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# Ultrafine particle exposure for bicycle commutes in rush and non-rush hour traffic: A repeated measures study in Copenhagen, Denmark☆

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ABSTRACT

Ultrafine particles (UFP), harmful to human health, are emitted at high levels from motorized traffic. Bicycle commuting is increasingly encouraged to reduce traffic emissions and increase physical activity, but higher breathing rates increase inhaled UFP concentrations while in traffic. We assessed exposure to UFP while cycling along a fixed 8.5 km inner-city route in Copenhagen, on weekdays over six weeks (from September to October 2020), during morning and afternoon rush-hour, as well as morning non-rush-hour, traffic time periods starting from 07:45, 15:45, and 09:45 h, respectively. Continuous measurements were made (each second) of particle number concentration (PNC) and location. PNC levels were summarized and compared across time periods. We used generalized additive models to adjust for meteorological factors, weekdays and trends. A total of 61 laps were completed, during 28 days (~20 per time period). Overall mean PNC was 18,149 pt/cm$^3$ (range 256–999,560 pt/cm$^3$) with no significant difference between morning rush-hour (18003 pt/cm$^3$), afternoon rush-hour (17560 pt/cm$^3$) and late morning commute (17560 pt/cm$^3$) [p = 0.85]. There was substantial spatial variation of UFP exposure along the route with highest PNC levels measured at traffic intersections (~38,000-42000 pt/cm$^3$), multiple lane roads (~38,000-40000 pt/cm$^3$) and construction sites (~44,000-51000 pt/cm$^3$), while lowest levels were measured at smaller streets, areas with open built environment (~12,000 pt/cm$^3$), as well as at a bus-only zone (~15,000 pt/cm$^3$). UFP exposure in inner-city Copenhagen did not differ substantially when bicycling in either rush-hour or non-rush-hour, or morning or afternoon, traffic time periods. UFP exposure varied substantially spatially, with highest concentrations around intersections, multiple lane roads, and construction sites. This suggests that exposure to UFP is not necessarily reduced by avoiding rush-hours, but by avoiding sources of pollution along the bicycling route.

## 1. Introduction

Ambient air pollution is the leading environmental risk factor to human health and is responsible for about 4.5 million premature deaths globally each year (Health Effects Institute, 2020). The health burden related to particulate matter (PM) of diameter <2.5 μm ($PM_{2.5}$) and nitrogen dioxide ($NO_2$) has been studied extensively (European Environment Agency, 2020; Health Effects Institute, 2020). However, epidemiological evidence on the health effects of ultrafine particles (UFP; PM of diameter <0.1 μm) is limited (Morawska et al., 2019; Ohlwein et al., 2019), due to a lack of regulation and monitoring of UFP. Yet, toxicological evidence suggests that UFP are potentially more harmful to health than larger particles largely due to their bio-reactivity: small size and high surface-to-mass ratio allowing penetration deep into the airways and translocation via the circulatory system to organs while carrying large amounts of potential toxins (Schraufnagel, 2020).

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Bicycling is increasingly encouraged as a healthy and sustainable form of mobility in cities around the world. It serves both to increase physical activity and to reduce emissions from motorized traffic, resulting in improved air quality. However, the combination of increased breathing rates and immediate proximity to traffic while bicycling increases inhaled doses of pollutants, including UFP, raising concerns on whether the harms related to air pollution exposure outweigh the health benefits of physical activity gained by bicycling. Human observational and experimental studies have shown small changes in the body due to UFP exposure during bicycling, even among healthy individuals and at low street-level concentrations, which can have adverse effects on respiratory (Matt et al., 2016; Strak et al., 2010) and cardiovascular (Cole-Hunter et al., 2016; Jacobs et al., 2010; Kubesch et al., 2014, 2015; Weichenthal et al., 2011) health.

In cities, UFP are mainly emitted from motorized traffic and are characterized by large spatial and temporal variation (Morawska et al., 2008). Concentrations at the street-level can be magnitudes higher than background levels measured by fixed-site monitoring stations (de Nazelle et al., 2017). However, epidemiological studies on the health effects of UFP usually rely on daily mean of UFP measured at background monitors or annual mean of UFP levels predicted at residences, for short-term or long-term health effects studies, respectively. Personal monitoring studies provide valuable insights into the substantial temporal and spatial variability in UFP exposure during daily commutes in traffic microenvironments, which is not captured by exposure proxies (daily or annual means) typically used in epidemiological studies.

Exposure to UFP during commuting on a bicycle in urban areas is determined by various factors such as traffic volume and composition on the chosen route and meteorological factors. As such, routes with closer proximity to traffic, with a higher density of cars and trucks, and higher volume of heavy diesel traffic generally result in increased exposures to UFP (Kaur et al., 2007; Knibbs et al., 2011). Passing vehicles, traffic jams and waiting at traffic lights further increase UFP concentrations experiences by a bicyclist (Boogaard et al., 2009; von Schneidemesser et al., 2019). Moreover, meteorological factors influence variation in UFP levels between different days and seasons of the year. Both temperature and wind speed have previously been found to be inversely related to UFP levels – the increase in temperature and wind speed leads to lower UFP levels (Hatzopoulou et al., 2013; Peters et al., 2014; Thai et al., 2008). Some studies have investigated UFP exposure while bicycling on different routes (high-vs. low-exposure traffic routes) within a city (Cole-Hunter et al., 2013, 2012; Hankey and Marshall, 2015; Luengo-Oroz and Reis, 2019; Pattinson et al., 2017; Qiu et al., 2019) or at different times of the day (Berghmans et al., 2009; Hankey and Marshall, 2015; Hatzopoulou et al., 2013; Hofman et al., 2018; Kaur et al., 2005; Peters et al., 2014; Qiu et al., 2019; Ragettli et al., 2013). Yet, none of these studies have been designed explicitly to compare rush-hour to non-rush-hour exposures.

This study took place in Copenhagen, which is heralded as one of the world's most bicycle-friendly cities. Increasing targeted efforts to improve conditions for bicyclists (such as investments in cycling infrastructure, expanding of cycling lines and parking spaces) result in steadily rising numbers of people using bicycles. In 2018, 49% of Copenhagen's inhabitants used bicycles for their daily commutes to places of work or education, increasing from 38% in 2009 (City of Copenhagen, Technical and Environmental Administration, (TMF), Mobility, 2019). This drive for active, individual mobility has been further encouraged in response to social distancing measures to help reduce the recent coronavirus disease infection spread (COVID-19) (Sundhedsstyrelsen, 2020). Moreover, in the aftermath of global COVID-19 societal lockdowns, places of work and/or study have facilitated more flexibility for physical attendance. Individuals may choose to work fully or partly from home, or when they commute, and so have more agency over their potential peak exposure to air pollution from commuting.

In order to evaluate UFP levels experienced by a commuter when making this choice, the current project aimed to assess UFP exposure when bicycle commuting in rush-hours compared to non-rush-hour traffic time periods in Copenhagen, Denmark. To meet this objective, we monitored particle number concentration (PNC) in the bicyclist's breathing zone repeatedly while bicycling on a fixed route in central Copenhagen at three different times of the day (rush-hours compared to non-rush-hours) during six consecutive weeks in September and October 2020.

