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Inhaled particle counts along bicycle commute routes of low and high motorised traffic

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ABTRACT

Frequent exposure to ultrafine particles (UFP) is associated with detrimental effects on cardiopulmonary function and health. UFP dose and therefore the associated health risk are a factor of exposure frequency, duration, and magnitude of (therefore also proximity to) a UFP emission source. Bicycle commuters using on-road routes during peak traffic times are sharing a microenvironment with high levels of motorised traffic, a major UFP emission source. Inhaled particle counts were measured along popular pre-identified bicycle commute route alterations of low (LOW) and high (HIGH) motorised traffic to the same inner-city destination at peak commute traffic times. During commute, real-time particle number concentration (PNC; mostly in the UFP range) and particle diameter (PD), heart and respiratory rate, geographical location, and meteorological variables were measured. To determine inhaled particle counts, ventilation rate was calculated from heart-rate-ventilation associations, produced from periodic exercise testing. Total mean PNC of LOW (compared to HIGH) was reduced ($1.56 \times e^4 \pm 0.38 \times e^4$ versus $3.06 \times e^4 \pm 0.53 \times e^4$ ppcc; $p = 0.012$). Total estimated ventilation rate did not vary significantly between LOW and HIGH (43 ± 5 versus 46 ± 9 L·min; $p = 0.136$); however, due to total mean PNC, accumulated inhaled particle counts were 48% lower in LOW, compared to HIGH ($7.6 \times e^8 \pm 1.5 \times e^8$ versus $14.6 \times e^8 \pm 1.8 \times e^8$; $p = 0.003$). For bicycle commuting at peak morning commute times, inhaled particle counts and therefore cardiopulmonary health risk may be substantially reduced by decreasing exposure to motorised traffic, which should be considered by both bicycle commuters and urban planners.

Key words: Bicycle commuting; motorised traffic; ultrafine particles; exposure concentration; inhaled particle count.

Abbreviations: bpm, beats per minute; CBD, central business district; PM, particulate matter; PD, particle diameter; PNC, particle number concentration; ppcc, particles per cubic centimetre; UFP, ultrafine particle.

1. INTRODUCTION

Atmospheric ultrafine particles (UFP) can be defined as those with a diameter of < 0.1 μm, and these particles constitute the dominant diameter range within particle number concentration (PNC) values (Knibbs et al., 2011). Interest in the health implications of UFP has increased in the last two decades (Russell and Brunekreef, 2009; Wichmann and Peters, 2000), with general agreement that UFP possess greater toxicity potential than coarser particles due to relatively higher concentrations and surface area per mass (Donaldson et al., 2002; Li et al., 2003; Pietropaoli et al., 2004; Wåhlin et al., 2001). Further, UFP has a greater ability to move through and beyond the pulmonary system (Elder et al., 2006; Nyström et al., 2009) so far as to elicit detrimental effects on the cardiovascular and nervous systems (Chan et al., 2004; McCreanor et al., 2007).

UFP exposure, and thus associated health risk, can vary with distance from a major emission source such as a motorised traffic corridor (Strak et al., 2010; Zuurbier et al., 2010). Proximity to motorised traffic emissions has been positively-correlated to pulmonary dysfunction and biomarkers of systemic inflammation (Jacobs et al., 2010). Accordingly, several studies have investigated the efficacy of reducing proximity to major roads to lower exposure concentrations when bicycle commuting (Giles et al., 2011). In addition to emission source proximity; commute duration will influence the potential UFP exposure of bicycle commuters (Hertel et al., 2008). Short episodes of particulate matter (PM) exposure may only elicit acute health detriment, however frequent episodes (e.g. daily commute-related exposure) could lead to increased susceptibility to chronic disease development in susceptible individuals (Dominici et al., 2006; Pope III, 2007). The effects of UFP on health, especially long-term, are not as well characterised as those of coarser PM.

Due to practical limitations associated with sensitivity, size and weight of monitoring equipment, limited knowledge is available on UFP exposure of bicycle commuter participants. Further, knowledge on the efficacy of lowering the exposure to motorised traffic to reduce UFP exposure is not comprehensive (Knibbs et al., 2011). Therefore, it was hypothesised that: 1) using a bicycle commute route of lower exposure to motorised traffic (predominantly-determined by commute proximity to motorised traffic) will facilitate a significant reduction in PNC, compared to a bicycle commute route of higher motorised traffic exposure; 2) mean heart rate and associated pulmonary ventilation rate (as indices of physical effort) will not vary significantly between bicycle commute routes of low and high motorised traffic exposure; 3) variation of inhaled particle counts will predominantly be determined by PNC levels rather than physical effort (indicated by heart and ventilation rate).

