Impact of route choice and period of the day on cyclists' exposure to black carbon in London, Rotterdam and São Paulo

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Research highlights

- ▶ Cyclists exposure assessment to BC in the cities of London, Rotterdam and São Paulo.
- ▶ BC concentrations were higher in the morning-peak hours in São Paulo and Rotterdam.
- ▶ In London, mean BC concentrations were higher during the evening peak hours.
- ▶ Cyclists using the alternative routes were mostly less exposed to BC.
- ▶ Important findings to consider in planning new cycle networks with lower exposure levels.

Abstract

Cyclists are exposed to direct traffic emissions due to their proximity to on-road vehicles. Several studies associate black carbon (BC) exposure with both mortality and morbidity caused by cardiovascular and respiratory diseases. We did a comparative assessment of cyclists' exposure to BC in three cities: London, Rotterdam and São Paulo. We measured personal exposure to BC during the peak and off-peak hours in all three cities using the same instrument. Three origin-destination (O-D) pairs, each with two routes, for a total of six routes, were chosen in each city. The first route of each O-D pair was along busy major roads and the other perceived to be clean passing close to green/blue/quiet areas. This work brings together results from three different Latin American and European cities, with an aim to understand the BC exposure variabilities while cycling during peak and off-peak hours, identify main pollution hotspots resulting in enhanced exposure and associate the measured concentrations with proximity to green areas and waterways. BC concentrations were higher during the morning-peak hours compared with evening-peak hours in Rotterdam and São Paulo. London showed an opposite trend, with higher concentrations during evening hours. In most cases, the cyclists using the alternative route were found to be less exposed to BC in London and São Paulo. In Rotterdam, the differences in absolute concentrations between main and alternate routes were modest. Each city is different but the common features among all were that the exposure is related to route choice, a period of the day and proximity with the mobile sources. These

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findings have implications in terms of considering the pollutants exposure when establishing new cycle routes.

Keywords: Exposure assessment; Commuter exposure; Cycle users; Black carbon; Mobile measurements

1. Introduction

Cycling is becoming a popular choice of travel mode in many urban areas, which is reflected by an increase in the number of cyclists, development of cycle-sharing systems, and investment in cycleways (Midgley, 2011; Pucher and Buehler, 2017). The societal benefits of cycling in urban areas are related to improved health and well-being (Hartog et al., 2010), commuting time and money savings, promotion of social inclusion and producing less air pollution, noise and congestion (Johansson et al., 2017; Rojas-Rueda et al., 2011). However, cycling is also associated with health and safety hazards due to the exposure to high concentrations of traffic emissions, especially during peak commuting period (Hartog et al., 2010; Tainio et al., 2016). On-road vehicles are a dominant source of air pollution in urban areas (Kumar et al., 2018a). Cycle commuters are particularly vulnerable because of them being on or close to the roads. Their ventilation rate, which is the volume of air inhaled over a unit time, is also two to four times higher to those for car or bus passengers (Zuurbier et al., 2009; Apparicio et al., 2016). This means that the inhaled dose is relatively larger in a cyclist when compared to a car or bus passenger exposed to the same concentration when ventilation rates and trip duration are taken into consideration (Kumar et al., 2018b).

Several studies associate the exposure to Black Carbon (BC) with total and cardiovascular mortality, blood pressure and respiratory disease (Geng et al., 2013; Jansen et al., 2005; Mordukhovich et al., 2009). In urban areas, BC comes mainly from fossil fuel combustion, and the main source are motor vehicles emissions, in particular, diesel vehicles (Kumar et al., 2018a). Based on the panel and time-series studies, there is enough evidence of daily variations in BC concentrations with all-cause and cardiovascular mortality and cardiopulmonary hospital admissions (Janssen et al., 2012). Moreover, Gan et al. (2013) found that exposure to higher levels of wood smoke pollution was associated to hospitalizations due to chronic obstructive pulmonary disease (COPD) and that BC can be a carrier of compounds derived from combustion process that can be toxic. They found a 6% increase in COPD hospitalization and 7% increase in COPD mortality associated with an elevation equivalent to $0.8 \mu\text{g}/\text{m}^3$ of elemental carbon. Despite the deleterious effects of BC on human health (Grahame et al., 2014; Janssen et al., 2012), there are no recommendations or thresholds values established for their concentrations in ambient air.

BC concentrations near the road can be affected by a number of factors such as vegetation and local dispersion conditions governed by surrounding built-up environment and atmospheric

and traffic conditions. Vegetation shrubs or hedges can work as a bio-filter for traffic emissions in near-road environments (Abhijith et al., 2017; Abhijith and Kumar, 2019; Chen et al., 2016). Dispersion close to the roadsides is usually governed by the traffic-induced turbulence (Carpentieri and Kumar, 2011). Atmospheric turbulence then becomes dominant at distances away from the road (Al-Dabbous and Kumar, 2014). Concentrations usually decrease with increasing distance from the road. For example, higher pollutant concentrations are usually observed near the road during low wind speeds compared with an opposite trend during higher wind speeds (Karner et al., 2010; Pasquier and André, 2017). In urban street canyons, surrounding built-up environment around roads can obstruct the natural wind flows and result in either reducing or increasing atmospheric advection and air pollution dispersion depending mainly on the wind direction and position on the street (Vardoulakis et al., 2003). For example, high concentration of pollutants were observed on the leeward side of street canyons under perpendicular wind conditions (Afiq et al., 2012; Zhang et al., 2015). Close to waterways, the wind speed may increase (Ruel et al., 1998) due to little obstruction to wind flows caused by built-up urban structures and consequently favouring the dispersion of pollutants.