## 2. Methods

### 2.1. Study design

In six consecutive weeks between September 1st and October 9th, 2020, repeated measurements of a fixed 8.5 km route were completed on bicycle in Copenhagen. This route covered mostly high-traffic streets frequently used by bicycle commuters (Fig. 1) (City of Copenhagen, Technical and Environmental Administration, (TMF), Mobility, 2019). Along the entire route, measurements were made on dedicated bicycling lanes directly adjacent to streets with motorized traffic. Three time periods during weekdays were chosen for monitoring based on known rush-hour traffic times (Teknik og Miljøforvaltningen/The Technical and Environmental Administration and Center for Trafik og Byliv/-Centre of Traffic and Urban Life, 2015): repeats (laps) were started at 07:45 h ('morning rush-hour') and 15:45 h ('afternoon rush-hour') in order to cover typical times of commutes to and from work. An additional lap was started at 09:45 h ('late morning') in order to observe UFP concentrations at an alternative, later time for commuting in the morning, evaluating whether lower exposure to UFP can be achieved if bicycling outside typical rush-hours. In total, 61 laps were completed in the study period, where the number of laps did not differ substantially between weeks and time periods. One member of the project team (Marie Bergmann) completed all cycling laps, maximizing consistency of study conduct.

Data collection for this study took place in Copenhagen in September and October 2020, when society was mostly re-opened after lockdown in the spring of 2020 due to the COVID-19 pandemic. Relevant for this study, total traffic counts in Denmark were comparable to those in the previous year, with small reductions of 2–8% in weeks 36–41 in 2020 compared to the same weeks in 2019 (Vejdirektoratet, 2021).

### 2.2. Personal exposure monitoring

A handheld nanoparticle counter ('DiSCmini'; Testo SE & Co. KGaA, Germany) was used to measure PNC, which largely represents UFP (Hofman et al., 2016), at 1-s intervals during bicycling. The instrument's impactor was connected to a flexible, manufacturer-provided polymer sampling tube, connected to the instrument, and was fixed close to the collarbone to allow air sampling within the breathing zone (Fig. S1). The DiSCmini measures PNC within the particle diameter range of 10–300 nm (modal diameter) with an impactor for particle size cut-off at 700 nm, up to 1 million particles per cubic centimeter of air (pt/cm$^3$). For quality control purposes, according to manufacturer recommendation, 'zero checks' were performed immediately before and after measurements using a HEPA filter. Also, according to manufacturer recommendation, measurements were not done on days or at times with precipitation or high humidity (>90%).

Concurrent geospatial coordinates were recorded with a GPS watch ('Forerunner 920XT'; Garmin Ltd., USA).

Meteorological information, as hourly means (coinciding with lap times) of temperature, relative humidity and wind speed, was obtained from the Danish Meteorological Institute.

### 2.3. Instrument co-location

The route was designed to include two municipal air quality

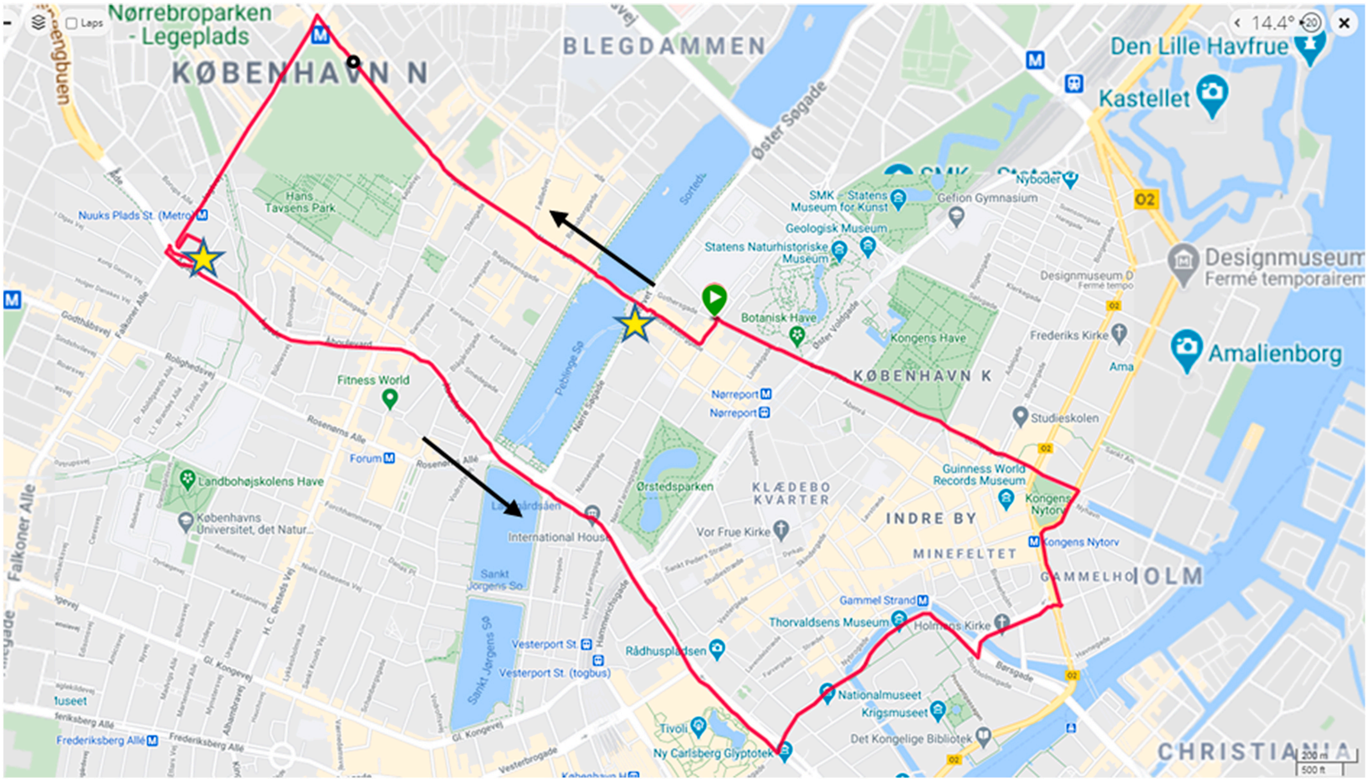


**Fig. 1.** Map of the bicycling route measured for particle number concentration. (Image courtesy of Google Maps). Green-bubbled arrow represents start of route, while red line represents exact route in the direction of black arrows (counter-clockwise). Municipal UFP monitoring stations are marked with yellow stars. The cycling route total length is ~8.5 km, starting and ending at the intersection Gothersgade/Øster Farimagsgade and following, among others, Nørrebrogade, Jagtvej, Åboulevard, HC Andersens Boulevard, Holmens Kanal and Gothersgade. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

monitoring stations (Krügersgade and Søtorvet), which started operating on September 25th, 2020, both located at the side of major streets (Fig. 1). Both stations are equipped with a “GRIMM 5421” condensation particle counter, which measures particles with a minimum diameter of 7 nm. For ten days during the study period, corresponding to 19 individual cycling laps, hourly PNC data was available from these stations. Further, verification of data was made by co-location at one monitoring station (Krügersgade) at the end of the measurement campaign in October for 13 days.

