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Assessment of cyclists' exposure to ultrafine particles along alternative commuting routes in Edinburgh

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ABSTRACT

An effective promotion of commuting by bicycle requires a set of complementary actions, with one of the key measures being the definition of bike-friendly routes, both in terms of road safety and exposure to air pollution. In this study, bike commuters' exposure to ultrafine particles (UFP) was assessed using mobile measurements and video recording along three alternative routes from central Edinburgh to the science and engineering campus of the University of Edinburgh. Results indicate significant differences in UFP exposure across the three alternative routes, with mean particle number counts (PNC) of 7,990, 9,824 and 19,310 particles/cm^3 respectively. With respect to the different types of bike infrastructure present along routes, the findings suggest that bicycle boxes (spaces at intersections that allow cyclists to position themselves ahead of vehicle traffic) are effective for reducing UFP exposure and that using shared bus-bike lanes should be avoided where possible. Heavy duty vehicles (i.e. buses and trucks) and construction sites were identified as the main sources of peaks in UFP exposure. All routes in the city of Edinburgh showed markedly lower PNC levels than those reported by studies conducted in other cities. The findings of this study can inform the implementation of bike-sharing schemes and the design of future cycling infrastructure, for example in the context of developing the low emission zone proposed for implementation across Edinburgh for 2020.

1. Introduction

Since 1950, global population has increased from 2.5 billion to 7.8 billion, and it is expected to reach 9.8 billion by 2050 (United Nations, 2017). This increase in population has been accompanied by substantial growth of urban populations and has contributed to air pollution challenges in cities all around the world. One of the key contributors to the decline in urban air quality has been the high number of motor vehicles associated with the increase in population density (Colvile et al., 2001). Encouraging active transport for commuting, for instance by bicycle, as an alternative to using motorized vehicles has been identified as a key policy intervention for not only tackling urban air pollution, but also reducing congestion, decreasing transport-related greenhouse gases emissions and improving public health by combatting sedentary lifestyles.

Route choice has been identified to have a substantial effect on the cyclist's exposure to air pollutants (Cole-Hunter et al., 2012; Hankey and Marshall, 2015), which have been linked to adverse health effects such as respiratory diseases and hypertension (Pope and Dockery, 2006). Two main factors that influence the cyclist's exposure along the route and can be affected by changing routes are: traffic (composition, speed, flow, etc.), which determines the overall on-road pollutant concentrations, and cycling infrastructure, which affects the amount of pollutants the cyclist is eventually exposed to. Studies have shown that cyclists' exposure to many pollutants is relatively similar or even lower when compared with other means of transport (Kingham et al., 2013; Kumar et al., 2018; Okokon et al., 2017). However, because of their increased ventilation rate, the amount of pollutants inhaled may be higher and thus health effects associated stronger (Int Panis et al., 2010).

Ultrafine particles (UFP, defined as particles with an aerodynamic diameter smaller than 100 nm) present a special case with respect to other urban air pollutants. At present, no epidemiologically or health-risk based UFP guideline levels have been established in any national or regional legislation despite of their potential harmful health effects (Knibbs et al., 2011). One complication arises from the fact that UFP

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concentrations are marked by a high spatio-temporal variability (Wu et al., 2015), so exposure to this pollutant cannot be modelled accurately using the fixed-site monitoring networks that are used for other pollutants, including larger particles. At the same time, existing regulatory monitoring sites are not currently required to measure UFP routinely, due to the lack of legislative or regulatory drivers. Mobile measurements present one viable approach for assessing an individual's exposure to UFP and have been used in previous studies aiming at improving our understanding of the spatio-termporal variability of UFP in urban environments (Steinle et al., 2013).

Several studies have assessed cyclists' exposure to UFP over the past 10 years. Most of them were carried out in Europe, and exposure to larger particulate matter (i.e. $PM_{2.5}$ and PM_{10}) and other pollutants (e.g. black carbon, NO_2 or noise) was often assessed simultaneously to UFP exposure. Some investigations compared the UFP exposure of commuters using different means of transport (e.g. bus, car or bicycle) across similar routes (Boogaard et al., 2009; Int Panis et al., 2010; Kaur et al., 2005; Kaur and Nieuwenhuijsen, 2009; Kingham et al., 2013; Okokon et al., 2017; Ragettli et al., 2013; Zuurbier et al., 2010) whereas others analyzed only cyclists' exposure across different routes (Berghmans et al., 2009; Cole-Hunter et al., 2012; Dekoninck et al., 2015; Hankey and Marshall, 2015; Hatzopoulou et al., 2013; Jarjour et al., 2013; Peters et al., 2014; Strak et al., 2010; Thai et al., 2008; Vinzents et al., 2005).

This paper aims at studying cyclists' exposure to UFP along three alternative cycle routes from Edinburgh's city center to King's Buildings campus, where the science and engineering college of the University of Edinburgh is located. Focusing on routes between the two main campus locations (central Edinburgh and King's Buildings) is interesting due to the high number of people moving back and forth on a daily basis: the engineering college accounts for more than 2,700 staff and 8,000 students. In addition, there are alternative travel options available along mostly green and residential routes, as well as streets with high traffic volumes. The three main objectives of the study are: (1) assessing the UFP exposure of bike commuters along the three pre-defined routes, (2) comparing the results obtained with similar studies conducted in other cities and (3) identifying the sources that contribute to exposure peaks when cycling. Assessing which route is more cycle-friendly in terms of air pollution will provide valuable information for the promotion of recommended routes. Currently, only 13% of University's population commutes by bike (The University of Edinburgh, 2016) and the University wants to increase the share of active travel trips as one measure to help becoming carbon neutral by 2040 (The University of Edinburgh, 2018a). Policy makers can use the outcomes of this study for promoting recommended routes and to decide where to implement improvements in road infrastructure (e.g. designating cycle lanes) in order to encourage bike use. In addition, the results can be used for defining the implementation areas requirements of the Low Emission Zone (LEZ) proposed in Edinburgh for 2020 in an integrated fashion, taking active transport and cycling into account.

