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Cyclists' exposure to air pollution and road traffic noise in central city neighbourhoods of Montreal

Philippe Apparicio [a,*], Mathieu Carrier [a], Jérémy Gelb [a], Anne-Marie Séguin [a], Simon Kingham [b]

[a] Centre Urbanisation Culture Société, Institut national de la recherche scientifique, 385 Sherbrooke Street East, Montréal, Québec H2X 1E3, Canada
[b] GeoHealth Laboratory, Department of Geography, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

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ABSTRACT

It is well known that bicycling in urban areas has beneficial effects on people's health and well-being. On the other hand, urban cycling, especially during the morning and evening commute, may be associated with health and safety risks due to potentially high levels of exposure to air pollution, road noise, and high traffic density. Few studies have, however, measured cyclists' exposure to noise and air pollution simultaneously.

The objective of this research is to evaluate cyclists' exposure to air pollution and noise in central city neighbourhoods of Montreal and to identify the impact on exposure of associated local factors such as weather conditions, the day and time, the type of road, bicycle path or lane used and the characteristics of the immediate environment around the cyclist's route.

A total of 85 bicycle trips were analyzed, representing 422 km of travel and nearly 25 h of data collection. The mean exposure levels were 70.5 dB(A) for noise and 76 μg/m^3 for nitrogen dioxide (NO_2). A very weak negative correlation was found between the two measures of exposure ($R^2 = -0.07$, $p = 0.005$).

The results of the spatial regression models show that the morning commute and trips on collector roads and on-street bike lanes and shared bike lanes have significant and positive impacts on exposure to air pollution and noise. On the other hand, some factors are only significant for one or the other of the two types of exposure.

1. Introduction

Cycling is becoming an increasingly popular mode of transportation in many North American and European cities. Montreal is no exception, having seen a constant increase in the number of cyclists, with, in 2010, more than a third of the city's adults (36%) claiming to cycle once a week or more (Vélo Québec, 2010). Montreal also has a relatively well developed bike-sharing scheme (Fuller et al., 2013). Nevertheless, although it is increasing, the modal share of cycling to commute from home to work is still relatively low on the Island of Montreal (2.24% in 2006 and 2.90% in 2011, according to Statistics Canada data). Urban planners are becoming more and more in favour of the use of the bicycle, as seen in the desire to extend cycling networks in cities, and in the setting up of bike-sharing schemes (Buehler and Pucher, 2012). The benefits of use of the bicycle in urban areas on people's health and well-being are now well known (Bigazzi and Figliozzi, 2014). On the one hand, cycling allows people to increase their level of physical activity and thus improve their cardiovascular fitness (Oja et al., 1998), while reducing the risk of chronic diseases (diabetes, cardiovascular diseases, certain types of cancer) (Gordon-Larsen et al., 2009; Hamer and Chida, 2008; Woodcock et al., 2009), overweight and obesity (Bassett et al., 2008), and fostering better mental health and quality of life (Daley, 2008). Traveling by bicycle also has positive effects on the environment in urban areas, with the bicycle producing far less air pollution and noise than the car (Hatzopoulou et al., 2013; Rojas-Rueda et al., 2011).

Despite these widely-documented positive benefits, cycling downtown, especially during the commute, may be associated with health and safety risks due to potentially high levels of exposure to air pollution, road noise, and high traffic density (De Hartog et al., 2010), as cyclists travel on roads shared with motor vehicles or on cycling routes adjacent to or near main roads (Badland and Duncan, 2009; Kaur et al., 2007). Like pedestrians, cyclists are more physically exposed and thus have an increased risk of injuries and fatalities compared with car and public transit users (Elvik, 2009; Pucher and Dijkstra, 2003).