Thus, the route choice (Bigazzi et al., 2016; Hertel et al., 2008; Jereb et al., 2018) along with the period of the day (Apparicio et al., 2016; Hankey and Marshall, 2015; Targino et al., 2016) are important determinants of cyclists' exposure. There are limited studies quantifying the exposure to BC considering the effect of the route choice and the period of the day, and even lesser that compare the exposure of cyclists' in different cities from separate countries using the same set of instruments. Covering such features is one of the key characteristics of our article.

London, Rotterdam and São Paulo are important employment centers in their regions that have considerable differences in urban morphology, density, and transport infrastructure. Moreover, in South America, there are scarce studies related to the air quality exposure of the population to traffic. Cycling accounts for about 27% of trips in The Netherlands (KiM, 2018) as opposed to 2% of all trips in the UK (Department of Transport, 2018) and nearly the same (2%) in Brazil (ANTP, 2018). This work aims to understand the variabilities in cyclists' exposure to BC during peak and off-peak hours at the selected routes in the three cities, identify pollution hotspots and the association between the measured concentrations and variables such as distance to green areas, and waterways in studied cities. These variables can easily be taken into account by transport policy measures.

2. Methodology

2.1 Description of case study areas

London is the capital city of the United Kingdom (UK), situated on the River Thames with an area of 1572 km², around 8.8 million inhabitants (Office for National Statistics, 2017) and counting 3.1 million licensed vehicles, of which 2.7 million are cars (Department for

Transport, 2018). In Greater London, 35% of the trips are made by car, 33% by walking, 13% by bus/tram, 9% by underground, 6% by national rail and only 3% by cycling (Transport for London, 2017). Despite the small cycling modal share, there are more than 730,000 cycling trips per day and the number of trips grew by 8.8% between 2016 and 2017 and by 154% since 2000 (Transport for London, 2017).

The city of Rotterdam is part of the Randstad region of the Netherlands. It is approximately 20 km away from the coast and is the second largest city in the Netherlands with 624,000 inhabitants (City of Rotterdam, 2015). It is also one of the most polluted cities in the country and has one of the biggest ports in the world. In terms of transport supply, the city's public transport network includes a metro, heavy rail (trains), light rail (trams), buses and boats (ferries), and a bicycle network with nearly 600 km of cycle paths. However, as with most Dutch cities, the cycle accounts for an important segment of the daily modal share as single trips or as part of a larger multimodal trip, particularly in combination with the train. In Rotterdam, 40% of the trips related to work/study are by cars, 32% by public transport and 24% by cycles (Geemente Rotterdam, 2018).

The city of São Paulo is the main urban area of South America with an extent of approximately 1,521 km². It has a population over 12 million (IBGE, 2018). Moreover, in São Paulo the vehicular fleet of the municipality of São Paulo has been increasing alarmingly (Kumar et al., 2016). In June 2017, approximately 8 million vehicles were registered, of which 70% were automobile type (DENATRAN, 2017). In 2017, a survey about the impact of the cycle use in São Paulo (CEBRAP, 2018) showed that 38% of the trips are done using public buses as the main transport mode, followed by cars (19%) and by active mode (30%). Cycles represented 2% of the transport mode trips. The city has almost 500 km of cycleways that is becoming more popular, partly also due to the economic crises.

Unlike London and Rotterdam, São Paulo is a Latin American megacity that has about 261,000 active cycle users. The understanding of cyclists' exposure in São Paulo is limited, there is only a pilot study conducted by Targino et al. (2018). All three cities present a different socio-economic conditions and traffic fleet (e.g., São Paulo using biofuel) and using the same set of instruments and experimental methodology make it possible to enhance the understanding of exposure to cycle users in the three cities.

2.2 Route selection

Three origin-destination (O-D) pairs – one main route and one alternative route for each O-D pair – giving a total of six cycling routes were chosen in each city (Figure 1). These O-D pairs were selected in such a way that they can represent different regions of the city, route characteristics, traffic proximity and cycle infrastructures. The main routes included segments of roads with high traffic and street canyons, and the alternative routes lower traffic, green

areas (parks, squares, grass and forest areas) and closer to waterways, when possible. We used the typical traffic conditions on Google Traffic feature on Google Maps during the cycle runs to select the alternative routes with less traffic. This feature calculates the average speed of the road by analyzing the GPS data transmitted by mobile phones. To make the discussion simpler, we created a code for each route that contains three characters. The letter corresponding to the city (i.e., L: London, R: Rotterdam or S: São Paulo), the number corresponding to the O-D pairs (1-3) and the letters, A or B, to indicate the main or alternative route, respectively.

