Characterizing Traffic-Related Ultrafine Particles in Roadside Microenvironments: Spatiotemporal Insights from Industrial Parks

Sultan F.I. Abdillah¹,²,³, Sheng-Jie You²,³, Ya-Fen Wang²,⁴*

¹ Department of Civil Engineering, Chung Yuan Christian University, Zhongli, Taoyuan 32023, Taiwan
² Department of Environmental Engineering, Chung Yuan Christian University, Zhongli, Taoyuan 32023, Taiwan
³ Center for Environmental Risk Management, Chung Yuan Christian University, Zhongli, Taoyuan 32023, Taiwan
⁴ Sustainable Environmental Education Center, Chung Yuan Christian University, Zhongli, Taoyuan 32023, Taiwan

ABSTRACT

Ultrafine particles (UFPs; PM<0.1) and black carbon (BC) were measured at different roadside microenvironments in the vicinity of the urban industrial park area. Simultaneous measurement campaigns were conducted at industrial roadside (IN), residential roadside (RS), and urban background (UB) throughout different seasons. Spatiotemporal variability as well as correlations between pollutants and confounding factors (traffic profiles and meteorological conditions) were analyzed. The observed average roadside UFPs particle number concentration (UFPs PNC) and BC concentrations were in the order of IN (38,000 ± 9,000 # cm⁻³ and 2,500 ± 600 ng m⁻³) > RS (25,000 ± 8,000 # cm⁻³ and 1,900 ± 300 ng m⁻³) > UB (23,000 ± 9,000 # cm⁻³ and 1,400 ± 300 ng m⁻³). Furthermore, 11.26%–16.06% and 20.35% –24.32% increases of the average UFPs PNC and BC mass concentrations were identified during cold period at all measurement sites. Additionally, peak average concentrations of UFPs PNC and BC were identified at IN and RS during morning rush-hour and weekdays periods, following the diurnal profiles of traffic flux compositions and total vehicle number per day. Intra-urban spatial variability of UFPs was identified between roadsides and urban background (IQR/M ratio ≥ 2, p ≤ 0.05), highlighting the heterogeneity characteristic of the pollutant. Both pollutants at IN and RS were significantly influenced by traffic activities, while at UB, they were associated with meteorological conditions and secondary emission. Elevated levels of pollutants identified in this study have exceeded typical “high-level” UFPs according to WHO AQG 2021, indicating an intensified exposure risk for pedestrians and residents. This study serves as reference for future epidemiological study related to roadside UFPs in typical urban microenvironments such as industrial park areas.

Keywords: Black carbon, Roadside microenvironments, Spatiotemporal variability, Ultrafine particles, Urban industrial park

1 INTRODUCTION

Current studies have highlighted the impacts of ultrafine particles (UFPs) and black carbon (BC) on human health (HEI, 2013; Silva et al., 2022; Zhang et al., 2022; Zhu et al., 2023). Chronic exposure to these pollutants has been linked with cardiovascular disease (CVD), chronic obstructive pulmonary disease (COPD), pre-term birth, and congestive health failures. Typically, the emitted particles which considered as UFPs are particulates with diameter size below 100 nm (Abdillah and Wang, 2023). UFPs may originate from various anthropogenic emission sources including industrial
activities, construction activities, coal and biomass burning, cooking activities, and traffic activities (Chen et al., 2022; Abdillah and Wang, 2023). Among those, emissions from traffic activities have been regarded as an important source for not only UFPs, but also BCS (Isley et al., 2017; Liati et al., 2018; HEI, 2022; Huyen et al., 2023). Furthermore, UFPs generated from the traffic could potentially be more toxic as they carry various types of toxic compounds such as heavy metals, trace elements, and toxic chemicals (Ramirez et al., 2020). These particular findings have escalated the exposure risk of traffic-related UFPs to typical residents and pedestrians, especially in urban areas where very high traffic activities are commonly found (He et al., 2023; Pradhan et al., 2023).

Owing to their size, UFPs possess distinct characteristics in terms of properties and concentrations (Cassee et al., 2015; Presto et al., 2021; Abdillah and Wang, 2023). Their concentrations are heavily dependent on numerous factors including, emission sources, environmental conditions, and also physicochemical processes that may happen among gaseous precursors in the presence of differences emission profiles (Li and Signorell, 2021; Chen et al., 2023). For instance, the gas pollutants (SO₂, NOₓ) emitted from vehicles exhaust could condense immediately to produce secondary particles through photochemical reactions (Jeong et al., 2022; Abdillah et al., 2024). Therefore, the spatiotemporal variations of UFPs in roadside environments ought to be more complicated than traditional coarse particles such as PM₂.₅ or PM₁₀.