2. Materials and methods

2.1. Study routes and design

The study took place in Edinburgh, the capital city of Scotland (United Kingdom). The choice of Bristo Square (latitude 55.946010, longitude −3.188908) (Fig. 1) as the starting point for the three routes was motivated by four reasons. First, it is located in central Edinburgh, next to the main campus of the University and in the vicinity of different student accommodation halls. Second, the bus stop for the University shuttle bus to the engineering campus (King's Buildings) is located there. In addition, eight different bus lines (some of them going to the King's Buildings campus area) stop at this location (Lothian Buses, 2018). Finally, the proposed bike hiring scheme in Edinburgh will have a hub at Bristo Square and several locations nearby (e.g. George Square)

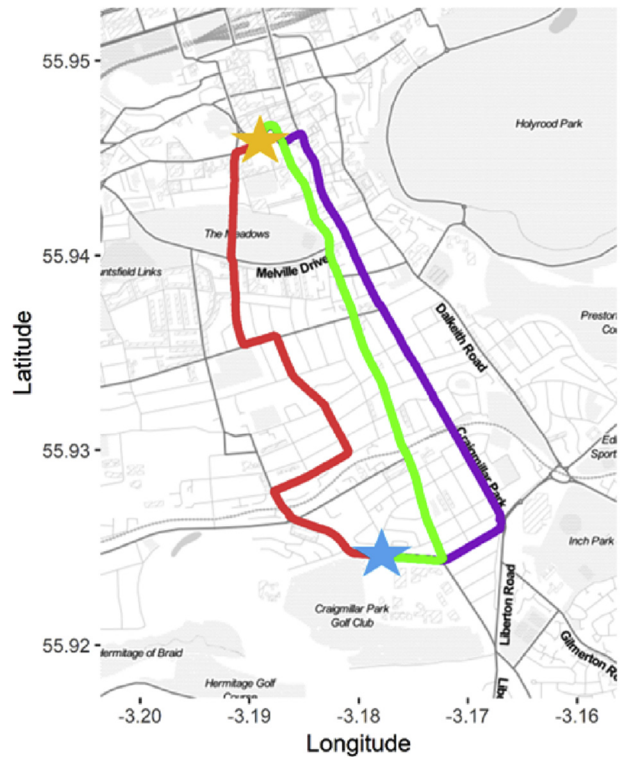

Fig. 1. Overview of routes. The starting point is represented by the yellow star and the end point is represented by the blue star. Purple, green and red lines represent the three alternative routes (route H, M and L respectively).

(The University of Edinburgh, 2018b). All routes end at King's Buildings gate 1 (latitude 55.924548, longitude −3.177246), which is located at the intersection between Max Born Crescent and West Mains Road. This gate was selected because it is the one used by the shuttle bus for entering the campus (see Fig. 1).

The choice of the routes was done taking into account that they have similar length and slope but might have substantially different air pollution levels. Therefore, the two main factors considered for their definition were (1) the relative traffic intensity (qualitatively classified based on the authors' knowledge of the area) and (2) the presence of different types of infrastructure for cyclists. Three alternative routes were studied:

Route H heads south through South Clerk St, Newington Road, Minto Street and Craigmillar Park. Then, it turns west and continues along West Mains Road to the final destination. It is the route with highest traffic density, since the majority of the streets form part of the trunk road A701. In addition, many bus lines travel along these roads (e.g. 15 different lines stop at Minto St) (Lothian Buses, 2018). In terms of bike infrastructure, most of the route has a shared bus-bike lane (Edinburgh Council, 2018) (Fig. 2, A). Therefore, cyclists do not directly share the road with most passenger cars, but are constantly affected by bus overtaking.

Route M runs mostly parallel to route H. It heads south through Buccleuch Street, Causewayside, Ratcliffe Terrace and Mayfield Road. The last part of the route is identical to route H, heading west along West Mains Road before reaching the end point. Traffic intensity along this route is substantial, but less than route H. There are fewer bus lines and the majority of the bus stops along the route have only two or three lines (Lothian Buses, 2018). Most of the route has a bike-only lane (Edinburgh Council, 2018) (Fig. 2, B).

Route L, in contrast, heads west from Bristo Square and then continues south through the Meadows until Beaufort Road, where it turns east. It then turns south again into Lauder Road. At the end of Lauder Road, it turns west (Relugas Road) and continues along Blackford Ave.

Fig. 2. Exemplary images of cycling infrastructure along alternative routes. Route H accounts mostly for a shared bike-bus lane (A), route M for a bike-only lane (B) and route L for off-road paths (C1) and residential streets without any cycling infrastructure C2).

This route then finishes as well at gate 1 of King's Buildings. Traffic density on this route is comparatively low: motorized traffic cannot access the park area of the Meadows and the rest of the streets serve predominantly quiet residential areas. In fact, most of the streets in this route belong to the quiet route number 6 (George Square – King's Buildings) designated by Edinburgh Council (Edinburgh Council, 2018). Apart from the off-road paths across the Meadows, there is hardly any dedicated infrastructure for cyclists along this road (Fig. 2, C1 and C2).

2.2. Instrumentation

A Testo DiSCmini handheld nanoparticle counter (Testo SE & Co. KGaA, Germany) was used for measuring the UFP particle number count (PNC) (# cm^{-3}). PNC is defined as the total number of particles per unit volume of air. It is used as a proxy for measuring UFP, since around 90% of the total PNC belongs to the UFP diameter range (Morawska et al., 2008), while the UFP size range does not contribute a substantial amount to overall particle mass. The Testo DiSCmini is a miniature, portable matter aerosol diffusion size classifier that obtains the PNC by measuring the electrical current produced by deposition of the charged particles on its two different stages. It has an accuracy for measuring PNC between 10 nm and 300 nm of ± 30% (Fierz et al., 2011). The instrument was placed in a backpack worn by the rider and a Tygon™ flexible polymer sampling tube was used to allow air sampling within the breathing zone. This type of tube was chosen considering its good performance when used together with unipolar diffusion chargers like the DiSCmini, even if its use (as the use of any other sampling tube) influences the measurements (Asbach et al., 2016). The distance to the mouth was approximately 20 cm (Fig. 3), which is within the 30 cm recommended margin (Int Panis et al., 2010). The used sampling frequency was 1 s and the data was stored as .CSV files on an internal SD memory card.

