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# Changes in upper and lower carbon monoxide concentrations during butane heater operation in an enclosed tent

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**Article**

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# Abstract

Carbon monoxide (CO) concentrations within a tent may vary with height and duration of heater operation, complicating the interpretation of incident reconstructions. We measured CO and oxygen ($O_2$) at 0–10 cm and 140–150 cm above the floor during three full-scale trials with a liquefied-butane heater. Paired readings were analyzed at 3-min intervals from 3 to 39 min. Mean CO increased from 40.33 to 93.33 ppm at the upper position and from 8.67 to 101.67 ppm near the floor; descriptive linear slopes were 1.509 and 2.684 ppm/min, respectively. At 30 min, upper-minus-lower differences were − 2, −2 and + 4 ppm. All three differences were negative from 33 min onward. The 3–39 min time-weighted mean nevertheless remained higher at the upper position (62.99 versus 51.10 ppm). Mean $O_2$ declined from 20.03 to 16.80 vol% above and from 20.90 to 17.97 vol% below. Thus, the early upper CO excess was followed by higher near-floor readings in each trial, with variation in transition timing. These findings show why both measurement height and elapsed time matter when interpreting a tent reconstruction; they do not establish an individual inhaled dose.


# Introduction

Carbon monoxide (CO) produced by incomplete combustion remains an important cause of accidental poisoning in homes, temporary shelters and recreational settings [1, 2]. Camping incidents have been associated with gas appliances and charcoal used for cooking or heating, including fatal exposures that occurred while occupants were sleeping [3–5]. Experiments in tents and snow shelters have shown that the measured CO concentration varies with appliance design, fuel, burner condition, enclosure geometry and ventilation [6–8].

Previous tent experiments have characterized peak CO concentrations and differences between appliances, fuels and shelter designs [6–8]. Whether the upper and lower concentrations maintain the same ordering during continuous heater operation is less clear. Multi-height measurements in remote field facilities recorded the highest CO concentrations at upper sampling positions [9], whereas CO introduced into a chamber without a continuing heated source became well mixed across heights [10]. The different source and enclosure conditions limit direct comparison, but indicate that vertical concentration differences need to be examined over time.

During combustion, buoyancy transports warm gases upward, while cooling, entrainment and air exchange affect their subsequent distribution [10–12]. The concentration measured at a particular location therefore depends on more than the molecular mass of CO. This has practical relevance to occupants sleeping near the tent floor and to forensic examinations of submitted tents and heaters. Postmortem toxicology can establish evidence of CO exposure, but the preceding environmental conditions must be assessed from the scene and other evidence [13–15].

We conducted a full-scale reconstruction using the tent and liquefied-butane heater submitted in a fatal incident investigation. The primary objective was to describe changes in the paired upper-minus-lower

CO difference during continuous operation. We also examined variation among runs, summarized CO concentrations over the observed interval and documented oxygen ($O_2$) depletion at the same positions.

## Results

# Carbon monoxide accumulation at two heights

CO accumulated at both monitoring positions over the 3–39 min observation interval (Fig. 2a). At 3 min, the upper mean was 40.33 ppm (range 40–41 ppm), compared with 8.67 ppm (8–9 ppm) near the floor. At 39 min, the lower mean was 101.67 ppm (100–104 ppm) and the upper mean was 93.33 ppm (91–97 ppm).

The fitted slope of the mean CO profile was 1.509 ppm/min at the upper position and 2.684 ppm/min near the floor ($R^2$ = 0.986 and 0.988, respectively; Table 1). Run-specific slopes ranged from 1.471 to 1.549 ppm/min above and from 2.641 to 2.753 ppm/min below. The lower-position slope was greater in every run. Residuals from the individual fits varied systematically with time (Fig. 3a,b), indicating departures from a constant rate within the observation interval.