2. METHODS

2.1. Project Design

Using a purpose-built bicycle-based system, popular pre-determined bicycle commute routes traversing Brisbane from the North, East, South and West suburbs to the CBD were repeatedly monitored, with variations of both high and low exposure to motorised traffic at morning peak traffic time, to: 1) quantify real-time and total mean PNC; 2) associate real-time and total mean heart rate to pre-determined heart-rate-ventilation associations; 3) compare particle exposure concentrations, heart-rate ventilation associations and inhaled particle counts between high and low motorised traffic exposure variations of popular pre-determined bicycle commute routes.

2.1.1. *Exposure Profile Monitoring*

Popular commute routes and times for monitoring were identified and selected from previous research of regional bicycle commuters (Burke et al., 2010; Cole-Hunter, In Review). The participant (primary investigator) rode two pre-selected routes from four different origins (North, East, South, West suburbs) to the same destination (CBD), which were altered as either high (HIGH) or low (LOW) exposure to motorised traffic. The route conditions of HIGH or LOW were monitored in a counter-balanced order, on consecutive weekdays. Monitoring of each condition occurred on three different occasions to provide three return-trip data sets per condition and direction, for a total of twenty-four return trip data sets. The morning, rather than afternoon, commute peak hour was monitored because of commute departure time consistency, as well as meteorological consistency and reliability (Ayoko et al., 2005). The mean bicycle commute inbound departure time was indicated to be approximately 07:15, therefore the return trips (i.e. inbound and outbound) were performed between approximately 07:00 and 08:00.

The monitoring period covered the months of December (2010) and January (2011), with a recess during the regional work holiday period (27th December, 2010 to 4th January, 2011) as related commuting traffic volume and thus emissions were expected to be atypical. Due to unfortunate circumstances (a major floodwater event in south-east Queensland in January, 2011) commute monitoring was also recessed from 11th to 18th January, 2011, as the Brisbane CBD was closed for business due to floodwater inundation, and some of the pre-determined commute routes were closed due to flooding and infrastructure damage.

This was a single-participant study with self-experimentation conducted in accordance with the principles of the Declaration of Helsinki. The participant was a 24 year old male of good health who is moderately aerobically-trained, with no history or indication of cardiopulmonary disease, normal lung function ($FEV_1/FVC \geq 80\%$), normal Body Mass Index (23.5 $kg \cdot m^2$), a resting heart rate of < 80 bpm, and a maximal aerobic capacity of 52 mL·kg·min.

2.1.2. Geography of Monitored Region

Brisbane is Australia's third largest city, and the capital of the state of Queensland, located on the state's southern coast. It is separated by a large river, named after the city, and is consequently located in a low-lying floodplain, with several large hills of up to 300 m in height and bordered to the west by a coastal range. At a latitude of 27º South, the regional climate is sub-tropical, being cool and dry in Winter between June to August, and humid and wet in Summer between December to February. The city has a population of approximately two million people, which has continued to grow by approximately two percent annually for the last two decades (Statistics, 2011). Brisbane's motorised traffic volume is currently moderate compared to the two larger Australian cities, Sydney and Melbourne; however, along with population growth, motorised traffic numbers are increasing, particularly due to residential development in outer suburbs and satellite towns (Statistics, 2011). Industrial air pollution sources include a major airport, seaport, and oil refineries approximately 15 km north-east from the central business district (CBD), a coal power station approximately 30 km south-west of the CBD, and various factories in the outer suburbs.

2.2. Air Quality Monitoring

2.2.1. In-Commute Particle Exposure Concentration and Diameter

Real-time PNC and particle diameter (PD) were recorded and logged in-commute with 16-second means using a portable, compact (165 x 95 mm) and lightweight (750 g) UFP monitoring unit (Aerasense NanoTracer; Philips, The Netherlands). The NanoTracer device is capable of measuring PNC [0 – e^6 particles per cubic centimetre (ppcc)] and PD [10 – 300 nanometres (nm)] via particle-charging rather than particle-condensation (Marra et al., 2009). Calibration of the NanoTracer was performed in an exposure chamber of low PNC with 48 hours of continuous recording and subsequent referencing to a water-based condensation particle counter (WCPC 3781; TSI Inc., USA) at the end of the monitoring period. Accordingly, an appropriate correction factor was applied to raw data prior to analyses (see *2.7 Statistical Data Analysis*, Methods, below). In-commute PNC and PD data were viewed post-commute with NanoReporter software (Philips, The Netherlands).