A smartwatch POLAR M200 (Polar Electro Oy, Finland) was used for recording GPS coordinates during the experiment. The default sampling frequency of 1 s was used and the data was automatically stored in the cloud using the smartwatch app. After each experiment, datapoints were exported using the POLAR website to .GPX and .CSV files for the analysis.

A GoPro Hero 2014 (GoPro, Inc., CA, USA) portable camera was used for recording the trips and identifying the events that contributed to the peaks in PNC encountered along the routes. The quality settings used for the videos were 720p and 60fps, which was the least memory consuming setting. Videos were stored as .MP4 files on a micro SD memory card on the camera. The video camera was placed facing front, attached to one of the shoulder straps of the backpack (Fig. 3).

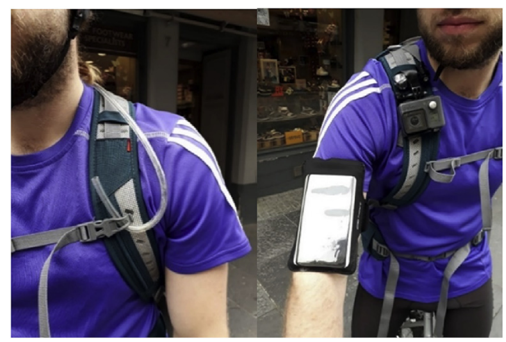

Fig. 3. Experimental setup. Left picture shows the DiSCmini inlet located next to the breathing zone. Right picture shows the GoPro video camera positioned facing front.

2.3. Dates and time

Data collection took place during two consecutive weeks from the 18th of June to the 1st of July of 2018. Only weekdays from this period were chosen as study days, since the experiment aimed to analyze cyclists' exposure when commuting to the University for working or studying (i.e. from Monday to Friday). One of the expected ten days of data collection (Wednesday the 20th of June), there was heavy rain and measurements did not take place because the Testo DiSCmini is not waterproof. Video material was recorded only during the last day of measurements (Friday the 29th of June) to conduct an in depth analysis of sources contributing to UFP exposure peaks.

The single participant of the study (age 26, good health condition) performed three return bike trips every day, one along each of the predefined routes. Following similar studies (Cole-Hunter et al., 2012), data from both outbound and return trips was collected. This was done considering that wind and other meteorological conditions can have a substantial influence on the measured UFP PNC concentration depending on which side of the street the measurements are done on (Wu et al., 2015). Bike trips took place every day between approximately 08:00 and 09:30. Most of the lectures at the University start between 08:30 and 09:30 and therefore it is the most common time slot for University-based commuters. Morning rush hour is often used in similar studies (Karanasiou et al., 2014; Strak et al., 2010; Thai et al., 2008; Zuurbier et al., 2010) and preferred over afternoon/evening rush hour because of its higher commute departure consistency (Cole-Hunter et al., 2012).

2.4. Experimental procedure and data analysis

The internal clocks of the devices were synchronized prior to the data collection period. Every day before starting the bike trips, the DiSCmini was warmed up for 30 min. Its correct functioning was checked using a HEPA filter before (and after) the measurements, following the manufacturer's recommendations. Then, it was placed inside the backpack, the inlet tube was attached to the backpack shoulder strap and the participant put on the other wearable devices. The rider performed consecutive return trips on the three routes starting at 08:00. After finishing every return trip, the rider stopped at the start point (Bristo Square) and checked the correct functioning of the instrumentation before proceeding with the next return trip. The route order changed every day to minimize potential bias due to departure time variation (e.g. route order of day 1 was H-M-L and day 2 was L-H-M). The measurements were usually finished by 09:30 and the cyclist recorded any special event noticed while cycling in a journal for later evaluation.

Data from the .CSV files of the GPS smartwatch and DiSCmini were merged and synchronized, and collated into a new .CSV file using a common timestamp. The sessions were divided into different tracks (routes) using the “lap” feature of the smartwatch. Data analysis was done with the open source software R (R Core Team, 2014). PNC concentrations were visually inspected alongside the GoPro camera video recordings on screen.

3. Results

3.1. General statistics

The participant did a total of 54 single (27 return) trips during the nine sampling days. From the 54 single trips, 18 were done in each of the three alternative routes. A total distance of 187.2 km was cycled during the approximately 14 h of data collection. Video recording of day 9 provided approximately 90 min of video material.

3.2. Variations in exposure to UFP PNC

3.2.1. Daily comparison

In absolute terms, PNC showed a high variability depending on the day and route (Fig. 4). Mean PNC ranged from 2,033 # cm^{-3} (route L, day 1) to 34,197 # cm^{-3} (route H, day 3). Median PNC ranged from 1,193 # cm^{-3} (route L, day 1) to 18,284 # cm^{-3} (route H, day 8). Regarding the dispersion of the data points, some days all three routes had a relatively narrow and similar interquartile range (IQR), whereas on other days the IQR was greater and showed more variability between alternative routes. For example, on day 2 the IQR was below 5,000 # cm^{-3} for every route, whereas on day 6 the IQR showed a high variability at 19,473 # cm^{-3} for route H, 5,816 # cm^{-3} for route M and 3,597 # cm^{-3} for route L. Maximum observed PNC did not show any clear trend. The highest maximum PNC for route M was 3,699,015 # cm^{-3} (day 6), for route L 2,646,550 # cm^{-3} (day 6) and for route H 1,478,977 # cm^{-3} (day 8). The lowest minimum PNC were found for every route on day 1: 150 # cm^{-3} (route L), 178 # cm^{-3} (route H) and 179 # cm^{-3} (route M).

When comparing the summary statistics between alternative routes, route H showed the majority of days with the highest PNC values for most parameters. On the other hand, route L accounted for the majority of days for the lowest PNC values for most parameters (Table 1).

