehicle (EV, $N=6$) and internal combustion engine vehicle (ICEV, $N=3$) fire experiments.

	3.0 m		4.5 m	
	Median	Range	Median	Range
Σ 16 Priority PAHs				
EV	0.144	0.060–0.270	0.117	0.053–0.215
ICEV	0.137	0.130–0.226	0.264	0.137–0.264

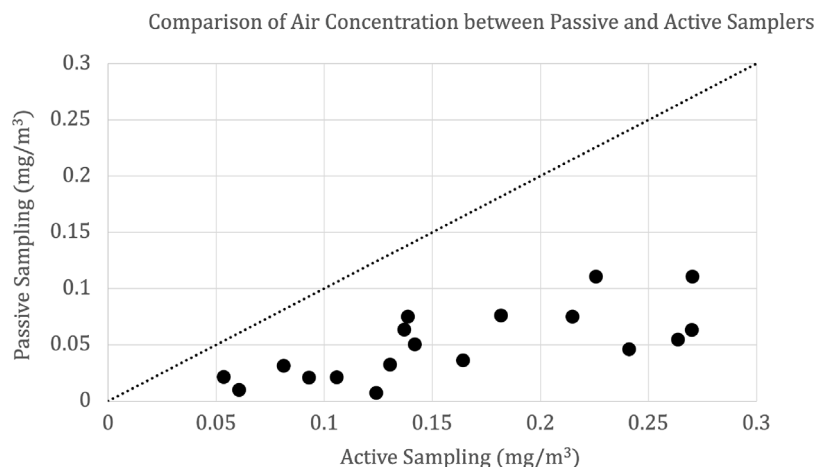


Fig. 6. Comparison of estimated polycyclic aromatic hydrocarbon concentrations between passive sampling with silicone samplers and active sampling. The dotted line represents a 1:1 line.

3.3. Passive sampling

3.3.1. PAHs

Polycyclic aromatic hydrocarbon (PAH) concentrations in the air were estimated based on the mass collected on the silicone samplers placed around the vehicles. Concentrations of each PAH from silicone samplers are listed in Supplemental Tables A.14 and A.15. Calculated air concentrations for each PAH are listed Supplemental Tables A.16 and A.17. Mass and calculated concentrations of dibenzofuran, while not a PAH, are also included (Supplemental Tables A.15 and A.17). Calculated air concentrations for naphthalene, benzo[a]pyrene, and the benzo[a]pyrene-relative toxicity equivalence are presented in Table 5. The summed concentrations of the priority PAHs are presented in Fig. 5.

Median concentrations for most individual PAHs and the summed PAHs were greater in ICEVs than in EVs. For naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, the ICEVs were nearly (and in some cases more than) double the value of the EV fire emissions. Naphthalene was the most abundant PAH at the 3.0 m and 4.5 m locations, which is consistent with previous exposure assessments evaluating fire effluent during training fires [9,53]. At the 4.5 m sample location, naphthalene comprised 40% of the total PAHs for ICEVs and 42% for EVs. Phenanthrene was present in the highest quantities in the plume, comprising 13% of total PAHs for the ICEVs and 40% for the EVs. PAHs with higher molecular weights were present in much lower quantities than PAHs with lower molecular weights.

Concentrations of PAHs from passive and active air sampling were compared (Fig. 6). Passive sampling values were generally lower than active sampling values with a root-mean squared error of $0.12 \text{ mg}/\text{m}^3$ (~31% lower). These comparisons suggest that in this environment passive samplers report lower total concentrations of PAHs present in the air than PAH concentrations measured with active air sampling. The calculated concentrations reported here assume a constant uptake based on the published uptake rates at ambient temperatures ($20.7 \pm 0.2^\circ\text{C}$) reported by Tromp et al. [44], though temperatures in the fire tests reported here increased with the fire size. The sampled

PAHs varied greatly in their molecular weight and presence in the air as vapor or particulate. Further research is necessary to address the uptake of both vapor and particulate compounds on silicone samplers and examine the relative sampling rates of individual compounds.

