

# Polycyclic aromatic hydrocarbon exposure during commuting: A comparative analysis of Bus and Tuk-Tuk in Phnom Penh

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**Abstract.** This study evaluated and compared the levels of exposure to PM<sub>2.5</sub> and selected polycyclic aromatic hydrocarbons (PAHs) among commuters using two common transportation modes, city buses and Tuk-Tuks, in Phnom Penh, Cambodia. Sampling was conducted over 14 days using personal air samplers worn by commuters to capture the in-vehicle pollutant concentrations. The results showed that the Tuk-Tuk commuters consistently experienced significantly higher exposures than the bus commuters. The average PM<sub>2.5</sub> concentration in Tuk-Tuks was  $115.9 \pm 36.3 \mu\text{g}/\text{m}^3$ , compared with  $76.0 \pm 39.7 \mu\text{g}/\text{m}^3$  for buses. PAH exposure also followed this trend, with Tuk-Tuk commuters exposed to average PAH concentrations of  $23.40 \pm 6.70 \text{ ng}/\text{m}^3$ , whereas bus commuters were exposed to  $4.88 \pm 1.43 \text{ ng}/\text{m}^3$ . Among the PAHs analysed, benzo[*a*]pyrene (BaP), indeno[1,2,3-*cd*]pyrene (IDP), and benzo[*ghi*]perylene (BghiP) were the most dominant compounds. Diagnostic ratios consistently identified liquid fossil fuel combustion as the primary source of pollution. The higher exposure associated with Tuk-Tuk usage is attributed to its open-air design, which offers minimal protection against ambient pollutants, in contrast to the relatively enclosed environment of city buses. This study highlights the urgent need for improved air quality management and urban transportation planning in Phnom Penh. Interventions should focus on promoting cleaner transportation alternatives and implementing stricter emission regulations to safeguard commuter health.

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**Key words:** air pollution, bus, particulate matter, polycyclic aromatic hydrocarbons, Tuk-Tuk

## 1 Introduction

Air pollution is a major global health concern, and traffic is one of the primary sources, generating pollutants from both engine exhaust and non-exhaust processes. Among these pollutants, particulate matter (PM) poses a significant health risk, being linked to serious conditions such as lung cancer and respiratory diseases. In addition, PM carries hazardous compounds, most notably polycyclic aromatic hydrocarbons (PAHs), which are classified as carcinogens. PAHs are complex molecules composed of two or more fused benzene rings and are formed mainly due to the incomplete combustion of organic materials [1]. Atmospheric PAHs are a health concern because they can lead to respiratory issues, such as impaired lung function, bronchitis, and lung cancer. Due to these risks, both the European Community and the U.S. Environmental Protection Agency have designated PAHs as priority pollutants [2].

Due to rapid economic growth, urbanization, and industrialization, coupled with a rapidly increasing population, Cambodia, a country in Southeast Asia, has also been concerned about air pollution, especially in Phnom Penh city. The Clean Air Plan of Cambodia has identified transportation as one of the top three contributors to Cambodia's PM<sub>2.5</sub> and black carbon (BC) emissions [3]. Rapid economic growth in Cambodia has led to a surge in fuel consumption and industrial activity, resulting in air pollution levels that far exceed the safety standards set by the World Health Organization (WHO). In 2019, the population-weighted annual exposure to fine particulate matter (PM<sub>2.5</sub>) reached 22.1 µg/m<sup>3</sup>—more than four times the limit recommended by the WHO guidelines. This degree of pollution represents a severe public health crisis; in 2019 alone, exposure to ambient and household PM<sub>2.5</sub> was linked to approximately 17,000 premature deaths nationwide [3]. However, relying solely on stationary ambient monitoring data fails to capture the acute exposure variability experienced in high-risk microenvironments, particularly during daily commutes. In Phnom Penh, the transportation landscape is characterized by heavy congestion and the prevalence of open-air vehicles, such as motorcycles and tuk-tuks. Unlike passengers in enclosed automobiles, these commuters face direct, unfiltered exposure to vehicle emissions within urban street canyons, where pollutants are trapped and concentrated. Consequently, there is a critical lack of data regarding personal exposure to PM-bound PAHs in this demographic. This study investigated the concentration, distribution, and sources of PM<sub>2.5</sub>-bound PAHs, specifically comparing exposure levels between Bus and Tuk-Tuk commuters along a Phnom Penh City Bus Line. The findings will provide comprehensive and systematic data to support air quality management, not only in Phnom Penh but also in other Southeast Asian regions with similar urban environments.