The comparison between outward and return trips of every route showed a high variability across days (Fig. S1). For route H, outward trips showed higher mean and median PNC than return trips in six out of the nine days (67%). Route M had higher mean and median PNC in the outward trip than in the return trip in four out of the nine days (44%). For route L, the mean and median PNC measured in the outward trip was higher than in the return trip in three out of the nine days (33%) of data collection.

3.2.2. Overall route comparison

With the results from the return trips of the nine measurement days aggregated, route H accounts for the highest 25th percentile, median, mean and 75th percentile. Route M has the second highest 25th percentile, median, mean and 75th percentile and route L accounts for the lowest values for all these parameters (Fig. 5).

Mean PNC for route H (19,310 # cm^{-3}) is 2.4 times the mean PNC recorded on route L (7,990 # cm^{-3}) and 2 times route M mean PNC (9,824 # cm^{-3}). The median follows a similar pattern, being route H median PNC (7,310 # cm^{-3}) 1.7 times route L median PNC (4,442 # cm^{-3}) and 1.5 times route M median PNC (4,977 # cm^{-3}) (Table 2).

ANOVA and T-Tests were performed on PNC values aggregated from the nine days on which data collection took place to validate the differences found on mean PNC across routes (Table 3). The results obtained in all tests (F > F Critical and t Statistical < − t Critical Two-Tail; P-value < 0.05) rejected the null hypothesis, which stated that the mean PNC of the routes included on each test are equal.

3.3. Visual inspection of PNC peaks

Visual inspection of the video material synchronized with the PNC data from day 9 showed the events that produced peaks in PNC (Fig. 6). All the identified PNC peaks were higher than the extreme value boundaries of their corresponding route (Table 4). Route H peaks reached substantially higher values than the corresponding extreme value boundary (e.g. ≈ 1,000,000 # cm^{-3} or ≈ 850,000 # cm^{-3} vs. 30,552 # cm^{-3}), whereas route M and L peaks were (still far) but closer to their corresponding extreme value boundaries (e.g. ≈ 80,000 # cm^{-3} vs. 16,915 # cm^{-3} and ≈ 100,000 # cm^{-3} vs. 8,570 # cm^{-3} respectively).

The two highest peaks of route H are up to one order of magnitude higher than the peaks identified in other routes (Fig. 6). Maximum values of route H were substantially higher than those from route M and L in most of the other days, with the exceptions of days 4 and 6 (Table 5). Therefore, and taking into account that those peaks were linked to suitable high exposure events identified by video recording, it can be argued that the high values obtained are likely actual PNC values and not measurements artifacts.

The events were classified in three categories according to their source: construction related, heavy duty vehicles (HDVs) related and light duty vehicles (LDVs) related. In general terms, HDVs produced the highest peaks, followed by construction sites and LDVs. Most of the peaks caused by HDVs and LDVs occurred while overtaking and being overtaken by buses and cars, respectively. The majority of peaks produced by construction sites took place in the nearby of vehicles such as excavators or crane cars.

In addition, an increase in PNC was observed in every route next to road intersections, right before the location of the traffic lights. Route tracks passing near construction sites or along busy roads showed not only instantaneous peaks for PNC, but also a sustained over time increase in PNC levels along the whole route. For example, the only part of route L that is not green in Fig. 6 (PNC ≤ 10,000 # cm^{-3}) is Blackford Ave, which accounts for substantially more intense traffic than the rest of the route.

4. Discussion

4.1. Route comparison

Route H showed the highest PNC levels of the three alternative routes (Fig. 5), which can be attributed mainly to two factors. The first reason is the more intense traffic that is present on this route with respect to routes M and L. It can be argued that the higher number of bus lines that circulates through this route compared to the other two has a