Table 1
Summary of concentration profiles and descriptive linear fits

| Outcome | Upper 140–150 cm | Lower 0–10 cm |
|---|---|---|
| CO at 3 min, ppm; mean (range) | 40.33 (40–41) | 8.67 (8–9) |
| CO at 39 min, ppm; mean (range) | 93.33 (91–97) | 101.67 (100–104) |
| CO fitted slope, ppm/min | 1.509 | 2.684 |
| CO fit $R^2$ | 0.986 | 0.988 |
| Run-specific CO slope range, ppm/min | 1.471–1.549 | 2.641–2.753 |
| Observed 3–39 min CO time-weighted mean, ppm; mean (range) | 62.99 (62.67–63.21) | 51.10 (50.83–51.50) |
| $O_2$ at 3 min, vol%; mean (range) | 20.03 (19.8–20.3) | 20.90 (20.7–21.1) |
| $O_2$ at 39 min, vol%; mean (range) | 16.80 (16.7–16.9) | 17.97 (17.9–18.0) |
| $O_2$ fitted slope, percentage points/min | −0.08455 | −0.08590 |
| $O_2$ fit $R^2$ | 0.980 | 0.988 |
| Run-specific $O_2$ slope range, percentage points/min | −0.09176 to −0.07894 | −0.08736 to −0.08425 |

Fits describe the mean profiles from 3 to 39 min without extrapolation. Ranges refer to three repeat runs. Time-weighted means were calculated separately by trapezoidal integration over 3–39 min. $R^2$, coefficient of determination.

Over 3–39 min, the time-weighted mean CO concentration was 62.99 ppm at the upper position (range among runs 62.67–63.21 ppm) and 51.10 ppm near the floor (50.83–51.50 ppm). The upper value was greater in every run, despite the higher near-floor reading at 39 min. These averages describe the monitored locations over the measured interval and exclude the first 3 min after ignition.

## Change in the paired carbon monoxide difference

The mean upper-minus-lower CO difference decreased from + 31.67 ppm at 3 min to − 8.33 ppm at 39 min, with some variation between successive readings (Fig. 2b). At 27 min, the differences were + 1, 0 and + 4 ppm in runs 1–3. At 30 min, the corresponding values were − 2, −2 and + 4 ppm; their mean of zero therefore combined differences of opposite sign. All three differences were negative at 33 min (− 2, − 9 and − 4 ppm) and remained negative at 36 and 39 min (Table 2). Run 1 changed sign between 27 and 30 min, whereas run 3 changed sign between 30 and 33 min. In run 2, equal readings at 27 min lay between a positive difference at 24 min and a negative difference at 30 min.

Table 2
Paired CO differences around the change in recorded concentration ordering

| Run | ΔCO 24 min | ΔCO 27 min | ΔCO 30 min | ΔCO 33 min | ΔCO 39 min |
|---|---|---|---|---|---|
| 1 | + 8 | + 1 | -2 | -2 | -9 |
| 2 | + 11 | 0 | -2 | -9 | -7 |
| 3 | + 9 | + 4 | + 4 | -4 | -9 |
| Mean | 9.33 | 1.67 | 0.00 | -5.00 | -8.33 |
| SD | 1.53 | 2.08 | 3.46 | 3.61 | 1.15 |

ΔCO = upper CO − lower CO, in ppm. Zero is an equality of recorded values, not proof of atmospheric equality. At 30 min the mean masks opposite signs among runs. All three runs were negative at 33, 36 and 39 min. SD is the sample standard deviation of the three paired differences.

## Oxygen depletion

$O_2$ declined at both monitoring positions (Fig. 2c). The upper mean fell from 20.03 vol% (range 19.8–20.3 vol%) at 3 min to 16.80 vol% (16.7–16.9 vol%) at 39 min. Near the floor, the mean decreased from 20.90 vol% (20.7–21.1 vol%) to 17.97 vol% (17.9–18.0 vol%). Fitted slopes were − 0.08455 and − 0.08590 percentage points/min at the upper and lower positions, respectively (Table 1). The upper mean remained lower throughout the observation interval. Residuals from the individual $O_2$ fits are shown in Fig. 3c,d.