2.2.2. Ambient UFP Concentration

Ambient hourly mean UFP concentrations of Brisbane CBD were recorded by a WCPC 3781 (TSI Inc., USA) and logged in a meta-database at the air monitoring station of the Queensland University of Technology (QUT). The station is located on the sixth floor of a building in QUT's south-eastern CBD campus and is of equivalent height to the Southeast Freeway which is approximately 100 m south-west of the station. The freeway, which has mild traffic congestion during peak times, consists of four lanes each both inbound and outbound.

2.3. Geographical Positioning and Plotting

To geographically co-ordinate in-commute data, and profile HIGH and LOW inhaled particle counts, a small (72 x 47 x 20 mm), lightweight (65 g) and portable GPS unit (BT-Q1000X; QSTARZ, Taiwan) with a 4 second logging frequency was utilised. A geodatabase, collating repeated single trip data sets, was used with GIS software (ArcGIS; Esri, USA) to graphically represent inhaled particle counts along the monitored commute routes. Effectively, four GPS points were associated with one PNC and PD mean (as the PNC and PD data were obtained with a 16 second logging frequency). Thus, only the fourth GPS log was co-ordinated with each UFP log. Visually, counts were colour-coded [dark green (< 1.0 x e^4 ppcc), light green

(1.0 to 5.0 x e^4 ppcc), orange (5.0 to 15.0 x e^4 ppcc) and red (> 15 x e^4 ppcc)] according to previous research highlighting typical urban background and micro-environmental counts (Boogaard et al., 2010; Vinzents et al., 2005; Zuurbier et al., 2010).

2.4. Estimated Ventilation and Inhaled Particle Counts

In-commute heart rate was recorded in real-time using a personal physiological monitoring unit (Equivital EQ-01; Hidalgo Ltd., Cambridge, UK) with a logging frequency of five seconds. In-commute inhaled particle count was estimated as the product of in-commute PNC and ventilation rate [estimated from heart and ventilation rate association curves (r^2 = 0.95 - 0.99) produced by maximal exercise testing]. As commute monitoring occurred over a six week period the heart and ventilation rate association equations were re-acquired every two weeks, with all maximal exercise tests performed using a protocol of 30 Watt increments every four minutes until exhaustion (Stewart and Stewart, 2007).

2.5. Meteorological Variables

To explain potential anomalies of in-commute data due to circumstantial weather events, local and regional meteorological variables were monitored. A small (127 x 45 x 28 mm) and lightweight (102 g) weather tracker (Kestrel K4000; Nielsen-Kellerman Co., USA) recorded and logged in real-time the in-commute temperature, relative humidity, and barometric pressure. Additionally, the Australian Bureau of Meteorology Climate Database (Meteorology, 2011) was accessed for hourly regional measures of temperature, humidity, wind direction and speed, air pressure, and precipitation.

2.6. Commute Observations Journal

Similar to meteorological variables, observations explaining potential anomalies of in-commute data such as events of motorised traffic congestion and construction work adjacent to commute route were noted post-commute. Local weather observations such as sudden windy or wet conditions, which may affect atmospheric particle dynamics, were also noted.

2.7. Statistical Data Analysis

Intra-directional repeated trip commute data of HIGH and LOW means and ranges were calculated and collated where appropriate. Multivariate repeated measures analysis of variance (ANOVA) were performed using predictive analytics software (PASW Statistics Data Editor, V18.0; IBM Corporation, USA) to signify variation of PNC, heart and ventilation rate for LOW and HIGH within and between directions. Estimated marginal means were then referenced to qualify and quantify any significant variation between LOW and HIGH or directional trip data. Further, estimated marginal means of individual factors and factor interactions were calculated, along with descriptive statistics. Within-subject factors were 'proximity to motorised traffic' (LOW/HIGH, two levels) and 'direction' (N/E/S/W, four levels). Pearsons bivariate correlations were performed between 'proximity to CBD' and LOW/HIGH values of PNC, heart and ventilation rate, and inhaled particle counts.

