# Exposure to air pollutants among cyclists: A comparison of different cycling routes in Perth, Western Australia

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## ABSTRACT

Cycling is often promoted as a means of reducing vehicular congestion, greenhouse gases, noise and air pollutant emissions in urban areas. It is also endorsed as a healthy means of transportation in terms of reducing the risk of developing a range of physical and psychological conditions. However, people might not be aware of the negative health impacts of cycling near heavy traffic. This study aimed to compare personal exposure to particulate air pollution among cyclists commuting in Perth, Western Australia.

The study involved 122 number of cyclists riding bicycles in four different routes: two routes within community areas (Route 1 and Route 2) and two routes near freeways (Route 3 and Route 4). The participants were males and females aged between 20 and 55 years with the selection criteria including non-smokers who cycle at least 150 km/week – ideally along one of the four study routes. Personal exposure of respirable particulate air pollution during cycling at the high and low level of exertions (self-perceived) were assessed. Ambient concentrations of selected air pollutants were also measured at each cycling route.

We found that Route 3 appeared to be the most polluted route and concentrations of nitrogen dioxide and sulphur dioxide exceeded the Australian standards. This study concluded that personal exposure to respirable particles was influenced by the speed, time of cycling and seasonal variation.

*Keywords:* Ambient air pollution, road traffic, particulate matter, criteria air pollutant, bicycle route, cyclist.

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## Introduction

Air pollution represents one of the biggest environmental health risks affecting people around the world (Achilleos et al. 2017; Checa Vizcaíno et al. 2016; Moore et al. 2016; Requia et al. 2018). The WHO (2018) estimated that 58% of outdoor air-pollution-related premature deaths were due to strokes and ischaemic heart disease, 18% due to chronic obstructive pulmonary disease and acute lower respiratory infections, and 6% of deaths due to lung cancer in 2016.

To reduce the harmful impacts of air pollutants on human health, WHO has developed a series of air quality guidelines (WHO 2000) for selected pollutants, such as particulate matter (PM), sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$) and ozone ($O_3$). These pollutants, along with carbon monoxide (CO) and lead, are classified as 'criteria air pollutants' (WHO 2005; Zhou et al. 2019). In Australia, there has been significant progress in controlling the emission of air pollution to comply with the National Environment Protection Measures (NEPM) standard (Department of Water and Environmental Regulation 2018; Environmental Protection Agency South Australia 2019); however, the recommended PM concentration levels are yet to be achieved as levels often exceed the national standard in most large cities, including Perth, Western Australia (Department of Environment and Conservation 2010; Hannelly 2017). Since these pollutants have been significantly associated with human mortality and morbidity, it is necessary to monitor and control the emission of PM in various micro-environments (Chen et al. 2016; Erbas et al. 2016; Salimi et al. 2018).

Traffic-related emissions are commonly recognised as a significant source of air pollutants, representing 23% of greenhouse gases globally (Azhar Khan et al. 2014; Leipzig 2010). Traffic emission mainly consists of CO, hydrocarbon, nitrogen oxides (NOx), and PM (Choudhary and Gokhale 2016; Mahesh et al. 2018; Sapkota et al. 2012), the majority of which result from the incomplete combustion of fuel. The concentrations of these pollutants are significantly higher in urban areas, especially near busy roads and freeways (Azmi et al. 2010; Brugge et al. 2016; Moshammer et al. 2018). It is widely acknowledged that air pollution emissions from vehicles have adverse impacts on human health (Dons et al. 2012; Okokon et al. 2017), however, the inhalation intensity appeared to vary greatly between commuters such as car or bus passengers and cyclists (Peters et al. 2014; Ragettli et al. 2013).

A limited number of studies have been conducted to compare the exposure levels of air pollutants among different modes of commuters including car, bus or ferry commuters, bicycle riders, and pedestrians, and most with conflicting results (Badland and Duncan 2009; Chertok et al. 2004; Farrar et al. 2001; Knibbs and de Dear 2010). The inconsistency in the study's results were due to various reasons including small sample size, differences in research design, trip mode, choice of route and type of equipment used to measure air pollution (Knibbs et al. 2011; Namdeo et al. 2016; Xie et al. 2017). One of the best examples is the study conducted by Hunter et al. (2012) in Australia who measured exposure to particle-number concentrations among cyclists in Brisbane. According to this study, the concentrations of particulate-number near high-traffic roads were higher ($14.08 \times e^8 \pm 1.77$) compared to low-traffic roads ($6.71 \times e^8 \pm 1.30$), during morning peak hour. However, the study was somewhat limited in scope and methodology as the monitoring was conducted during the holiday season when the traffic volume is significantly reduced. Majority of other similar studies were conducted in large urban settings (Peters et al. 2014; Strak et al. 2010) where commuters were in close vicinity to vehicle emissions (Hatzopoulou et al. 2013a; Mueller et al. 2015). The general trends from previous research showed that cyclists were likely to receive higher exposures to traffic air pollution due to their close proximity to vehicle emissions and their increased minute exertion (MacNaughton et al. 2014; Panis et al. 2010; Ramos et al. 2016). Even though there are conflicting outcomes regarding vehicular pollution and its exposure, several epidemiological studies have already established the association between traffic emission and adverse health outcomes among cyclists, including respirable-related diseases (Barkovich et al. 2012; Nwokoro et al. 2012). To evaluate the impact of air pollution inhalation on human health, better estimates of exposure to particulate matter in the human respiratory system is highly recommended. This study aimed to determine the exposure to air pollutants under different micro-environments among cyclists commuting in Perth, Western Australia.