3.3.2. PFAS

Two of the 37 PFAS measured were detected above the detection limit in all samples (Fig. 7). Perfluoropropanoic acid (PFPrA) and trifluoroacetic acid (TFA) were both present at all three sampling locations. Median values were consistently greater in the ICEVs than in the EVs, with statistically significant differences at the 3.0 m for both compounds and at the 4.5 m sampling location for PFPrA. Unlike the other compounds reported here, median values for both PFPrA and TFA were generally greater at the 3.0 m and 4.5 m positions than they were in the plume. TFA is a fluorine-based compound that may be present as a result of the decomposition of hydrofluorocarbon134a (HFC-134a) [54], which is commonly used as a refrigerant in vehicle air conditioning systems [55]. It is possible that as the vehicles' refrigerant systems were damaged during the fires and as the HFC-134a was exposed to high temperatures, it decomposed into TFA. PFPrA is an ultra-short chain PFAS and may be a combustion by-product of larger PFAS chains, such as those used in the previously mentioned refrigerants or water and stain resistant treatments for vehicle seats. More research is needed to understand the sources of PFAS and the differences between EV and ICEV fires.

3.4. Limitations

This study sought to quantify the contaminants produced during vehicle fires (ICEVs and EVs). Data were collected for a number of compounds and reported values represent the average air concentrations across the duration of the experiment. However, air concentrations of all compounds fluctuated as the fire was initiated, developed, and decayed. Peak concentrations of compounds were not able to be evaluated with the current sampling methodology. Peak concentrations may be highly relevant for responding firefighters' exposure potential and risk.

