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Effects of bike lane features on cyclists' exposure to black carbon and ultrafine particles

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Abstract

Cyclists might experience increased exposure to air pollution due to their active travel mode and to the proximity to traffic. Several local factors, like meteorology, road and traffic features, and bike lanes features, affect cyclists' exposure. This paper investigates the effect of the features of the bike lanes on cyclists' exposure to airborne fine and ultrafine particulate matter and black carbon in the mid-sized city of Piacenza, located in the middle of the Po Valley, Northern Italy. Monitoring campaigns were performed by means of portable instruments along a 40-min urban bike route with bike lanes, characterized by different distances from the traffic source (on-road cycle lane, separated cycle lane, green cycle path), during morning and evening workday rush hours. The proximity to traffic significantly affected cyclists' exposure to UFP and BC: exposure concentrations measured for the separated lane and for the green path were 1-2 times and 2-4 times lower for the on-road lane. Conversely, exposure concentrations to PM10, PM2.5 and PM1 particle mass were not influenced by traffic proximity, without any significant variation between on-road cycle lane, separated lane or green cycle path.

Keywords: cyclists' exposure, black carbon, ultrafine particles, urban air quality, mobile monitoring.

1 Introduction

The shift from motor vehicle use to an active transport mode like bicycling for short trips in urban areas has been considered helpful to reduce traffic volume and related air pollution emission but also to improve public health thanks to the increased physical activity (Jarjour et al., 2013; de Nazelle et al., 2010). However,

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due to their proximity to the traffic source cyclists might be exposed to higher concentrations of traffic-related atmospheric pollutants (MacNaughton et al., 2014). Some studies that directly compared the exposure concentrations, i.e.: the concentrations to which a person is exposed, among different urban transport modes (Suárez et al. 2014; Quiros et al., 2013; Ragettli et al., 2013) reported contrasting results and highlighted the dependency of the exposure levels on a large number of variables, such as road characteristics and meteorological conditions (de Nazelle et al. 2012; Int Panis et al., 2010). However, most of the available evidence for urban cycling suggests that: i) the higher the volume of motorized traffic the greater the cyclists' exposure to traffic-related pollutants, and in particular to ultrafine particles (UFPs, diameter smaller than 0.1 μm) and black carbon; ii) bicycle paths that offer lateral separation between the cyclists and the motorized traffic reduce the concentration they are exposed to, as increased exposure concentrations are associated with increased proximity to traffic (Schepers et al., 2015). Additionally, exposure to both high-average levels and to short-duration concentration peaks of UFPs and black carbon particles is more likely to occur because of the proximity to the emission sources (Spinazzè et al. 2015; Kendrick et al., 2013). Furthermore, bike riding can result in higher particle deposition in the alveolar region since an active travelling mode (e.g., cycling) results in higher minute ventilation, because of increasing breathing frequency and larger tidal volume due to physical effort (Hofmann, 2011), and in higher lung deposition rate of inhaled particles which increases with exercise (Daigle et al., 2003; Chalupa et al., 2004).

Conversely, reductions in cyclists' exposure have been observed when they take alternative routes along lower trafficked roads (Good et al., 2015; Strak et al., 2010; Zuurbier et al., 2010). Thus, a proper selection of the travelling route through an urban area, as well as travelling outside rush hours, can reduce the exposure of cyclists to both primary traffic-related pollutants and to secondary pollutants (Hertel et al., 2008). However, as far as cycling networks and infrastructures are concerned, there is still a lack of knowledge and little research on how they can affect cyclists' exposure to traffic related atmospheric pollutants (Farrel et al., 2015).

This work provides some additional piece of information by investigating the effect of cycle lane and road features on cyclists' exposure concentration to airborne particulate matter, namely focusing on ultrafine particles and black carbon, based on field measurements performed while travelling different routes in a mid-sized city in Northern Italy. Comparisons between the UFP and BC exposure levels measured along the selected routes are presented, accounting for the season and for the time of the day. The impact of route choice on cyclists' exposure during commuting trips is also estimated through a Monte Carlo approach, based on the measured data.