### 2.4. Statistical analysis

First, all time points where the HEPA filter was attached were excluded (13% of the total dataset), and data with a particle diameter equal to zero (<0.01% of the total dataset) and PNC above 1 million (<0.01% of the total dataset) were removed for quality control purposes. PNC and diameter were aggregated as means per each individual lap and merged with means of meteorological factors at the corresponding time. Next, PNC levels, particle size, temperature and wind speed were described as mean, standard deviation (SD), median, range and interquartile range (IQR) of all laps combined and separately for the three times of the day. Mean PNC for the three time periods (morning rush-hour, late morning, afternoon rush-hour) was compared using ANOVA tests.

The influence of meteorological factors (temperature, wind speed) on PNC was evaluated applying Generalized Additive Models (GAM) with a Poisson distribution (Wood and Scheipl, 2020).

*The GAM equation used is as follows:*

PNC $\sim s$(wind speed, $k = 4$) + $s$(temperature, $k = 4$) + factor(day of week) + $s$(time trend)

Where: $k$ is the number of degrees of freedom;

$s$ is a smoothing term for time trend, wind speed or ambient temperature.

For validation of DiSCmini data, comparisons were made to the municipal air quality monitoring stations that are located on the cycling route. Lap PNC means were compared to time-coinciding hourly means at both stations using t-tests and Spearman correlation tests. Further to this, with co-location of the DiSCmini at Krügersgade for 13 days following our measurement campaign, we compared hourly and daily means of either instrument using Spearman correlation tests and Bland Altman plots.

Mean of all monitored data was calculated at 1 × 1 m cell size along the route within a 10 m buffer and visualized using ArcGIS (Environmental Systems Research Institute (ESRI), 2011).

All statistical (excluding geospatial) analyses were performed in R statistical software (version 4.0.2) (R Foundation for Statistical Computing, 2021). Statistical significance was accepted at $p < 0.05$.

## 3. Results

### 3.1. Data availability and validation

Approximately 149,300 data points were collected in total during 28 days between September 1st and October 9th, 2020, from 61 repeated cycling laps, which lasted approximately 40 min each. Out of these, 20, 21 and 20 laps were conducted at morning rush-hour, late morning and afternoon rush-hour times, respectively.

At the end of the study period, the 13-day co-location period showed that data from the DiSCmini was comparable to a regulatory-grade air quality monitor (“GRIMM 5412”). Hourly and daily mean PNC measured by both instruments were correlated with 80.5% and 96.7% (Spearman correlation-test, $p < 0.0001$), respectively. The GRIMM 5412 measured higher PNC (24-h mean: 5129 pt/cm$^3$) than the DiSCmini (24-h mean: 4823 pt/cm$^3$). See Supplementary material (Figs. S2 and S3) for further graphical comparison of both instruments' hourly PNC means during co-location.

Coinciding hourly means, from the time periods of bicycling, were seen as significantly different between the DiSCmini and the two GRIMM 5412 that were passed along the route (both: *t*-test, p = 0.0003). Bicycling trip means of PNC were on average almost twice as high as GRIMM 5412 PNC at the same time (bicycling trip mean: 17,727 pt/cm$^3$; Krügersgade station mean: 9642 pt/cm$^3$; Søtorvet station mean: 9726 pt/cm$^3$).

### 3.2. Personal exposure levels

Table 1 shows summary statistics for lap-means of PNC, particle size and meteorological factors during the study period. Mean PNC during all cycling laps combined was 18,345 pt/cm$^3$. For respective times of the day, mean PNC was 18,556, 18,882 and 17,569 pt/cm$^3$ (morning rush-hour, late morning and afternoon rush-hour), which were not significantly different from each other (ANOVA: p = 0.85). After adjustment for meteorological factors, there was a larger, yet still insignificant (p = 0.12), difference between trip times, with the highest PNC during late (non-rush-hour) morning trips (Fig. S4). Mean particle size was largest during morning rush-hour (48 nm) and decreased for late morning (35 nm) and afternoon rush-hour (29 nm), being significantly different from each other (ANOVA: p = 0.003).

During the study period, the mean levels of PNC showed a high variability depending on the day across the three trip times combined, ranging from ~8000 pt/cm$^3$ to ~37,000 pt/cm$^3$ (Fig. 2). However, there was no clear temporal trend for daily PNC, nor between different days of the week or for weekly averages during the study period (Figs. S5 and S6). In contrast, peaks in PNC were observed during the single laps (Fig. S7), indicating the importance of spatial variation in UFP levels along the route.

Geospatial of all lap data illustrated 'hot' and 'cold' spots (representing high and low levels, respectively) of PNC along the route. PNC hot-spots were seen close to intersections and roundabouts with traffic signals (~38,000-42000 pt/cm$^3$) and along busy roads (~38,000-40000 pt/cm$^3$), as well as close to a construction site (~44,000-51000 pt/cm$^3$), which was passed on the route (Fig. 3 and Fig. S8). Notably, only one of the two regularly passed construction sites was seen as a PNC hotspot (b), which might be related to active earthworks at this site, whereas the other site (a) was less active and located on a bridge, with better natural ventilation. Segments waggregates ith low mean PNC were identified in a small side street to heavy traffic and at segments with less traffic and a more open built environment (~12,000 pt/cm$^3$). Notably, PNC was higher on a segment of the route with a typical 'street canyon' (~24,000 pt/cm$^3$), a narrow street with buildings on both sides, compared to ~18,000 pt/cm$^3$ at an open segment next to a canal directly after (Fig. S9). Also notable, a traffic-restricted, bus-only zone that was passed along the route had lower mean PNC (~15,000 pt/cm$^3$) than segments directly before (~17,000 pt/cm$^3$) and after (~24,000 pt/cm$^3$), see Supplementary Fig. S10.

### 3.3. Effect of meteorological factors on personal exposure levels

Our adjustment for meteorological factors showed a significant influence by the weather. Wind speed and temperature combined explained 46% of the deviance in PNC (all time periods combined), with respective 20% and 25% explained by wind speed and temperature, separately. Smoothing plots are given in Supplemental Fig. S11, where wind speed is suggested as having an inverse relationship with PNC, while no clear pattern can be seen for temperature.

## 4. Discussion

In this repeated measures study, exposure to UFP along popular routes for bicycling commuting in central Copenhagen was not significantly different between morning (07:45–08:30 h) and afternoon (15:45–16:30 h) rush-hours, nor late morning (non-rush-hour) traffic time periods (09:45–10:30 h). Contrary to our initial hypothesis, lower UFP exposure could not be achieved by commuting at a non-rush-hour traffic time. After excluding the effects of temperature and wind speed on UFP levels, the late morning, non-rush-hour time showed even higher concentrations than morning and afternoon rush-hours. While this difference was not statistically significant, it could potentially be explained by factors such as a different traffic composition at this time (such as a higher share of commercial diesel traffic) (Knibbs et al., 2011), nucleation events or other non-traffic related sources such as restaurant cooking emissions.