Recent investigations pertaining to traffic-related pollutants have deployed different methods including on-road mobile measurement and roadside fixed measurements with varying distances or urban profiles (Vouitis et al., 2014; Wu et al., 2015; Nie et al., 2022; Rajagopal et al., 2023). Most of the studies have reported a particularly high level of UFPs particle number concentrations (UFPs PNC) and BC in the roadside microenvironments. For instance, Nie et al. (2022) have identified approximately 21,000 ± 14,000 # cm⁻³ of UFPs PNC and 3,600 ± 2,900 ng m⁻³ of BC in the roadside of major highway in Xian, China. These levels of UFPs concentrations are considered “high” and may become one of the complementing factors which contribute to the increased adverse health effects according to the WHO Air Quality Guideline 2021 (WHO, 2021). More importantly, roadside UFPs studies have identified intra-urban spatial variability characteristic of UFPs which have led to a highly varying number concentrations within one small urban area (Weichenthal et al., 2014; Wu et al., 2015; Zheng et al., 2021). These results have highlighted the critical role of traffic activities to the UFPs concentrations in urban profiles, specifically in developed cities where high amount of vehicle activities can be identified every day.

Currently, there are limited studies that have investigated the spatiotemporal variability of these traffic-related UFPs at the roadside microenvironments. Investigating the fate of these traffic-related pollutants near the road is essential to determining the change of concentration and their distribution from the traffic emission source to the ambient air. Furthermore, it would also elucidate the differences in particle concentration distribution between different roadside conditions and various emission profiles (traffic number and vehicle compositions). Therefore, this study aims to characterize the spatiotemporal variations of UFPs PNC and BC mass concentrations at different roadside microenvironments in the vicinity of the urban industrial park area. Furthermore, correlations between pollutants and potential contributing factors (traffic activities and meteorological conditions) were also investigated in this study. The findings of this study may contribute to an essential future investigation of roadside UFPs in specific microenvironments such as industrial parks, which are still relatively unknown.

2 METHODOLOGY AND INSTRUMENTATIONS

2.1 Overview of Study Sites

In this study, measurements were conducted at different types of roadside environments in industrial park area located in Zhongli district (24°57′25″N, 121°13′25″E), Taoyuan City, Taiwan (Fig. 1(a)). It has a total area of 76.52 km² with total population around 397,083 people per 2017 (TYCG, 2021). This district is included in one of the designated sites for Taoyuan Industrial Park developmental plan (Fig. 1(b)). Taoyuan houses a diverse range of industry clusters from food manufacturing, textile, chemical, automotive, logistics, aviation, optoelectronics, and biotechnology (TYCG, 2021).
Fig. 1. (a) Overview of study area in Taiwan, (b) Taoyuan city industrial park plan (TYCG, 2021), (c) and (d) area distribution of Zhongli industrial park and measurement locations.

The industrial park vicinity covers two district profiles of industrial and residential areas where both are connected by different roads (Figs. 1(c–d)). Between both areas, there is a community park which is designated as urban background area in this study. The average daily traffic volume on the industrial roadside can reach up to 12,000 vehicles day\(^{-1}\) and 3,500 vehicles day\(^{-1}\) on the residential roadside. The main difference between these two roadside profiles is their emission sources profiles. Industrial activities and heavy-duty vehicles mainly contributed to the pollutant concentrations in the industrial roadside. On the other hand, the primary emission source in the residential roadside come from different vehicle composition such as small trucks, pick-ups, and motorcycles.

2.2 Measurement Campaigns

Seasonal data collection campaigns which consisted of 6 weeks of measurement activities were conducted at three corresponding sampling sites (Fig. 1). The measurement activities were rolled out on 4–24 July 2022 for the warm period and 31 October–20 November 2022 for the cold period. Daily measurement for UFPs PNC, BC mass concentration, meteorological conditions, and vehicle activities were conducted continuously at each of the respective sampling sites by two pairs of personnel (Table S1). The daily measurement durations were 10-hours (08.00 AM–18.00 PM) and pollutant concentrations were collected at 1-minute measurement interval. In total, 3-weeks of daily measurements data were obtained for each seasonal measurement period, with 1-week data collected for urban background (UB) and 2 weeks of simultaneous measurement data for the industrial (IN) and residential roadside (RS).

Measurements for IN was conducted at Jilin N. Road, Zhongli District, Taoyuan City, 320, Taiwan. This roadside was chosen as it exists adjacent to several industrial plant facilities which become the main part of Zhongli Industrial Park. As for RS, the measurement was done in Jili 11th
Fig. 2. Detailed measurement locations in Industrial Roadside (IN), Residential Roadside (RS), and Urban Background (UB).

Road, Zhongli District, located approximately 1 km from the outer part of the industrial park. UB measurement was carried out in Zhongshan community park located at the center of IN and RS (Fig. 2). No measurement activities were conducted during rain to preserve the mobile sampling instruments used in this study.

2.3 Measurement Instruments and Calibrations

Several high-time-resolution measurement instruments for UFPs and BCs were put inside a housing platform which has been fixed at each roadside microenvironment prior to daily monitoring activities. The distance between the housing platform (measurement point) and the roads was set to 1.25 meters. The measurement inlet was 150 cm above ground (breathing height of average Asian adults). In UB, instrument housing was set up on the gazebo platform in the middle of the community park. Portable external power sources were used to maintain the portable instruments lifetime. All instruments have been calibrated according to their factory standards, and their inter-comparability has been ensured prior to the measurement activities. The list of measurement instruments and their associated parameters are summarized in Table S2.