2 Methods

Monitoring routes

Monitoring campaigns were performed in the urban area of Piacenza, Italy, a mid-sized city with about 100,000 inhabitants located right in the middle of the Po Valley at about 60 m a.s.l.. Despite its location in a context mostly rural and less urbanized compared with the largest metropolitan areas of the region, PM levels in Piacenza hardly comply with the air quality limits, especially as far as the PM10 daily limit is concerned.

Monitoring campaigns were performed during two weeks in July and September 2011 with two daily sessions, on morning (9.00-10.00) and evening workdays' rush hours (17.30-18.30); an additional 1-week monitoring campaign, still with morning and evening sessions, was performed in December 2012. In order to investigate the role of cycle lane and road features on cyclists' exposure concentration, four route sectors were travelled during each monitoring session:

- Sector 1 - on-road cycle lane: in this city-centre road the cycle lane is marked on the right side of road and cyclist and vehicles travel adjacent without a real separation. The road is bordered on both sides by 3-4-storey buildings creating a street canyon.
- Sector 2 - green cycle path: in this sector the cycle path passes through a green area where motorized vehicle are banned. The cycle path is paved with asphalt. The green area is about 50 meters large and it is bordered by the Sector 1 and Sector 2 roads.
- Sector 3 - separated cycle path: in this sector the cycle lane is separated form the motorized vehicles lane by a row of parallel parking lots. A minimum distance of about 2.5 m exists between cyclists and traffic flow. The road is bordered by buildings on one side and by a green area on the other side, where the cycle path runs. Sector 3 is part of the ring road that runs around the historical city centre.
- Sector 4 - no cycle lane: in this road sector cyclists and vehicles share the same lanes, without any kind of separation. The road is bordered on both sides by 3-4-storey buildings as for Sector 1, still creating a street canyon but with cross section wider than in Sector 1. Sector 4 is part of the outer ring road of the city centre.

Crossing the city in the East-West direction, the four sectors were selected because they may be taken by cyclists travelling from the South-Western residential areas to the train station (North-East of the city centre) for daily commuting. Route sectors, each about 1.5 km long, were travelled consecutively (i.e. not in parallel) following the same order (S1, S2, S3, and S4) in each session. Due to their rather small length, during each session the sectors were travelled three times, collecting about 15-20 concentration data.

Instruments

During the monitoring campaigns two portable instruments for particle number and black carbon measurement were held in a backpack keeping the instrument inlets near the breathing zone

Real-time particle number concentration (PNC) was measured by means of a portable condensation particle counter (P-Trak, TSI Model 8525, USA). P-Trak is able to measure the PNC in the 20-1000 nm size range ($PNC_{0.020-1}$) at 1-min time resolution, detecting particle concentration up to $5 \cdot 10^5$ cm^{-3}. Ambient air drawn into the instrument is first saturated with isopropyl alcohol vapour that then condenses onto the particles, causing them to grow into a larger droplet detectable by means of a photo-detector when flashed by a focused laser beam. Despite its measurement range extending beyond 100 nm, P-Trak data are commonly regarded as UFP concentration data since in urban areas particles with diameter below 100 account for the majority of the total particle number (Morawska et al. 2008); therefore, in this work $PNC_{0.020-1}$ data are presented as UFP data.

Concurrently with PNC measurements, equivalent black carbon concentration (EBC) was measured by means of a portable micro-aethalometer AE51 with 1-min time resolution. Ambient air is drawn by a pump inside the instrument through a Teflon-coated borosilicate glass fiber filter where particles are collected. The rate of change in the attenuation of transmitted light (880 nm wave length) due to continuous collection of aerosol deposit on the filter is measured. Then, black carbon concentration is derived based on the assumption that the change in aerosol light attenuation is proportional to black carbon concentration through a constant called mass absorption cross section. Following literature recommendations (Petzold et al. 2013), hereafter the term equivalent black carbon (EBC) is used instead of black carbon (BC) because the absorption properties have been measured by an optical technique.

3 Results

The distributions of 1-minute concentration data for EBC and UFP measured along the selected sectors during the morning and evening sessions are summarized in the box-plots presented in Figure 1-2 and in Figure 3-4 for the cold and warm season, respectively. Peak concentration data, identified as outliers according to Tukey's method (Tukey, 1977) are also plotted. Though regarded as outliers from the statistical standpoint, these data actually correspond to infrequent situations of high exposure concentrations occurring at busy crossroads or as a consequence of "big emitters" exhaust plumes.