While there was little variation in PNC in regards to the time of the day or day of the week, there was large spatial variation in PNC along the cycling route. Peak concentrations were observed along busy road segments with traffic congestion (~38,000-40,000 pt/cm$^3$), traffic lights or roundabouts with traffic lights (~38,000-42,000 pt/cm$^3$), as well as at construction sites (~44,000-51,000 pt/cm$^3$) and street canyons (~24,000 pt/cm$^3$). Lowest PNC was observed on streets with low traffic or road segments in more open areas and 'ventilation' such as side

**Table 1**
Summary of lap-means of PNC, particle size and meteorological factors on 28 weekdays during the study period (September 1st – October 9th, 2020), overall and for morning rush-hour (07:45–8:30 h), late morning (09:45–10:30 h) and afternoon rush-hour (15:45–16:30).

| Parameter | Mean | SD | Min-Max | 25th pctl. | Median | 75th pctl. |
|---|---|---|---|---|---|---|
| ***PNC (pt/cm$^3$)*** | 18,345 | 7577 | 7131–36668 | 12,621 | 17,054 | 22,138 |
| *Morning rush-hour* | 18,556 | 9947 | 7131–36668 | 10,777 | 16,619 | 23,747 |
| *Late morning* | 18,882 | 7091 | 7268–35,945 | 15,254 | 17,621 | 23,655 |
| *Afternoon rush-hour* | 17,569 | 5331 | 9831–30154 | 14,660 | 15,956 | 19,716 |
| ***Particle size (nm)*** | 37 | 18 | 14–96 | 25 | 32 | 40 |
| *Morning rush-hour* | 48 | 22 | 14–93 | 32 | 45 | 61 |
| *Late morning* | 35 | 17 | 18–96 | 24 | 30 | 38 |
| *Afternoon rush-hour* | 29 | 7 | 15–42 | 24 | 27 | 34 |
| ***Temperature (°C)*** | 15.0 | 3.6 | 5.8–25 | 12.6 | 14.6 | 17.5 |
| *Morning rush-hour* | 12.4 | 2.4 | 5.8–17.5 | 10.8 | 12.1 | 14.2 |
| *Late morning* | 14.2 | 2.1 | 8.6–17.9 | 12.7 | 14.3 | 15.3 |
| *Afternoon rush-hour* | 17.8 | 2.9 | 12.7–25 | 15.9 | 17.9 | 19.4 |
| ***Wind Speed (m/s)*** | 3.4 | 1.6 | 0.3–7.7 | 2.2 | 3.5 | 4.5 |
| *Morning rush-hour* | 2.7 | 1.4 | 0.3–5.6 | 1.4 | 3 | 3.5 |
| *Late morning* | 3.3 | 1.5 | 0.3–6.6 | 2.2 | 3.3 | 4.3 |
| *Afternoon rush-hour* | 4.2 | 1.3 | 1.7–7.7 | 3.5 | 4.3 | 5 |

Abbreviations: PNC, particle number concentration; pt/cm$^3$, particles per cubic centimeter of air; nm, nanometer; m/s, meters per second; SD, standard deviation; min, minimum value; max, maximum value; pctl., percentile.

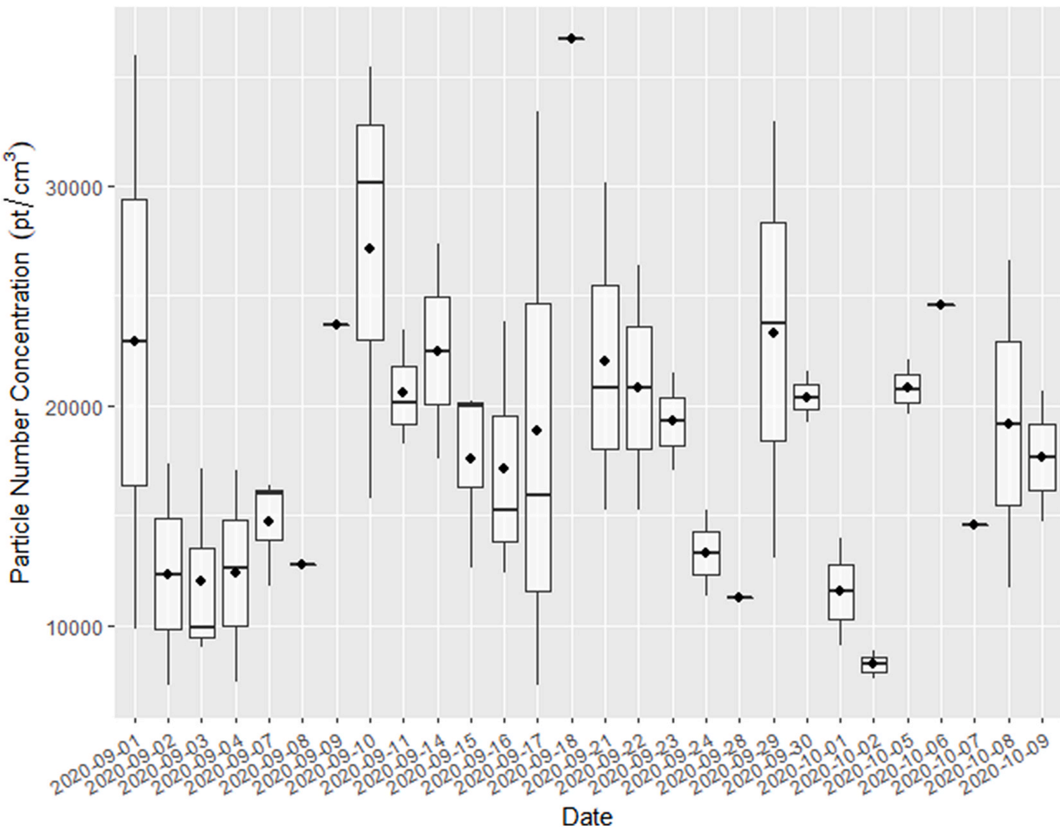


**Fig. 2.** Boxplot with daily variation in lap-means of PNC (morning rush-hour, late morning and afternoon rush-hour combined) on 28 weekdays during the study period (September 1st – October 9th, 2020, unadjusted for meteorological factors). Graphs present the 25th, 50th, and 75th percentile (box range and horizontal line), minimum and maximum values (whiskers) and mean (dots).

streets to heavy traffic (~12,000 pt/cm$^3$), as well as at streets that are bus-only zone (~15,000 pt/cm$^3$). These findings suggest that bicyclists may reduce their potential peak exposure to UFP not by changing when they commute, but by which route they take. Moreover, meteorological factors (wind speed, temperature) were important predictors of the large daily variation in commute PNC. Furthermore, mean personal PNC exposure while bicycling was about twice as high as that measured simultaneously by road-side monitoring stations. This finding suggests the importance of personal, mobile monitoring for UFP exposure assessment, accounting for bicyclists' interaction with motorized traffic, i.e. their physical proximity to congestion associated with the crossing of intersections.