In London, the chosen origins were Liverpool (L1), Lancaster Gate (L2) and Stockwell (L3) while the destination was Waterloo Station. L1 is located in the City of London containing the primary central business district of London and is a popular destination for commuters. L2 gives access to the entrance of Hyde Park, a public park with 142 ha and an important leisure center of the city. L3 is a neighbourhood of Lamberth area with social housing and is ethnically and socially diverse.

In Rotterdam, the destination was the Rotterdam Central Station, which is an important jobs center in the city. Additionally, Rotterdam Central also allows for fast connections by public transport to other locations. This is an important consideration in the Netherlands given the importance of bike-and-ride. The origins were Tarwebuurt (R1), Bospolder (R2) and Crooswijk (R3). The selected origins are three of the postcode areas with the highest poverty rates in the Netherlands.

In São Paulo, the origins were Anhangabaú (S1), Ibirapuera (S2) and Faria Lima (S3) and the destination was Paulista Avenue. S1 is located in the central region of São Paulo and was the main financial district back in the 50s. It is a region with strong commercial activity and a frequent destination of people coming for work. S2 is located inside the Ibirapuera Park, which is an urban park with 158 ha and a recreation and sports center of the city. S3 is one important avenue and commercial and financial center. In all three cities, the destinations were places with high accessibility to jobs.

Table 1 compiles characteristics of the six routes in each city in terms of traffic, length (km), total cycled (km), distance of the cyclist to the road and a small description of the main features of the route.

2.3 Instrumentation and data collection

Measurements were carried out between October 2017 and February 2018 in the three cities, starting in Rotterdam (October 2017), London (December 2017) and São Paulo (February 2018). These months avoided the rainy days when the ambient environment is usually clear. Average temperature range during the monitoring days was 6.0 to 15.5°C in London, 13.1 to 15.6°C in Rotterdam and 19.0 to 28.7°C in São Paulo. The relative humidity varied between 68 – 89% in London, 84 – 95% in Rotterdam and 48 – 83% in São Paulo, and

the wind speed ranged from 2 to 9 m/s in London, 2 to 7 m/s in Rotterdam and 2 to 6 m/s in São Paulo. The greater variability in meteorological conditions in terms of relative humidity and temperature were in São Paulo and in terms of wind speed in London.

BC concentrations were monitored using the same portable aethalometer, MicroAeth AE51 (AethLabs) equipment, in all three cities. It is a widely used instrument for mobile measurements, as used by several studies for exposure assessments summarised by Cepeda et al. (2017). The flow rate was set to 100 mL min⁻¹ at 10 s time resolution. It measures the attenuation of the light transmitted through a filter strip where particles are collected continuously. Sometimes, when the air fraction sampled has very low BC concentrations, the incremental change in light can be affected by instrumental/optical noise, leading to constant or negative values in the data set. To avoid this, the MicroAeth filter strip was changed each day after about every six hours of sampling. The original data was post-processed with the Optimized Noise-reduction Averaging algorithm (ONA; Hagler et al., 2011) to smooth the BC time series.

The instrument was carried inside a backpack and a foam layer was wrapped around it to minimize vibrations. The inlet tube was positioned in the breathing zone. Cycling runs were made during the morning peak (MP; 07:00–10:00h; local time), afternoon period (AP; 12:00–14:00 h) and evening peak (EP; 16:30–19:00h) hours in London and São Paulo. In Rotterdam, the measurements were performed in the morning and evening-peak hours only because of logistics constraints. The position of the instrument was continuously recorded using a mobile App called “my tracks” with the resolution of 5 s in London and São Paulo. In Rotterdam, Strava App was used. For every trip, we carefully took note of the time when the equipment was turned on/off during sampling. In total, fifteen volunteer-cyclists participated in the study. In all cycling runs, first, we cycled the route A and then route B of the same O-D pair. It was practically infeasible to run simultaneous measurements on each of the six routes in each city owing to requirements of volunteers and equipment. We cycled the chosen routes multiple times during fixed hours to achieve statistically reliable values of measured BC.

2.4 Data analyses

Data processing and statistical analysis were performed with the statistical software R (v 3.3.1, R Core Team, 2016). Since the distribution of BC concentration frequency is skewed and not normally distributed, Generalized Linear Models (GLM) were used to assess the association between the route and period of the day with the measured BC concentrations. *Gamlss* package was used to fit the models (Stasinopoulos and Rigby, 2007). The model that had the best fit to the data was found to be the Box-Cox t distribution (BCT). This model considered the interaction effects between route and period of the day since the generalized likelihood ratio test (p-value <0.001) was significant for all cities and O-Ds. For each O-D in all cities, an adjusted BCT model was fitted. The model considered the route and period of the

day. Since past studies associate analogous variables with outcomes in air pollution and exposure (Apparicio et al., 2016; Hoek et al., 2008; MacNaughton et al., 2014; Rose et al., 2009), our model used the following control variables:

- (i) road density: a sum of the length of the roads that fall within a search radius by the circle's area, (defined in Silverman, 1986), as a proxy for exposure to traffic-related air pollutants emissions;
- (ii) distance to green areas: shortest straight-line distance between the measurements and green areas as a proxy for presence of vegetation (parks, squares, grass and urban forests); and
- (iii) distance to waterways: shortest straight-line distance between the measurements and waterways, as a proxy for presence of open spaces.