## 2 Methodology

### 2.1 Sampling strategy

The study was conducted in Phnom Penh, the capital city of Cambodia, along city bus line 7 connecting the north to the south regions of Phnom Penh. The total length is approximately 21.4 km with the total number of bus stops of 96. Sampling was conducted along Phnom Penh City Bus Line 7, originating at the Kilometer No. 9 terminal and terminating at the Veal Sbov terminal. The data collection campaign spanned 14 days (February 18, 2025, to March 3, 2025). To ensure concurrent data, trips for both transport modes (Bus and Tuk-Tuk) commenced simultaneously, maintaining an average travel speed of approximately 40 km/h. Each sampling

day consisted of two round trips: a morning shift (starting at 06:30) and an afternoon shift (starting at 14:00). Due to traffic variability, one round trip duration ranged from 2–3 hours for Tuk-Tuks and 3–4 hours for buses.

Commuter PM<sub>2.5</sub> exposure was monitored using a personal air sampler assembly consisting of an impactor (Model ATPS-20H, SIBATA Sci. Tech., Tokyo, Japan) connected to a portable suction pump (Model MP-Σ100 HNII, SIBATA). The pump was operated at a constant flow rate of 1.5 L/min. Particle size selection was achieved via a metal impaction plate coated with silicon grease positioned immediately downstream of the inlet to remove particles larger than PM<sub>10</sub>. Particles 2.5–10 μm passed through the impaction plate and were also collected on the grease-coated plate. The target PM<sub>2.5</sub> fraction was collected on a 20 mm Emfab filter (TX40HI20-WW, Pall Life Sciences, Ann Arbor, MI, USA). Samples were stored at -20°C until chemical analysis. Prior to gravimetric analysis, the filters were equilibrated in a controlled weighing chamber for a minimum of 48 hours.

To capture daily integrated exposure, the filters were not replaced between the morning and afternoon shifts; thus, each sample represented the cumulative exposure of one full day (morning and afternoon combined), resulting in a total of 48 samples. The time spent waiting at the stations or outside the vehicles was excluded from the recording. The data collectors were non-smokers and were required to wear protective masks throughout the sampling period to minimize bias and ensure safety. In Tuk-Tuks, the sampler was positioned directly behind the driver, and in buses, the sampler was seated near the door. Logbooks were used to record travel times, traffic anomalies, and exposure-related incidents.

## 2.2 PAH extraction and analysis

Ten PAHs, including fluoranthene (Flu), pyrene (Pyr), benz[*a*]anthracene (BaA), Chrysene (Chr), benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF), benzo[*a*]pyrene (BaP), Dibenzo[*a,h*]anthracene (DBA), benzo[*ghi*]perylene (BghiP) and indeno [1,2,3-*cd*]pyrene (IDP) (Supelco Park, Bellefonte, PA, USA) were analysed in this study.

The PM<sub>2.5</sub> filter samples were extracted with 10 mL of dichloromethane (DCM) using ultrasonication for 10 min. The extract was filtered, and the extraction process was repeated to optimize the recovery. The extract was spiked with 20 μL of internal standard (benzo[*a*]anthracene-*d*<sub>12</sub>, 100 ppb) and 20 μL of dimethyl sulfoxide (DMSO). The solvent was reduced using a centrifugal evaporator at 40°C. Finally, the resulting DMSO solution was mixed in 180 μL of acetonitrile (ACN) and sonicated for 2 minutes. The final solution was aliquoted into HPLC vials for analysis.

PAH concentrations were determined using a high-performance liquid chromatography (HPLC) system (Shimadzu, Japan) equipped with a fluorescence (RF-20Axs) detector. Chromatographic separation was achieved using two tandem Inertsil ODS-P columns (4.6 mm I.D. × 250 mm, 5 μm particle size; GL Sciences, Tokyo, Japan) protected by a guard column (10 × 4.6 mm I.D.). The column temperature was maintained at 20°C. The mobile phase consisted of 100% ACN delivered isocratically at a flow rate of 1.8 mL/min. The total runtime was 60 min. The RF-20Axs detector operated on two channels using programmed wavelength switching (time-programmed excitation and emission pairs) to optimize the sensitivity for individual PAHs. Quantification was performed using the internal standard. To ensure data quality, standard mixtures were analysed within every sample batch to monitor retention time shifts and instrument stability.