They also breathe in various road transportation-related air pollutants that may be harmful to human health in fairly large quantities and during episodes of prolonged exposure: carbon monoxide (CO), black carbon (BC), nitrogen dioxide (NO_2), volatile organic compounds (VOC), ultrafine particles (UFPs), and fine particulate matter ($PM_{2.5}$ and PM_{10}) (Hoek et al., 2013; Schepers et al., 2015). The existence of positive associations between exposure to these pollutants and pulmonary illnesses, such as asthma (Brauer et al., 2003; Salam et al., 2008), cardiovascular diseases (Brugge et al., 2007) and certain types of cancers (lung and prostate) (Gauderman et al., 2007; Parent et al., 2013) has been extensively demonstrated. Moreover, as Int Panis et al. (2010)

* Corresponding author.
E-mail address: philippe.apparicio@ucs.inrs.ca (P. Apparicio).

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note, because of their physical activity, cyclists often have much higher respiration rates than people who travel by car (ventilation is 4.3 times higher for cyclists than for car drivers). They consequently inhale more air pollutants over the same period of time.

Prolonged exposure to high levels of noise generated by road traffic can also cause health problems and have detrimental effects on individuals' well-being. Noise in fact stimulates the central nervous system and endocrine system, which alters the homeostatic state of the human body and accelerates cardiac function (Ising and Kruppa, 2004). It consequently increases the risks of high blood pressure and cardiovascular disease (Babisch, 2011; Babisch et al., 2005; Bluhm et al., 2007). Road traffic noise may also lead to problems associated with annoyance and psychological stress, thus reducing the well-being of exposed individuals (Michaud et al., 2008; Öhrström, 2004; Öhrström et al., 2006; Stansfeld et al., 2000). At high decibel levels over long periods, noise may also result in hearing loss (Barbosa and Cardoso, 2005). To our knowledge, despite these negative effects, few studies have simultaneously analyzed cyclists' exposure to air pollution and road traffic noise. Boogaard et al. (2009) have carried out pioneering work in this field in eleven Dutch cities. Two recent studies have also added significantly to our knowledge in this area (Dekoninck et al., 2013; Dekoninck et al., 2015). In the first study, the authors measured cyclists' exposure to black carbon (BC) and noise in Ghent (Belgium) and constructed various generalized additive models (GAMs) to predict exposure to the BC air pollutant based on mobile noise measurements, meteorological conditions (wind speed) and a street canyon index. The authors used a similar approach in the second study, but in two very different geographic contexts (Ghent in Belgium, and Bangalore in India).

The aim of our study is thus to make a contribution in this area, by paying particular attention to cyclists traveling through the central neighbourhoods of Montreal.

1.1. Factors influencing exposure to air pollutants and road traffic noise

Over the past two decades, numerous studies have examined cyclists' individual exposure to air pollutants. Most compare cyclists' exposure with that of users of other modes of transport (car, public transit, walking). Although it is difficult to present an exhaustive list, studies of this kind have been performed in many cities and countries around the world, and especially in Brisbane and Sydney in Australia (Cole-Hunter et al., 2012; Knibbs and de Dear, 2010), Christchurch (Kingham et al., 2013) and Auckland (Dirks et al., 2012) in New Zealand, Bogotá in Colombia (Fajardo and Rojas, 2012), Beijing in China (Huang et al., 2012), Montreal (Hatzopoulou et al., 2013), Ottawa (Weichenthal et al., 2012) and Vancouver in Canada (Thai et al., 2008), Boston (MacNaughton et al., 2014), Santa Monica (Quiros et al., 2013), Berkeley (Jarjour et al., 2013) and Seattle (Hong and Bae, 2012) in the United States, Barcelona in Spain (De Nazelle et al., 2012; Moreno et al., 2015), Brussels, Louvain-la-Neuve and Mol in Belgium (Int Panis et al., 2010), Arnhem (Zuurbier et al., 2010) in the Netherlands, Copenhagen in Denmark (Rank et al., 2001) and London, England (Adams et al., 2001).

These studies were conducted by focusing on cyclists traveling through the city and rural areas at predefined periods of time over preset routes. The studies have allowed researchers to show, on the one hand, a considerable variation in the levels of exposure to air pollution in urban settings and, on the other hand, to identify the local factors associated with this variation (Bigazzi and Figliozzi, 2014). However, there are far fewer studies examining the factors influencing cyclists' exposure to road traffic noise. These factors can be grouped into four categories: weather conditions, time of day and day of the week, characteristics of the urban environment and traffic density.