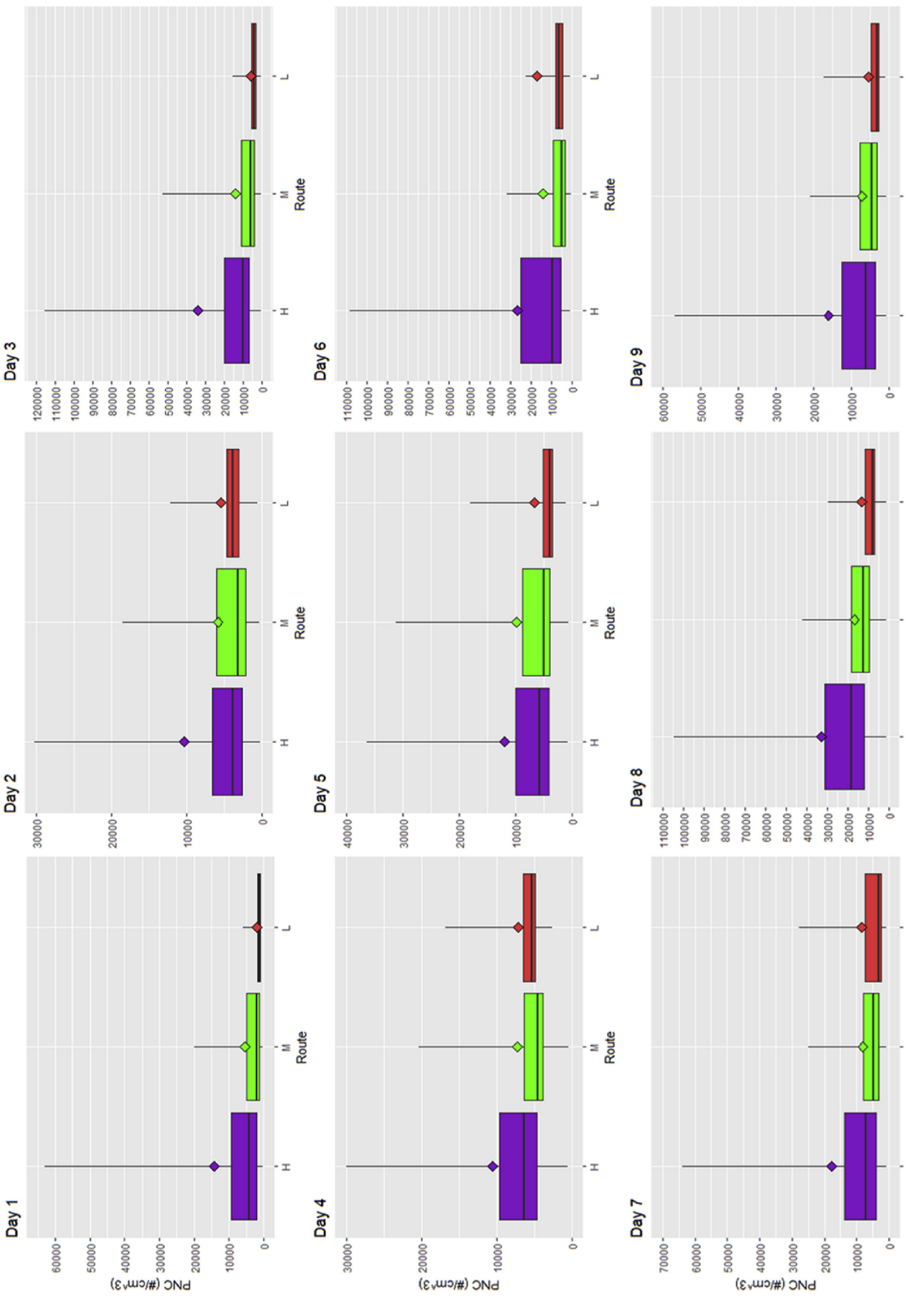

Fig. 4. PNC (# cm^{-3}) summary statistics by day and route. Horizontal lines represent the median, diamonds represent the mean, boxes represent the 25th-75th percentiles and whiskers represent the 5th-95th percentiles.

Table 1
Number of days (from a total of 9) with highest and lowest PNC values recorded on all routes.

Parameter	H		M		L	
	Highest	Lowest	Highest	Lowest	Highest	Lowest
75th percentile	9	0	0	1	0	8
Mean	9	0	0	2	0	7
Median	8	0	0	1	1	8
25th percentile	7	0	0	3	2	6

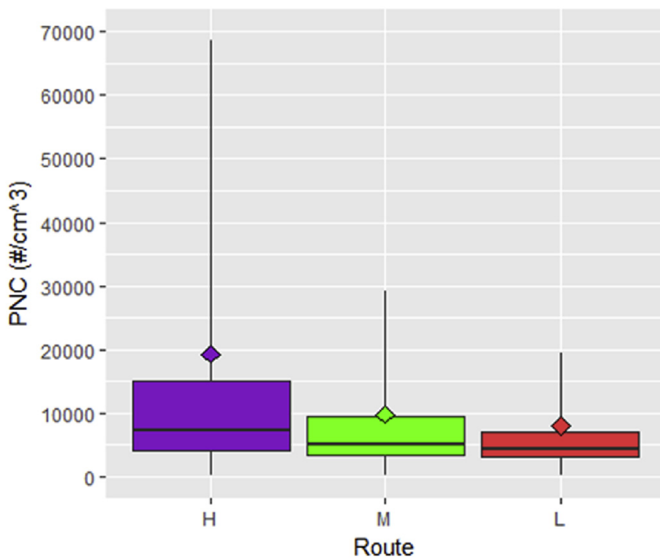

Fig. 5. PNC (# cm^{-3}) summary statistics for each route.

Table 2
PNC summary statistics ratios by route relative to route L.

Route	1st Quartile	Median	Mean	3rd Quartile
H	+37%	+65%	+142%	+116%
M	+9%	+12%	+23%	+37%

Table 3
Results of statistical tests (ANOVA and T-Test for two samples assuming unequal variances) performed with a significance level α = 0.05.

Test (routes)	F	F Critical	P-value	t Statistical	t Critical Two-Tail
ANOVA (L, M, H)	265.511	2.996	0.00E+00	–	–
T-Test (L, M)	–	–	1.87E-04	−3.737	1.960
T-Test (L, H)	–	–	5.64E-96	−20.865	1.960
T-Test (M, H)	–	–	1.41E-65	−17.146	1.960

significant effect on the measured PNC levels. Diesel vehicles account for high UFP emissions compared to petrol vehicles (Fruin et al., 2008; Wang et al., 2012) and the majority of the Lothian Buses fleet in Edinburgh is composed of diesel models, with the only exceptions of some hybrid vehicles (Lothian Buses, 2017). In addition, most of the route goes through streets that form part of the trunk road A701, which is an important artery for HDVs. Almost all HDVs use diesel engines, which account for higher UFP emissions than petrol engines and LDVs in general (Morawska et al., 2008). The second reason for the higher UFP exposure measured in this route is the cycling infrastructure present along the road. UFP have a very high spatio-temporal variability (especially when compared with larger PM sizes) (Wu et al., 2015) so the distance of the cyclist to motorized vehicles has great influence on the UFP exposure. Most of the road along route H has a shared bus-bike lane (Fig. 2), which accounts for higher exposure of cyclists to UFP than separated bike paths (Kendrick et al., 2011) or off-road paths like the ones present in route L (Thai et al., 2008). Moreover, because of the presence along route H of this type of cycle infrastructure, cyclists have to constantly deal with bus overtaking, which is an event that has been proven to produce peaks on cyclists' UFP exposure (Boogaard et al., 2009) (Fig. 6).

On the other hand, route L showed the lowest UFP exposure levels from the three alternative routes. The same reasons that explained the higher exposure measured along route H can be applied here. First, the traffic along this route is less intense than in the other two. Part of the route (i.e. The Meadows) does not have any traffic at all, and the rest of the route mostly goes through quiet streets located in residential areas. In addition, only a few bus lines travel along streets that belong to this route. The second reason was again the cycle infrastructure, which in route L mostly consisted on two different types (Fig. 2). First, off-road paths like the ones from the Meadows, which have been proven to reduce exposure of cyclists to UFP when comparing them with shared bike lanes (Thai et al., 2008), like the ones present along route H. Apart from the Meadows, the majority of streets belonging to route L do not account for any special bike infrastructure. Even if bikes and motorized vehicles share all the road space in these streets, the absence of bike infrastructure did not yield to high UFP exposure episodes because of the little traffic present.