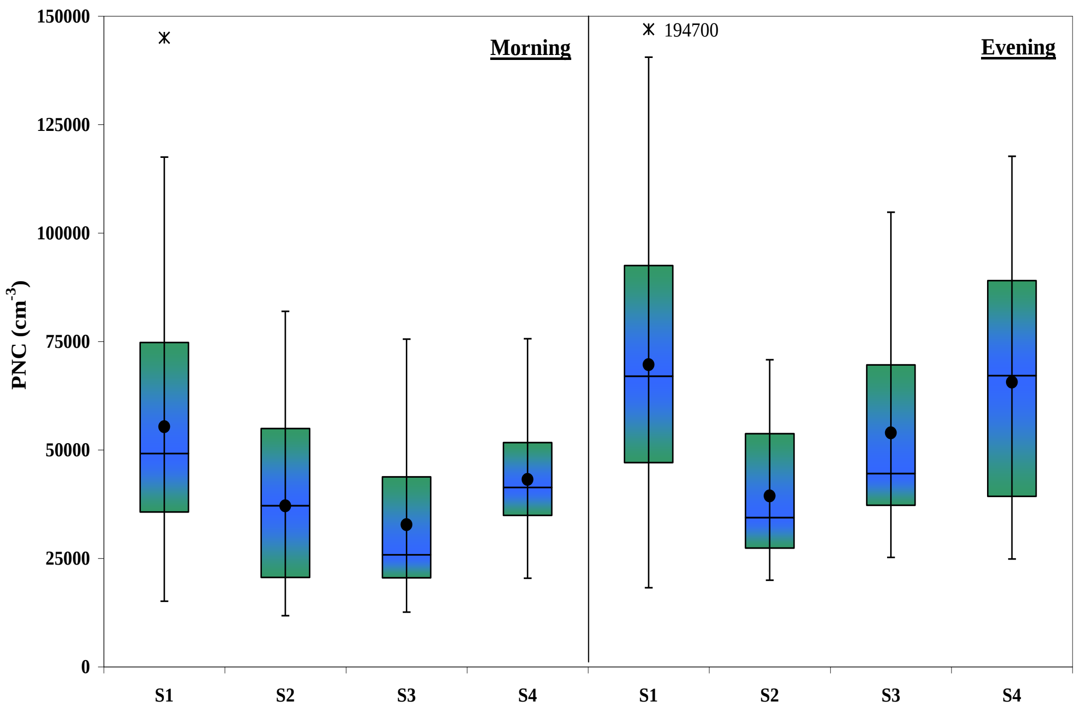

Figure 1. Box-plots of 1-min concentration data for UFP in the cold season.

As usually observed, cold season concentrations are always higher than the corresponding warm season values, as a consequence of both less favorable meteorological conditions (lower wind speed, shallower boundary layer) and of stronger emissions (traffic and space heating, including biomass burning for domestic heating). However, it can be noticed that the cold/warm season ratio is larger for UFPs than for EBC (3.7 vs. 2.1), because of the additional contribution of secondary particle formation, particularly favored by low-temperature conditions.