Several studies have measured UFP exposure while bicycling, mostly in Europe and North America (an overview is provided in Supplemental Table S1), but none have been designed explicitly to compare rush-to non-rush-hour exposures. Among them, some studies compare exposure at different times of the day (Berghmans et al., 2009; Hankey and Marshall, 2015; Hatzopoulou et al., 2013; Hofman et al., 2018; Kaur et al., 2005; Peters et al., 2014; Qiu et al., 2019; Ragettli et al., 2013) or on different routes (high-vs. low-exposure traffic routes) within a city (Cole-Hunter et al., 2012; Hankey and Marshall, 2015; Luengo-Oroz and Reis, 2019; Pattinson et al., 2017; Qiu et al., 2019). Other studies have compared UFP exposure for different modes of transportation, such as car, bus, metro or bicycle (Boogaard et al., 2009; de Nazelle et al., 2012; Int Panis et al., 2010; Kaur and Nieuwenhuijsen, 2009; Kingham et al., 2013; Okokon et al., 2017; Ragettli et al., 2013; Strasser et al., 2018; Zuurbier et al., 2010). Six studies conducted in Belgium, Canada, Switzerland, China and the UK found higher UFP levels during morning rush-hours compared to afternoon rush-hours (Berghmans et al., 2009; Hatzopoulou et al., 2013; Hofman et al., 2018; Kaur et al., 2005; Qiu et al., 2019; Ragettli et al., 2013), which we did not see in our study. Others have found increasing UFP levels in relation to closer proximity to traffic (Cole-Hunter et al., 2013, 2012; Hankey and Marshall, 2015; Luengo-Oroz and Reis, 2019; Pattinson et al., 2017). Generally, comparability between these studies is limited due to different study protocols, measurement devices and study settings. As such, our findings from Copenhagen, a city with relatively low levels of air pollution and a high share of bicycle commuters, cannot easily be generalized to other study settings with different air pollution levels, traffic characteristics or rush-hour times. There is a need for more studies, especially in settings with higher levels of air pollution.

Among the available studies, two studies were identified that used DiSCminis, as the current study did, and were done in the European cities of Basel and Edinburgh. While cycling on a route in Basel at different times of the day, mean PNC was 22,660 pt/cm$^3$ (Ragettli et al., 2013). In Edinburgh, cycling was done in high-, medium- and low-traffic contexts and mean PNC was 19,310, 9824 and 7990 pt/cm$^3$, respectively (Luengo-Oroz and Reis, 2019). Thus, our finding of mean PNC of around 18,000 pt/cm$^3$ in a high-traffic setting is comparable, and somewhat lower than those found in Basel and Edinburgh. Besides the DiSCmini, personal exposure to UFP has been monitored using a 'P-trak Ultrafine Particle Counter', which measures particles in a wider size range of 20–1000 nm. In Antwerp, Belgium, mean PNC of 16,463 and 9986 pt/cm$^3$ was measured during morning (06:00–09:00 h) and afternoon rush-hours (15:00–19:00 h), respectively (Hofman et al., 2018). Another study in Vancouver found levels of 16,226 and 9367 pt/cm$^3$ on a downtown and a residential route, respectively (Cole et al., 2018). Our study's finding of 18,003 and 17,560 pt/cm$^3$ mean PNC in a high-traffic setting during morning and afternoon rush-hours respectively are higher than in these previous studies, especially for afternoon rush-hours. However, this could be a result of different traffic time periods used for defining afternoon rush-hour in our (15:45–16:30 h) and Hofman