A one-tailed paired T-test was performed with the inbound and outbound return trip PNC data. For HIGH and LOW, preliminary analysis of trip data indicated that outbound trip (i.e. the return leg of the morning journey) PNC means were significantly lower than the inbound trip, potentially indicating a decrease in motorised traffic proximity (due to riding on the other side of the road, opposite to the flow of peak motorised traffic). For this reason, only inbound trip data was used for comparison between the inter-directional route alterations of motorised traffic exposure. Individual and multi-directional means were analysed separately to elucidate any influence of geography, specifically altitude, on in-commute heart and therefore ventilation rate. Additionally, local and regional PNC values collected in-commute and sourced from ambient monitoring databases, respectively, were compared.

3. RESULTS

3.1. Bicycle Commute Route Characteristics

Approximately 70% of LOW was designated off-road bicycle path (that is, physically and spatially separated from motorised traffic), with backstreets taken when designated off-road bicycle paths were not available. North LOW traversed creeks and parklands, while East LOW followed the Brisbane River, with approximately 80% as designated off-road bicycle paths. Comparatively, South and West LOW which ran adjacent to major motorised traffic corridors, being the Pacific Motorway and the Centennial Highway, respectively, consisted of approximately 60% designated off-road paths. See Figure 1 and Table 1.

Congestion events observed during commute monitoring were positively-correlated to mean particle number concentration [PNC (p = 0.002)], with HIGH North having a significantly higher occurrence of congestion events compared to LOW North [0.33 ± 0.58 versus 0.00 ± 0.00; F(3,6) = 8.826; p = 0.013]. Construction events were highly positively-correlated with particle diameter [PD (p = 0.007)], with LOW East having a significantly higher occurrence of construction events compared to HIGH East [2.00 ± 1.00 versus 0.00 ± 0.00; F(3,6) = 11.000; p = 0.007]. See Table 1.

INSERT TABLE 1 HERE

3.2. Inhaled Particle Counts

3.2.1. Particle Concentration and Diameter

Total Mean PNC (all-directional) was significantly reduced in LOW compared to HIGH [$F(1,2) = 83.876$; $p = 0.012$]; however, there was only a significant reduction of mean PNC with North LOW compared to North HIGH [$F(3,6) = 2.336$; $p = 0.007$]. Mean PD was not significantly different in HIGH compared to LOW [$F(1,2) = 6.537$; $p = 0.125$], and there was no significant difference in PD between the four directions [$F(3,6) = 1.288$; $p = 0.361$]. See Table 2.

The morning hourly mean PNC in Brisbane CBD, as measured at the International Laboratory for Air Quality and Health (ILAQH), QUT, was $10.1 \times e^4 \pm 3.6 \times e^4$ (ranging from $3.3 \times e^4$ to $14.9 \times e^4$) ppcc. Regional mean PNC ($11.8 \pm 6.8 \times e^4$ ppcc) and PD (57 ± 11 nm) were not significantly different between LOW or HIGH or inter-directionally. Local mean PNC and PD values were not correlated with corresponding mean regional values. See Table 1.

For HIGH and LOW, the outbound trip (that is, the return component of the morning journey) PNC means were generally significantly lower than the inbound trip ($p = 0.049$). This was particularly significant with HIGH (inbound = $36.9 \times e^4 \pm 21.9 \times e^4$ ppcc; outbound = $26.4 \times e^4 \pm 13.3 \times e^4$ ppcc; $p = 0.017$) compared to LOW (inbound = $16.6 \times e^4 \pm 7.5 \times e^4$ ppcc; outbound = $14.3 \times e^4 \pm 8.5 \times e^4$ ppcc; $p = 0.048$).

Eleven out of twelve (92%) inbound means of HIGH were significantly greater (with the remaining non-significantly greater) than outbound; however, only four out of twelve inbound means of LOW were significantly greater (with the remaining non-significantly greater) than outbound.

INSERT FIGURE 1 HERE

3.2.2. Heart Rate, Estimated Ventilation Rate and Inhaled Particle Count

Heart rate was not significantly different between LOW and HIGH [F(1,2) = 5.880; *p* = 0.136]. However, East LOW elicited a significantly lower heart rate than East HIGH [F(3,6) = 26.848; *p* = 0.001]} and LOW of all other directions {123 ± 5 bpm and 140 ± 3 bpm [F(3,6) = 6.001; *p* = 0.031]}. Subsequently, estimated minute ventilation ($\dot{V}_E$) was not significantly different between LOW and HIGH [F(1,2) = 0.016; *p* = 0.910]. However, $\dot{V}_E$ was significantly lower for East LOW compared to LOW of all other directions [F(3,6) = 6.231; *p* = 0.028]. See Table 1.