Route M represents an intermediate situation between routes H and L. With respect to the main sources of UFP, it accounts for heavier traffic and has more bus lines than route L, but its streets are less busy and less bus lines circulate than in route H. With respect to UFP exposure reduction, its bike infrastructure is also somewhere in between the other two routes. It has cycle-only lanes (Fig. 2), which provide lower UFP exposure than the shared bus-bike lanes present in route H. This cycle infrastructure avoids the constant high exposure episodes produced by bus overtaking (Boogaard et al., 2009) but does not provide the same lower UFP exposure as the off-road paths present along route L.

4.2. Events that cause UFP peaks

The majority of events that caused the highest peaks on UFP exposure (Fig. 6) were associated to the proximity of HDVs to the cyclist. In route H, most of the high exposure episodes were produced by the presence of buses, which have been previously pointed out as one of the main road sources of particles in the UFP range (Wang et al., 2012). In routes M and L, most of the highest peaks were related to the presence of different HDVs (e.g. trucks) instead of buses. The lower number of bus lines present along these routes has likely contributed to this.

The second set of events linked to PNC peaks were those related to the presence of construction sites located next to the road. Visual inspection of the video material allowed to differentiate two main UFP sources within this group. The first group of sources are construction HDVs (trucks and non-road mobile machinery), which are normally diesel and therefore account for high UFP emissions (Morawska et al., 2005). The second group of sources included the different types of civil engineering works done in the construction sites. The case of civil engineering works that involve high abrasion processes (e.g. machining materials) should be especially considered. This type of processes normally accounts for substantial generation of PM with a large fraction of it belonging to fine ranges (Dasch et al., 2005).

The third identified group of events that caused peaks on PNC levels were those related to the proximity of LDVs. Along route H and M, these events normally caused lower peaks than HDVs and construction sites. However, in route L less HDVs and construction sites were present, so LDVs' peaks played a more important role in the cyclist's UFP exposure than in other routes (Fig. 6). Overtaking, being overtaken and cycling

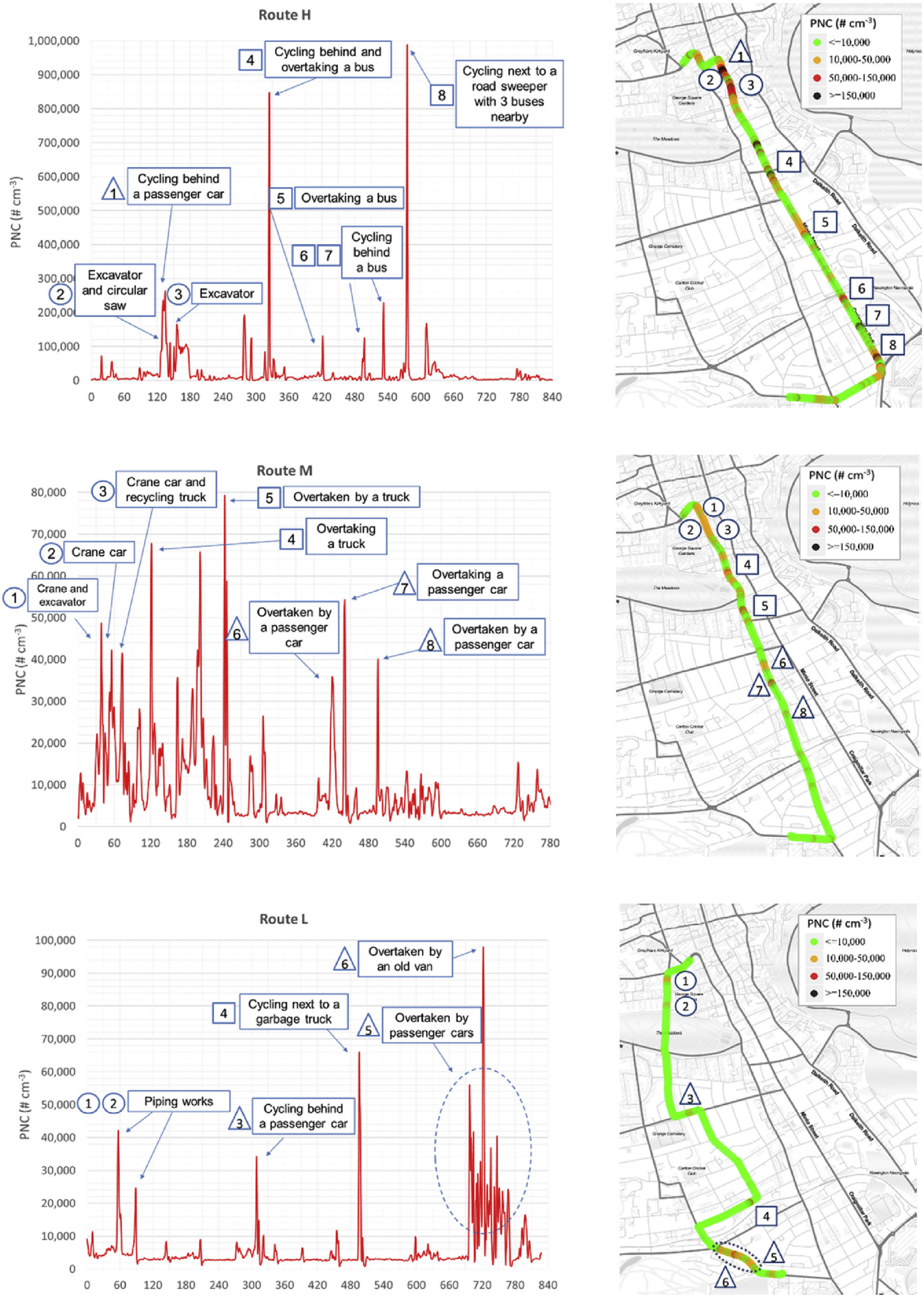

Fig. 6. Sources of PNC peaks on routes H (top), M (center) and L (bottom) during the outbound trip of day 9. Peaks originated by construction sites, HDVs and LDVs are represented by circles, squares and triangles respectively.