## Materials and Methods

### *Study Design*

The study subjects were males and females selected randomly from Perth cycling clubs, Curtin University and the general community. Participants were selected based on a set of eligibility criteria and were asked to complete a short online questionnaire through Survey Monkey. The Survey Monkey is a tool that allows users to create their own surveys by using questions format templates (www.surveymonkey.com). The eligibility criteria for participating in the study included non-smoker (comprising those who had never smoked and former smokers who quit smoking at least 10 years ago), aged between 20 and 55 years who cycle at least 150 km/week-ideally along one of the four study routes. Further, participants who had cardiovascular and other chronic health conditions (but not asthma) were excluded from the study. Potential participants who had asthma were accepted in the study because according to the Australian Bureau of Statistics in 2018, approximately 2.7 million (11.2%) Australians had asthma diagnosed by a doctor (Australian Bureau of Statistics 2018).

The sample size of 122 subjects was estimated to detect a large effect of 0.40 (according to Cohen's effect conventions) between groups (four routes: two in high and two in low traffic density); two exertions (high vs low), and two seasons (warm vs cold) with a power of 80% at 5% significance level. Accounting for less than a 20% drop out rate, 156 subjects were sufficient for the study.

In this study, we applied the definition of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for warm and cold seasons. The warm season is defined as the yearly period when the average daily temperature is greater than $16^0$C and the cold season with an average daily temperature of less than $12^0$C (Mahony et al. 2006; Penman et al. 2006).

### *Selection of cycling routes*

Four cycling routes were selected from the Perth Metropolitan area as very popular among cyclists (Fig.1) based on the number of vehicles and information provided by the Department of Main Roads (Main Roads 2002). Two routes were selected from the suburban area named as "community routes" which are away from major traffic roads (Route 1 and Route 2). The other two were located in areas close to freeways named as "major routes" (Route 3 and Route 4) where the movement of vehicles is significantly higher compared to the suburban roads. Routes 1 is situated near Coode St in South Perth Esplanade, which is near the south bank of Swan River (Sir James Mitchell Park). The city of Perth is located approximately 1 km north of this route. According to Main Roads WA, the average weekly (Monday to Friday) number of vehicles that passed in Mill Point Road in 2015–2016 (two years period) was 21,120, including both cars and trucks (https://trafficmap.mainroads.wa.gov.au/map). The distance between Mill Point Road and Route 1 is approximately 200-245 metres. Although Mill Point Road is not classified as a busy road, it is located close to a diesel-powered ferry station (Mends St Jetty), car parks, restaurants and a major intersection point. Route 2 is located on Railway Parade in Welshpool, which is situated southeast of the Perth CBD (approximately 8.8 km). The average weekly number of vehicles counted for this route in 2015–2016 was 2,630 including both cars and trucks. The surrounding neighbourhood consists of residential houses, schools, a railway line (20 metres away) and light industries such as repair and sprays painting (within 100-800 metres). This route is also close to Sevenoaks Street (approximately 10 metres away) and two intersection points located within approximately 60 metres away from the sampling site. Routes 3 is located in South Perth near the Mill Point Reserve, 5.0 km from the Perth CBD and on average 7 metres away from the Kwinana Freeway. The Kwinana Freeway is considered as one of the busiest freeways within the Perth Metropolitan area, with private cars, public buses, and heavy trucks moving from both directions – south and north of Perth's CBD. The average weekly number of vehicles counted in 2015–2016 was 193,252 (Main Roads, 2018). Route 4 is located close to Richmond Reserve, North Perth which is on average 7 metres away from the Mitchel Freeway. This route is about 3 km away from the Perth CBD and it is also close to two other major roads: Oxford Street (approximately 220 metres away) and Vincent Street (approximately 230 metres away). The average vehicular flow on the Mitchell Freeway per week during 2015–2016 was 161,184. Each study route was 5 km long from the start to the endpoints.

**Perth in Australia** **Route 1 Community Route** **Route 2 Community Route**

**Route 3 Major route** **Route 4 Major route**

**Fig. 1 Maps of four cycling routes in Perth, Australia** ***(Sources: Google and Routes-Garmin Connect)***

### *Ambient air pollution and meteorological data monitoring*

The ambient particulate air pollution with different size including $PM_1$, $PM_{2.5}$, $PM_4$ (respirable), $PM_{10}$ and $PM_{Total}$ was measured in the selected four cycling routes. Selected gases such as CO, nitric oxide (NO), $NO_2$, $SO_2$, were also monitored.

The equipment used in the study included a DustTrak$^{TM}$ DRX Aerosol Monitor 8533b (TSI Inc., MN, USA), Testo 350 gas analyser, TSI-P-Trak Model 8525, Diffusion Dryer DDU 570**,** Thermodenuder TDD 590, Universal Scanning Mobility Particle Sizer (USMPS) 2700 and Anemometer. The DustTrak was set up at about 0.5 metres above the ground level at each route and measured concentrations of PM. The equipment was programmed to record data every 10 seconds during the sampling duration for a period of four hours. In addition to the real-time monitoring, a 37 mm filter cassette was used for gravimetric sampling of PM. Testo 350 gas analyser simultaneously measures CO, NO, $NO_2$ and $SO_2$. A USMPS was used to measure the size and number concentration of ultrafine particles (UFP). The TSI-P-Trak ultrafine condensation particle counter model 8525 was used as an alternative device to measure the UFP levels in the ambient air. Meteorological parameters including temperature, relative humidity and wind speed were recorded using Anemometer. Measurements were conducted in the morning for approximately 4 hours at each cycling route whilst participants were cycling, starting at 6:30 am which is considered the peak hour traffic times in Perth (Hannelly 2017; Hunter et al. 2012). The rainfall data used in this research was provided by the Department of Bureau of Meteorology (BOM).