2.3.1 UFPs particle number concentrations (UFPs PNC)

A pair of portable condensation particle counters (TSI CPC 3007) was used to measure the number concentrations of ultrafine particles (# cm\(^{-3}\)) during the study. This particle counter instrument could quantify UFPs PNC with sizes ranging from 10 nm–1000 nm. It operates in the concentration range between 1–100,000 # cm\(^{-3}\). The instruments principle works by relying on the surface condensation process of ultrafine particles. Afterward, condensed ultrafine particles will be counted by laser optical counter at downstream part of the instrument.

2.3.2 Black carbon (BC)

The BC mass concentration (ng m\(^{-3}\)) was measured by utilizing portable Aethalometer (MicroAeth AE51). This instrument estimates the BC concentration through the light absorption principle. Briefly, BC was estimated by dividing the value of attenuated light intensity (I) with the amount of light intensity which is passing through the clean filter paper (I₀), as written in Eq. (1).
The estimated equivalent BC mass concentration value was then calculated by MicroAeth AE51 instrument by the infrared light attenuation at 880 nm wavelength by Eq. (2):

$$BC \left( \text{ng m}^{-3} \right) = \frac{10^6}{\sigma_{ATN}} \times \left[ \frac{A \times \Delta ATN}{100 \times Q \times \Delta t} \right]$$

where, $\sigma_{ATN}$ represents mass attenuation coefficient of BC, $Q$ represents inlet flow rate (m$^3$s$^{-1}$) of MicroAeth AE51, $A$ represents filter paper area, and $\Delta t$ represents the measurement time.

Acquired BC concentration data were processed prior to further analysis to compensate optical noise generated from loading effect on filter paper that led to a decreased value of $\Delta ATN$ (negative measurement results). Therefore, an R package which could process the BC dataset by using optical noise-reduction averaging algorithm (ONA) was applied to correct the data (Hagler et al., 2011; Sanjeev, 2020). In short, ONA recognize the $\Delta ATN$ between consecutive readings and removes data spikes associated with $\Delta ATN < 0.05$. ONA then averages BC mass concentration data throughout time intervals associated with $\Delta ATN = 0.05$.

### 2.3.3 Meteorological data

Hourly meteorological conditions data including relative humidity (RH), wind direction (WD), wind speed (WS), and temperature were obtained from Taiwan Central Weather Bureau (TCWB) observation data platform (TCWB, 2022). The acquired weather data was selected from the online monitoring results of the local weather station which was located near to the study area.

### 2.3.4 Traffic activities and vehicle compositions

Throughout the whole measurement campaign, two pairs of personnel manually recorded traffic compositions using digital tally at each roadside microenvironment. Recorded traffic activities data were categorized into heavy vehicles, gasoline cars, and motorcycles. It should be noted that the profile of heavy vehicles in industrial roadside was completely different than in residential roadside area. Heavy vehicles at IN consisted of heavy-duty containers, city buses, industrial vehicles (excavator, forklifts, tractors), and trucks. On the other hand, heavy vehicles at RS consisted of only small trucks and minibuses which occasionally drove across the road.

### 2.4 Data Analysis

Descriptive statistic method was used to organize all collected data and visualize the spatiotemporal variability of UFPs PNC and BCs. Obtained data were dynamically averaged at 1-h time resolution by conducting t-test of variance analysis. Outliers (outside 95% CI) were also removed prior to analysis. Pearson’s $r$ correlation was used to analyze the correlations between potential confounding factors (traffic activities and meteorological data) and observed pollutants concentrations. In addition, interquartile range/median ratio (IQR/M) ratio analysis was deployed to investigate the existence of intra-urban spatial variability of the roadside ultrafine particles (Rakowska et al., 2014; Wu et al., 2015). Briefly, intra-urban spatial variability between each measurement site could be identified if the difference of IQR/M ratio are $\geq 1.5$ (Wu et al., 2015). Figures and statistical analysis results were generated from OriginPro software (OriginLab, v2022).