### 3 Results and Discussion

#### 3.1 Commuter exposure to PM<sub>2.5</sub>

The analysis of exposure levels revealed a distinct mode-dependent pattern (Table 1). Tuk-tuks exhibited significantly higher PM<sub>2.5</sub> levels than buses in the overall assessment ( $p < 0.05$ ). The most pronounced difference occurred on weekdays, where the mean concentration in tuk-tuks reached 119.8 compared to 69.4  $\mu\text{g}/\text{m}^3$  in buses. During the sampling period, elevated PM<sub>2.5</sub> levels may have been influenced by the ongoing construction of the Preah Monivong flyover, which caused daily traffic congestion at the Kbal Thnal intersection. Construction activities and heavy traffic likely contributed to increased dust and emissions, affecting the air quality along the route and potentially affecting the exposure levels recorded in this study. These findings align with previous research, indicating that open or semi-open transportation modes typically result in higher exposure to traffic-related air pollution. Furthermore, these values significantly exceeded both the WHO and the Ministry of Environment (MoE) of Cambodia guidelines. The WHO recommends 24-hour and annual means of 15  $\mu\text{g}/\text{m}^3$  and 5  $\mu\text{g}/\text{m}^3$ , respectively, whereas the MoE establishes limits of 50  $\mu\text{g}/\text{m}^3$  and 25  $\mu\text{g}/\text{m}^3$ , respectively. Active commuters in urban microenvironments face an elevated risk of exposure to air pollutants. Current health risk assessments often underestimate this burden by relying on data from stationary monitoring sites rather than personal exposure measurements. This reliance often leads to an underestimation of cumulative pollution intake during commuting. Although commuting represents only a fraction of daily activity, it disproportionately contributes to the total daily inhalation dose of air pollutants. However, it is important to note that these data are based on preliminary testing, and long-term monitoring would likely provide more accurate and comprehensive results.

**Table 1.** Average PM<sub>2.5</sub> mass concentrations in Bus and Tuk-Tuk.

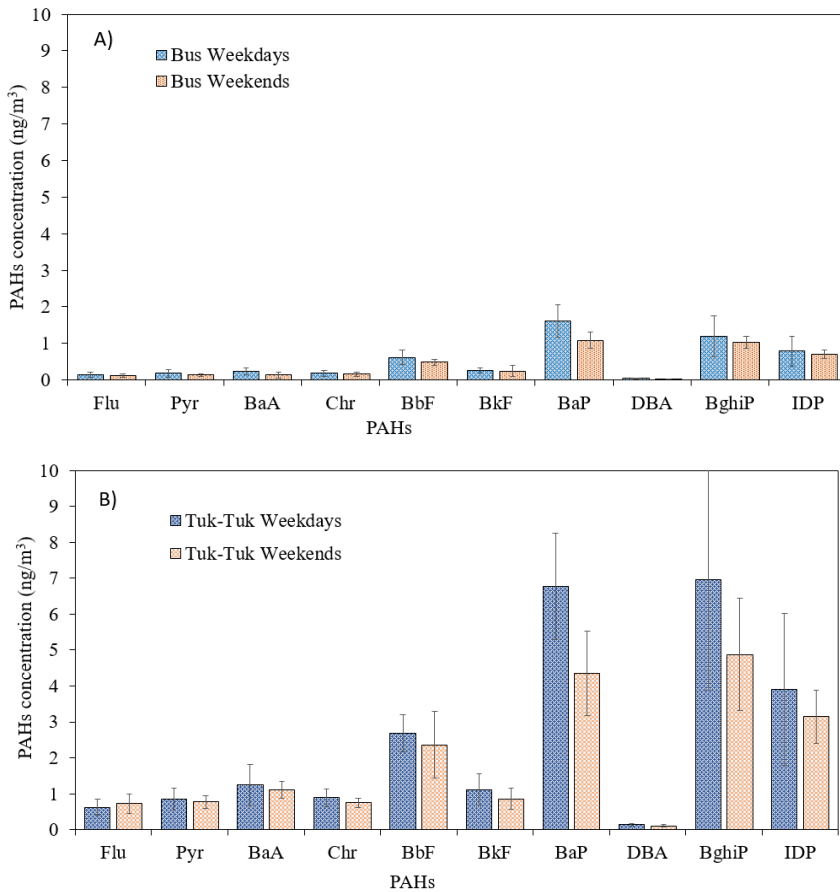
	Average PM <sub>2.5</sub> mass concentration ( $\mu\text{g}/\text{m}^3$ )	
	Bus	Tuk-Tuk
Weekdays	69.4 $\pm$ 42.4	119.8 $\pm$ 46.6*
Weekends	89.2 $\pm$ 35.0	108.2 $\pm$ 26.0
Overall	76.0 $\pm$ 39.7	115.9 $\pm$ 36.3*

\* PM<sub>2.5</sub> concentrations of Tuk-Tuks were significantly higher than those of buses ( $p < 0.05$ ).