It is possible to add further variables to describe the local environment around the measurement routes (e.g., number of trees and meteorological data). However, the availability of data in all three cities was not the same. Thus, we selected only these three variables to standardise the variables and assure their quality in all cities.

ArcGIS (Esri Inc.) was used for generating the route maps, the spatial distribution of average BC concentrations and to calculate the control variables used in the adjusted model. The variables (ii) and (iii) were calculated using the Euclidean Distance tool and the variable (i) the Line Density tool. The roads/avenues, waterways and land use (green areas) data were obtained from the OpenStreetMap contributors.

3. Results and Discussion

3.1 Overall differences in BC concentrations

Figure 2 shows the average concentrations of the BC overall sampling periods and routes in each of the three cities. The average BC concentration in Rotterdam ($1.7 \mu\text{g}/\text{m}^3$) were relatively lower by 2.8–3.3 times than those in London ($4.7 \mu\text{g}/\text{m}^3$) and São Paulo ($5.5 \mu\text{g}/\text{m}^3$). Interestingly, these concentrations in London were comparable to those in São Paulo (Figure 2a). Although these were lower than those measured by de Nazelle et al. (2012) in Barcelona, Spain ($8.5 \mu\text{g}/\text{m}^3$) and Li et al. (2015) in Shanghai ($6.6 \mu\text{g}/\text{m}^3$). Our concentrations in Rotterdam were slightly lower to those ($3.1 \mu\text{g}/\text{m}^3$) measured by Okokon et al., (2017) in Rotterdam and Dons et al. (2012) in the city of Mol, Belgium ($3.2\text{--}3.6 \mu\text{g}/\text{m}^3$). However, these were nearly similar to those measured by MacNaughton et al. (2014) in Boston (USA) for cycle paths ($1.7 \mu\text{g}/\text{m}^3$).

Gan et al. (2011) performed an epidemiologic study identifying traffic-related air pollutants that are associated with the risk of coronary heart disease (CHD) morbidity and mortality. They found that an elevation in the average concentration of BC equivalent to $0.8 \mu\text{g}/\text{m}^3$ elemental carbon, which was associated with a 3% increase in CHD hospitalization and a 6% increase in CHD mortality. According to our results, this means that the cyclists in São Paulo are in average

more susceptible to coronary events such as CHD hospitalization and mortality than those in London and Rotterdam cyclists, given a clear linear exposure–response relationship between BC and coronary events (Gan et al., 2011). Moreover, studies found that typical BC mass concentration values range from about $0.001 \mu\text{g}/\text{m}^3$ for remote Antarctic locations to more than $1 \mu\text{g}/\text{m}^3$ for polluted urban air (Chylek et al., 2015) and our measured concentrations pass well over those values in all three cities.

As seen in Table 2, route (S1A) in São Paulo showed the highest concentrations for BC ($10.8 \mu\text{g}/\text{m}^3$); these were higher by over three-times than those on (S2B, $3.2 \mu\text{g}/\text{m}^3$) and nearly twice to those at the other four routes. In London, the route (L2A) had the highest concentrations of BC ($6.2 \mu\text{g}/\text{m}^3$) that were over two-fold higher than those on (L3B, $2.7 \mu\text{g}/\text{m}^3$). Rotterdam showed the smallest averages among the three cities. For example, route (R1B) had the highest concentrations ($1.8 \mu\text{g}/\text{m}^3$) and the lowest on (R2A) ($1.6 \mu\text{g}/\text{m}^3$). The differences in route averaged minimum and maximum concentrations in Rotterdam were only ~15% compared with ~41% and ~50% for London and São Paulo, respectively (Table 2). These variances between cities reflect differences in the composition, the volume of traffic, fuel types and the built-up environments influencing dispersion around the routes.

Vehicular emission is a main source of air pollution in an urban area. This is true for London and São Paulo, but in Rotterdam there is also an influence of the Port of Rotterdam. Despite the presence of the port, Rotterdam showed the smallest BC averages among the three cities. This can be expected due to the fact that London has a traffic fleet of 3.1 million licensed vehicles (~9400 buses) compared with 8 million (~14000 buses) in São Paulo. The total number of vehicles in the whole of Netherlands approaches to nearly 11 million vehicles (Statistics Netherlands, 2016). Besides, there is a unique case of large-scale use of biofuels in São Paulo (Kumar et al., 2016). While in London the public vehicles run mostly on diesel or are hybrid electric (Transport for London, 2018), the majority of buses and trucks in São Paulo are diesel powered with 7% biodiesel blend (Kumar et al., 2016). The use of biodiesel decreases the emission of carbon monoxide, hydrocarbons and particles (including BC) but increases the emission of nitrogen oxides and carbon dioxide (Nogueira et al., 2014). Our results suggest that BC concentration levels are more associated with the number of diesel vehicles circulating in each the city. In addition, the annual mean concentration of particles $\leq 2.5 \mu\text{m}$ in diameter ($\text{PM}_{2.5}$), that includes the BC fraction, for the year of 2016 follows the same trend as in our measured BC, i.e., 17, 12 and $11 \mu\text{g}/\text{m}^3$ in São Paulo, London and Rotterdam, respectively (WHO, 2018). It suggests that the data obtained at the air quality stations could potentially indicate the average outdoors exposure of the population.