## 3 RESULTS AND DISCUSSIONS

### 3.1 Seasonal Variability of Roadside UFPs and BCs

Initially, the overall concentrations of UFPs PNC and BC throughout the whole measurement campaigns were varied between three corresponding sampling sites. IN exhibited the highest
average of UFPs PNC and BC concentration ($\pm 38,000 \pm 9,000 \# \text{cm}^{-3}$ and $25,000 \pm 600 \times 10^3 \text{ng m}^{-3}$) and then it was followed by RS with ($25,000 \pm 8,000 \# \text{cm}^{-3}$ and $1,900 \pm 300 \text{ng m}^{-3}$), and UB with ($23,000 \pm 9,000 \# \text{cm}^{-3}$ and $1,400 \pm 300 \text{ng m}^{-3}$). However, throughout different seasons UFPs PNC and BC concentrations were obviously higher during cold period compared to warm period. The average meteorological conditions observed in this study are presented in Table 1. The average UFPs PNC and BC in IN during cold period could reach up to $41,200 \pm 10,400 \# \text{cm}^{-3}$ and $2,720 \pm 610 \text{ng m}^{-3}$, which was significantly higher compared to warm period with $35,500 \pm 8,600 \# \text{cm}^{-3}$ and $2,260 \pm 460 \text{ng m}^{-3}$ (Table S3). In overall, 11.26%–16.06% and 20.35%–24.32% increase of average UFPs PNC and BC mass concentrations were identified during cold period at all measurement sites. Furthermore, the measurement results have at three sites have also shown a substantial increase in the distribution of average hourly concentrations for UFPs PNC and BC (Figs. S1(a–d)). The underlying reasons on why the pollutants concentrations were higher during cold period might be related to the characteristics of atmospheric behavior in a lower temperature condition.

During typical winter or cold conditions, lower levels of atmosphere exhibits higher condensation sink and lower solar intensity than in other seasons (Young et al., 2012; Pikridas et al., 2015). Therefore, the conditions could inhibit the rate of particle growth in the upper atmosphere, leading to a higher concentrations of pollutants (Argyropoulos et al., 2016; Cheung et al., 2016). In addition, the temperature inversion phenomena which often occur during the cold seasons may suppress vertical transport and vertical mixing process of the particles via stable stratification process (Li et al., 2019; Rose et al., 2021). On the other hand, temperatures during warm season vary more widely within a day, leading to an intensified vertical mixing effects compared to cold season (Agudelo-Castañeda et al., 2019). In summary, lower temperature during cold period may promote the accumulation of pollutants. Hence, it may explain the seasonality of UFPs PNC and BC observed in this study.

Furthermore, similar seasonality characteristics were also identified in several urban settings. For instance, Cheung et al. (2016) reported a higher level of UFPs PNC during winter ($17,400 \pm 4,700 \# \text{cm}^{-3}$) compared to summer ($16,700 \pm 7,600 \# \text{cm}^{-3}$) in ambient air of Taipei, Taiwan. On the other hand, Kurppa et al. (2015) have also reported a substantial increase of UFPs PNC during winter in Helsinki, Finland. These findings could further highlight the effects of seasonality on the concentrations of roadside UFPs PNC and BC. As have been previously mentioned, the occurrence of seasonal variations on the UFPs PNC is highly related to the solar intensity and condensation sink conditions of the atmosphere (Pikridas et al., 2015; Cheung et al., 2016; Chen et al., 2017). On the other hand, solar intensity may also vary throughout diurnal cycle, when highest solar intensity can be observed at noon and lowest at midnight (Lee et al., 2021; Young et al., 2023). In the cold period, all sampling sites (IN, RS, UB) demonstrated strong peaks for UFPs PNC and BC as the result of lower atmospheric ventilation (Figs. 3(a–f)). Interestingly, the semi-diurnal profiles of observed UFPs PNC and BC during winter were not significantly different compared to warm period apart from their concentrations level (Figs. 3(a–f)). However, it is important to notice that IN and RS exhibited distinct semi-diurnal concentrations trends compared to UB.

IN and RS possessed similar semi-diurnal patterns where strong peaks were identified during typical morning and evening rush hours at the period of 08.00–11.00 and 15.00–18.00 (Figs. 3(a–d)). However, the peak concentration at UB was only identified during the noon period and it gradually decreased until evening (Figs. 3(e–f)). The average semi-diurnal profiles of UFPs PNC and BC at IN and RS indicated the combined effects of traffic activities and atmospheric ventilation patterns (Gani et al., 2021). On the other hand, the UFPs PNC trend in urban background might follow the daily variation of solar intensity, indicating that majority of the observed PNC were from secondary emission process (Nie et al., 2022). This finding is notably different from other typical roadside

### Table 1. Summary of average meteorological conditions observed during study.

<table>
<thead>
<tr>
<th>Meteorological Factors</th>
<th>Warm Period</th>
<th>Cold Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>29.57°C</td>
<td>23.58°C</td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>74.73%</td>
<td>81.62%</td>
</tr>
<tr>
<td>Wind Speed (m s⁻¹)</td>
<td>1.99 m s⁻¹</td>
<td>2.89 m s⁻¹</td>
</tr>
<tr>
<td>Frequent Wind Direction</td>
<td>West</td>
<td>East</td>
</tr>
</tbody>
</table>
3.2 Peak Periods Concentrations

Figs. 4(a–b) highlighted the weekly variations of average UFPs PNC and BC concentrations during warm and cold periods. The daily hourly average of UFPs PNC and BC concentrations gradually increased from Monday to Friday in the weekdays period. Afterwards, the concentrations were significantly dropped during the weekend period for both pollutants. For instance, the UFPs PNC and BC in warm period at IN during weekdays could reach up to $37,700 \pm 7,400$ # cm$^{-3}$ and $2,350 \pm 500$ ng m$^{-3}$, whereas during weekend the average was only $29,900 \pm 8,900$ # cm$^{-3}$ and $2,050 \pm 280$ ng m$^{-3}$ (Table 2). It was also observed that the weekly variations of UFPs PNC and BC at IN were similar with RS. However, UB exhibited distinct trend that might be attributed to the difference of emission profile.