## Discussion

In all three trials, the early upper CO excess was followed by higher readings near the floor. The transition occurred at different recorded times: two runs had negative upper-minus-lower differences at 30 min, while the third remained positive. The zero mean at that time obscured this variation. Examining paired readings within each run was therefore necessary to distinguish the common temporal pattern from differences in its timing.

The endpoint and interval average described different aspects of the CO record. Although the near-floor concentration was higher at 39 min, the earlier upper excess was sufficient to produce a higher time-weighted mean at the upper position in every trial. An endpoint reading would miss this earlier difference, while an early upper reading would not describe the later conditions near the floor. For reconstruction purposes, the relevant evidence is the concentration history at each monitored location.

The early upper excess is consistent with upward transport of warm combustion products. Higher upper-position CO concentrations have also been reported in field measurements [9]. In the present tent, however, that ordering did not persist throughout heater operation. Cooling and recirculation under restricted ventilation may have contributed to the later near-floor excess. Experimental studies of thermal stratification and channel fires show that buoyancy can produce layering and that CO and temperature distributions need not coincide [11, 12]. Without temperature, airflow or air-exchange measurements, the contribution of these processes cannot be separated in this reconstruction.

The concentrations were within the broad range reported for fuel-burning appliances in temporary shelters. Betten et al. found that fuel type and tent design affected CO accumulation [6]. Thurman et al. reported stove-specific peak mean concentrations of 67–207 ppm during 15-min tent trials [7], and Nielsen and Karlsen recorded peaks up to 120 ppm during short stove use in snow caves, with a marked increase when the burner was contaminated [8]. Differences in appliance output, burner condition and ventilation prevent direct comparison of accumulation rates. The present study adds paired upper and lower records during 40 min of continuous heater operation, showing how the spatial comparison changed within the same trial.

Higher near-floor CO late in the trials is relevant to incidents involving occupants sleeping close to the floor. The monitors did not measure concentrations at an individual airway, however, and posture, movement and respiration would affect exposure in an occupied tent. Estimation of carboxyhemoglobin or fatal exposure duration would require information beyond these environmental records. A forensic assessment must also consider postmortem toxicology, autopsy findings and the circumstances of the incident [13–15]. The reconstruction demonstrates progressive CO accumulation and $O_2$ depletion with the submitted apparatus under the tested conditions.

The $O_2$ records show that depletion accompanied CO accumulation at both positions. Similar fitted $O_2$ slopes occurred despite consistently different mean concentrations. A fixed quantitative relationship between CO production and $O_2$ consumption cannot be inferred, because the CO yield depends on combustion conditions and neither carbon dioxide nor fuel consumption was measured.

The three trials establish repeatability only for the tested, unoccupied tent–heater configuration. Measurements at two locations cannot describe the full spatial distribution or establish conditions in other shelters. Calibration and exchange of monitor assignments reduced potential bias, but residual instrument differences remain unquantified. Together with the 3-min sampling interval, this uncertainty limits interpretation of near-zero differences and prevents identification of a precise physical crossover time.

This reconstruction shows that the relative CO concentrations at upper and near-floor positions can change during continued heater operation. The higher endpoint concentration near the floor did not correspond to the higher interval average. Both sampling location and measurement time should therefore be retained when environmental measurements are used in a forensic interpretation of a tent incident.

## Methods

# Full-scale reconstruction

Three repeat trials were conducted with a dome-style camping tent measuring 260 × 260 × 150 cm (width × length × height) and a portable liquefied-butane heater measuring 250 × 210 × 310 mm. Both items had been submitted to the National Forensic Service after a fatal camping incident. Only the physical items were used. No case identifiers, biological specimens or human data were included.

The heater was placed at the center of the tent floor and operated continuously for 40 min. The opening and ventilation configuration was kept unchanged among runs, and no forced ventilation was introduced. After each trial, the heater was extinguished and the tent was ventilated before the next trial. The arrangement is shown in Fig. 1. Operation of a fuel-burning heater in an enclosed tent produces a toxic and oxygen-depleted atmosphere; this procedure should not be reproduced without institutional risk controls and suitable remote monitoring.