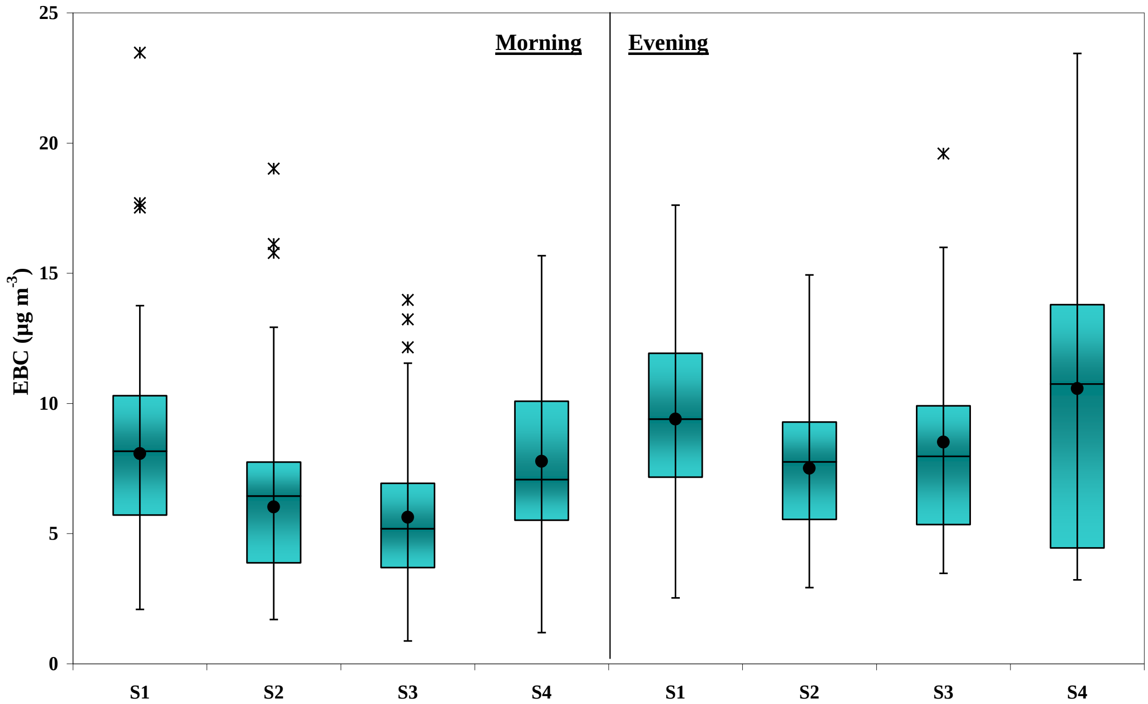

Figure 2. Box-plots of 1-min concentration data for EBC in the cold season.

In the cold season the sector-averaged concentrations for the morning session are in the $3.3·10^4$-$5.5·10^4$ cm^{-3} range for UFPs and in the 5.6-8.1 µg m^{-3} range for EBC; concentration ranges for the evening session are $3.9·10^4$-$7.0·10^4$ cm^{-3} and 7.5-10.6 µg m^{-3}, respectively. Corresponding figures for the warm season are $1.1·10^4$-$2.1·10^4$ cm^{-3} and 2.5-8.0 µg m^{-3} for the morning session and $0.8·10^4$-$1.7·10^4$ cm^{-3} and 1.5-6.6 µg m^{-3} for the evening session. Maximum concentration values in the cold season are in the $7.1·10^4$-$1.4·10^5$ cm^{-3} range for UFPs and in the 12-23 µg m^{-3} range for EBC, but mostly around 15 µg m^{-3}; warm season maxima are much lower, ranging between $2·10^4$-$4·10^4$ cm^{-3} for UFPs and between 4-15 µg m^{-3} for EBC. As the warm season distributions are shifted towards lower concentrations values, outliers are mainly observed in this season both for UFPs and EBC and more frequently for the sectors where the proximity to vehicle exhaust is higher (i.e.: S1 and S4). However the highest UFPs outliers are around $5·10^4$ cm^{-3}, that is in the same orders of the average values for the cold season; conversely, EBC outliers at the most trafficked sectors are up to about 20 µg m^{-3}, that is even greater than the cold season maximum levels. The comparison between morning and evening data shows an opposite seasonal behavior: in the cold season concentrations are basically higher in the evening than in the morning whereas in the warm season evening data are similar or slightly lower than the morning data.

This behavior is related to the diurnal development of the planetary boundary layer (PBL), significantly different in the two seasons: indeed, the evening session took place after sunset in the cold season with a reduced PBL depth as solar radiation was no longer active; conversely, in the cold season the PBL was still high in the morning, thus providing a similar volume for the dispersion of the pollutants. Regardless for the season, sector-averaged UFPs and EBC concentrations are strongly correlated (cold season: $R^2 = 0.85$; warm season: $R^2 = 0.67$; overall: $R^2 = 0.72$), thus confirming the relevant role of primary emission from traffic on roadside levels for both the pollutants. Such a correlation suggests that cyclists can be concurrently exposed to high UFPs and EBC levels while riding the bike route.