### *Personal exposure to particulate air pollutants*

Along with the monitoring of ambient air pollution concentration, personal exposure of respirable particulate matter among cyclists was conducted simultaneously. Participants scheduled for the sampling were introduced to the study and explained their rights to withdraw at any time. The SKC respirable sampler was used to measure the concentration of personal exposure to respirable particles among cyclists. The "waist bag" was used to hold the SKC pump and the cyclone was clipped onto the collar of the cyclist's shirt around 30 cm diameter of the breathing zone. During the sampling, the airflow rate of the SKC pump was maintained at 2 litres/minute. Before each test, the SKC pump was calibrated and charged, and the cyclone was made ready with the filter paper inside. Before and after sampling, the filter papers were desiccated for 24 hours to remove any moisture. The used filter paper was then analysed to determine the dust concentration according to the Australian Standard (AS 2985-2009).

During the personal exposure assessment, a Bio Harness 3.0 heart rate monitor was used to measure the heart and respiration rate of participants while cycling (Shields et al. 2013). This device was worn on the chest with the help of a strap that incorporates an electrocardiography (ECG) heart-rate and respiration-rate monitor. This monitor was linked to a portable modem that transmits sensor-reading data and Global Positioning System (GPS) coordinates to a computer via its software. Also, it provides a facility to detect and transmit single-lead ECG signals to be received by Bluetooth-/USB-enabled EGC instruments.

Each cyclist was expected to ride 10 km (from the start to the turnaround point and back to the initial location). At the beginning of each test, participants were asked to ride the bike slowly and maintain 65% of their maximum heart rate (E1), representing the ‘low exertion rate’. During the second part of the test, participants were asked to ride the bike as fast as they could to maintain 85–90% of their heart rate (E2), and it was considered the ‘high exertion rate’. The maximum heart rate was estimated as per the formula provided by Robergs and Landwehr (2002) below. After completing the ‘low exertion’ round trip, the participants were requested to continue cycling at ‘high exertion’.

**Heart Rate = HRmax=220-participants’ age**

### *Statistical Analysis*

After completing the environmental and personal measurements of PM, the logged data were recovered from the monitoring equipment (Dust Trak, Testo, USMPS, P-Trak and Anemometer) for further analysis. Negative data from the DustTrak were considered missing values. Descriptive statistics were used to summarise the sample characteristics.

Kruskal-Wallis test was used to assess the differences in mean concentrations of PMs ($PM_1$, $PM_{2.5}$, $PM_4$, $PM_{10}$, and $PM_{total}$) and selected gases (CO, $NO_2$, NO, and $SO_2$) among the four traffic routes. If an overall significant difference was confirmed, the Mann-Whitney U test was further used as a post hoc test to examine the difference between each pair of routes. Spearman rank correlation coefficient was computed to assess the association between the air pollutant variables (PMs and selected gases) and the meteorological parameters (rainfall, humidity, wind velocity and temperature). The above procedure was carried out first on the overall data and then replicated separately for data disaggregated by ‘warm’ and ‘cold’ season to assess the seasonal variations of air pollutants patterns. In addition, the Wilcoxon signed-rank test was applied to assess the difference in personal exposure concentrations of the cyclists between cold and warm seasons.

All data were analysed using IBM SPSS version 22.0 (IBM SPSS Statistics for Window, Version 22.0. Armonk, NY: IBM Corp). All tests were two-sided and a p-value of less than 0.05 was considered statistically significant.

## Results

### *Demographic characteristics of the study subjects*

A total of 122 individual cyclists participated in the study and their demographic characteristics and physical parameters by gender are presented in Table 1.

**Table 1: Demographic characteristics and physical parameters of the participants (N=122) as per gender**

| **Participants' Characteristics** | **Male n (%)** | **Female n (%)** | **Total n (%)** |
|---|---|---|---|
| **Age (years)** | | | |
| 20–29 | 10 (10.1) | 4 (17.4) | 14 (11.5) |
| 30–39 | 20 (20.2) | 6 (26.1) | 26 (21.3) |
| 40–49 | 40 (40.4) | 8 (34.8) | 48 (39.3) |
| >49 | 29 (29.3) | 5 (21.7) | 34 (27.9) |
| **Smoking Status** | | | |
| Former Smoker | 29 (29.3) | 4 (17.4) | 33 (27.0) |
| Never smoked | 70 (70.7) | 19 (82.6) | 89 (73.0) |
| **Physical Measurements** | **Male (n=97) Median (IQR)** | **Female (n=21) Median (IQR)** | **Total Median (IQR)** |
| Height (m) | 1.8 (0.0) | 1.7 (0.1) | 1.8 (0.1) |
| Weight (kg) | 80.6 (13.2) | 64.0 (12.6) | 78.1 (16.0) |
| BMI (kg/m$^2$) | 25.2 (4.0) | 23.1 (4.8) | 24.9 (4.3) |
| **Heart Rate (bpm)** | | | |
| Low-Exertion Heart Rate | 119.1 (21.6) | 124.3 (31.3) | 119.3 (22.6) |
| High-Exertion Heart Rate | 146.8 (21.5) | 151.6 (26.4) | 147.5 (20.7) |
| **Breathing Rate (bpm)** | | | |
| Low-Exertion Breathing Rate | 26.7 (6.6) | 29.1 (8.5) | 26.8 (6.3) |
| High-Exertion Breathing Rate | 35.5 (9.6) | 41.4 (4.5) | 36.8 (9.5) |

Most of the participants, 99 (81.2%) were males and 23 (18.9%) were females aged between 20 and 55 years. Of the 122 participants, 33 (27.0%) were 'former smokers' and 89 (73.0%) 'never smoked', with a higher proportion of 'former smokers' among males (29.3%) than females (17.4%). On average, male participants had significantly higher BMI ($p<0.05$) when compared to females. Also, females had a higher mean heartbeat and breathing rate than males during both high- and low-cycling exertions.