Table 4
Day 9 PNC outliers and extreme value boundaries [# cm^{-3}], calculated with coefficients of 1.5 and 2 respectively.

Parameter	H	M	L
25^{th} percentile	3,621	3,250	2,801
75^{th} percentile	12,598	7,805	4,724
Outlier	26,064	14,638	7,609
Extreme	30,552	16,915	8,570

behind motorized vehicles were the situations of this group of events that caused the highest peaks. Fig. 6 shows that none of the highest exposure peaks recorded in any of the three routes occurred when the cyclist was waiting behind stopped cars at traffic lights or intersections. We assume that this is due to the idling engine generating less particle emissions when they are not moving. It can be argued that when traffic lights turn green, vehicles accelerate and increase their particle production and thus cyclist's UFP exposure. However, our analysis did not show any indication of high exposure peaks in comparison with the rest of the time.

The spatial visualization of the data also showed an increase of PNC next to traffic lights at road intersections (Fig. 6). The rise in UFP exposure took place in most cases before stopping at the traffic lights and not when the cyclist was waiting at them. This is explained because when cyclists are approximating to the traffic lights, they often overtake cars that are slowing down or already waiting at the red lights (exposing themselves to the cars' exhaust pollution) to place themselves ahead of vehicle traffic. In Edinburgh, these first positions next to the traffic lights are often reserved only to cyclists thanks to the cycle boxes (reserved spaces for cyclists ahead of motorized vehicles at intersections) and thus cyclists are not directly exposed to other vehicles' exhaust gases. The results from this study suggest that this kind of cycle infrastructure is very effective for reducing UFP exposure of cyclists, in addition to its other proved benefits (Hunter, 2000).

4.3. Comparison with other studies

Fig. 7 shows the mean PNC measured in similar studies together with the mean PNC obtained on the three alternative routes of this study. All the studies included in the comparison measured UFP exposure of cyclists. It is important to mention that not every study used the same air sampling device as this experiment (i.e. Testo DiSCmini), which likely influenced the results obtained. Not all devices have the same range for particle counting, which can bias the UFP count. For example, Berghmans et al. (2009) used a P-track Ultra fine Particle Counter (TSI Model 8525) that measures particles in the 0.02–1 μm range, whereas the Testo DiSCmini measuring range is 0.01–0.7 μm.

Route L showed the lowest mean PNC of the 40 measured routes and route M accounted for the third lowest. Route H was ranked in 29^{th} position. Knibbs et al. (2011) stated that 34,000 # cm^{-3} is the average mean for the bike studies that they included in their review of commuters' UFP exposure articles, but they used a more limited study set than this paper. Nevertheless, their average PNC of 34,000 # cm^{-3} is also substantially higher than the values measured along the three routes. Therefore, it can be argued that the mean PNC measured in this experiment are relatively low with respect to similar studies.

Several factors might explain this situation. First, UFP concentrations in Edinburgh are not very high when compared with other cities, as stated by Wu et al. (2015) in their study done with mobile measurements while walking. Second, the two weeks data collection period of this study took place during the end of June. Measurements done during the cold seasons (fall and winter, purple bars) often report relatively higher PNC than those done during the warm seasons (spring and summer, orange bars). The main reason is the lower traffic often present in spring and summer, partly because the presence of better weather favors active modes of transport, i.e. more people choose alternatives to the car such as cycling or walking for going to work. This decrease in the pollution generated by motorized vehicles might be especially significant in Edinburgh. The city and particularly the routes selected account for a high number of people linked to the different universities, who work or study there. During late spring and summer there are no lectures, many students go back to their hometown and the number of events and activities linked to the universities decreases. These factors reduce the number of university commuters and therefore the number of UFP sources. All things considered, UFP exposure of cyclists in Edinburgh is good compared with most of the cities where similar studies have been carried out.

4.4. Limitations

The time of the year when the measurements were done influenced the results. The data collection period of the study took place mostly in summer, which normally has less traffic and thus accounts for lower PNC levels than the rest of the seasons. It would be interesting to perform a similar study in winter and compare both results, like Wu et al. (2015) did in their study in Edinburgh. In addition, the proved influence of the meteorology on UFP exposure should be taken into account when drawing conclusions. All measurements were done in two consecutive weeks and the weather might have not been representative of the average weather in the city during the whole season.

5. Conclusions

The results from the study revealed that the route choice while commuting by bike from the University campus in central Edinburgh to the King's Buildings campus has a substantial influence on the exposure to UFP experienced by the cyclist. Two main factors contributed to the differences on exposure. The first factor was the overall on-road UFP concentration, which depends mostly on traffic and the activities from construction sites located next to the road. The second factor was the bicycle infrastructure present along the route, which affects the proportion of particles that actually comes in contact with the cyclist due to the relative position on the road.

Two main recommendations can be derived from the findings of the study for promoting cycling between the two campus locations. The first advice is to avoid routes that go partly or entirely along the trunk road A701 (e.g. South Clerk Street or Newington Road), which accounted for the highest UFP exposure of all measured streets. The second recommendation is to try to ride as much as possible through green spaces and small streets located in residential areas, as the ones that form most of route L.

The measured PNC along the three routes were relatively low compared with the majority of similar studies done in other cities. Data collection for this research was done in summer, when traffic in

Table 5
Maximum PNC (# cm^{-3}) recorded on each route.