Looking at the routes by city, a comparable trend was observed for London and São Paulo. For example, the main routes in both cities showed higher concentrations of BC as opposed to the alternative routes. In Rotterdam, the concentrations on main and alternate routes were nearly

similar. These differences in BC concentrations are reflected from the relatively higher IQR for São Paulo, followed by London and Rotterdam (Table 2).

Looking at the routes by the time of the day, the highest BC concentrations were found during the morning trips in Rotterdam and São Paulo (Table 2) and during evening trips in London (Figure 2b). In London, the afternoon trip concentrations were the smallest, lower by 3% than morning-peak and by 11% than evening trips. In São Paulo, the average concentrations during afternoon and evening peaks were nearly similar but these were lower by 49% than morning trips (Table 2). In Rotterdam, morning concentrations were 13% higher than evening concentrations.

3.2 Overview of spatial variation

Figure 3 shows the spatial variation of the BC average concentration in the selected cycle routes. BC hotspots – referred to the areas with higher concentrations of air pollutants (Goel and Kumar, 2014) – were expected on the routes towards the city centers. In London, the routes (L1A and L2A) passing through wider streets and close to the City of London showed higher concentrations when compared to the other routes (Figure 3a; Table 2). In São Paulo, the route (S1A) connecting Paulista Avenue to the city center showed higher average values (Table 2). These higher averages are indicative of frequent hotspots along those routes, as seen in Figure 3c. None of these routes showed an increasing concentration gradient towards the city center (Figure 3), suggesting that the measured BC concentrations were largely influenced by the traffic conditions.

Previous studies have shown that traffic lights and/or signalized traffic intersections experience elevated particulate matter mass concentrations (Wang et al., 2008, Kumar and Goel, 2016). Therefore, it is expected that the measured cyclists' exposure was affected by the congested traffic flow conditions. Since both São Paulo and London showed the largest concentrations among the three cities (Figure 2a), their main routes clearly showed a higher spatial BC concentration, owing to busier streets and frequent traffic interruptions than on alternative routes (Figure 3a,c; Table 2). In Rotterdam, BC hotspots were less evident in a particular route, but some can be seen in specific road segments at all routes, even though they were less intense when compared to other two cities (Figure 3b).

3.3 Spatial variation by route and period of the day

Figure 4 shows the spatial variability of BC on different routes and periods of the day. GLM were used to test the association between route and period of the day after adjusting for road density, distance to green areas and distance to waterways. GLM results were applied on the data to assess the significance of the differences between alternative and main route via inter- (during different periods of the day; Table 3) and intra- (between periods of the day on the same route; Table 4) comparisons. The estimated coefficients, standard errors and p-values

of the GLM are in Supplementary Information Table S1. The estimates were predominantly statistically significant and different from zero. The main route during morning period was used as the reference category (Table S1).

In most cases, the alternative route had significantly lower average concentrations than the concentrations on the main route (p-value <0.001; Table 3) apart from a few exceptions. In Rotterdam, R2 and R3 had significantly higher means (8% and 16%, respectively) on the alternative route during evening hours (p-value < 0.001) and likewise at S3 in São Paulo during morning (38%; p-value <0.001) and afternoon trips (34%; p-value <0.001) (Table 3). In Rotterdam, although the differences in statistical terms were significant, these differences in absolute concentrations were modest ($0.2 \mu\text{g}/\text{m}^3$). In São Paulo, the differences were significantly higher (p-value <0.001), and the differences in terms of absolute concentration between main and alternative routes during morning trips were $3.0 \mu\text{g}/\text{m}^3$ and only $0.7 \mu\text{g}/\text{m}^3$ during afternoon trips. S3 had higher values on the alternative route because a part of (S3B) route was along Dr. Arnaldo Avenue, one of the largest avenues in the region and with an intense traffic of vehicles, as also evident from in excess of $8 \mu\text{g}/\text{m}^3$ over the whole route during morning hours (Figure 4c).

On the main routes, the mean BC concentration during morning trips were higher than those during evening and afternoon in the three cities (p-value <0.001), except for (L2A) route where the difference was not significant in the afternoon trips (p-value = 0.015), and the concentration was significantly higher during evening trips than those during morning (42%; p-value <0.001) (Table 4). Comparing evening with afternoon hours, in most cases, the average concentration during evening-peak was significantly higher than during afternoon trips (p-value <0.001). The only exception was on (S2A) route, where the concentration of the afternoon trips was higher (62%; p-value <0.001; Table 4).

In all alternative routes in London, mean BC concentrations were significantly higher during evening trips when compared to morning and afternoon trips (p-value <0.001) while the differences between morning and afternoon trips were not significant (p-value >0.090; Table 4).