***Background concentration of particulate matter***Table 2 presents the average background concentrations of ambient particulate matter ($PM_1$, $PM_{2.5}$, $PM_4$, $PM_{10}$, $PM_{Total}$) according to the cycling route. The concentration of smaller particles ($PM_1$) tends to be higher in Route 1, while in Route 3 larger particles ($PM_{2.5}$ and $PM_{10}$) were the predominant size particle fractions recorded in the study. The results demonstrated a statistically significant difference in concentrations for most particulate matters except $PM_{10}$.

In order to determine any seasonal difference in ambient PM concentrations, measurements were collected twice per year, during the warm and cold seasons (Table 2). Consistently, Route 3 in the cold season and Route 1 in warm season appeared to be the most polluted routes.

### *Background concentration of selected gases*

Results of measurements for CO, NO, $NO_2$ and $SO_2$ are shown in Table 3. Elevated levels of NO, $NO_2$ and $SO_2$ were recorded in Route 3 except for CO. We established a statistically significant difference ($p<0.05$) in the concentration of all gases between the four cycling routes. Due to missing data during the warm season, gas concentrations are only available for Route 1 and Route 4. It appears that Route 1 is more polluted than Route 4 but the difference was not significant ($p>0.05$).

**Table 2: Statistical comparison of ambient PM concentrations (μg/m$^3$) according to cycling routes and season (n=454 observations)**

| **Particulates** | **Route** | **Overall** | | | | | | **Cold Season** | | | | | **Warm Season** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **n** | **Median (IQR)** | **Min** | **Max** | **p-value$^{\infty}$** | **n** | **Median (IQR)** | **Min** | **Max** | **p-value$^{\infty}$** | **n** | **Median (IQR)** | **Min** | **Max** | **p-value$^{\infty}$** |
| **PM$_{1}$** | 1 | 130 | 12.9 (8.8)$^{ab}$ | 3.3 | 73.6 | <0.001 | 52 | 10.6 (7.4)$^{ae}$ | 6.7 | 32.6 | 0.002 | 78 | 13.2(9.2)$^{ea}$ | 3.3 | 73.6 | <0.001 |
| | 2 | 36 | 9.9 (5.6) $^{ac}$ | 4.0 | 23.0 | | 18 | 5.4 (6.1) $^{ac}$ | 4.0 | 15.2 | | 18 | 10.3(7.1) $^{a}$ | 5.2 | 23.0 | |
| | 3 | 144 | 12.5 (7.2) $^{ce}$ | 5.8 | 34.7 | | 64 | 13.0 (7.9)$^{cd}$ | 6.5 | 34.7 | | 80 | 9.3 (6.9) $^{d}$ | 5.8 | 20.9 | |
| | 4 | 144 | 8.1 (6.7) $^{be}$ | 2.6 | 135.0 | | 52 | 8.6 (8.2)$^{ed}$ | 2.6 | 29.1 | | 92 | 7.7 (6.7) $^{ed}$ | 3.1 | 135.0 | |
| **PM$_{2.5}$** | 1 | 130 | 13.0 (8.7) $^{ab}$ | 3.4 | 74.3 | <0.001 | 52 | 11.6 (7.7)$^{a}$ | 6.8 | 33.3 | 0.003 | 78 | 13.3(8.6)$^{e}$ | 3.4 | 74.3 | 0.002 |
| | 2 | 36 | 10.6 (7.0) $^{ac}$ | 4.1 | 24.3 | | 18 | 5.569 (7.3)$^{ac}$ | 4.1 | 15.5 | | 18 | 10.6 (7.7) | 5.5 | 24.3 | |
| | 3 | 144 | 13.3 (7.2) $^{ce}$ | 6.4 | 35.0 | | 64 | 14.1(7.8)$^{cd}$ | 6.6 | 35.0 | | 80 | 9.7 (7.6) $^{d}$ | 6.4 | 21.8 | |
| | 4 | 144 | 8.1 (7.8)$^{be}$ | 2.8 | 137.1 | | 52 | 9.2 ( 8.7)$^{d}$ | 2.8 | 30.1 | | 92 | 8.1 (7.3) $^{ed}$ | 3.2 | 135.1 | |
| **PM$_{4}$** | 1 | 130 | 13.0 (8.0)$^{ab}$ | 3.5 | 75.2 | <0.001 | 52 | 12.6 (8.3)$^{ae}$ | 7.0 | 34.7 | 0.001 | 78 | 13.5 (8.0)$^{e}$ | 3.5 | 75.2 | 0.001 |
| | 2 | 36 | 11.0 (8.3)$^{ac}$ | 4.4 | 25.0 | | 18 | 5.8 (8.7)$^{ac}$ | 4.4 | 15.8 | | 18 | 11.0 (8.0) | 6.0 | 25.0 | |
| | 3 | 144 | 14.1 (7.2)$^{ec}$ | 6.6 | 35.3 | | 64 | 14.6 (7.4)$^{cd}$ | 6.6 | 35.3 | | 80 | 10.4 (8.0) $^{d}$ | 6.9 | 22.8 | |
| | 4 | 144 | 8.4 (8.4)$^{be}$ | 2.8 | 138.6 | | 52 | 10.0 (9.5)$^{ed}$ | 2.8 | 31.4 | | 92 | 8.4 (8.1) $^{ed}$ | 3.4 | 138.6 | |
| **PM$_{10}$** | 1 | 130 | 13.5 (11.8)$^{ab}$ | 3.6 | 76.9 | 0.001 | 52 | 13.4 (9.6) $^{ae}$ | 7.1 | 37.6 | 0.002 | 78 | 13.5 (11.5)$^{be}$ | 3.6 | 76.9 | 0.006 |
| | 2 | 36 | 12.8 (10.1)$^{a}$ | 5.1 | 27.5 | | 18 | 6.6 (10.6)$^{ac}$ | 5.1 | 17.1 | | 18 | 12.8 (6.7) $^{f}$ | 9.7 | 27.5 | |
| | 3 | 144 | 14.9 (8.7)$^{e}$ | 6.7 | 35.9 | | 64 | 14.9 (6.1)$^{cd}$ | 6.7 | 35.9 | | 80 | 11.8 (11.1)b | 7.5 | 24.7 | |
| | 4 | 144 | 10.7 (14.8)$^{be}$ | 3.0 | 140.2 | | 52 | 12.0 (11.8)$^{ed}$ | 3.0 | 33.9 | | 92 | 9.4 (14.7) $^{ef}$ | 4.4 | 140.2 | |
| **PM$_{Total}$** | 1 | 130 | 13.9 (18.2) | 3.6 | 77.6 | 0.082 | 52 | 13.6 (11.0)$^{ab}$ | 7.2 | 41.7 | 0.002 | 78 | 17.0 (25.6)$^{be}$ | 3.6 | 77.6 | 0.018 |
| | 2 | 36 | 15.9 (10.6) | 6.0 | 31.3 | | 18 | 7.0 ( 11.1)$^{ac}$ | 6.0 | 18.5 | | 18 | 15.9 (6.4)$^{f}$ | 14.4 | 31.3 | |
| | 3 | 144 | 16.0 (12.6) | 6.7 | 36.1 | | 64 | 16.0 (6.653)$^{bcd}$ | 6.7 | 36.1 | | 80 | 12.6 (14.4)b | 8.0 | 36.0 | |
| | 4 | 144 | 12.4 (15.1) | 3.0 | 140.6 | | 52 | 13.9 (15.4)$^{d}$ | 3.0 | 35.8 | | 92 | 11.2 (38.5) $^{ef}$ | 5.0 | 140.6 | |