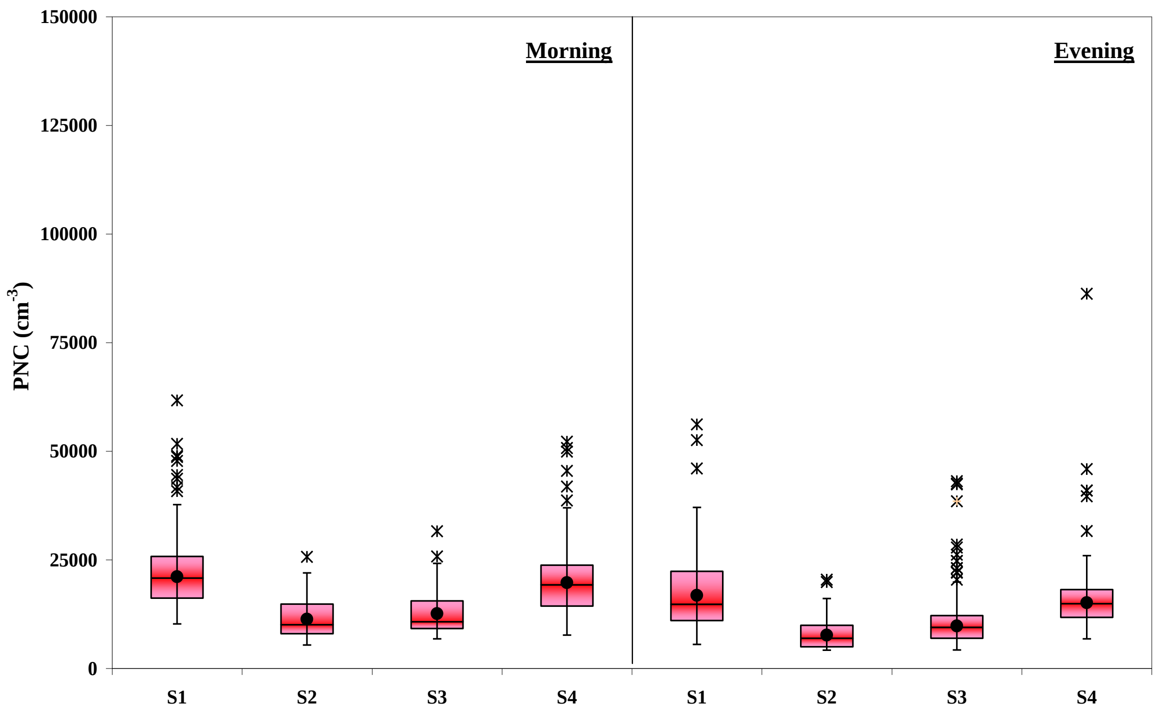

Figure 3. Box-plots of 1-min concentration data for UFP in the warm season.