Firstly, wind measured along the roads in question encourages the dispersion of air pollutants (Dekoninck et al., 2013; Hatzopoulou et al., 2013; Kingham et al., 1998; Quiros et al., 2013) and precipitation washout increases the washout of pollutants (Thai et al., 2008). Temperature and humidity can also have an impact on air pollution (Hatzopoulou et al., 2013; Kingham et al., 1998; Thai et al., 2008). This is why several portable devices for measuring air pollution have temperature and humidity sensors.

Secondly, morning and evening peak hours, especially on Thursday and Friday, are generally associated with high levels of air pollution (De Nazelle et al., 2013; Dons et al., 2012). Inversely, they may be associated with lower levels of noise pollution because traffic moves more slowly during these peak periods (Boogaard et al., 2009).

Thirdly, the proximity of the bicycle path to motor vehicle traffic lanes (Kingham et al., 2013; Knibbs and de Dear, 2010; Thai et al., 2008), the type of road, intersection and bicycle path or lane (Boogaard et al., 2009; MacNaughton et al., 2014), and the street canyon geometry (Dekoninck et al., 2013) can also have a significant impact on the exposure to air pollution. Some recent studies have also shown that urban vegetation can influence the deposition and dispersion of air pollutants (Janhäll, 2015), as well as the level of noise (Peng et al., 2014). In addition, in one recent study on cyclists' exposure to air pollution in Boston, MacNaughton et al. (2014) found that density of vegetation reduced exposure to BC and NO_2 pollutants.

Fourthly, traffic flows (Cole-Hunter et al., 2012; Hatzopoulou et al., 2013; Hong and Bae, 2012), the number of large trucks (Dons et al., 2012; Knibbs and de Dear, 2010) and the number of traffic lanes (Bigazzi and Figliozzi, 2014) can of course have a substantial impact.

1.2. Research objectives

The present study has two main objectives. The first objective is to simultaneously evaluate cyclists' exposure to air pollution and noise in central city neighbourhoods, something that few studies have done to date (Boogaard et al., 2009; Dekoninck et al., 2013; Dekoninck et al., 2015). Our second objective is to identify the local factors significantly influencing exposure to air pollution and road traffic noise, in paying particular attention to weather conditions, the day and time of the cyclists' travel, the type of road and bicycle path or lane used and the characteristics of the immediate environment around the cyclist's route.

2. Methods

2.1. Data collection

Data collection was based on the use of three types of devices: 1) ten Aeroqual Series 500 Portable Air Quality Sensors, 2) ten Bruel and Kjaer Personal Noise Dose Meters (Type 4448) and 3) ten Columbus V-990 GPS Data Loggers. The Aeroqual devices have two sensors—nitrogen dioxide (NO_2) and temperature and humidity sensors—that record the average NO_2 value ($\mu g/m^3$), the temperature in degrees Celsius and the percentage of humidity every minute. The Bruel and Kjaer meters record the average decibel levels (dB(A)) every minute (Laeq 1 min). As recommended by the manufacturer, all Personal Noise Dose Meters (Type 4448) were calibrated once a day using the Sound Calibrator Type 4231.

Ten students were selected according to the following criteria: they had to live on the Island of Montreal, they had to cycle through the city every weekday, and they could not change their mobility practices during the study period. The study was conducted during three weeks in September and October (2015-09-28 to 2015-10-14), on dry weekdays (Fig. 1). This period was selected because, according to the Quebec Ministry of Transportation (MTQ, 2016), September and October are the months with the highest annual average daily traffic flows in Montreal. The students had to travel by bicycle for half of this period, and to use public transit for the other half of the period. Only the trips by bicycle were analyzed in the context of this study. In addition, we only retained trips of at least 5 min (mean = 17.6 min; std. = 7.3), for a total of 85 bicycle trips, and a total of 422 km and 1494 min (nearly 25 h). The trips