Route	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9
H	560,661	450,051	1,218,621	235,851	851,815	542,466	702,396	1,478,977	987,418
M	149,235	161,119	431,473	212,667	361,454	3,699,015	291,043	171,235	78,066
L	60,505	144,946	127,483	72,188	110,855	2,646,550	486,455	564,626	97,962

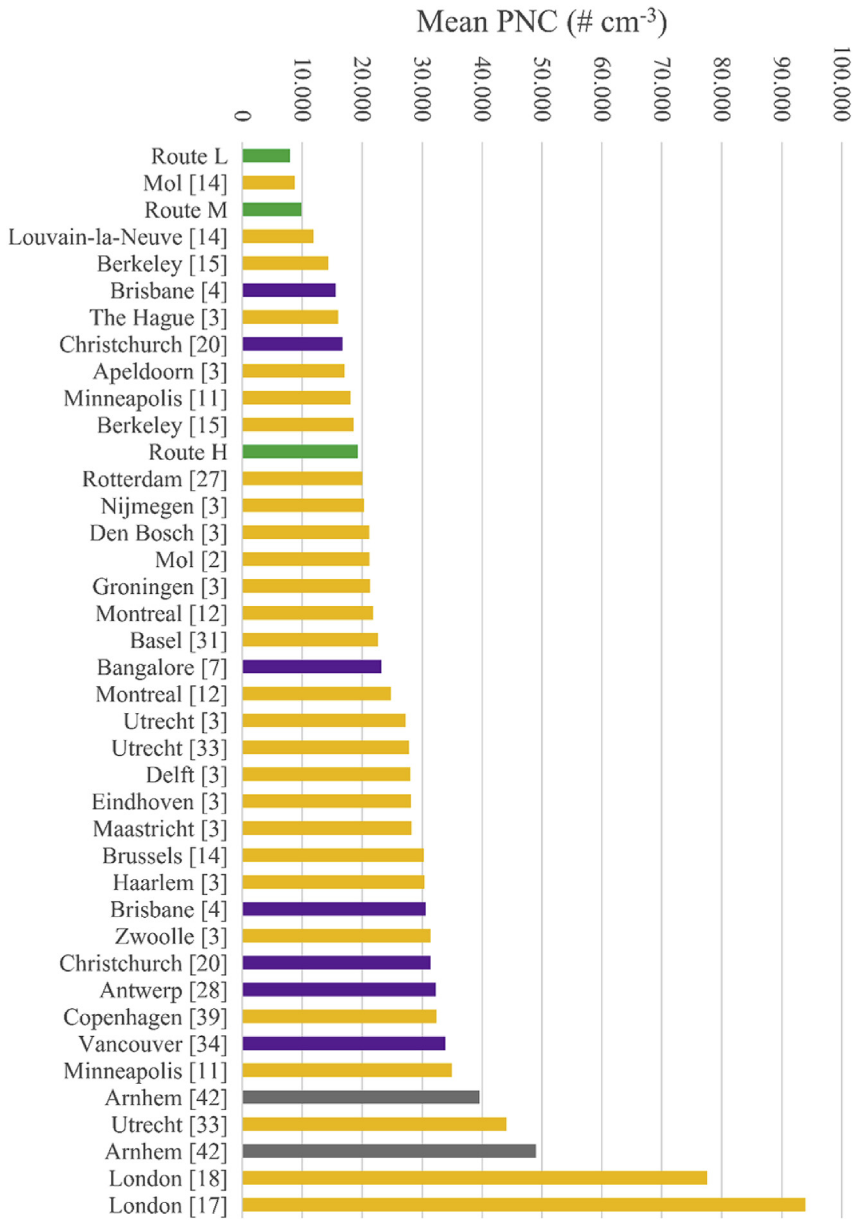

Fig. 7. Mean PNC (# cm^{-3}) measured in bike commuting studies. Green bars represent results from the current study, orange bars are results from studies done in spring/summer, purple bars are results from studies done in fall/winter and grey bars are results from studies whose data collection dates were not available or that were done during all year round. Christchurch value represents the median PNC since the mean PNC was not available. The number in brackets refers to the article position as cited in the bibliography.

Edinburgh is typically less intense because of the decrease on activities at the universities and public school holidays, among other reasons. This may have contributed to the low UFP exposure values obtained with respect to other studies. Nevertheless, it should be considered that spring and summer are the seasons when more people use their bikes in the city, so it makes sense to assess the cyclists' exposure in the periods of time when biking is most popular.

Analyzing the influence of the different types of cycling infrastructures on cyclists' exposure provided some useful insights for future urban planning. Bicycle boxes located next to the traffic lights at intersections showed a high effectivity for reducing the UFP exposure of cyclists. When they are used, cyclists avoid much of the tailpipe exhaust pollution generated by motorized vehicles. Cyclists would be directly exposed to this pollution if they would have to wait in the traffic lights 'pit lane' next to the rest of vehicles. Another conclusion is that shared bus-bike lanes should be avoided by cyclists where possible. Diesel HDVs are major contributing sources of UFP and cyclists often have to deal with bus overtaking when riding along roads with this type of cycle infrastructure. Finally, the use of off-road paths should be especially encouraged, so cyclists limit as much as possible their contact with the main traffic UFP sources, in addition to reducing accident risks. Where construction sites are present, temporary bike paths should be installed as far away as possible from them to avoid the high PNC peaks produced by the construction traffic (primarily HDVs) and stationary machinery operations (e.g. generators).

Choosing routes with the best cycle infrastructure might reduce cyclists' exposure, but it would not reduce the overall UFP levels present on the streets. Tackling urban air pollution in a sustainable way requires policies orientated to limit the emissions from the main sources identified in this study (traffic and construction sites), which would also help mitigating climate change by reducing the overall CO_2 emissions. Overall on-road UFP levels would be lower if emissions from these sources were better regulated, and thus cyclists' exposure to UFP would depend less on the available cycling infrastructure.

All things considered, it can be argued that promoting cycling as a safe and sustainable alternative to motorised road transport requires complementary efforts in different areas. Some of the key points are regulating the emissions from the identified main sources, installing bike-friendly road infrastructures and providing cyclists with information about which routes should be used or avoided.

Author contributions

J.L-O. designed the experiment, conducted the data collection and analysis of results under the supervision of S.R. S.R. provided background to the analysis, generated/revised figures and contributed to the analysis and discussion of results. This research was conducted as part of a MSc degree research project.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2019.01.020.

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