In the alternative routes in Rotterdam and São Paulo, most of the comparisons showed a significantly higher BC means in the morning-peak when compared to the afternoon or evening-peaks (p-value <0.001), except on (R2B) route between morning and evening-peaks since the difference was not significant (p-value = 0.033) (Table 4). In São Paulo, the mean difference between evening and afternoon trips was not significant (p-value >0.232), except in route (S1B) in which the concentrations at evening-peak were significantly higher than the afternoon trips (8%; p-value <0.001) (Table 4).

3.4 Influence of green areas and waterways on BC concentrations

Looking closely at some parts of the routes, three green areas were chosen, one from each city (Figure 5), to understand the influence of green areas on the average BC concentrations. These areas were Hyde Park on (L2B) in London (Figure 5a), Het Park on (R1B) in Rotterdam (Figure 5b), and Ibirapuera Park on (S2B) in São Paulo (Figure 5c). When the cycle lane inside Hyde park approaches to the edge of the park, a rise in BC average concentration can be clearly seen (Figure 5a). The average BC deep inside the park remained below $3.0 \mu\text{g}/\text{m}^3$ compared with the overall average ($4.4 \mu\text{g}/\text{m}^3$) of the route (L2B). Similar observations can be made for São Paulo (Figure 5c) where average BC concentrations stayed below $2.0 \mu\text{g}/\text{m}^3$ inside Ibirapuera Park compared with the overall average ($3.2 \mu\text{g}/\text{m}^3$) of the route (S2B). On (S2A), the route circled the park from the outside on Pedro Álvares Cabral Avenue and thus larger concentration was measured (Figure 5c), owing to the promity to the vehicular emission source. In contrast, average BC concentrations in Het Park, Rotterdam were $1.9 \mu\text{g}/\text{m}^3$ (Figure 5b) compared with the overall average ($1.8 \mu\text{g}/\text{m}^3$) of the route (R1B). As earlier noted, the variability in the measurements in Rotterdam was very small (Table 2), so even if in the Park the concentrations were not smaller than its surroundings (Figure 5b), the absolute concentration is still very low.

Our findings for BC substantiate the related work. For example, Pattinson et al. (2017) measured ultrafine particles, carbon monoxide and fine particulate matter at three different distances from the traffic flow simultaneously while cycling in a central city park area of Christchurch (New Zealand). They found about 20–30% (p-value <0.01) lower concentrations at the sidewalk that were 7 m away from the road, and even lower by 40–50% (p-value <0.01) at the path that were 19 m away from the road, when compared to the main road. Apart from the distance from the road traffic that parks bring to pathways within them, there is also deposition of pollutants on to the surfaces of vegetation (Abhijith et al., 2017; Janhäll, 2015). For example, Yin et al. (2011) measured particulate matter and gaseous pollutants outside and inside six different parks in Pudong District in Shanghai (China). They reported reduced concentrations inside the parks at ground-level by up to 35% in total suspended particles, 27% in sulphur dioxide and 21% in nitrogen dioxide compared with those outside the park. The key factors noted for this decrease were the density of vegetation and distance to the pollutant source such as road traffic.

Likewise, we assessed the effect of waterways on the BC concentrations. Such scenarios could only be found on the routes in London and Rotterdam (Figure 6). In London close to the Westminster Bridge (Figure 6a), the average concentrations were below $3.0 \mu\text{g}/\text{m}^3$ compared with the route (S2B) average of $4.4 \mu\text{g}/\text{m}^3$. The average concentrations on the cycle path (L1B) on the River Thames side were also smaller than $3.0 \mu\text{g}/\text{m}^3$ compared with the route (L1B) average of $4.1 \mu\text{g}/\text{m}^3$. In Rotterdam on Erasmus Bridge (R1A, Figure 6b), the average concentration level was less than $1.6 \mu\text{g}/\text{m}^3$ over the bridge, compared with a relatively higher

average concentration ($1.9 \mu\text{g}/\text{m}^3$) on the margin of River New Meuse in the direction to the city center can be seen in Figure 6b. The above observations indicate a positive influence of waterways in the form of reduced exposure. The effect of lakes (Doskey and Andren, 1981; Hewson and Olsson, 1967) and sea breeze (Bornstein and Thompson, 1981) on air pollution dispersion have been discussed in the past but quantification of such effects are not readily available for comparison with our results.

In summary, the above observations indicate that the spatial distribution of average BC concentration relating to the period of the day, route choice and proximity to green areas and waterways can positively influence the BC exposures to cyclists. The estimated GLM coefficients for the control variables (Table S1) were smaller than $0.03 \mu\text{g}/\text{m}^3$. The variability in BC concentrations is explained mostly by the period of the day and by the route in the models.

4. Summary, Conclusions and Future Work

We assessed cyclists' exposure to BC in London, Rotterdam and São Paulo at selected main and alternative routes during the morning, afternoon and evening hours. We found that average BC concentration in São Paulo was the highest among the studied cities and closer to those measured in London. Rotterdam had the smallest mean exposure among the three cities. Average BC concentrations in London and São Paulo were larger during the morning-peak compared with afternoon trips. During evening-peak hours, the average BC concentrations were the largest in London. Unlike the other two case studies, in London the evening peak had higher mean concentrations than any other time of the day.