Minute inhaled particle counts, as a product of PNC and $\dot{V}_E$, were significantly reduced with LOW compared to HIGH [F(1,2) = 333.755; *p* = 0.003]; however, there was only a significant reduction with LOW compared to HIGH within the North route [F(3,6) = 1.916; *p* = 0.228]. Accumulated inhaled particle count, as a product of $\dot{V}_E$, PNC and commute duration, was significantly reduced with LOW compared to HIGH [F(1,2) = 3477.915; *p* < 0.001]; however, as with minute inhaled particle count, there was only a significant reduction with LOW compared to HIGH within the North route [F(3,6) = 1.913; *p* = 0.229]. There was no significant interaction between direction and proximity [F(3,6) = 1.592; *p* = 0.287]. See Table 2.

INSERT FIGURE 2 HERE

3.3. In-commute and Regional Meteorology

In-commute and regional weather values of temperature, humidity and air pressure did not vary significantly between direction or route alteration, with in-commute and regional measurements being highly positively-correlated to each other (p < 0.001). Similarly, regional weather values of wind direction and speed, and precipitation, did not vary significantly between monitoring events. See Table 1.

PNC was weakly negatively-correlated with in-commute, however not regional, humidity (p = 0.048; p = 0.228, respectively). Further, PD was negatively-correlated with in-commute, although not regional, temperature (p = 0.041; p = 0.650, respectively). Regional precipitation was highly positively-correlated with PD (p = 0.004).

4. DISCUSSION

The results of this study indicate that using a bicycle commute route of lower (LOW), compared to higher (HIGH), motorised traffic exposure (predominantly-determined by proximity of commute to motorised traffic) will facilitate a significant reduction in PNC levels. Further, the potential in-commute inhaled particle count of a bicycle commuter will predominantly be determined by in-commute PNC rather than physical effort (indicated by heart and pulmonary ventilation rate).

4.1. In-commute and Regional Particle Measurements

A significant reduction of PNC was observed in LOW compared to HIGH; however, the magnitude of the reduction varied between directions and was not always apparent. Subsequently, PD was observed to be lower in HIGH compared to LOW between directions, reflecting a greater proximity to fresh petrol combustion emissions (Morawska et al., 1998). Further, the mean PD identified in this study is within the range typically associated with light-duty petrol vehicles, reflecting the dominance of such vehicles in this region (Morawska et al., 1998). Smaller particles (which tend to agglomerate into larger particles with time) are associated with a higher PNC and therefore a greater potential for adverse health effects (Knibbs et al., 2011). The observation that motorised traffic congestion events were significantly positively-correlated to mean PNC (that is, increased motorised traffic numbers produces an increased mean PNC) highlights UFP as the dominant fraction of particle emissions. Meanwhile, the observation that construction events were significantly positively-correlated with PD is likely attributable to diesel machinery exhaust rather than to the creation and distribution of dust and debris from soil and material manipulation.

A previous comprehensive study by ILAQH indicated a mean regional background PNC of 7.4 x e^3 ppcc and a median PD of 40 nm; particle spectral analysis and vapour gas correlation suggested a strong association with motor vehicle emissions (Morawska et al., 1998). Over a decade later, mean regional background PNC at ILAQH has increased marginally to 10.0 x e^3 ppcc, and PD slightly decreased to 38 nm, potentially attributable to rapid regional population growth and associated increased motorised traffic volumes in the area surrounding ILAQH. Recently, a five-year study indicated that despite mean regional background PNC levels being lower compared with other international cities, proximity to a freeway increased total PNC by 105% (Mejıa et al., 2008). There is a significant correlation between motorised traffic emissions of vapour gas and ultrafine particles at street level (Wåhlin et al., 2001); however, background concentrations have been shown to be an inaccurate measure of personal PM exposure in some urban environments (Kaur et al., 2005). In the current study, local and regional hourly mean PNC and PD were not correlated, indicating the importance of in-commute monitoring for *in-situ* exposure studies and accurate estimation of air pollutant inhalation.