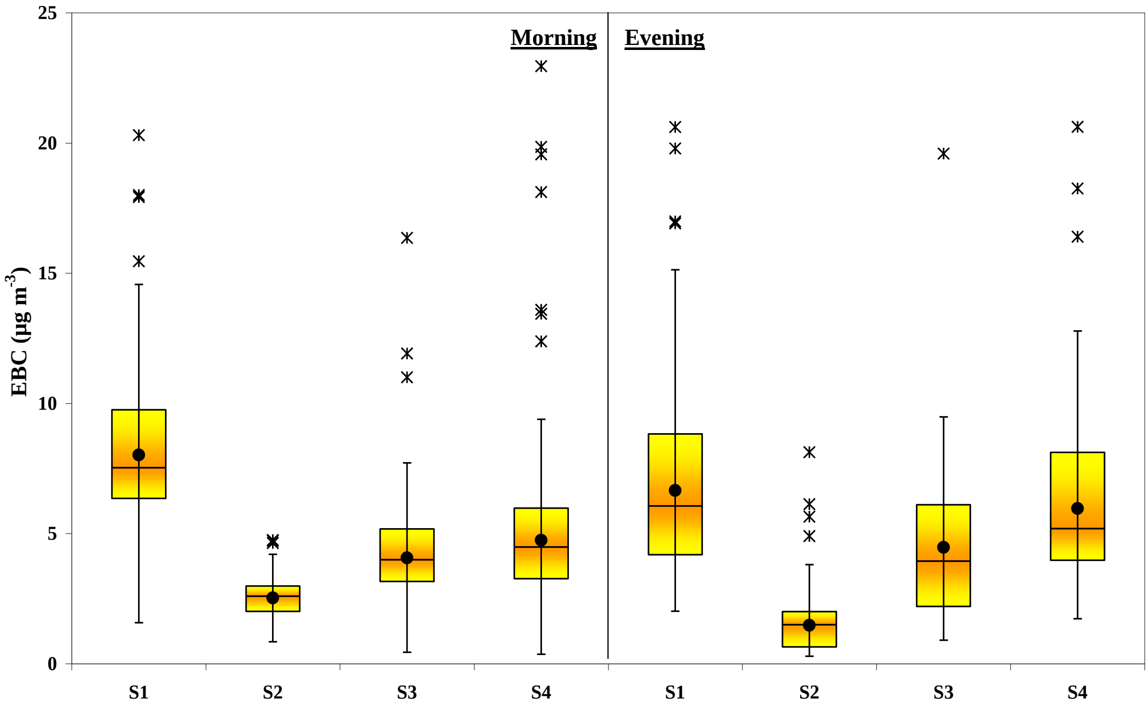

Figure 4. Box-plots of 1-min concentration data for EBC in the warm season.

4 Discussion

UFPs exposure concentration levels reported in this work are in substantial agreement with literature data, reporting cyclists' exposure levels in the $1.6\cdot10^4$-$2.8\cdot10^4$ cm^{-3} range in Italy, Switzerland, Belgium and The Netherlands (Spinazzè et al. 2015; Ragettli et al., 2013; Int Panis et al., 2010; Strak et al., 2010; Berghmans et al., 2009) but up to $4.5\cdot10^4$-$8.4\cdot10^4$ cm^{-3} in other Dutch studies and in Spain (de Nazelle et al., 2012; Zuurbier et al., 2010; Kaur et al., 2006); reported summertime exposure concentration levels for cyclists in a trafficked road in Milan are about $3\cdot10^4$ cm^{-3} (Ozgen et al., 2016).

Relative differences between average road sectors exposure concentrations observed in our work are summarized in Table 1. With respect to sector S1, in Sectors S2 and S3, where proximity to traffic is reduced, the average exposure concentrations show reductions in the 22%-54% range for UFPs and in the 9%-78% range for EBC depending on season and time of the day. Less relevant reductions are observed for Sector S4, where proximity to traffic doesn't change significantly but the wider cross road section reduces the urban canyon effect present in the narrower sector S1.

Table 1. Relative differences between the average exposure concentrations for road sectors S2, S3 and S4 with respect to Sector S1.

	Season	Morning session			Evening session		
		S2	S3	S4	S2	S3	S4
UFPs	Cold season	32.9%	40.8%	22.0%	43.4%	22.5%	5.7%
	Warm season	46.3%	40.2%	6.5%	54.2%	41.9%	9.9%
EBC	Cold season	25.3%	30.3%	3.6%	20.1%	9.4%	-12.5%
	Warm season	68.4%	49.3%	40.9%	77.8%	32.9%	10.4%

Similar relative reductions for cycling infrastructures are reported in literature. Comparing cyclists' exposure concentrations between roadside cycle lane and separated cycle track (through parallel parking lots) in Portland, Kendrick et al. (2011) reported significantly lower average levels for UFPs, with differences ranging between 8%-38% depending on traffic volume, and fewer exposure concentration peaks on the cycle track. Cole-Hunter et al. (2013) reported a 35% decrease in particle number exposure concentration on alternative route of lower proximity to traffic in Brisbane. Farrel et al. (2015) reported a 41% decrease in UFP levels between bike trails and major roadways and almost no change between separated bike tracks and major roadways in Montreal; conversely, they report a decrase in black carbon levels for both separated bike tracks (19%) and bike trails (40%). Influence of vehicular volume is also reported as concentration decrease is less relevant for local roads then for major roads. MacNaughton et al. (2014) reported 20% and 50% increased average exposure concentration levels to black carbon on designated bike lanes and bike lanes compared with bicycle paths in Boston.

Despite some overlap in the distributions of concentration data, most of the sector-averaged values are statistically different, especially in the warm season, according to paired t-test results at 5% significance level. In particular, S2 mean concentrations (i.e.: green path data) are always statistically lower than those of all the other sectors in the warm season, with the only exception for UFPs on mornings when compared to sector S3. Conversely, the average concentrations for sectors S1 and S4 (i.e.: the most trafficked sectors with roadside bike lanes) never show statistically significant differences except for EBC on mornings, when the S1 mean is almost twice as high as S4 mean (8.0 $\mu g\ m^{-3}$ vs. 4.7 $\mu g\ m^{-3}$).