As expected, the enhanced BC exposure at the main routes was largely influenced by the traffic, as shown by visible pollution hotspots at high trafficked dual-carriage roads, usually in street canyons, or across major intersections and also by the significant differences calculated by GLM. The results showed smaller concentrations through green, quiet or blue areas suggesting that the proximity of the cyclist to the road is an important exposure component. The findings for all the O-D pairs in London and a few in São Paulo (S1 and S2) suggest that choosing an alternative route over the main route has the potential to reduce their average BC exposure during all periods of the day. In some cases, for example, S3 in São Paulo showed higher exposure on alternative routes than on the main route. In Rotterdam, the trend suggested taking an alternative route during morning hours. However, the absolute differences in concentrations during alternative and main routes were modest.

The lack of availability of some specific data limited our analysis. For example, performing spatial regression models to determine the factors such as the influence of urban density and presence of trees and meteorological conditions on average BC concentration in each city would provide further insight to understand the determinants of BC exposure. We recommend

that future research should consider adding further variables, especially regarding traffic conditions and the estimate of effective deposition doses of inhaled BC in the lungs depending on the ventilation rate, deposition fraction, concentration and duration of exposure.

Our findings add further evidence to strengthen the view that the choice of the routes (i.e. busy versus quiet) and period of the day (peak versus non-peak) affect appreciably the BC exposure to cyclists. Nevertheless, the most effective way to reduce the exposure is reducing emissions at the source. However, reduced exposure to cyclists at alternative routes reinforce the considerations to avoid highly-trafficked roads by maintaining a distance from major roads. Therefore, making use of green and open spaces in route choice planning and/or development of new routes is an important consideration. Moreover, the evidences are emerging on the effectiveness of roadside vegetation barriers in reducing exposure in near-road environments (Abhijith and Kumar, 2019) and thus, the use of green barriers between cyclists and roads (wherever practically possible) is another important intervention.

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Figure 1. Description of the chosen cycle routes in the city of (a) London, (b) Rotterdam and (c) São Paulo. The colors represent the different O-D pair selected. The full line represents the main routes and the pointed lines, the alternative routes. (map data © OpenStreetMap contributors)

Figure 2. Boxplot of BC concentration ($\mu\text{g}/\text{m}^3$) measured in London, Rotterdam and São Paulo. Boxes represent 25th and 75th percentile, central line the median, point the average, bars outside the box represent 1.5-times the interquartile range and circles the outliers

Figure 3. Spatial distribution of BC average concentration ($\mu\text{g}/\text{m}^3$) for (a) London, (b) Rotterdam and (c) São Paulo in the selected routes. The averages were calculated for each small segment of streets ($\sim 50\text{m}$). The scale is kept differently for Rotterdam due to low measured concentrations. (map data © OpenStreetMap contributors).

Figure 4. Spatial distribution of BC average concentration for (a) London, (b) Rotterdam and (c) São Paulo, in the selected routes during MP: morning, AP: afternoon and EP: evening-peak hours. The averages were calculated for each small segment of streets (~50 m). The scale is kept differently for Rotterdam due to low measured concentrations. (map data © OpenStreetMap contributors).

Figure 5. Detailed spatial distribution of BC average concentration for (a) London, (b) Rotterdam and (c) São Paulo near green areas. The scale is kept differently for Rotterdam due to low measured concentrations. Circled areas indicate hotspots referred in the text.

Figure 6. Detailed spatial distribution of BC average concentration ($\mu\text{g}/\text{m}^3$) for (a) London and (b) Rotterdam near waterways. The scale is kept differently for Rotterdam due to low measured concentrations. Circled areas indicate hotspots referred in the text.

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Table 1. Traffic conditions, length (km), total cycled (km), distance of the cyclist to the road and a brief description of each of the routes.

City	Code	Origin	Destination	Traffic	Length (km)	Total cycled (km)	Distance of the cyclist to the road	Description of route
London	L1A	Liverpool	Waterloo	high	4.5	54.5	on-street/lane	Major roads
	L1B			medium	4.4	61.7	path/on-street	Along River Thames
	L2A	Lancaster		high	6.1	73.2	on-street	Major roads
	L2B	Gate		low	6.1	73.6	path/lane	Park
	L3A	Stockwell		medium	4.2	50.9	lane	Major roads
	L3B			low	4.8	57.1	on-street	Quiet roads
Rotterdam	R1A	Tarwebuurt	Rotterdam CS	high	5.1	40.8	path/on-street	Major roads
	R1B			medium	5.1	45.9	path/on-street	Het Park/River
	R2A	Bospolder		high	3.0	27.0	path/on-street	Major roads
	R2B			low	3.6	32.4	lane/on-street/path	Along small channels
	R3A	Crooswijk		medium	3.3	29.7	path/lane	Major roads
	R3B			low	2.4	19.2	on-street/path	Along small channels
São Paulo	S1A	Anhangabaú	Paulista	high	2.6	31.2	lane	Major roads
	S1B			medium	3.6	43.2	on-street	Quiet roads/Squares
	S2A	Ibirapuera		high	5.8	69.6	path/lane	Major roads
	S2B			low	6.4	76.8	on-street/lane	Quiet roads/Park
	S3A	Faria Lima		medium	3.8	45.6	lane/on-street	Major roads
	S3B			low	5.6	67.2	on-street	Quiet roads

Table 2. Descriptive statistics showing the data availability, arithmetic mean (Mean), standard deviation (SD), median and interquartile range (IQR) of BC concentrations (in $\mu\text{g}/\text{m}^3$) on each route and period of the day. trips = number of one-way trips. n = number of data points. NA = number of not available data points (10 s average).