4.2. Estimated in-commute ventilation and inhaled particle counts

The higher $\dot{V}_E$ of bicycle commuters will increase the count of inhaled particles, typically exposed to short but high PNC peaks, compared to the lower but longer PNC peaks for car and bus passengers (Peters et al., 2004). Previous research has shown an approximate two-fold increase of $\dot{V}_E$ in bicycle commuters compared to motor vehicle occupants (van Wijnen et al., 1995; Zuurbier et al., 2010), however cycling speed was relatively low (12 km·hr, eliciting a mean $\dot{V}_E$ of 23.5 L·min) compared to the current study (20 km·hr, mean $\dot{V}_E$ = 44.2 L·min) which was guided by pilot research (Cole-Hunter, In Review). Thus, $\dot{V}_E$ differences between active and motorised transport participants could be larger than previously thought. While the current study did not perform any inter-modal comparisons, the total mean PNC (of approximately 3.0 x e4 ppcc) of HIGH was similar to that which has been found previously in motor vehicle cabins (Wallace and Ott, 2010). Further, a PNC lung deposition increase of 4.5-fold during exercise compared to rest has been observed (Daigle et al., 2003).

The current study showed that while $\dot{V}_E$ did not vary significantly between HIGH and LOW, local mean PNC was significantly greater with HIGH compared to LOW and was positively-correlated to the proximity of the CBD. The significantly-higher inhaled pollutant counts potentially experienced by active, compared to motorised, transport participants are believed to be outweighed by the benefits of exercise and reduced combustion emissions to participant and public health, respectively (de Hartog et al., 2010). However, bicycle commuting should be supported with appropriate infrastructure facilitating commute routes with reduced proximity to motorised traffic and therefore their emissions, particularly for individuals with pre-disposing physiological-susceptibilities (Cole-Hunter, In Review; Kingham et al., 2011).

4.3. Meteorological Influence

Higher humidity and precipitation for LOW compared to HIGH may have limited the degree of efficacy to reduce motorised traffic, and consequently reduce UFP, exposure during bicycle commuting. While increased regional precipitation reduced the mean regional PD, an increased regional temperature was associated with an increased mean regional PD. Further, higher regional humidity had a weak association with lower regional PNC, a relationship seen previously (Knibbs et al., 2011). A high wind speed can dilute PNC of the size range observed in the current study (Charron and Harrison, 2010), with the magnitude of dilution determined by wind direction relative to the individual (Hitchins et al., 2000), which was not accounted for in this study.

4.4. Additional Information

It has been previously shown that urban bicycle commuters using a route of high motorised traffic intensity could be exposed to a PNC of 40 - 60% greater than a route of lower motorised traffic intensity (Adams et al., 2001; Kaur et al., 2005; Strak et al., 2010). However, the difficulty of classifying off-road and on-road bicycle path infrastructure, theoretically indicative of low and high exposure to motorised traffic, respectively, has been noted in similar studies of other cities (Boogaard et al., 2009; Zuurbier et al., 2010). In the current study, two commute routes classified as off-road (South and West LOW) ran adjacent to major motorised traffic corridors. Consequently, marginal PNC reductions of LOW from HIGH for South and West were less compared to North and East directions. Further, heart rate values were greatest with West HIGH direction perhaps due to extensive altitude fluctuations associated with the Eastern extent of a coastal range, with hills up to 300 m above sea level, and conversely lowest with East LOW because of proximity to the Brisbane River. East LOW elicited a significantly lower heart rate than East HIGH, and therefore, estimated ventilation rate was significantly lower for East LOW compared to LOW of all other directions; however, speed was similar between the different proximities and directions.

Overall, it was considered that the North route provided the best example of the LOW and HIGH condition, as LOW ran consistently through ‘green-spaces’ while HIGH ran consistently along a busy main road used by buses and trucks, which is reflected in the resulting mean PNC values. Accordingly, it is important to consider topography, such as proximity to major roads and physically-demanding terrain due to influence on air pollution and ventilation, respectively, when assessing the exposure potential of bicycle commuters.