The seasonality of UFPs PNC and BC could also be identified in the weekly concentration variations of these pollutants (Figs. 4(a–b)). For example, the average weekdays UFPs PNC and BC concentrations at IN during winter could reach up to $45,800 \pm 8,700$ # cm$^{-3}$ and $2,850 \pm 650$ ng m$^{-3}$, which was obviously higher than the weekdays concentration during warm period with $37,700 \pm 7,400$ # cm$^{-3}$ and $2,350 \pm 500$ ng m$^{-3}$. The same instances were also identified during weekend where the average concentrations in residential roadside reached up to $20,400 \pm 4,400$ # cm$^{-3}$ and $1,810 \pm 270$ ng m$^{-3}$ during winter and $17,200 \pm 4,900$ # cm$^{-3}$ and $1,480 \pm 260$ ng m$^{-3}$. These findings indicated specific emission patterns of UFPs PNC and BC during certain peak periods throughout the week.

Furthermore, observed roadside UFPs PNC and BC concentrations in this study exhibited distinct concentration patterns during morning (08.00–11.00) and afternoon (15.00–18.00) peak/rush periods (Figs. 5(a–d)). In overall, measured UFPs PNC and BC concentrations were considerably higher during peaks period compared to non-peak period. Average UFPs PNC during morning peaks period at IN were 14.73% and 23.65% higher compared to non-peak periods in warm and cold periods. Additionally, morning peak BC concentrations at IN were also 11.39% and 19.73%
higher. This result is relatively similar to previous on-road study in the urban road of Taipei, Taiwan. It was reported that during rush hour period (08.00–10.30 and 17.00–19.30), the amount of UFPs PNC and BC concentrations significantly increased up to 34.80% and 31.80% (Lin et al., 2022). Furthermore, ~95% increase of traffic-related air pollutants (TRAPs) concentrations was also identified in the roadside area of urban highway in Oakland, USA during morning rush hour period (Gani et al., 2021). The substantial increase during this peak period might reflected the dependence of UFPs PNC and BC concentrations towards the instance of traffic composition and flux during that specific period (Wang et al., 2008; Bergmann et al., 2022).

Apart from that, it can be inferred that the average concentrations of UFPs PNC and BC during morning peaks were considerably higher compared to afternoon peak at both IN and RS. Similar studies suggested that the increased concentrations during morning peak was due to the combination effects of peak vehicle flux and intensified solar irradiation rate which promote new particle formation (NPF) event in the roadside (Cheung et al., 2016; Gani et al., 2021; Nie et al., 2022). On the other hand, the peak hours variation of BC concentrations might be solely attributed to the higher number of vehicle flux observed in the morning period compared to the afternoon period (Lin et al., 2022). These findings further suggest the evidence of peaks period variations of UFPs PNC and BC concentrations that were successfully observed in this study.

### 3.3 Intra-Urban Spatial Variability of Roadside UFPs and BCs

Fig. 6 portrayed the IQR/M ratio distributions between UFPs PNC and BC mass concentrations at three corresponding measurement sites. Intra-urban spatial variability of UFPs PNC between roadside sites (IN and RS) and UB were identified proven by the IQR/M ratio difference of > 1.5. Furthermore, BC in UB also exhibited intra-spatial variability with IQR/M ratio of 1.5 times higher than IN. This identified characteristic was retained through the cold period for UFPs PNC while for BC, it was disappeared during the season change. It is important to note that the approximate
Fig. 5. Morning (08.00–11.00) and afternoon peak (15.00–18.00) distribution of average UFPs PNC and BC concentration during (a) and (b) warm period and (c) and (d) cold period.

Fig. 6. IQR/M ratio of UFPs PNC and BC concentration in warm and cold period.
distance between each sampling site is approximately less than 1 km (Fig. 1). These findings highlighted the potential occurrence of intra-urban spatial variability in this study.

Interestingly, the result of this analysis could be used to explain the difference between concentrations level identified at roadsides (IN and RS) and UB. The distinct concentration variations among these three sites could be described by the intra-urban spatial variability characteristic that was possessed by the UFPs PNC. This result is consistent with Wu et al. (2015) where they reported intra-spatial variability between roadside environment with IQR/M ratio difference of up to 3 times higher compared to the other sites. This finding may imply that roadside UFPs PNC in specific roadside microenvironments such as in urban industrial park areas might possess different types of spatial heterogeneity compared to other traditional types of pollutant (e.g., PM$_{10}$, PM$_{2.5}$, NO$_x$, SO$_x$).