## Gas monitoring

CO and $O_2$ were recorded concurrently with two MultiRAE Lite portable multigas monitors (PGM-6208; RAE Systems by Honeywell, San Jose, CA, USA) equipped with electrochemical CO and $O_2$ sensors. The manufacturer's datasheet specifies a nominal CO range of 0–500 ppm with 1 ppm resolution and an $O_2$ range of 0–30 vol% with 0.1 vol% resolution [16]. Sensor-specific accuracy and response time are not reported in that document. The instruments were calibrated according to the manufacturer's procedure before testing.

One monitor sampled at 140–150 cm above the floor, near the tent roof, and the other at 0–10 cm above the floor. Instrument assignments were alternated between consecutive runs so that neither monitor remained exclusively at one height. Measurements were aligned to a common elapsed-time reference.

The analysis used synchronized values at 3-min intervals from 3 to 39 min after ignition, producing 13 paired observations at each height in each run.

## Outcomes and calculations

The experimental unit was the run (n = 3), with repeated measurements within each run. The primary outcome was the paired difference between the upper and lower CO readings in the same run:

$\Delta CO(t) = C_{upper}(t) - C_{lower}(t)$ (1)

Positive values indicated a higher recorded upper concentration and negative values a higher recorded near-floor concentration. Opposite signs at consecutive observations identified an observed transition interval. Exact zeros were retained and reported separately rather than treated as positive or negative; no crossover time was interpolated. Secondary outcomes were the CO and $O_2$ profiles, descriptive fitted rates and the time-weighted mean CO from 3 to 39 min. The latter was calculated within each run as the sum of trapezoidal areas between successive measurements divided by 36 min, and then summarized across runs. This calculation assumes linear interpolation between the recorded values and excludes 0–3 min.

# Statistical analysis

Individual run values and ranges are reported with means in the main text and tables. For ΔCO, the standard deviation was calculated from the three within-run differences, preserving the pairing; upper and lower standard deviations were not combined as independent errors. Serial observations were not treated as independent experimental replicates. No hypothesis tests, confidence intervals for between-position effects or population-level comparisons were calculated.

Ordinary least-squares lines provided descriptive summaries over 3–39 min:

$\hat{C}(t) = b_0 + b_1 t$; $e(t) = C(t) - \hat{C}(t)$ (2)

Here, C(t) is the observed concentration, $\hat{C}(t)$ is the fitted value, $b_0$ and $b_1$ are the fitted intercept and slope, and e(t) is the residual. Lines were fitted to the mean profile and separately to each run. $R^2$ summarizes agreement with a straight line over the observed time points. Residuals from the individual fits were plotted against time to examine departures from linearity (Fig. 3). The fits were used to summarize the records, without extrapolation or interpretation of the intercept as the concentration at ignition. Additional decimal places in calculated values do not imply precision beyond the sensor resolution. Calculations were performed in Python 3.12.14 with NumPy 2.3.5 and SciPy 1.17.0.

## Declarations

# Ethics statement

The study used physical objects only. It did not involve human participants, animals, personal data or biological material. Institutional ethics review and informed consent were therefore not required.

# Data availability

The measurements and derived data supporting this study are available from the corresponding author on reasonable request.

# Competing interests

The author declares no competing interests.

# Author Contribution

J.K. conceived and designed the study, conducted the experiments, curated and analyzed the data, prepared the figures and wrote and revised the manuscript.