4.5. Limitations

The current study had several foreseen limitations. Firstly, only a single participant was used to estimate inhaled particle count; however, commute behaviour such as distance, speed, time of day and direction were informed by previous research of 156 participants (Cole-Hunter, In Review). Secondly, only morning peak commute times were monitored; however, this was done to represent more consistent commute performance times and utilise more reliable meteorological conditions. It was originally intended to use both the inbound and outbound legs of each return trip to increase sample size, however statistical analyses highlighted that typically the PNC for the outbound legs were significantly lower than the inbound legs. Further, no information on motorised traffic counts was collected; however, it is reasonable to argue that inbound HIGH legs would have a greater proximity to morning peak traffic compared to HIGH outbound legs (travelling opposite to the major flow of peak traffic, and later in time). Thirdly, the use of a Philips NanoTracer for field exposure monitoring is novel and reliability during active transport is not yet established; however, the vast majority of data collected was deemed valid, the measurement accuracy was calibrated in controlled conditions against a well-established WCPC standard, and tilt errors previously experienced with fluid-reliant particle measuring instruments, for example as a result of liquid alcohol flooding an optical chamber, were not possible. Unfeasibly low PNC and exact repeat logs of particle measurements were deemed invalid data, but incidents were rare and excluded from analyses.

4.6. Conclusion

In conclusion, routes of lower motorised traffic exposure facilitate a reduced mean PNC without significant variation in estimated ventilation rate, thereby reducing the inhaled particle count (and plausibly also dose), compared to routes of higher motorised traffic exposure. Thus, it is recommended that frequent bicycle commuters (particularly those with an adverse pre-disposition to combustion emission exposure) and urban planners better consider bicycle commute routing in regards to motorised traffic exposure.

ACKNOWLEDGEMENTS

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TABLES

Table 1 – Commute characteristics of bicycle commute route variations of low and high motorised traffic exposure

COMMUTE MEASURE	LOW					HIGH				
	North	*East*	*South*	*West*	**Total**	*North*	*East*	*South*	*West*	**Total**
Distance (km)	12 ± 1	11 ± 1	12 ± 1	10 ± 1	**11 ± 1**	10 ± 1	10 ± 1	12 ± 1	10 ± 1	**10 ± 1**
Duration (min)	34 ± 4	38 ± 1	38 ± 3	29 ± 4	**35 ± 2**	29 ± 1	30 ± 1	36 ± 2	33 ± 1	**32 ± 1**
Speed (km·hr)	21 ± 1	19 ± 1	19 ± 1	20 ± 1	**20 ± 1**	20 ± 1	19 ± 1	20 ± 1	18 ± 1	**19 ± 1**
Temperature (°C)	25.2 ± 1.7	23.5 ± 2.3	25.4 ± 3.0	26.3 ± 0.6	**25.1 ± 1.0**	26.9 ± 1.7	26.8 ± 0.3	27.0 ± 3.9	26.0 ± 1.4	**26.7 ± 0.3**
Humidity (%)	73.3 ± 13.5	85.0 ±10.5	63.7 ± 27.3	68.3 ± 4.7	**72.6 ± 6.4**	66.3 ± 5.5	67.7 ± 4.7	61.0 ± 9.0	63.7 ± 5.9	**64.7 ± 1.7**
Air Pressure (hPA)	1007 ± 1	1007 ± 6	1006 ± 4	1007 ± 3	**1007 ± 1**	1003 ± 2	1007 ± 4	1005 ± 6	1005 ± 7	**1005 ± 1**
Precipitation (mL)	14 ± 20	34 ± 19	5 ± 9	0 ± 0	**13 ± 1**	0 ± 0	1 ± 1	0 ± 0	19 ± 33	**5 ± 5**
Wind Speed (km·hr)	6.3 ± 4.0	5.7 ± 1.5	10.0 ± 4.6	6.7 ± 0.6	**7.2 ± 1.3**	3.7 ± 2.9	7.7 ± 6.7	6.7 ± 0.6	8.3 ± 7.5	**6.6 ±1.1**
Regional PNC (x e^4)	0.95 ± 0.46	1.18 ± 0.58	0.90 ± 0.39	1.02 ± 0.34	**1.01 ± 0.81**	1.13 ± 0.36	0.94 ± 0.36	0.93 ± 0.51	1.00 ± 0.60	**1.00 ± 0.15**
Regional PD (nm)	52 ± 14	45 ± 5	63 ± 7	54 ± 5	**54 ± 1**	67 ± 5	64 ± 13	53 ± 8	66 ± 11	**63 ± 3**

All values are Mean ± Standard Deviation. Temperature, humidity and air pressure were measured in-commute with a portable device. Precipitation and wind speed were measured at regional weather stations. Regional particle measurements were performed at the air monitoring station of the Queensland University of Technology (QUT) in the Brisbane CBD, Australia.