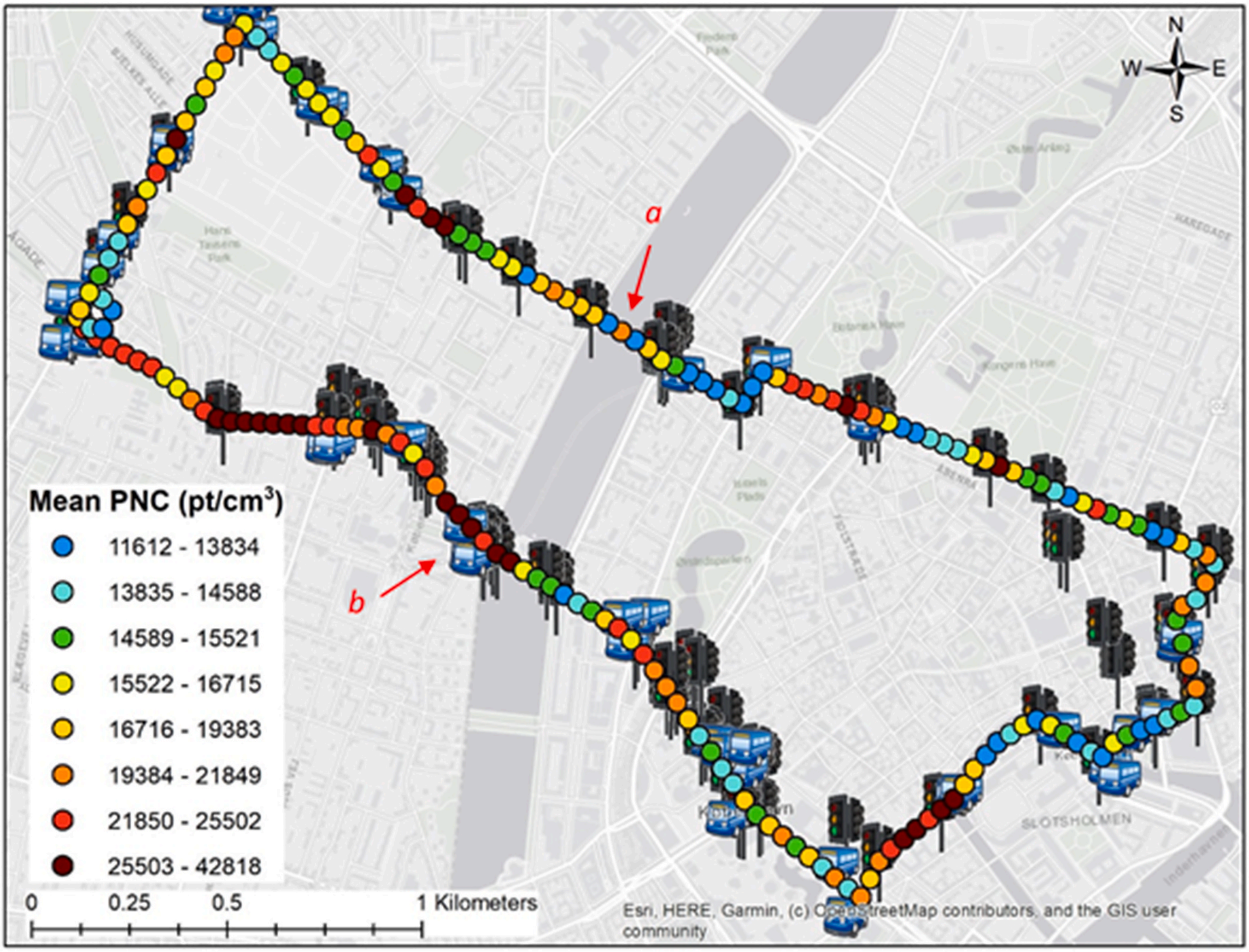


**Fig. 3.** Spatial aggregation of mean PNC within a 10 m radius around points every 20 m (morning rush-hour, late morning and afternoon rush-hour combined) on 28 weekdays during the study period (September 1st – October 9th, 2020). PNC data was spatially aggregated from all laps to show 'hot' and 'cold' spots along the cycling route of inner-city Copenhagen, Denmark. Points visualize mean measurements at every 50 m along the route. Traffic lights and bus stops along the route are indicated on this map. Two sites, directly on the route, where construction work was done during large parts of the study period (*a*: September 1st – October 6th; *b*: September 14th – October 9th), are marked with red arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al.'s study (15:00–19:00 h). Several other studies, for example, in Barcelona (de Nazelle et al., 2012), Antwerp (Peters et al., 2014), Arnhem (Zuurbier et al., 2010) and Utrecht (Strak et al., 2010) found considerably higher PNC, ranging between ~28,000 on a low-traffic route in Arnhem and ~75,000 in central Barcelona. There is only a single study that has quantified exposure to UFP while commuting in rush-hour (exact time period not reported) on weekdays in Copenhagen in 2005 on a route comparable to ours, which reported an average exposure of 32,400 pt/cm$^3$ (Vinzents et al., 2005). Here, a different particle counting method (TSI 3007 condensation particle counter) was used, which measures particles between 10 to above 1000 nm, a larger size range than the DiSCmini (which we used). Average exposure in that study was considerably higher than our study, and may reflect previously observed improvements in local UFP levels over the 15 years between their and our study (Ellermann et al., 2020). Another study on bicyclists' exposure to air pollutants (nitrogen oxides, carbon monoxide and PM) was conducted in Copenhagen in 2007, where exposure levels on different types of routes were simulated and compared with each other (Hertel et al., 2008). The authors concluded that choosing routes with lower exposure, such as along less trafficked streets, as well as bicycling outside of rush-hours can significantly reduce accumulated air pollution exposure while bicycling. Future research could consider a comparison of different types of routes (e.g., low exposure route vs. the shortest route) for UFP exposure in Copenhagen.

Notably, bicyclists in a study in Germany were found to mostly underestimate their exposure to air pollution while commuting on bicycle (Ueberham et al., 2019). Participants of this and another study, however, expressed a willingness to change their daily commuting routes in order to avoid high exposures (Cole-Hunter et al., 2015; Ueberham et al., 2019). Thus, studies such as ours can provide valuable insights into spatial and temporal patterns of exposure, which can be used to inform urban health planning and risk communication, for closing the gap in exposure awareness and providing people with agency for change and healthier alternatives for their daily bicycling routes.

### 4.1. *Strengths & limitations*

Strengths of this study include repeated measurements with a precise study protocol, using a benchmark personal particle counter sampling within the human breathing zone. The DiSCmini has been suggested to be appropriate to use for personal exposure studies, with reasonably good agreement with regulatory-grade particle counters (Kaminski et al., 2013; Mills et al., 2013), which we saw in our study. The availability of background PNC from two fixed-site monitoring stations, facilitated a data validation protocol of comparisons with coinciding data from one-third of our total number of laps performed, and a co-location period totalling 13 days immediately following our bicycling study period. Further, adjusting for meteorological factors was performed to show their meaningful influence on our results, which is not done in all exposure studies.

This study has some limitations. Firstly, we are aware of DiSCmini device measurement drift, meaning that measurement precision is potentially questionable at higher concentrations and an offset may be required. The manufacturer specifies the device's accuracy for measuring PNC with ±30%, in agreement with studies that have compared the DiSCmini to regulatory-grade Scanning Mobility Particle Sizers (SMPS) (Kaminski et al., 2013; Mills et al., 2013). Secondly, our study period only covers late summer/autumn, and we can therefore not determine the impact of seasonal variations on the measured exposure levels. Season has an important influence on UFP, and levels are typically higher in winter than in summer (Morawska et al., 2008). Furthermore, we lack data on other possible determinants of variability in UFP exposure during commute, such as residential heating and commercial (e.g. pizza ovens) wood burning, background UFP levels, rider speed, wind direction, street layout, green and blue spaces, etc.

## 5. Conclusion

Exposure concentration levels of UFP while bicycling in central Copenhagen did not appear to differ between rush-hour and non-rush-hour, nor morning and afternoon rush-hour, commute time periods. This suggests that exposure to UFP is not necessarily reduced by avoiding rush-hours. However, large (3-fold) spatial contrasts in exposure were observed along the route: the highest exposure levels were seen at intersections, in roads with heavy traffic or near construction sites; the lowest exposure levels were seen in low-traffic roads (e.g., bus zones), or streets with wide and open areas. That is, cyclists during their commutes should be encouraged, when possible, to avoid routes that are congested with traffic and closed in space, and choose alternative, less polluted routes. Urban planning policies aimed at reducing air pollution levels, such as closing road segments to private motorized traffic and moving cycling lanes away from busy roads, would minimise exposure of cyclists to air pollution and maximise benefits to their health.

## Credit author statement

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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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## Appendix A. Supplementary data

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## References

Berghmans, P., Bleux, N., Panis, L.I., Mishra, V.K., Torfs, R., Van Poppel, M., 2009. Exposure assessment of a cyclist to PM10 and ultrafine particles. Sci. Total Environ. 407, 1286–1298. https://doi.org/10.1016/j.scitotenv.2008.10.041.

Boogaard, H., Borgman, F., Kamminga, J., Hoek, G., 2009. Exposure to ultrafine and fine particles and noise during cycling and driving in 11 Dutch cities. Atmos. Environ. 43, 4234–4242. https://doi.org/10.1016/j.atmosenv.2009.05.035.

City of Copenhagen, Technical and Environmental Administration, (TMF), Mobility, 2019. The bicycle account 2018. Copenhagen city of cyclists [WWW Document]. URL5.31.2021. https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1962.

Cole, C.A., Carlsten, C., Koehle, M., Brauer, M., 2018. Particulate matter exposure and health impacts of urban cyclists: a randomized crossover study. Environ. Health 17, 78. https://doi.org/10.1186/s12940-018-0424-8.

Cole-Hunter, T., Jayaratne, R., Stewart, I., Hadaway, M., Morawska, L., Solomon, C., 2013. Utility of an alternative bicycle commute route of lower proximity to motorised traffic in decreasing exposure to ultra-fine particles, respiratory symptoms and airway inflammation – a structured exposure experiment. Environ. Health 12, 29. https://doi.org/10.1186/1476-069X-12-29.

Cole-Hunter, T., Morawska, L., Solomon, C., 2015. Bicycle commuting and exposure to air pollution: a questionnaire-based investigation of perceptions, symptoms, and risk management strategies. J. Phys. Activ. Health 12, 490–499. https://doi.org/10.1123/jpah.2013-0122.

Cole-Hunter, T., Morawska, L., Stewart, I., Jayaratne, R., Solomon, C., 2012. Inhaled particle counts on bicycle commute routes of low and high proximity to motorised traffic. Atmos. Environ. 61, 197–203. https://doi.org/10.1016/j.atmosenv.2012.06.041.