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# Figures

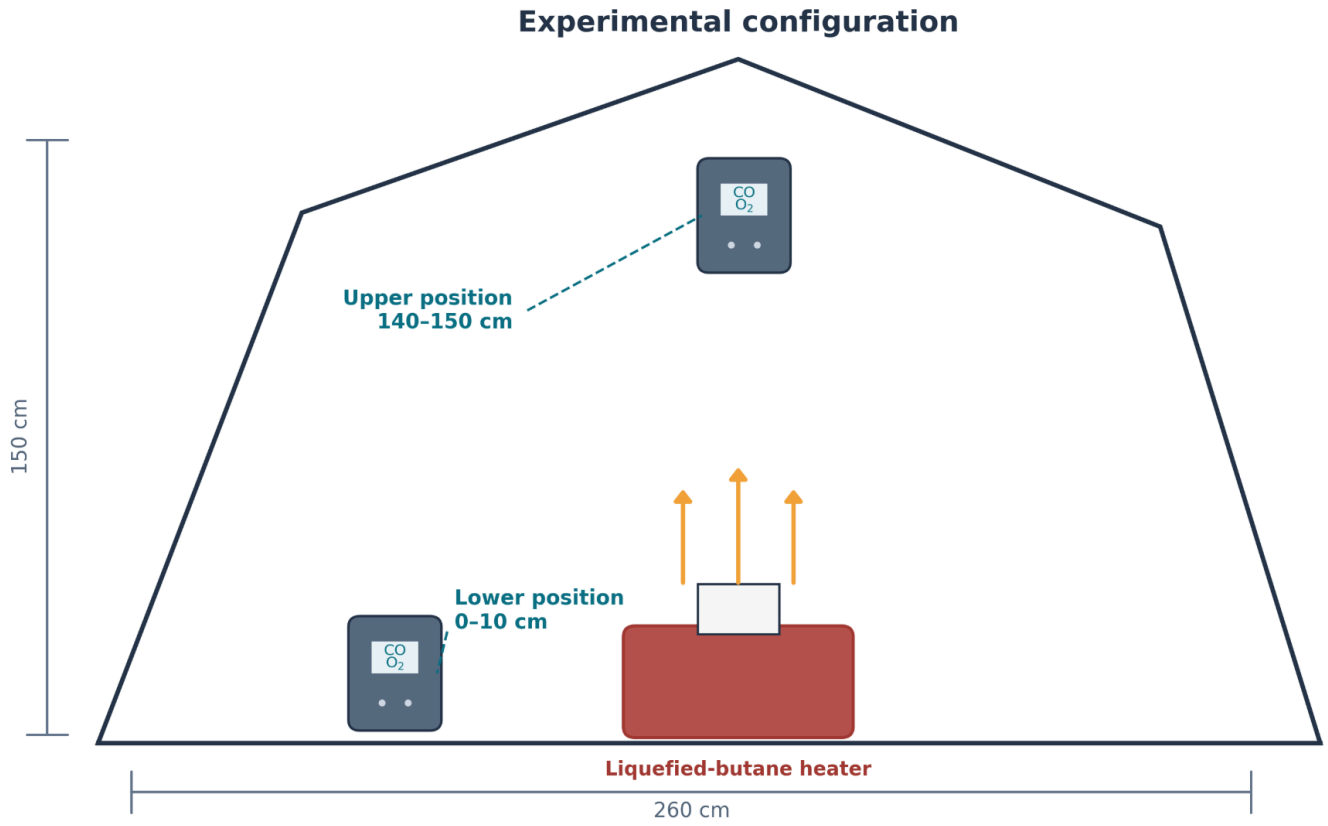



**Figure 1**

Experimental configuration. A portable liquefied-butane heater was positioned centrally in a 260 × 260 × 150 cm camping tent. CO and $O_2$ were measured concurrently at 140–150 cm and 0–10 cm above the floor. The heater was operated for 40 min in three repeat runs. Monitor assignments were alternated between heights, and the tent was ventilated between runs. The drawing is schematic; arrows indicate anticipated upward transport from the heated source, not measured airflow.