Table 2 – Exposure characteristics along bicycle commute route variations of low and high motorised traffic exposure

COMMUTE MEASURE	**LOW**					**HIGH**				
	North	*East*	*South*	*West*	**Total**	*North*	*East*	*South*	*West*	**Total**
PNC (x e^4; particles·cm^3)	1.26* ± 0.71	1.42 ± 0.89	1.95 ± 0.89	1.63 ± 0.72	**1.56* ± 0.38**	4.83 ± 1.87	2.88 ± 1.71	2.78 ± 0.69	1.73 ± 0.84	**3.06 ± 0.53**
PD (nm)	44 ± 13	51 ± 10	39 ± 5	43 ± 9	**44 ± 3**	37 ± 3	35 ± 2	35 ± 4	39 ± 8	**36 ± 1**
F_H (beats·min^{-1})	141 ± 3	$123^{\#}$ ± 9	141 ± 1	142 ± 3	**137 ± 2**	136 ± 2	138 ± 9	137 ± 6	143 ± 5	**138 ± 3**
$\dot{V}_E$ (L·min^{-1})	49 ± 8	$41^{\#}$ ± 7	39 ± 11	44 ± 9	**43 ± 5**	50 ± 10	49 ± 13	37 ± 7	55 ± 17	**46 ± 9**
Minute Inhaled (x e^8; particle count)	6.32* ± 0.29	5.49 ± 0.30	1.03 ± 0.49	8.43 ± 0.34	**7.63** ± 1.48**	11.3 ± 0.91	6.45 ± 0.73	5.07 ± 0.33	3.22 ± 0.31	**14.6 ± 1.84**
Accumulated Inhaled (x e^{10}; particle count)	2.22* ± 1.25	1.92 ± 1.19	3.85 ± 1.89	2.52 ± 1.27	**2.63** ± 0.65**	6.44 ± 2.42	3.91 ± 2.03	4.63 ± 1.11	3.31 ± 1.92	**4.57 ± 0.62**

All values are Mean ± Standard Deviation. * denotes $P < 0.05$, ** $P < 0.01$, LOW lower than HIGH equivalent variable. # denotes $P < 0.05$, lower than equivalent directional mean of LOW or HIGH. PNC = particle number concentration, PD = particle diameter, F_H = heart rate, $\dot{V}_E$ = minute ventilation. According to one-way ANOVA, the total accumulated inhaled particle concentration (all-directional), as a product of $\dot{V}_E$, PNC and commute duration, was significantly reduced with LOW compared to HIGH [$F(1,2) = 3478$; $p < 0.001$].

FIGURES

Figure 1 – Particle number concentrations along bicycle commute routes with higher and lower motorised traffic exposure from Brisbane North, East, South and West Suburbs to the Central Business District

Using ArcGIS, real-time particle number concentrations were plotted as multiple morning inbound trip means along pre-determined popular bicycle commute routes from the North, East, South and West Suburbs of Brisbane into the Central Business District (CBD). Coloured markers are used to indicate inhaled particle counts according to geographical location, represented by dark green (<1.0 x e^4 particles), light green (1.0 to 5.0 x e^4 particles), orange (>5.0 to 15.0 x e^4 particles), and red (>15.0 x e^4 particles). Total Mean PNC (all-directional) was significantly reduced in LOW compared to HIGH [$F(1,2) = 83.876$; $p = 0.012$]; however, there was only a significant intra-directional reduction of mean PNC with North LOW compared to North HIGH [$F(3,6) = 2.336$; $p = 0.007$].

Figure 2 –Inhaled particle count accumulation along bicycle commute routes with higher and lower motorised traffic exposure and increasing proximity to Brisbane Central Business District

The repeated multi-directional morning inbound means of particle number concentration and calculated ventilation (via heart-rate-ventilation associations) produced an accumulated inhaled particle count, which is plotted with increasing proximity (by time) to Brisbane's Central Business District (CBD) from the outer-suburbs. At approximately half-way to the CBD, the accumulated inhaled particle count along the route of highest exposure to motorised traffic ('HIGH') increased in rate compared to the altered route of lowest motorised traffic ('LOW'). ** On arrival to the CBD, the inhaled particle count accumulated of HIGH was approximately twice that of LOW.

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