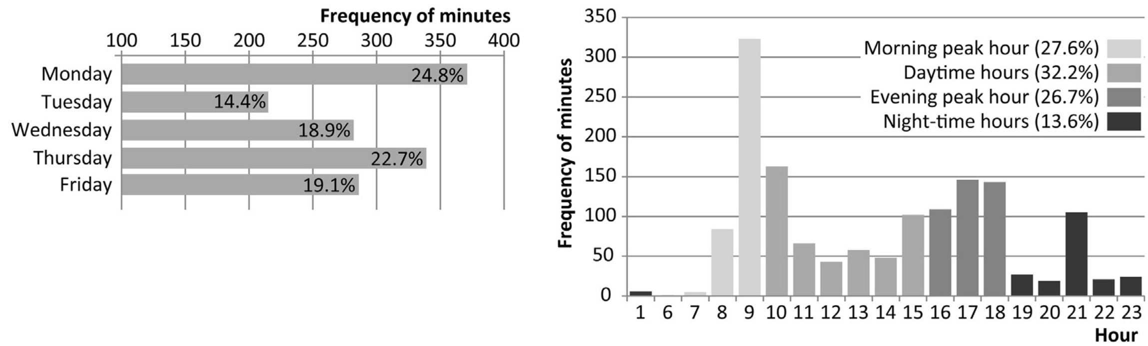

Fig. 1. Day and time of data collection.

were all made in central city neighbourhoods on the Island of Montreal (mean Euclidean distance to city centre = 3.5 km; std. = 1.8). More than half of the data was collected during peak hours (27.6% from 7 am to 9 am and 26.7% from 4 pm to 6 pm, Fig. 1).

This study was carried out on the territory of the Island of Montreal, which had a population of 1.9 million inhabitants in 2011, according to the Canadian census data for that year. Although only 2.90% of the population in the study area bicycles to work, this proportion rises to over 10% in certain parts of the central boroughs on the Island of Montreal. All of the trips analyzed in this paper were made in the central boroughs of the study area. These boroughs are characterized by the highest urban densities in the entire Island of Montreal, and by a significant concentration of the main traffic arteries that link the central business district to the access to the bridges and the principal suburbs in the metropolitan area. The result is that the concentrations of traffic-related air pollutants and the levels of road traffic noise are highest in these areas due to the high traffic densities in these locations (Carrier et al., 2016a; Carrier et al., 2016b).

2.2. Modeling air pollution and road traffic noise exposure

Two models were constructed to predict the levels of exposure to air pollution and noise. The independent variables introduced into the models can be grouped into three categories (Table 1). Firstly, several predictors are related to the day and time of the trip and to weather conditions. The days from Tuesday to Friday were included as dummy variables (Monday being the reference category). The days were divided into four periods: morning peak hour (7 am to 9 am), daytime hours (10 am to 3 pm), evening peak hour (4 pm to 6 pm) and night-time hours (7 pm to 6 am, as the reference period). For weather conditions, the temperature and percentage of humidity were measured once a minute by the Aeroqual devices, whereas the wind speed was extracted for each hour of the day from one of the pages of the Government of Canada website (http://climate.weather.gc.ca/).

Secondly, several indicators were included to describe the route taken by the cyclist. For each one-minute segment of the trip, we calculated the time in minutes during which the cyclist traveled on different types of roads (arterial road, collector road or local street) and bicycle paths or lanes (off-street bicycle path, on-street bicycle path, bike lane or shared bike lane, Fig. 2).

To do this, we used the Adresses Québec (AQ Réseau) road network, which classifies the various roads and streets as, for example: arterial roads, which enable through traffic to travel over long distances and which often have four lanes; collector roads, which are generally used by through traffic or for access to important amenities; and local streets, which primarily serve residential areas (Gouvernement du Québec, 2015). In regard to the annual average daily traffic (AADT), arterial roads can be used by 10,000 to 30,000 vehicles a day, compared with fewer than 12,000 vehicles a day on collector roads and fewer than 1000 on local streets (Transportation Association of Canada, 1999).

The cycling network was constructed by combining various sources of data on bicycle paths obtained from the municipalities of Montreal, Longueuil and Laval and OpenCycleMap. This network was then merged with the Adresses Québec road network. As for the GPS tracks of the cyclists, these GPS tracks were linked to the network by using a map-matching algorithm written in Python with the GDAL library. The results of the map-matching for each trip were validated in a GIS and modified as needed.