### 3.4 Potential Influences of Meteorological Conditions and Traffic Activities

In typical urban microenvironments, the behaviors of UFPs PNC and BC are heavily dependent on various factors, specifically traffic activities and meteorological conditions such as relative humidity, wind direction, wind speed. Similarly, it was hypothesized from seasonality and peak periods analysis that UFPs PNC and BC at IN and RS were originated from traffic activities, while the concentrations at UB was linked to secondary particle emission. The secondary particle emissions process of UFPs PNC are highly influenced by the concentrations of gaseous precursors and specific meteorological conditions (Abdillah and Wang, 2023). Hence, these two factors were considered as the main confounding factors that might influence observed pollutant concentrations in this study.

The summary of observed meteorological conditions and semi-diurnal traffic profiles in this study are presented in Fig. 52, Fig. 53, and Fig. 54. The effect of meteorological conditions to UFPs PNC was more visible at UB, particularly. The semi-diurnal profile of RH was inversely proportional to UFPs concentration at UB (Fig. 52 and Fig. 3(e)). Typically, the variation of RH is also inversely correlated with solar radiation. RH and solar radiation normally played a significant role during NPF process of secondary UFPs (Lee et al., 2021; Zilli Vieira and Koutrakis, 2021). In addition, the scatter plot correlation between UFPs PNC and BC at UB (Fig. 55) indicated that there was no significant correlation between UFPs PNC and BC ($r = -0.04$). These findings have further highlighted the distinct source variation and meteorological effects which occurred at UB during the study period. The observed UFPs PNC at UB would likely consist of secondary UFPs that were influenced by the conditions of RH and solar radiation during NPF process.

On the other hand, influences from traffic related activities on UFPs PNC and BC were obviously identified at IN and RS. Significant correlations were found between UFPs PNC and BC at both IN (r = 0.80, p < 0.005) and RS (r = 0.87, p < 0.05) (Fig. 55). BC is the main tracer pollutant of vehicle exhaust emission from traffic activities (Tang et al., 2022). Furthermore, the peaks in vehicles fluxes at both roadside microenvironments were also simultaneously identified during the daily peak periods of UFPs PNC and BC at morning (08.00–11.00) and evening rush (15.00–18.00) periods (Fig. 54 and Figs. 3(a–d)). The highest average flux and UFPs PNC at both roadsides were identified during peak morning rush period (09.00–10.00) with 1,288–1,409 vehicle/hour and 59,500 # cm$^{-3}$ and 221–262 vehicle/hour and 41,100 # cm$^{-3}$ for IN and RS during cold season. Furthermore, the average UFPs PNC and BC concentration were considerably higher during weekdays at IN and RS (Table 2) in conjunction with the weekly total vehicle flux per day during weekdays (Fig. 56). These findings further highlight the potential influence of traffic activities to the pollutants.

One of the main strengths of this study is related to the different traffic composition observed at IN and RS. In order to assess the extent of contributions for each type of vehicle towards observed UFPs PNC and BC, Pearson’s r statistical method was deployed throughout the measurement datasets (Fig. 7). In overall, UFPs PNC and BC possessed positive significant correlation with number of vehicles observed throughout the whole study ($p \leq 0.01$). For instance, UFPs PNC and BC at IN and RS were significantly correlated with total hourly vehicle flux (IN: r = 0.64 and 0.56, p ≤ 0.01) and (RS: r = 0.80 and 0.70, p ≤ 0.01). More specifically, UFPs PNC and BC at IN exhibited significant correlations with different types of traffic profiles in the strength order of heavy vehicles ($r = 0.69$ and 0.55, $p \leq 0.01$) > motorcycles ($r = 0.63$ and 0.61, $p \leq 0.01$) > gasoline vehicles ($r = 0.40$ and 0.29). Whereas on the other hand, UFPs PNC and BC at RS were positively correlated with the
**Fig. 7.** Pearson’s $r$ correlation heatmap between UFPs PNC and BC and potential confounding factors. Note: Motor = Number of motorcycles; Heavy = Number of heavy vehicles; Gasoline = Number of gasoline cars; TotalVec = Total vehicle numbers.

order of gasoline vehicles ($r = 0.68$ and $0.62$, $\rho \leq 0.01$) > heavy vehicles ($r = 0.58$ and $0.66$, $\rho \leq 0.01$) > motorcycles ($r = 0.51$ and $0.39$, $\rho \leq 0.05$).

From this result, it can be noted that emission from heavy industrial vehicles might have dominated the UFPs PNC and BC at IN, while the UFPs PNC and BC at RS was possibly dominated by gasoline vehicles (Fig. S7). These findings imply that UFPs PNC and BC concentrations are highly dependent on the source emission profiles and might not be constrained to the spatial scale of the urban environment. The spatial variability of UFPs PNC could exist even in the small and specific urban microenvironment such as in the different roadside profiles of urban industrial park area (Cassee et al., 2019). Furthermore, modest correlations between WS and RH and the pollutants were also identified at IN and RS. This result could highlight the possibility of dispersion/dilution phenomena that occurred due to the wind turbulences generated either from traffic activities or wind speed and direction (Kumar et al., 2008). The significantly inversed proportional correlations between RH and UFPs PNC at UB (Fig. 7) could also possibly explain the influences of RH to the secondary emission process that were discussed earlier. These findings have further highlighted the potential confounding effects of traffic activities and meteorological conditions on the roadside UFPs and BC concentrations.