London	route	trips	n_{BC}	NA_{BC}	Mean (SD)	Median (IQR)
	L1A	12	1904	0	5.8 (5.6)	4.4 (4.6)
	L1B	14	1792	1	4.1 (4.2)	2.9 (2.8)
	L2A	12	2937	0	6.2 (6.6)	4.2 (5.0)
	L2B	12	2271	0	4.4 (4.6)	3.0 (3.3)
	L3A	12	1859	1	4.6 (5.0)	3.0 (4.1)
	L3B	12	2126	0	2.7 (4.1)	1.7 (1.7)
	period	trips	n_{BC}	NA_{BC}	Mean (SD)	Median (IQR)
	MP	26	4752	2	4.6 (4.8)	3.1 (4.1)
	AP	24	3816	0	4.5 (6.1)	2.7 (3.5)
	EP	24	4321	0	5.0 (5.2)	3.5 (3.7)
Rotterdam	route	trips	n_{BC}	NA_{BC}	Mean (SD)	Median (IQR)
	R1A	8	970	0	1.7 (1.2)	1.5 (1.1)
	R1B	9	1066	0	1.8 (2.2)	1.3 (1.0)
	R2A	9	482	0	1.6 (1.5)	1.3 (1.0)
	R2B	9	720	0	1.7 (2.1)	1.3 (0.8)
	R3A	9	706	0	1.6 (1.4)	1.4 (1.0)
	R3B	8	540	0	1.7 (1.4)	1.5 (1.0)
	period	trips	n_{BC}	NA_{BC}	Mean (SD)	Median (IQR)
	MP	28	2482	0	1.8 (1.5)	1.5 (0.9)
	AP	-	-	-	-	-
	EP	24	2002	0	1.6 (1.9)	1.2 (1.0)
São Paulo	route	trips	n_{BC}	NA_{BC}	Mean (SD)	Median (IQR)
	S1A	12	1168	5	10.8 (11.5)	7.3 (8.6)
	S1B	12	1854	4	5.4 (7.0)	3.4 (4.0)
	S2A	12	2445	0	4.6 (4.9)	3.5 (4.0)
	S2B	12	2482	8	3.2 (5.2)	1.9 (1.8)
	S3A	12	1946	0	6.3 (7.2)	2.8 (10.1)
	S3B	12	2151	2	5.7 (8.0)	2.4 (6.7)
	period	Trips	n_{BC}	NA_{BC}	Mean(SD)	Median(IQR)
	MP	24	3727	10	8.5 (8.8)	6.3 (7.9)
	AP	24	4258	4	4.2 (6.2)	2.3 (3.4)
	EP	24	4061	5	4.2 (6.4)	2.2 (3.2)

Table 3. Relative comparisons of average BC concentrations between alternative (B) and main route (A) calculated from adjusted GLM results.

	London			Rotterdam			São Paulo		
Period	L1	L2	L3	R1	R2	R3	S1	S2	S3
MP	-57%▼	*	-52%▼	-18%▼	-12%▼	*	-28%▼	-35%▼	38%●
AP	-29%▼	-12%▼	-28%▼	-	-	-	-41%▼	-78%▼	34%●
EP	-28%▼	-23%▼	-18%▼	-4%▼	8%●	16%●	-30%▼	-31%▼	*

- ▼ concentration on A is higher than on B
● concentration on B is higher than on A
* the difference is not significant (p-value>0.001)
- no measurements during AP in Rotterdam

Table 4. Relative comparisons of average BC concentrations between periods of the day on the same route calculated from adjusted GLM results.

		London			Rotterdam			São Paulo		
Route Comparison		L1	L2	L3	R1	R2	R3	S1	S2	S3
Main (A)	AP - MP	-40%▼	*	-36%▼	-	-	-	-49%▼	-35%▼	-75%▼
	EP - MP	-22%▼	42%●	-35%▼	-23%▼	-14%▼	-38%▼	-54%▼	-76%▼	-70%▼
	EP - AP	32%●	31%●	*	-	-	-	*	-62%▼	21%●
Alternative (B)	AP - MP	*	*	*	-	-	-	-59%▼	-78%▼	-76%▼
	EP - MP	31%●	17%●	12%●	-10%▼	*	-26%▼	-55%▼	-74%▼	-76%▼
	EP - AP	34%●	15%●	16%●	-	-	-	8%●	*	*

- ▼ average BC concentration on MP is higher than on AP, or MP higher than on EP, or AP higher than EP
● average BC concentration on MP is smaller than on AP, or MP smaller than on EP, or AP smaller than EP
* the difference is not significant (p>0.001)
- no measurements during AP in Rotterdam