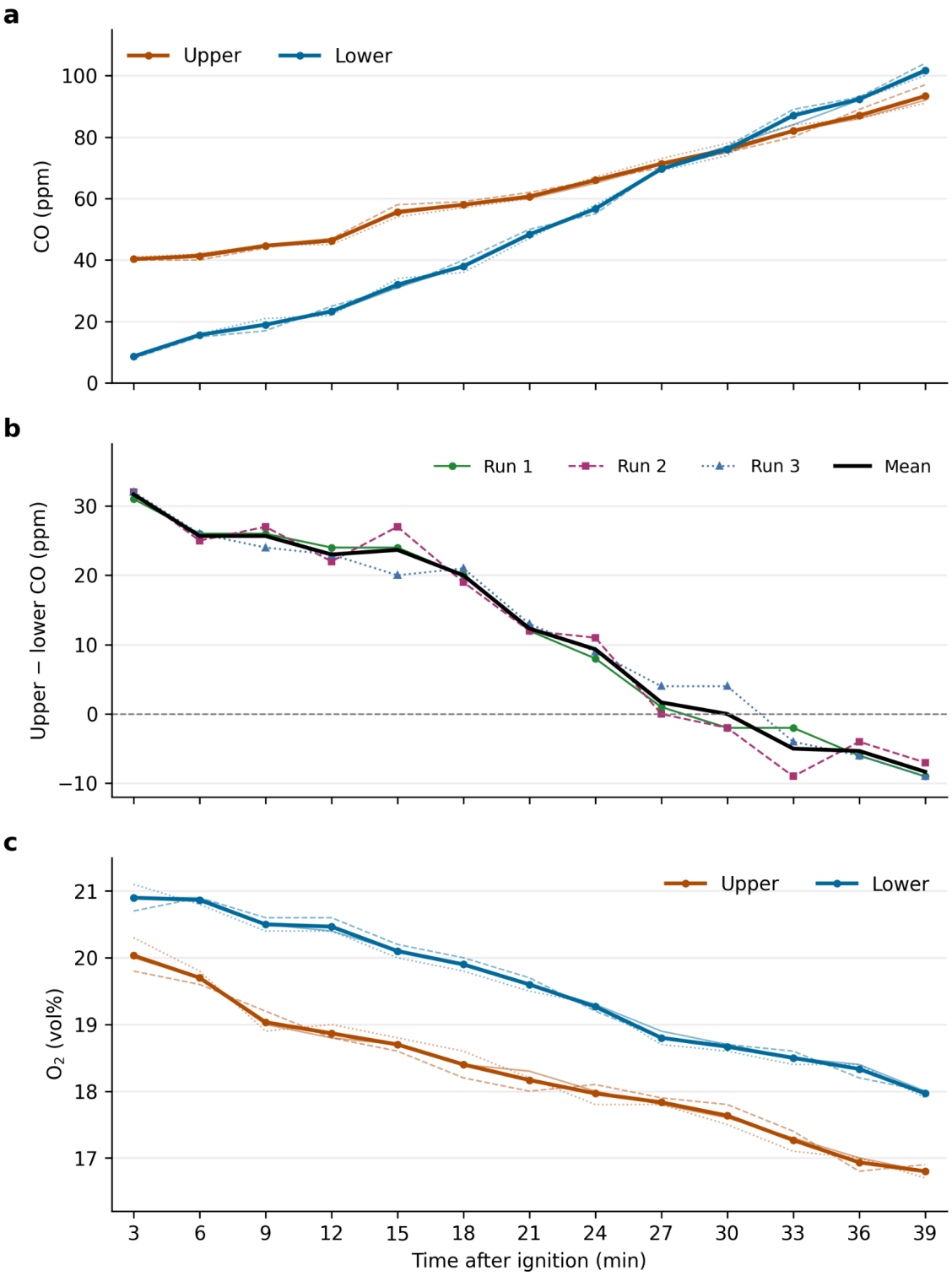



**Figure 2**

CO and $O_2$ concentrations during heater operation. (a) CO and (c) $O_2$ at the upper and lower positions; thin lines show individual runs and thick lines show arithmetic means. (b) Paired upper-minus-lower CO differences in runs 1–3 and their mean; the horizontal dashed line marks zero. Lines connect readings obtained at 3-min intervals.