### 4 STUDY LIMITATIONS AND IMPLICATIONS FOR FUTURE RESEARCH

Similar to other studies which used portable measuring instruments, there are several limitations in this study. First, due to instrument constraints, this study only focuses on quantifying UFPs PNC for particles above 10 nm and does not include any discussion about nanoparticles with diameter below 5 nm. Hence, the UFPs PNC measured at UB might be underestimated as the
dominant size of aged UFPs from secondary emission are in the range of 3–15 nm. In addition, traffic activities might also emit very small particles in the range of 2 to < 10 nm as results of aerosol and gas-to-particle phase emissions process of fuel burning. Hence, more adequate instruments and analysis methods such as SMPS and chemical content analysis of the UFPs are needed in the future. Correction algorithm was used to minimize the uncertainty generated from data noise for BC measurement. Furthermore, as various factors may affect the spatiotemporal variability of UFPs PNC, IQR/M ratio analysis method at three different sites might not be strong enough to confirm the characteristic. Further studies with more sampling points, longer time resolutions (i.e., 24-hour and multi-year sampling), and chemical characterizations are essential in the future.

Regardless of the limitations, this study has successfully reported the seasonal variations of UFPs PNC and BC concentrations at different roadside microenvironments in the vicinity of urban industrial park area. Observed results from this study have highlighted elevated risk of exposure in urban industrial park areas compared to other roadside microenvironments studies (Table 3). Based on the findings from this study and recent roadside studies, it can be noted that the average UFPs PNC concentrations in the roadside environments have exceeded the “high level” (> 20,000 # cm⁻³ at 1-h) according to the best practice statement of UFPs in WHO AQG 2021 (WHO, 2021). In addition, annual BC level above 1.15 µg m⁻³ were stated to be the one of the major factors that is associated with adverse health outcomes (WHO, 2021), and it is far below the observed roadside BC level from this study (2.2 µg m⁻³) and other studies. This would imply that roadside environments possess intensified exposure risks toward pedestrians and residents in a typically high-density building in urban environments. Future traffic-related UFPs exposure and health impact assessment (cohort) studies in specific roadside environments are essential to address this potential issue.

Furthermore, it is identified from this study that UFPs possessed intra-urban spatial variability characteristic which is different from traditional PMs. In other words, it emphasized the importance for different policies/approaches for managing resident and pedestrian exposure to these pollutants of concern. Currently, there are no specific guidelines for UFPs and BC. Reflecting on the unique properties of UFPs, they might require more specific approaches which account for their gas-to-particle phase emissions process of fuel burning. Hence, more adequate instruments and analysis methods such as SMPS and chemical content analysis of the UFPs are needed in the future. This study

Table 3. Comparison with previous roadside UFPs and BC measurement studies.