Cole-Hunter, T., Weichenthal, S., Kubesch, N., Foraster, M., Carrasco-Turigas, G., Bouso, L., Martínez, D., Westerdahl, D., de Nazelle, A., Nieuwenhuijsen, M., 2016. Impact of traffic-related air pollution on acute changes in cardiac autonomic modulation during rest and physical activity: a cross-over study. J. Expo. Sci. Environ. Epidemiol. 26, 133–140. https://doi.org/10.1038/jes.2015.66.

de Nazelle, A., Bode, O., Orjuela, J.P., 2017. Comparison of air pollution exposures in active vs. passive travel modes in European cities: a quantitative review. Environ. Int. 99, 151–160. https://doi.org/10.1016/j.envint.2016.12.023.

de Nazelle, A., Fruin, S., Westerdahl, D., Martinez, D., Ripoll, A., Kubesch, N., Nieuwenhuijsen, M., 2012. A travel mode comparison of commuters' exposures to air pollutants in Barcelona. Atmos. Environ. 59, 151–159. https://doi.org/10.1016/j.atmosenv.2012.05.013.

Ellermann, T., Nygaard, J., Nøjgaard, J.K., Nordstrøm, C., Brandt, J., Christensen, J., Ketzel, M., Massling, A., Bossi, R., Frohn, L.M., Geels, C., Jensen, S.S., 2020. The Danish Air Quality Monitoring Programme. Annual Summary for 2018. Aarhus University, DCE – Danish Centre for Environment and Energy, Copenhagen.

Environmental Systems Research Institute (ESRI), 2011. ArcGIS Desktop (Redlands, CA).

European Environment Agency, 2020. Air Quality in Europe - 2020 Report — European Environment Agency (Publication No. 9/2020). Publications Office of the European Union, Luxembourg.

Hankey, S., Marshall, J.D., 2015. On-bicycle exposure to particulate air pollution: particle number, black carbon, PM 2.5 , and particle size. Atmos. Environ. 122, 65–73. https://doi.org/10.1016/j.atmosenv.2015.09.025.

Hatzopoulou, M., Weichenthal, S., Dugum, H., Pickett, G., Miranda-Moreno, L., Kulka, R., Andersen, R., Goldberg, M., 2013. The impact of traffic volume, composition, and road geometry on personal air pollution exposures among cyclists in Montreal, Canada. J. Expo. Sci. Environ. Epidemiol. 23, 46–51. https://doi.org/10.1038/jes.2012.85.

Health Effects Institute, 2020. State of Global Air 2020. Special Report. Health Effects Institute, Boston, MA.

Hertel, O., Hvidberg, M., Ketzel, M., Storm, L., Stausgaard, L., 2008. A proper choice of route significantly reduces air pollution exposure–a study on bicycle and bus trips in urban streets. Sci. Total Environ. 389, 58–70. https://doi.org/10.1016/j.scitotenv.2007.08.058.

Hofman, J., Samson, R., Joosen, S., Blust, R., Lenaerts, S., 2018. Cyclist exposure to black carbon, ultrafine particles and heavy metals: an experimental study along two commuting routes near Antwerp, Belgium. Environ. Res. 164, 530–538. https://doi.org/10.1016/j.envres.2018.03.004.

Hofman, J., Staelens, J., Cordell, R., Stroobants, C., Zikova, N., Hama, S.M.L., Wyche, K. P., Kos, G.P.A., Van Der Zee, S., Smallbone, K.L., Weijers, E.P., Monks, P.S., Roekens, E., 2016. Ultrafine particles in four European urban environments: results from a new continuous long-term monitoring network. Atmos. Environ. 136, 68–81. https://doi.org/10.1016/j.atmosenv.2016.04.010.

Int Panis, L., de Geus, B., Vandenbulcke, G., Willems, H., Degraeuwe, B., Bleux, N., Mishra, V., Thomas, I., Meeusen, R., 2010. Exposure to particulate matter in traffic: a comparison of cyclists and car passengers. Atmos. Environ. 44, 2263–2270. https://doi.org/10.1016/j.atmosenv.2010.04.028.

Jacobs, L., Nawrot, T.S., de Geus, B., Meeusen, R., Degraeuwe, B., Bernard, A., Sughis, M., Nemery, B., Panis, L.I., 2010. Subclinical responses in healthy cyclists briefly exposed to traffic-related air pollution: an intervention study. Environ. Health 9, 64. https://doi.org/10.1186/1476-069X-9-64.

Kaminski, H., Kuhlbusch, T.A.J., Rath, S., Götz, U., Sprenger, M., Wels, D., Polloczek, J., Bachmann, V., Dziurowitz, N., Kiesling, H.-J., Schwiegelshohn, A., Monz, C., Dahmann, D., Asbach, C., 2013. Comparability of mobility particle sizers and diffusion chargers. J. Aerosol Sci. 57, 156–178. https://doi.org/10.1016/j.jaerosci.2012.10.008.

Kaur, S., Nieuwenhuijsen, M., Colvile, R., 2005. Personal exposure of street canyon intersection users to PM2.5, ultrafine particle counts and carbon monoxide in Central London, UK. Atmos. Environ. 39, 3629–3641. https://doi.org/10.1016/j.atmosenv.2005.02.046.

Kaur, S., Nieuwenhuijsen, M.J., 2009. Determinants of personal exposure to $PM_{2.5}$, ultrafine particle counts, and CO in a transport microenvironment. Environ. Sci. Technol. 43, 4737–4743. https://doi.org/10.1021/es803199z.

Kaur, S., Nieuwenhuijsen, M.J., Colvile, R.N., 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmos. Environ. 41, 4781–4810. https://doi.org/10.1016/j.atmosenv.2007.02.002.

Kingham, S., Longley, I., Salmond, J., Pattinson, W., Shrestha, K., 2013. Variations in exposure to traffic pollution while travelling by different modes in a low density, less congested city. Environ. Pollut. 181, 211–218. https://doi.org/10.1016/j.envpol.2013.06.030.

Knibbs, L.D., Cole-Hunter, T., Morawska, L., 2011. A review of commuter exposure to ultrafine particles and its health effects. Atmos. Environ. 45, 2611–2622. https://doi.org/10.1016/j.atmosenv.2011.02.065.

Kubesch, N., Nazelle, A.D., Guerra, S., Westerdahl, D., Martinez, D., Bouso, L., Carrasco-Turigas, G., Hoffmann, B., Nieuwenhuijsen, M.J., 2014. Arterial blood pressure responses to short-term exposure to low and high traffic-related air pollution with and without moderate physical activity. Eur. J. Prev. Cardiol. https://doi.org/10.1177/2047487314555602.

Kubesch, N.J., de Nazelle, A., Westerdahl, D., Martinez, D., Carrasco-Turigas, G., Bouso, L., Guerra, S., Nieuwenhuijsen, M.J., 2015. Respiratory and inflammatory responses to short-term exposure to traffic-related air pollution with and without moderate physical activity. Occup. Environ. Med. 72, 284–293. https://doi.org/10.1136/oemed-2014-102106.