In the cold season, most of the differences still remain significant, namely those between sector S2 and sectors S1 and S4, or non-significant, as those for sectors S1 and S4 (this time with the only exception for UFPs instead of EBC on mornings). Conversely, t-tests for the evening session data involving sector S3 show non-significant differences with sectors S1 and S4 for EBC, with average concentration levels still lower (8.5 μg m^{-3} vs. 9.4 and 10.6 μg m^{-3}) but no longer significantly different as in the warm season; additionally, a non-significant difference in UFPs levels with respect to sector S4 for the evening session is also observed, contrary to morning data.

Overall, in spite of the rather limited extension of the dataset, these results confirm that proximity to the traffic source is one of the main drivers affecting exposure concentration for cyclists. Indeed, sector S2, passing through a non-traffic area, and sector S3, thanks to the parking lots separating the bike lane, experience lower concentration levels than sectors S1 and S4, where the bike lane is simply on the rightmost part of the road. The impact of bike lane design is particularly strong for sector S3 where peak-hour traffic flow is higher than in Sectors S1 and S4 (about 2300 vehicles $hour^{-1}$ vs. about 1400-1500 vehicles $hour^{-1}$): indeed, the lower distance from traffic and the canyon-like configuration of these latter sectors overbalance the lower primary emissions. Canyon-like road features are particularly relevant for the narrow sector S1 where, regardless for season and time of the day, the highest concentrations are usually observed for both UFPs and EBC. However, sector-averaged concentration levels are also influenced by seasonality: actually, in the cold season concentrations levels tend to be more uniform as a consequence of the high background that reduces the effect of local scale emissions; additionally, the poor atmospheric dispersion favors the build up of airborne pollutants at the urban scale smoothing the contrasts between the sectors.

As these results suggest that a proper choice of the travel route across the city may affect the overall exposure to UFPs and EBC, the impact of route choice on cyclists' exposure during commuting urban trips has been assessed considering four alternative routes travelling from the South-Western residential areas to the train station for daily commuting. All routes are about 3.5 km long and are supposed to be ridden in 12 minutes. For each route, composite concentration subsets have been randomly generated drawing concentration data distributions from the sector-related distribution through iterative Monte Carlo technique. Such a probabilistic approach allows accounting for data variability within each sector, thus providing a more reliable assessment than simply relying of sector-averaged concentration values. Subsets for a reference route were formed based on sector S4 data (12 concentration data); the subsets for the three alternative routes were formed considering 6 data from the data distribution of sector S4 and 6 from those of sectors S1, S2, and S3. Cumulative exposure travelling to (in the morning) and from (in the evening) the train station have been then estimated in terms of total number of inhaled UFPs and total mass of inhaled EBC. As all routes are flat, no variation in exercise is considered and the same ventilation rate was used. The resulting frequency distributions of the computed cumulative exposures have been then compared in order to assess their variability in relation to the route choice. As shown in Figure 5, a worst-route choice can result in an increased cumulative exposure to UFPs up to about 50% with respect to the best option route, without any relevant difference between cold and warm season. Conversely, for EBC seasonality strongly affects the difference in cumulative exposure between worst- and best-route choice: indeed, a worst-route choice leads to an increased exposure around 20% in the cold season, but up to 90% in the warm season.