<table>
<thead>
<tr>
<th>Location</th>
<th>Source Profile</th>
<th>Measurement Period</th>
<th>Instruments</th>
<th>Avg. UFPs PNC (# cm⁻³)</th>
<th>Avg. BC (ng m⁻³)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanghai, China</td>
<td>Roadside</td>
<td>Summer: Aug–Sep 2017 Winter: Jan–Feb 2017</td>
<td>UFPs: Aerotrak 9306 BC: MicroAeth AE51</td>
<td>9,500 ± 6,100</td>
<td>4,010 ± 1,900</td>
<td>(Lin et al., 2022)</td>
</tr>
<tr>
<td>Taipei, Taiwan</td>
<td>On-road</td>
<td></td>
<td>UFPs: P-Trak 8525 BC: MicroAeth AE51</td>
<td>30,300 ± 15,000</td>
<td>3,520 ± 1,940</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>61,200 ± 56,911</td>
<td>3,930 ± 2,240</td>
<td></td>
</tr>
<tr>
<td>CTE, Singapore</td>
<td>1. Roadside</td>
<td>June–Aug 2021</td>
<td>UFPs: Testo DiscMini BC: MicroAeth AE51</td>
<td>61,700 ± 55,700</td>
<td>5,900 ± 3,800</td>
<td>(Tran et al., 2022)</td>
</tr>
<tr>
<td></td>
<td>2. Urban Back</td>
<td>July–Sep 2020</td>
<td>BC: MA AE200</td>
<td>10,500 ± 1,500</td>
<td>1,700 ± 1,200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Intersection</td>
<td></td>
<td>UFPs: WRAS 1.371 BC: MA AE200</td>
<td>21,000 ± 14,000</td>
<td>3,600 ± 2,900</td>
<td>(Nie et al., 2022)</td>
</tr>
<tr>
<td></td>
<td>2. Roadside</td>
<td></td>
<td></td>
<td>18,000 ± 13,000</td>
<td>3,100 ± 2,300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Urban Back</td>
<td></td>
<td></td>
<td>6,000 ± 3,000</td>
<td>1,900 ± 1,200</td>
<td></td>
</tr>
<tr>
<td>Xian, China</td>
<td></td>
<td></td>
<td></td>
<td>6,000 ± 3,000</td>
<td>1,900 ± 1,200</td>
<td></td>
</tr>
<tr>
<td>Zhongli, Taiwan</td>
<td>Industrial Roadside</td>
<td>Warm: 04–24 July 2022</td>
<td>UFPs: TSI CPC 3007 BC: MicroAeth AE51</td>
<td>35,500 ± 8,600</td>
<td>2,260 ± 460</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>Residential Roadside</td>
<td>Cold: 31 Oct–20 Nov 2022</td>
<td></td>
<td>41,200 ± 10,400</td>
<td>2,720 ± 610</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urban Background</td>
<td></td>
<td></td>
<td>22,400 ± 6,600</td>
<td>1,760 ± 340</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27,700 ± 7,700</td>
<td>2,130 ± 340</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22,200 ± 9,300</td>
<td>740 ± 250</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24,700 ± 9,400</td>
<td>920 ± 260</td>
<td></td>
</tr>
</tbody>
</table>
have showed major influences of different types of vehicles on the UFPs PNC level at roadside microenvironments. Hence, well-planned control policies for these particular emission sources could be beneficial to address the issue. Several stakeholders have supported the transition into non-combustion vehicle (EV cars) to pursue both net-zero goals and cleaner air quality (Li et al., 2016). However, UFPs might also be generated from non-exhaust process through brake and tyre wears (Piscitello et al., 2021; Abdillah and Wang, 2023). There are currently limited studies which comprehensively characterized the contribution of non-exhaust UFPs in the total UFPs PNC at roadside microenvironments. Hence, future roadside UFPs studies should also focus on this issue to provide substantial insight for stakeholders in developing suitable policies. Future UFPs study may also utilize AI-driven methods to assist in integrating real-time data features such as air quality or traffic vehicles image data that can be used to further analyze intra-urban spatial variability of UFPs or carbonaceous aerosol (Lin et al., 2023).

5 CONCLUSIONS

This study investigated the spatiotemporal variability of UFPs PNC and BC concentrations at different roadside microenvironments and urban background in the vicinity of urban industrial park area. Higher UFPs PNC and BC concentrations were identified at all sampling sites during cold period due to lower mixing and temperature inversion. In addition, peaks average concentrations of UFPs PNC and BC were identified at IN and RS during morning peaks and weekdays periods, following the diurnal profiles of traffic flux compositions and total vehicle numbers per day. Intra-urban spatial variability was identified between roadsides UFPs and urban background UFPs, highlighting the heterogeneity characteristic of UFPs. Furthermore, the findings in this study suggested that the concentrations of UFPs PNC and BC at IN and RS were significantly correlated with traffic activities, while at UB were associated with meteorological conditions and secondary emission. Observed UFPs PNC concentrations at IN were heavily influenced by heavy duty vehicles and motorcycles, while RS was heavily influenced by gasoline cars.

Elevated levels of roadside UFPs and BC identified in this study have exceeded the typical “high-level” of UFPs concentration according to WHO AQG 2021, indicating an elevated exposure risk for pedestrians and residents. Moreover, intra-urban spatial variability characteristic of UFPs and BC identified from this study have further highlighted their difference compared to the currently regulated PMs. Hence, future exposure estimation models in UFPs and BC health effect study should also account for this characteristic. This study may serves as reference for future epidemiological study related to roadside UFPs in specific urban microenvironments such as industrial park areas.

NOMENCLATURES

- Black carbon (BC);
- Cardiovascular disease (CVD);
- Chronic obstructive pulmonary disease (COPD);
- Optical noise-reduction averaging algorithm (ONA);
- New particle formation (NPF);
- Relative humidity (RH);
- Traffic-related air pollutants (TRAPs);
- Ultrafine particles (UFPs);
- UFPs particle number concentrations (UFPs PNC);
- Wind direction (WD);
- Wind speed (WS);

ACKNOWLEDGEMENTS

This work was supported by the financial aid from Chung Yuan Christian University, Taiwan (Project No. 109609432).

ADDITIONAL INFORMATION AND DECLARATIONS

Declaration of Interests

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.
Author Contribution Statement

Sultan F.I. Abdillah: Conceptualization, Data acquisition, Formal analysis, Investigation, Writing – Original Draft; Sheng-Jie You: Writing – Review, Supervision; Ya-Fen Wang: Conceptualization, Writing - Review, Supervision.

Supplementary Material

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.230295

REFERENCES


of ultrafine particles differ from other traffic-related air pollutants: lessons from long-term measurements at fixed sites and mobile monitoring. Environ. Sci.: Atmos. 1, 558–568. https://doi.org/10.1039/d1ea00058f