Luengo-Oroz, J., Reis, S., 2019. Assessment of cyclists' exposure to ultrafine particles along alternative commuting routes in Edinburgh. Atmos. Pollut. Res. 10, 1148–1158. https://doi.org/10.1016/j.apr.2019.01.020.

Matt, F., Cole-Hunter, T., Donaire-Gonzalez, D., Kubesch, N., Martínez, D., Carrasco-Turigas, G., Nieuwenhuijsen, M., 2016. Acute respiratory response to traffic-related air pollution during physical activity performance. Environ. Int. 97, 45–55. https://doi.org/10.1016/j.envint.2016.10.011.

Mills, J.B., Park, J.H., Peters, T.M., 2013. Comparison of the DiSCmini aerosol monitor to a handheld condensation particle counter and a scanning mobility particle sizer for submicrometer sodium chloride and metal aerosols. J. Occup. Environ. Hyg. 10, 250–258. https://doi.org/10.1080/15459624.2013.769077.

Morawska, L., Ristovski, Z., Jayaratne, E.R., Keogh, D.U., Ling, X., 2008. Ambient nano and ultrafine particles from motor vehicle emissions: characteristics, ambient processing and implications on human exposure. Atmos. Environ. 42, 8113–8138. https://doi.org/10.1016/j.atmosenv.2008.07.050.

Morawska, L., Wierzbicka, A., Buonanno, G., Cyrys, J., Schnelle-Kreis, J., Kowalski, M., Riediker, M., Birmili, W., Querol, X., Cassee, F., Yildirim, A., Elder, A., Yu, I.J., Ovrevik, J., Hougaard, K., Loft, S., Schmid, O., Stöger, T., Peters, A., Lucht, S., 2019. Ambient Ultrafine Particles: Evidence for Policy Makers. A Report Prepared by the 'Thinking outside the Box' Team.

Ohlwein, S., Kappeler, R., Kutlar Joss, M., Künzli, N., Hoffmann, B., 2019. Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence. Int. J. Publ. Health 64, 547–559. https://doi.org/10.1007/s00038-019-01202-7.

Okokon, E.O., Yli-Tuomi, T., Turunen, A.W., Taimisto, P., Pennanen, A., Vouitsis, I., Samaras, Z., Voogt, M., Keuken, M., Lanki, T., 2017. Particulates and noise exposure during bicycle, bus and car commuting: a study in three European cities. Environ. Res. 154, 181–189. https://doi.org/10.1016/j.envres.2016.12.012.

Pattinson, W., Kingham, S., Longley, I., Salmond, J., 2017. Potential pollution exposure reductions from small-distance bicycle lane separations. J. Transp. Health 4, 40–52. https://doi.org/10.1016/j.jth.2016.10.002.

Peters, J., Van den Bossche, J., Reggente, M., Van Poppel, M., De Baets, B., Theunis, J., 2014. Cyclist exposure to UFP and BC on urban routes in Antwerp, Belgium. Atmos. Environ. 92, 31–43. https://doi.org/10.1016/j.atmosenv.2014.03.039.

Qiu, Z., Wang, W., Zheng, J., Lv, H., 2019. Exposure assessment of cyclists to UFP and PM on urban routes in Xi'an, China. Environ. Pollut. 250, 241–250. https://doi.org/10.1016/j.envpol.2019.03.129.

R Foundation for Statistical Computing, 2021. R: the R project for statistical computing [WWW Document]. URL3.4.2021. https://www.r-project.org/.

Ragettli, M.S., Corradi, E., Braun-Fahrländer, C., Schindler, C., de Nazelle, A., Jerrett, M., Ducret-Stich, R.E., Künzli, N., Phuleria, H.C., 2013. Commuter exposure to ultrafine particles in different urban locations, transportation modes and routes. Atmos. Environ. 77, 376–384. https://doi.org/10.1016/j.atmosenv.2013.05.003.

Schraufnagel, D.E., 2020. The health effects of ultrafine particles. Exp. Mol. Med. 52, 311–317. https://doi.org/10.1038/s12276-020-0403-3.

Strak, M., Boogaard, H., Meliefste, K., Oldenwening, M., Zuurbier, M., Brunekreef, B., Hoek, G., 2010. Respiratory health effects of ultrafine and fine particle exposure in cyclists. Occup. Environ. Med. 67, 118–124. https://doi.org/10.1136/oem.2009.046847.

Strasser, G., Hiebaum, S., Neuberger, M., 2018. Commuter exposure to fine and ultrafine particulate matter in Vienna. Wien Klin. Wochenschr. 130, 62–69. https://doi.org/10.1007/s00508-017-1274-z.

Sundhedsstyrelsen, 2020. COVID-19: Risikovurdering, Strategi Og Tiltag Ved Epidemi I Danmark. Sundhedsstyrelsen.

Teknik og Miljøforvaltningen/The Technical and Environmental Administration, 2015. Center for Trafik Og Byliv/Centre of Traffic and Urban Life. Traffic in Copenhagen - Traffic figures 2009-2013.

Thai, A., McKendry, I., Brauer, M., 2008. Particulate matter exposure along designated bicycle routes in Vancouver, British Columbia. Sci. Total Environ. 405, 26–35. https://doi.org/10.1016/j.scitotenv.2008.06.035.

Ueberham, M., Schlink, U., Dijst, M., Weiland, U., 2019. Cyclists' multiple environmental urban exposures—comparing subjective and objective measurements. Sustainability 11, 1412. https://doi.org/10.3390/su11051412.

Vejdirektoratet, 2021. Trafikkens Udvikling I Tal [WWW Document]. Vejdirektoratet, 2.15.2021. https://vejdirektoratet.dk/side/trafikkens-udvikling-i-tal.

Vinzents, P.S., Møller, P., Sørensen, M., Knudsen, L.E., Hertel, O., Jensen, F.P., Schibye, B., Loft, S., 2005. Personal exposure to ultrafine particles and oxidative DNA damage. Environ. Health Perspect. 113, 1485–1490. https://doi.org/10.1289/ehp.7562.

von Schneidemesser, E., Steinmar, K., Weatherhead, E.C., Bonn, B., Gerwig, H., Quedenau, J., 2019. Air pollution at human scales in an urban environment: impact of local environment and vehicles on particle number concentrations. Sci. Total Environ. 688, 691–700. https://doi.org/10.1016/j.scitotenv.2019.06.309.

Weichenthal, S., Kulka, R., Dubeau, A., Martin, C., Wang, D., Dales, R., 2011. Traffic-related air pollution and acute changes in heart rate variability and respiratory function in urban cyclists. Environ. Health Perspect. 119, 1373–1378. https://doi.org/10.1289/ehp.1003321.

Wood, S., Scheipl, F., 2020. gamm4: generalized Additive Mixed Models using "mgcv" and "lme4.

Zuurbier, M., Hoek, G., Oldenwening, M., Lenters, V., Meliefste, K., van den Hazel, P., Brunekreef, B., 2010. Commuters' exposure to particulate matter air pollution is affected by mode of transport, fuel type, and route. Environ. Health Perspect. 118, 783–789. https://doi.org/10.1289/ehp.0901622.