#### 3.2 Commuter exposure to PAHs

Figure 1 shows the average concentration of PAHs in the bus and Tuk-Tuk samples during the sampling period. The results revealed a disparity in the exposure levels between the two transport modes. Commuters utilizing Tuk-Tuks (Fig. 1.B) were exposed to significantly higher PAH concentrations than bus passengers (Fig. 1.A) across all the measurements. The average of  $\Sigma_{10}\text{PAH}$  was 4.88  $\pm$  1.43  $\text{ng}/\text{m}^3$  in buses and 23.40  $\pm$  6.70  $\text{ng}/\text{m}^3$  in Tuk-Tuks. The high-molecular-weight PAHs such as BaP, IDP, and BghiP exhibited the highest concentrations on both buses and Tuk-Tuks, with BaP averaging 1.47  $\pm$  0.46 and 6.08  $\pm$  1.77  $\text{ng}/\text{m}^3$ , IDP averaging 0.77  $\pm$  0.35 and 3.69  $\pm$  1.88  $\text{ng}/\text{m}^3$ , and BghiP averaging 1.15  $\pm$  0.48 and 6.37  $\pm$  2.84  $\text{ng}/\text{m}^3$  in buses and Tuk-Tuks, respectively. Other studies have also reported that BghiP, IDP, and BaP were the dominant PAH species in other urban areas such as Taiwan, Bangkok, Beijing and Shanghai. Conversely, lower molecular weight PAHs such as Flu, BaA, and Chr were present at much lower levels. These compounds are more volatile and semi-volatile, and their gaseous

forms may not be efficiently captured by the particulate filters used in personal air samplers. Due to prolonged idling, traffic congestion, and longer travel durations during weekdays, PAH concentrations were higher on weekdays than on weekends.



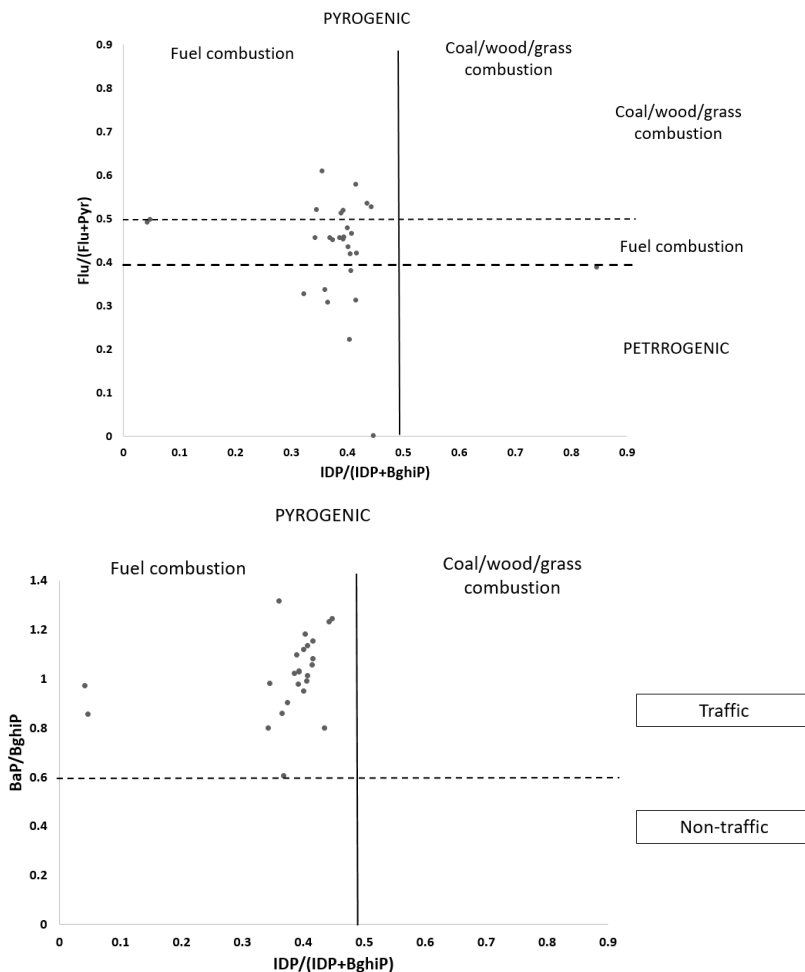
**Fig. 1.** Average PAH concentrations in A) Bus and B) Tuk-tuk.