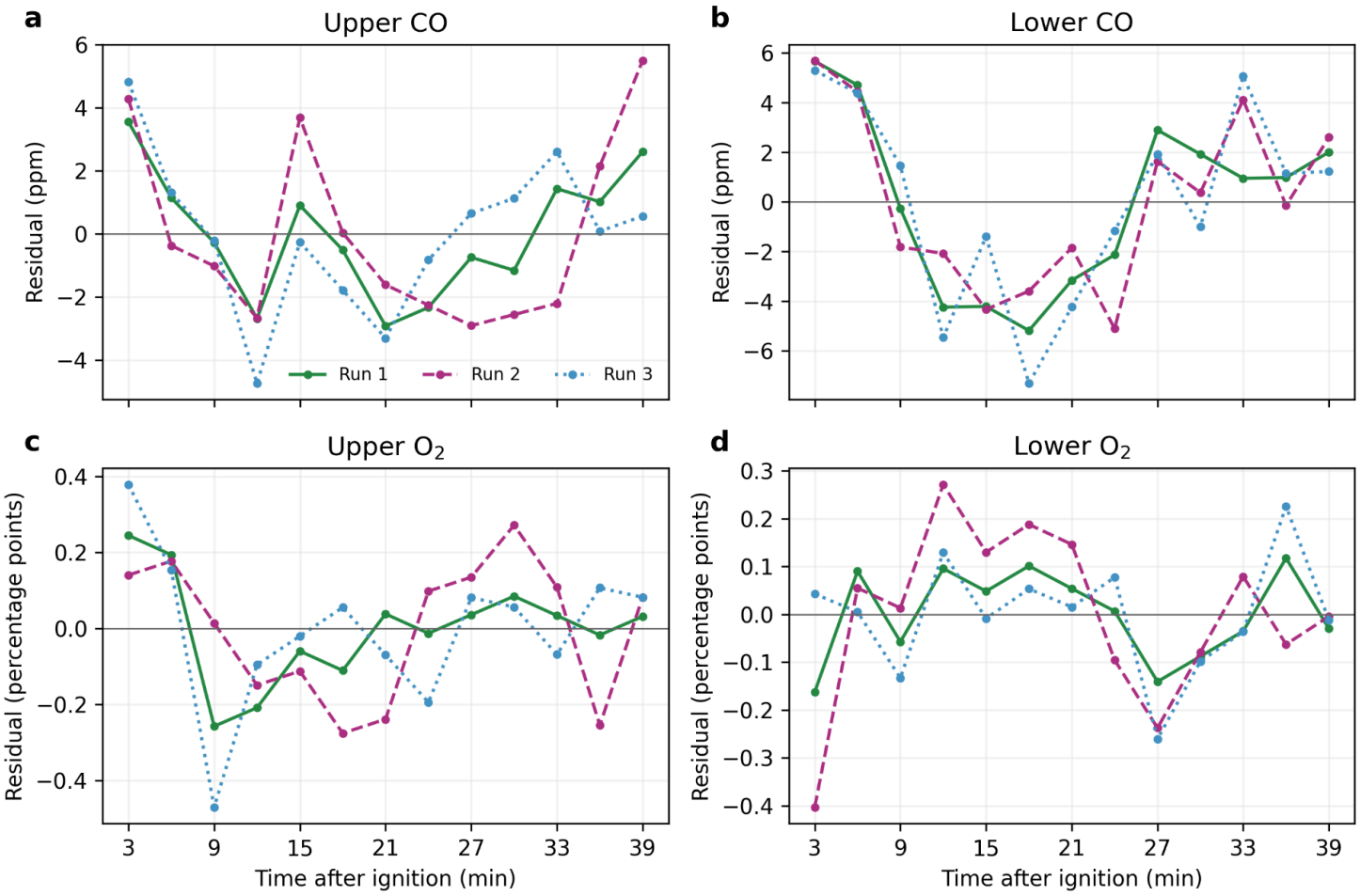



**Figure 3**

Residuals from the individual linear fits over 3–39 min. Panels show (a) upper CO, (b) lower CO, (c) upper $O_2$ and (d) lower $O_2$. Each curve represents one run. Residuals are observed minus fitted concentrations, expressed in ppm for CO and percentage points for $O_2$. Horizontal lines mark zero; connecting lines show the temporal pattern between observations. The residual structure indicates that the fitted slopes summarize the interval rather than a constant rate throughout each run.