*∞ Statistically significant difference between the four routes was assessed by using Kruskal-Wallis Test,*

*a,b,c,d,e,f same characters among four routes indicate statistically significant difference between two routes using Mann-Whitney U test; N indicates the number of observations.*

**Table 3: Statistical comparison of ambient concentration (ppm) of gases according to cycling routes and season (n=120 observations)**

| Gases | Route | Overall | | | | | | Cold Season | | | | Warm Season | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | n | Median (IQR) | Min | Max | p-value$^{\infty}$ | n | Median (IQR) | Min | Max | p-value$^{\infty}$ | n | Median (IQR) | Min | Max | p-value$^{\lozenge}$ |
| **CO** | 1 | 24 | 3.7 (7.6) | 1.9 | 9.8 | 0.088 | 6 | 3.3 (0.0)$^{a}$ | 3.3 | 3.3 | 0.001 | 18 | 4.2 (8.1) | 1.9 | 9.8 | 0.822 |
| | 2 | 6 | 0.8 (1.0) | 0.8 | 1.8 | | 6 | 0.8 (1.1)$^{acd}$ | 0.8 | 1.8 | | N/A | N/A | | | |
| | 3 | 26 | 2.1 (2.8) | 1.9 | 5.8 | | 26 | 2.1 (2.8) $^{ce}$ | 1.9 | 5.8 | | N/A | N/A | | | |
| | 4 | 64 | 4.1 (13.6) | 0.6 | 57.5 | | 40 | 4.3 (3.1) $^{de}$ | 0.6 | 18.5 | | 24 | 3.2 (56.5) | 1.0 | 57.5 | |
| **NO** | 1 | 24 | 0.2 (0.3)$^{a}$ | 0.0 | 0.8 | <0.001 | 6 | 0.3 (0.0)$^{a}$ | 0.3 | 0.3 | <0.001 | 18 | 0.2 (0.4) | 0.0 | 0.8 | 0.347 |
| | 2 | 6 | 0.1 (0.5)$^{b}$ | 0.1 | 0.6 | | 6 | 0.1 (0.5)$^{acd}$ | 0.1 | 0.6 | | N/A | N/A | | | |
| | 3 | 26 | 0.4 ( 0.2)$^{abe}$ | 0.1 | 1.1 | | 26 | 0.4 (0.2) $^{c}$ | 0.1 | 1.1 | | N/A | N/A | | | |
| | 4 | 64 | 0.2 (0.4)$^{e}$ | 0.0 | 1.7 | | 40 | 0.4 (0.5)$^{d}$ | 0.1 | 1.7 | | 24 | 1.1 (0.1) | 0.0 | 0.2 | |
| **$NO_2$** | 1 | 24 | 0.1 (0.2) $^{a}$ | 0.0 | 0.4 | <0.001 | 6 | 0.2 (0.0)$^{ab}$ | 0.2 | 0.2 | 0.048 | 18 | 0.1 (0.2) | 0.0 | 0.4 | 0.507 |
| | 2 | 6 | 0.1 (1.4)$^{c}$ | 0.1.1 | 1.5 | | 6 | 0.1 (1.4)$^{a}$ | 0.1 | 1.5 | | N/A | N/A | | | |
| | 3 | 26 | 0.4 (0.5) $^{ae}$ | 0.1 | 1.5 | | 26 | 0.4 (0.5)$^{e}$ | 0.1 | 1.5 | | N/A | N/A | | | |
| | 4 | 64 | 0.1 (0.1)$^{ce}$ | 0.0 | 1.3 | | 40 | 0.1 (0.3)$^{be}$ | 0.1 | 1.3 | | 24 | 0.1 (0.1) | 0.0 | 0.1 | |
| **$SO_2$** | 1 | 24 | 0.2 (0.3) | 0.0 | 0.4 | 0.221 | 6 | 0.2 (0.0)$^{a}$ | 0.2 | 0.2 | 0.020 | 18 | 0.3 (0.3) | 0.0 | 0.4 | 0.086 |
| | 2 | 6 | 0.1 (0.0) | 0.1 | 0.1 | | 6 | 0.1 (0.0)$^{ac}$ | 0.1 | 0.1 | | N/A | N/A | | | |
| | 3 | 26 | 0.2 (0.1) | 0.0 | 0.7 | | 26 | 0.2 (0.2)$^{c}$ | 0.0 | 0.7 | | N/A | N/A | | | |
| | 4 | 64 | 0.2 (0.4) | 0.0 | 0.6 | | 40 | 0.4 (0.3) | 0.0 | 0.6 | | 24 | 0.1 (0.2) | 0.0 | 0.2 | |