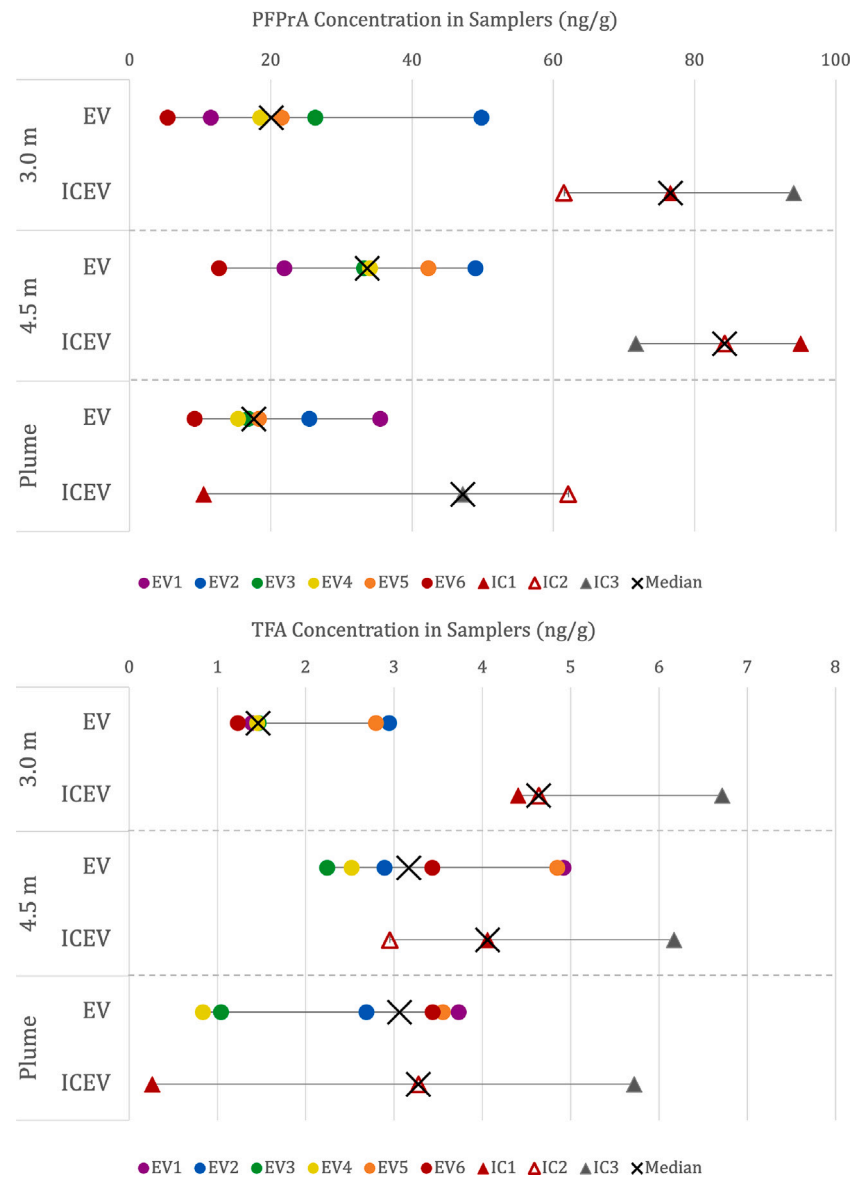


Fig. 7. Perfluoropropanoic acid (PFPrA, top) and trifluoroacetic acid (TFA, bottom) concentrations in the samplers (ng/g) during electric vehicle (EV, N = 6) and internal combustion engine vehicle (ICEV, N = 3) fire experiments. X represents the median of each group, while bars extend to the minimum and maximum values. Censored data were imputed values as described in the methods. Markers of the same color (red) represent vehicles of the same model across propulsion systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5

Select PAH concentrations in air ($\mu\text{g}/\text{m}^3$) as measured using passive silicone samplers during electric vehicle (EV, N=6) and internal combustion engine vehicle (ICEV, N=3) fire experiments and benzo[a]pyrene-relative toxicity equivalence.

	3.0 m			4.5 m			Plume		
	# NDs	Median	Range	# NDs	Median	Range	# NDs	Median	Range
Naphthalene									
EV	0	7.96	2.55–25.35	0	17.21	7.03–38.70	0	19.13	5.59–64.59
ICEV	0	19.33	10.64–26.58	0	24.39	21.31–46.98	0	29.98	12.74–87.98
Benzo[a]pyrene									
EV	0	0.03	0.01–0.09	0	0.05	0.01–0.10	0	0.57	0.15–2.74
ICEV	0	0.07	0.05–0.08	0	0.05	0.04–0.07	0	0.71	0.53–3.99
BaP _{TEQ}									
EV	–	0.14	0.06–0.31	–	0.18	0.08–0.35	–	1.67	0.39–5.43
ICEV	–	0.25	0.25–0.35	–	0.25	0.20–0.26	–	2.52	1.63–6.84

The “# NDs” column indicates the number of samples that were below the minimum detectable concentration (MDC).

Conducting large scale fire experiments of this magnitude indoors allows a high level of control over ambient conditions and limits any impacts of wind on the testing. However, the smoke production may

have overwhelmed the building’s exhaust capabilities and allowed for smoke to bank down towards the sampling locations rather than exit to the atmosphere. While difficult to quantify, this may have led to

elevated concentrations for the sampling locations around the vehicles. On the other hand, this behavior may be similar to conditions experienced during atmospheric inversion or when strong winds would force the plume towards the ground level. It is also possible that meandering and tilting of the plume, especially in the initial and final stages of fire development, could have resulted in under-sampling of some of the fire effluent at the plume location. Efforts were made to minimize this by placing the welding curtain above the vehicle to gather effluent throughout all stages of the fire. The welding blanket quickly filled with effluent because of the volume of smoke produced and spilled out all sides of the curtain, minimizing under-sampling. In addition, sampling within the plume was not conducted using isokinetic principles. This could have influenced the particle concentrations and size distributions collected on the active sampling media; although, such sampling biases would be less pronounced for combustion aerosol (typically $<1\ \mu\text{m}$ in aerodynamic diameter). However, these samples were not meant for compliance, but rather referent comparison points (e.g., plume above EV vs. ICEV and plume vs. area sampling locations). Another limitation was the relatively small number of experiments (six EVs, three ICEVs) due to the cost and complex nature of conducting large scale fire experiments of this magnitude. Testing order could potentially be a limitation, as it was not randomized, though cleaning between tests should minimize any potential accumulation of fire effluent. An ICEV was tested first, followed by all six EV experiments, then the final two ICEV experiments. Comparisons between active and passive sampling should continue to be evaluated. Additional research is needed to understand how passive samplers compare to active samples for different compounds and settings. It is possible that the state of the compound (gas or particulate) has an impact on the uptake rate of the silicone samplers.