### 3.3 Sources identified by PAH diagnostic ratios

The isomer ratios of selected PAH compounds are widely used as indicators for tracing transport pathways and identifying pollution sources. These diagnostic markers are particularly effective in differentiating between petrogenic (petroleum-derived) and pyrogenic (combustion-derived) origins. Source apportionment relies heavily on specific molecular markers, particularly those with a molecular weight of 202, such as the ratio of Flu to Flu+Pyr. For this ratio, values from 0.40 to 0.50 serve as critical transition points distinguishing between unburned petroleum and combustion emissions. Additionally, markers with a molecular weight of 276 were utilized; specifically, an IDP to IDP+BghiP ratio exceeding 0.50 is indicative of solid fuel combustion (grass, coal, or wood). A secondary, albeit less definitive, metric involves the BaP/BghiP ratio, which distinguishes between traffic and non-traffic sources [2].

To further distinguish the potential sources of PAHs in our data, the diagnostic ratios of individual PAHs, such as Flu/Flu+Pyr, BaP/BghiP, and IDP/IDP+BghiP, were used as indicators for source identification. Figure 2 shows the application of molecular indices for the evaluation of PAH contamination sources in buses and Tuk-Tuks in Phnom Penh. The

diagnostic ratios provide strong evidence that vehicular traffic is the predominant source of PAHs in the studied microenvironments. The plot of BaP/BghiP versus IDP/IDP+BghiP revealed that the vast majority of samples fell within the "Traffic" classification zone. Specifically, the BaP/BghiP ratios consistently exceeded the 0.6 threshold, with most values clustered between 0.8 and 1.3, which is a signature of mobile fuel combustion rather than stationary industrial sources [1]. The IDP/IDP+BghiP ratios were concentrated almost exclusively below 0.5, a range indicative of liquid fossil fuel combustion (gasoline and diesel) rather than solid fuels such as coal or wood. However, the vertical distribution of the Flu/Flu+Pyr ratio (Figure 2) suggests a more complex mixing of sources. Although many samples cluster within the 0.4–0.5 band characteristic of liquid fuel combustion, a significant subset of data points extends above the 0.5 threshold. Values exceeding 0.5 are typically associated with pyrogenic sources such as grass, wood, and waste combustion. Given the urban context of Phnom Penh, this likely reflects the influence of local non-traffic activities such as street-side cooking (charcoal) or open waste burning mixed with the dominant traffic exhaust plume.



**Fig. 2.** Application of molecular indices for evaluation of PAH contamination sources.

## 4 Conclusion

This study provides the first comprehensive assessment of personal exposure to PM<sub>2.5</sub>-bound PAHs in commuter traffic in Phnom Penh. Commuters utilizing open-air vehicles (Tuk-Tuks) were subjected to extreme levels of carcinogenic PAHs, whereas the closed environment of the public bus system significantly reduced exposure, acting as a protective barrier against direct exhaust plumes. Source apportionment using diagnostic ratios confirmed that vehicular traffic is the predominant driver of PAH pollution in these microenvironments. The diagnostic markers, specifically BaP/BghiP ratios significantly exceeding 0.6 and IDP/IDP+BghiP ratios typically below 0.5, pointed to liquid fossil fuel combustion (gasoline and diesel) rather than biomass or coal burning. While some evidence of mixed sources exists, the chemical signature matches the heavy congestion profile of the urban street canyons of Phnom Penh's. The dominance of high-molecular-weight PAHs, particularly the potent carcinogen BaP, raises serious concerns regarding public health. The exposure levels recorded for Tuk-Tuk passengers, especially on weekdays, suggest a substantial cumulative health risk for the workforce relying on this mode of transportation. This study provides evidence that the mode of transportation significantly influences personal exposure to hazardous air pollutants in Phnom Penh. These findings call for targeted air quality regulations, public awareness campaigns, and investments in cleaner public transport systems to safeguard commuter health and improve environmental conditions in the city. Further studies with larger sample sizes and longer monitoring periods are recommended to strengthen the evidence base and inform comprehensive policymaking.

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