*∞Statistically significant difference between the four routes was assessed by using Kruskal-Wallis Test, ◊ Statistically significant difference between the two routes was assessed by using Mann-Whitney U test,*

*a,b,c,d,e, Same characters among four routes indicate a statistical significant difference between two routes using Mann-Whitney U test; n indicates the number of observation*

### *Correlation between meteorological parameters and air pollutants*

Significant correlations were established between most of the selected air pollutants and meteorological parameters and the results are presented in Table 4. Particulate air pollution was significantly correlated with the temperature and rainfall whereas NO and $NO_2$ were significantly correlated with temperature, humidity and rainfall.

**Table 4: Correlation coefficients between meteorological parameters and air pollutants**

| **Air Pollutants** | **Wind Vel. (m/s) ($r_s$)** | **Temp. ($^0$C) ($r_s$)** | **Humidity (%) ($r_s$)** | **Rainfall (mm)( $r_s$)** |
|---|---|---|---|---|
| **PM (µg/m$^3$)** | | | | |
| $PM_1$ | -0.040 | -0.210** | -0.037 | 0.200** |
| $PM_{2.5}$ | -0.087 | -0.198** | -0.064 | 0.230** |
| $PM_4$ | -0.083 | -0.040** | -0.035 | 0.255** |
| $PM_{10}$ | -0.087 | -0.102* | -0.068 | 0.243** |
| $PM_{total}$ | -0.078 | -0.078 | -0.100 | 0.198** |
| **Gases (ppm)** | | | | |
| CO | 0.049 | -0.017 | -0.134** | 0.164** |
| NO | 0.139 | -0.235* | -0.243** | 0.131* |
| $NO_2$ | 0.057 | -0.383** | -0.332** | 0.304** |
| $SO_2$ | -0.260* | 0.007 | -0.094 | 0.148 |

*** Spearman correlation coefficient (rs) is significant at 5% significance level (two-tailed)*

**Spearman correlation coefficient (rs) is significant at 1% significance level (two-tailed)*

### *Personal concentrations of particulate matter among cyclists*

Personal exposure to respirable particles ($PM_4$) was compared between the cycling routes according to gender, season and cycling exertions (Fig 2). The statistical analysis showed that $PM_4$ concentration was significantly ($p=0.038$) higher among participants who cycled in Route 1 compared to the other routes which are consistent with the findings for ambient PM measurements for Route 1. Significantly higher $PM_4$ concentrations were recorded in Route 4 during the cold season compared with the warm season ($p<0.05$) and also in Route 1 during the low-speed compared with the high-speed ride ($p<0.05$). The study found that the male population was exposed to higher $PM_4$ concentrations in Route 1 compared to the female population although the difference was not significant ($p>0.05$).