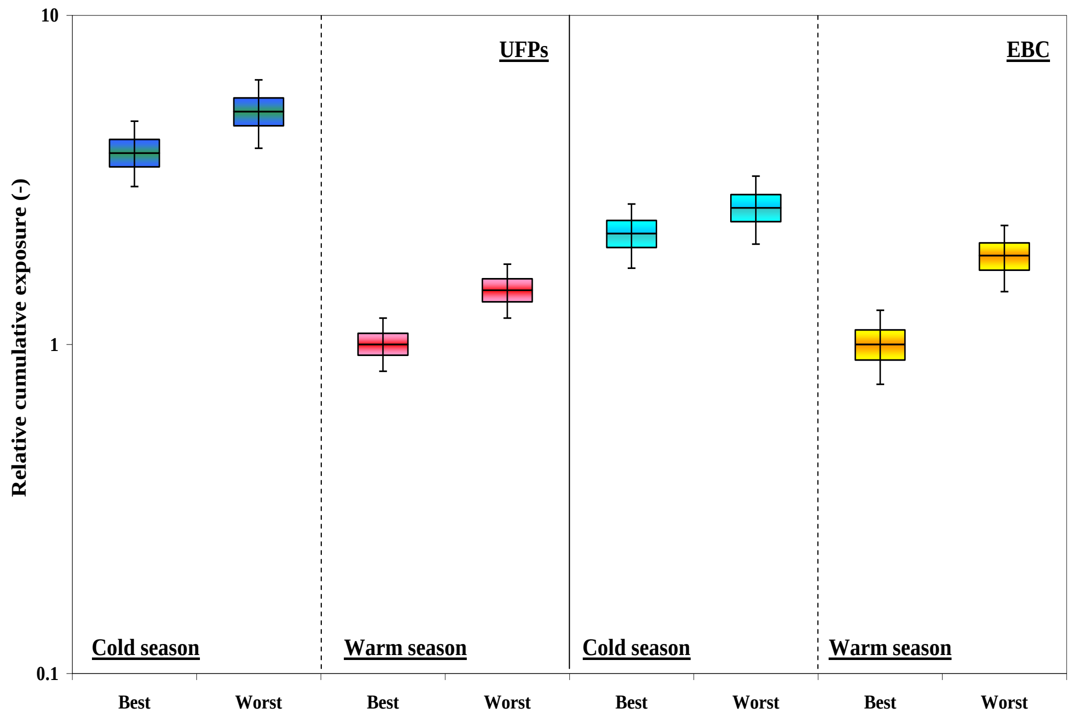

Figure 5. Box-plots of computed cumulative exposure to UFPs and EBC for best- and worst-case route choice for a commuter's ride in the urban area.

In the warm season, the best- and the worst-route choice are the same for UFPs and EBC: best choice is to pass through sector S2 on both trips, while the worst one is to pass through sector S1. In the cold season, as concentration levels tend to be more uniform, route choices also consider passing through sector S3 (morning trip) and Sector S2 (evening trip) as best option for both UFPs and EBC; for UFPs the worst-route choice is still the one passing through Sector S1 on both trips, whilst for EBC Sector S4 route on the evening trip leads to the higher exposure. Even though quite obvious, given the different concentration levels for the selected road sectors, these results provide a comparative and quantitative assessment of the extent of the different cyclists' exposure according to the travel route they choose. In particular, the route choice has a huge effect on EBC exposure in the warm season as the distance from the traffic source takes greater value when the concentrations of primary pollutants, as black carbon, are at their lowest levels and spatial concentration gradients within the urban area are stronger.

5 Conclusion

Ultrafine particles number and black carbon concentration have been measured in a mid-sized city in Northern Italy while travelling by bike urban routes in order to assess cyclists' exposure concentration levels and to investigate the effect of cycle lane and road features on their exposure.

Despite some limitations, mainly related to the limited dataset and to the non-concurrent route monitoring, the results confirm that reducing cyclists' proximity to traffic results in significantly lower exposure concentration levels. Indeed, where proximity to traffic is reduced, the average exposure concentrations show reductions in the 22%-54% range for UFPs and in the 9%-78% range for EBC depending on season and time of the day. Exposure concentrations are also affected by road features as the wider cross road section reduces the urban canyon effect, thus favoring the dispersion of traffic related pollutants. Seasonality is another relevant factor affecting exposure: the high concentration background in the cold season reduces the effect of local scale traffic emissions, thus smoothing the contrasts between the bike routes.

The impact of route choice in cyclists' exposure during commuting trips has been also estimated through a Monte Carlo approach, based on the measured data. These results show that, even for a short commuting trip in the urban area, a worst-route choice can result in an increased cumulative exposure to UFPs up to about 50% with respect to the best option route, without any relevant difference between cold and warm season. Conversely, for EBC seasonality strongly affects the difference in cumulative exposure between worst- and best-route choice: indeed, a worst-route choice leads to an increased exposure around 20% in the cold season, but up to 90% in the warm season.

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