3.5. Data interpretation and occupational relevance

While comparisons could theoretically be made between the concentrations measured in this study and occupational exposure limits set by various regulatory bodies, this should be done with caution. In addition to the previous limitations listed, the sampling in this study may not be representative of potential occupational exposures. Sampling positions in this study are representative of where a person might be standing near a vehicle with sampling occurring at the height of the breathing zone. However, firefighters would likely conduct suppression operations and move or reposition themselves throughout the attack (not remain in a single position). Additional sampling occurred above the vehicle in the plume, to characterize combustion products in a worst-case position or confined space (e.g. parking garage). Firefighters and bystanders would not be expected to be located in the plume above a burning vehicle. However, the more concentrated smoke plume could be pushed towards the ground depending on environmental conditions and pose immediate risk to life and health. Future studies should conduct personal air and biological (e.g., urinary, exhaled breath) sampling on firefighters responding to EV and ICEV fires to more accurately characterize their potential exposures.

4. Conclusions

This study examined the air concentrations and particulate characterization of products of combustion from EV and ICEV fires utilizing both active and passive sampling methodologies. Relative to ICEVs, EVs were exposed to the 30 kW ignition burner for longer, but once the vehicle was ignited, combustion times were similar. Ranges of VOC and PAH concentrations overlapped between EVs and ICEVs, though median concentrations for Benzene and PAHs were slightly greater for ICEVs. Concentrations of acid gases were similar between vehicle types, though importantly, particulate fluoride concentrations were substantially greater in the EV fires. Air concentrations of metals used in the construction of lithium-ion batteries were also substantially greater in

EV fires than in ICEV fires. Although the median concentrations of total inhalable particulate matter from EVs and ICEVs were comparable, the results suggest that the chemical composition of the particulate matter differs between vehicle types. Overall, the combustion products present during the combustion of both EV and ICEV present significant hazards to those near the fire, with additional metal and particular fluoride hazards produced in EV fires. Appropriate PPE, including respiratory protection, should be used even at distances removed from the vehicle.

CRedit authorship contribution statement

Richard M. Kesler: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Nathaniel Sauer:** Investigation. **Adam Barowy:** Supervision, Project administration, Investigation. **Chandler Probert:** Investigation. **Danielle L. Neumann:** Resources, Investigation, Formal analysis. **Alexander C. Mayer:** Writing – review & editing, Investigation. **Micah Niemeier-Walsh:** Investigation. **Kenneth W. Fent:** Writing – review & editing, Resources. **Heather M. Stapleton:** Writing – review & editing, Resources. **Gavin P. Horn:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH/CDC.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Throughout the supplemental tables, data are reported as the median and the range. Tables include a column for the number of non-detects, indicating the number of samples that were below the minimum detectable concentration (MDC). Since sample collection times varied, the MDC varied for each sample. When data were below the MDC, they were reported as “<MDC”, where the presented value is the MDC. When all samples were below the MDC, the range is presented as less than the lowest and highest MDC. In cases where $>50\%$ of samples were below the detection limit, a median was not computed. The Mann-Whitney U test, with significance set at $p = 0.05$, was used to test for differences between EV fires and ICEV fires. ICEV data with statistically significant differences from EV data are presented in Bold.

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.firesaf.2025.104558>.

Data availability

Data will be made available on request.

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