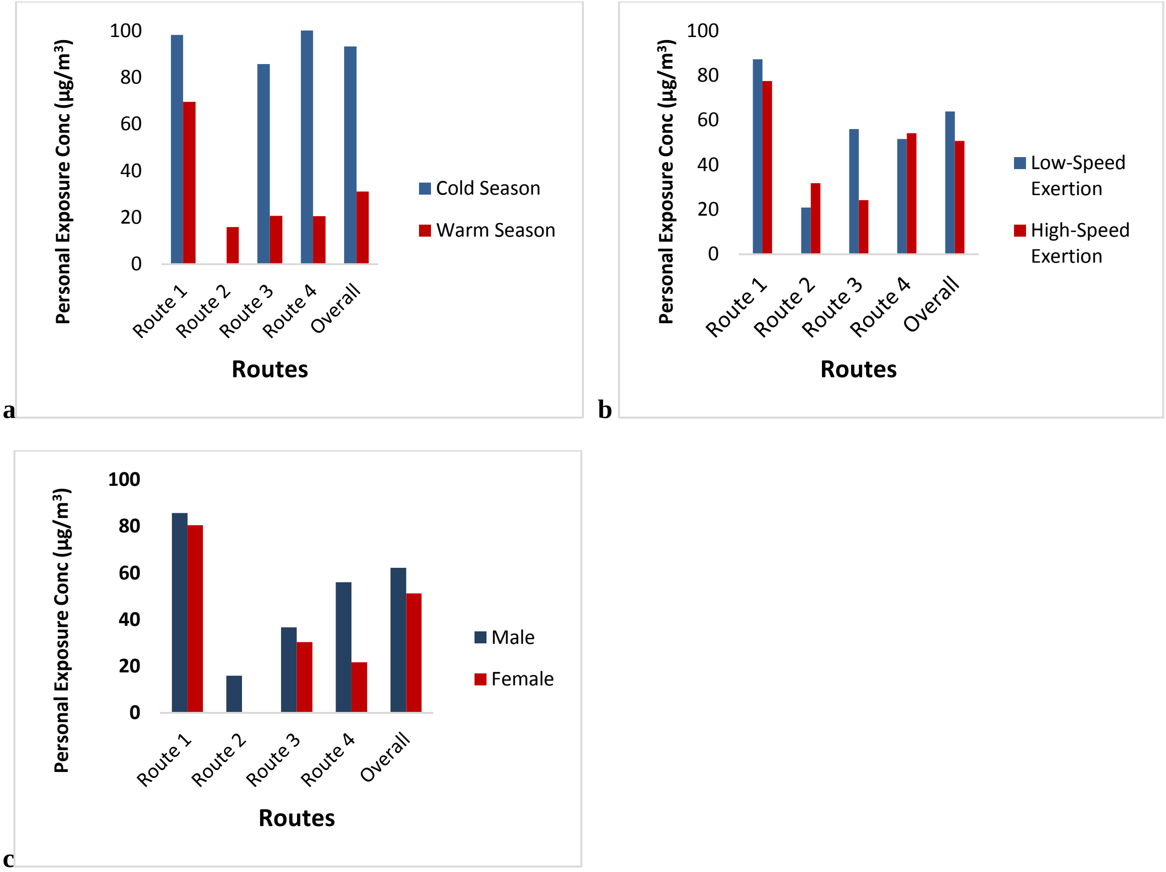

**Fig 2 Comparison of personal exposure to $PM_4$ among cyclists between routes according to a) seasons, b) cycling exertion and c) gender**

## Discussions

### *Ambient air quality*

This study measured concentrations of particulate matter and selected gases near different cycling routes within the Perth Metropolitan Area. Although elevated PM concentrations were measured for Routes 1 (community route) and 3 (major route), the concentrations were within the WHO 24 hours mean standards ($PM_{2.5}$-25 µg/m$^3$ and $PM_{10}$-50 µg/m$^3$). Higher $PM_{2.5}$ concentrations were recorded near Route 1 which was unexpected and can be explained with the close proximity of this cycling route to the diesel ferry station. This is in agreement with other studies conducted by Peng et al. (2016) and Knibbs et al. (2011) who measured increased concentrations of $PM_{2.5}$ among ferry commuters compared to cyclists, bus or automobile passengers and walkers. In addition, Corbett (2002) estimated 443 tons/year of PM emissions in the local environment of ports and attributed to the presence of ferry vessels. The other potential explanation for the higher PM concentrations recorded in Route 1 is the heavy and light vehicles parked close to the monitoring equipment especially during the morning rush hours when the number of vehicular movement with the engine running at the same time is very high. Studies have observed engine idling, which is common when a vehicle is about to start or stop in the parking area is associated with higher exposure to PMs compared with the moving vehicles (Liu et al. 2011; Ramachandran et al. 2005). During idling, the turbulent dispersion induced by the wake of a moving vehicle is absent which is the reason behind the high PM exposure. This is in agreement with the study conducted by Zhao and Zhao (2014), who reported higher PM concentrations near parking areas. Similarly, the study conducted by Li and Xiang (2013) also recorded higher concentrations of PMs at the entrance and exit of an underground parking area.

As expected, cyclists who were riding near Route 3 (major route) were exposed to higher concentrations of $PM_{2.5}$–$PM_{10}$ compared to those who used the other routes. A possible explanation for this observation is the high volume of traffic flow, which is the most common source of PMs (Barrowcliffe et al. 2002; Lin et al. 2016). The coarse fraction component ($PM_{2.5}$–$PM_{10}$) mainly comes from particles whirled up from the road by the wheels of the vehicles, whereas fine particles ($PM_{2.5}$) usually originate from fuel combustion. Several previous investigations have reported a correlation between high traffic volume and increment of PMs and our findings are consistent with these results (Boogaard et al. 2009; Kaur and Nieuwenhuijsen 2009; Kaur et al. 2005; Morawska et al. 2008). However, in most studies, preferences were given to UFPs and fine PMs since they are more closely related to traffic emissions, and fewer studies have explored respirable particulate matter.

Significant seasonal variations in PM concentrations were also observed in this study which is consistent with the results reported in a study by Mishra et al. (2012) showing that the PM concentrations are usually modified not only by the sources of pollution but also by the seasonal variations.

For selected gases, Route 3 appeared to be the most polluted in terms of exposure to NO and $NO_2$, and route 4 for exposure to CO and $SO_2$ concentrations compared to the other routes. The overall concentrations of $NO_2$ in all four routes were between 0.091–0.359 ppm and $SO_2$ was 0.074-0.241 ppm which exceeded the NEPM standards (National Environment Protection Council 2011; Northern Territory Environment Protection Authority 2015) i.e. $NO_2$ is 0.12 ppm per 1 day a year and $SO_2$ is 0.20 ppm per 1 day a year.

The higher concentration of gases in Routes 3 and 4 supports the hypothesis that high traffic volume is directly related to increased concentrations of ambient air pollution and suggests that cycling route choice can affect commuter’s exposure to air contaminants associated with vehicle exhaust. Moreover, these results support the findings of previous studies that also measured higher concentrations of gases (CO, $NO_2$ and PM) near routes of high traffic volume (Han and Naeher 2006; Zhang and Batterman 2013).

In addition to the traffic volume, some specific characteristics of urban environments, such as close proximity to major roads, street canyons, tree-lined streets, and infrastructure may also play a significant contribution to the level of air pollution in the cycling microenvironment. In this study, Routes 3 and 4 runs parallel with freeways (within 3–4 metres), which could be a reason for the elevated concentrations of gases compared to the other studied routes. In addition, during the measurements, we observed that there were only bushes and no trees between the cycling routes and the freeways. Trees act as a barrier and do not allow further dispersion of the gases. Therefore, the absence of trees further explains the higher concentration of pollutant gases near these routes. Similar findings were established by Hatzopoulou et al. (2013b) who proved that with every 5-metres increase in distance between cycling routes and traffic roads, the gaseous pollutants decrease by 2.5%.

### *Effect of meteorological parameters on air pollution*

This study established a significant correlation between ambient PM concentrations and meteorological factors such as rainfall, temperature, wind velocity and humidity which is consistent with the findings of other studies (Kittelson et al. 2004; Vinzents et al. 2005). We showed that the increase in precipitation significantly elevates PM concentrations which are demonstrated in the studies by Vardoulakis and Kassomenos (2008) and Jayamurugan et al. (2013). Wet conditions are generally associated with disturbed atmospheric conditions and trapped PMs which lead to increased exposure levels to PM.

Wind velocity which affects dilution and transport of vehicle emissions was found to be negatively correlated with gases in previous studies (Elminir 2007; Levy et al. 2003). In this study, the wind speed was negatively correlated with $SO_2$ concentrations which is in agreement with the similar finding from the study conducted by Zhang et al. (2015) who interpreted that horizontal dispersion is the major cause in decreasing gaseous concentration with the increase of wind velocity. However, all the other gases (CO, NO and $NO_2$) were positively correlated with wind velocity but the correlation was not significant. A negative correlation was also established between temperature and NO, $NO_2$ and CO which is in agreement with the study conducted by Jayamurugan et al. (2013) who revealed that $NO_x$ and CO have a very weak but negative correlation with temperature due to the convection process. The present study also demonstrated a negative correlation between gases pollutants and relative humidity. This is in agreement with the findings of a study conducted by Elminir (2005) who revealed that as relative humidity increases, the air pollutants absorb more water and increase their size and volume which makes them deposited in the ground.

Our findings suggest that meteorological factors should also be considered in quantitative evaluations of ambient air pollution to maximise the validity of the results.

### *Measured personal exposure to particulate matters*

According to previous research, cycling route choice as a proxy for traffic volume is likely to be an important determinant of exposure to commuters (Okokon et al. 2017; Tsai et al. 2008). In this study, personal exposure of $PM_4$ concentration among cyclists was observed to be significantly different between the four selected cycling routes. The highest median $PM_4$ exposure level was observed in Route 1 and this is in agreement with the measured ambient background concentrations of PM.

Significantly higher $PM_4$ concentration was measured during the cold season compared with the warm months of the year which is in agreement with the results from previous studies (Adams et al. 2001; Sørensen et al. 2005). Higher concentrations of particles recorded during the cold season may be due to the lower temperature which can increase the condensation and coagulation, leading to increased PM exposure levels (Elminir 2007; Morawska et al. 2008). However, this result is not in agreement with the findings of a study conducted in Dublin, Ireland where PM concentration exposure was found to be higher in summer than in winter (Adams et al. 2001; Zhang et al. 2015).

A significantly higher concentration of personal exposure to $PM_4$ was recorded during the low-speed compared with the high-speed riding and the results are consistent with the findings reported by Tsai et al. (2008). In the study, Tsai and colleagues (2008), demonstrated that the longer the time spent commuting, the larger the total intake of pollutants is. In this study, the time duration of cycling 10 km was longer during the low-speed ride compared to the high-speed ride.

This study acknowledges some limitations including the substitution of USMPS with the P-Trak due to the equipment breakdown. Also, due to the breakdown of the Testo 350 analyser during the warm season, no data was recorded during this time. In addition, due to the insufficient number of cyclists, many participants were asked to repeat more than one route in addition to the original route they participated in.

## Conclusions

This study contributes to a small but growing body of literature that investigates the network of relationships between active cycling, exposure to ambient PM levels and its association with health impacts (through the literature review). Based on the results, this study concludes that the concentration of air pollution in ambient air, the physiological parameters of cyclists and their activity patterns during cycling have a high impact on their pollution exposure. A detailed study on the association between personal exposure to particulate matters and adverse health impacts among cyclists can be a subject of future research.

This study concluded that cyclists may receive increased exposure to traffic-related air pollutants because of their increased exertion rate and close proximity to congested-traffic air pollution. Nevertheless, choosing a cycling route close to a low traffic road is not the only consideration in reducing exposure to air pollutants; it is essential to also consider nearby additional sources of pollution, such as ferry stations, industries and car parking areas. Furthermore, this study concludes that gender, season and exertion rate should be considered while calculating the exposure to particulate matter among cyclists. This can offer further accuracy in the findings and clarify the contribution of personal exposure to actual health effects among cyclists. The outcomes of this study suggest that weather conditions can also play a significant role in cyclists' exposure to particulate air pollution.

Finally, this study indicates that the best way to mitigate exposure to pollution among cyclists is to cycle on a designated network of streets that are 'bicycle boulevards,' away from pollution sources as suggested by Jarjour et al. (2013). The policymakers should, therefore, focus on preparing strategies for renovating technologies and adding vegetation near traffic roads and cycling routes; and reduce the emissions in the ambient air.

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