As their name indicates, off-street bicycle paths are off-road paths for the exclusive use of cyclists. On-street bicycle paths are also for cyclists only, but are set up on streets alongside traffic lanes (next to the sidewalk) and separated by a physical barrier (low wall, divider strip or bollard). Bike lanes are lanes reserved for cyclists marked off by a painted line only and therefore not protected by a divider strip or low wall. Shared bike lanes are roads shared by cyclists and motor vehicles, with a symbol of a bicycle painted on the road surface (Vélo Québec, 2009). For each one-minute segment of the trip, we also counted the number of intersections of two or more streets crossed by the cyclist.

For the total trips, amounting to 1494 min in all, the time spent on the different types of roads, paths or lanes was divided as follows: arterial road (389 min, 21.7%), collector road (575 min, 32%) and local street (236 min, 13.1%), bike lane or shared bike lane (303 min, 16.8%), on-street bicycle path (180 min, 10%) and off-street bicycle path

Table 1
Univariate statistics for the predictors of air pollution and noise exposure.

	Min	Max	Q1	Mean	Median	Q3	SD
Temperature (Celsius)	7.90	25.80	12.80	15.88	14.90	19.00	4.24
Humidity (%)	27.00	87.20	42.90	54.07	53.40	61.90	13.71
Wind (km/h)	0.00	38.00	16.00	21.90	23.00	28.00	8.22
Number of intersections crossed	0.00	8.00	1.00	2.53	2.00	4.00	1.66
Collector road (min)	0.00	1.00	0.00	0.39	0.00	1.00	0.47
Arterial road (min)	0.00	1.00	0.00	0.26	0.00	0.60	0.42
Local street (min)	0.00	1.00	0.00	0.16	0.00	0.00	0.35
Bike lane and shared bike lane (min)	0.00	1.00	0.00	0.20	0.00	0.08	0.38
On-street bicycle path (min)	0.00	1.00	0.00	0.12	0.00	0.00	0.31
Off-street bicycle path (min)	0.00	1.00	0.00	0.08	0.00	0.00	0.26
Number of trees per metre	0.00	52.93	0.05	0.14	0.10	0.14	1.39
Area of the 20 m buffer covered by buildings (%)	0.00	51.35	8.79	18.66	18.17	26.81	12.15
Area of the 20 m buffer covered by a park (%)	0.00	100.00	0.00	2.26	0.00	0.00	9.52
Land-use mix indicator	0.00	0.72	0.34	0.40	0.40	0.46	0.10
Off-street bicycle path: proximity to the street section (metres)	0.00	118.14	0.00	1.44	0.00	0.00	6.94

Min: minimum; Max: maximum; Q1: first quartile; Q3: third quartile; SD: standard deviation.

Fig. 2. Main types of bicycle paths and bike lanes in Montreal.

(113 min, 6.3%). It is important to note that the total of these minutes exceeds 1494 min, because if a cyclist used a bike lane or shared bike lane, we calculated both the time spent on this type of bike lane as well as the time spent on the type of road featuring the bike lane (that is, an arterial road, collector road or local street).

Since an off-street bicycle path's proximity to the closest section of road can have a significant impact on the levels of exposure to noise and air pollution, we created a variable of interaction between the time spent on an off-street bicycle path and the Euclidean distance to the nearest road. We did not include any variable relating to real-time traffic density in this study, as we were unable to obtain that type of data at the time.

Thirdly, to characterize the urban environment around the one-minute segment of the trip, three data sources were used: 1) a building footprint dataset produced by the City of Montreal dating from 2014, 2) a 2014 land-use map produced by the Montreal Metropolitan Community, and 3) a spatial inventory of all on-street public trees and off-street public trees (in parks and public squares) belonging to the municipality of Montreal. Next, we defined a 20-metre buffer zone around the one-minute segment and we calculated four indicators: the number of trees divided by the segment's length, the area covered by buildings, the area covered by a park, and the land-use mix using an entropy index calculated as follows:

$$\mathrm{H2} = -\sum \left(A_{ij}/A_j\right)\ \ln\left(A_{ij}/A_j\right)/\ \ln(k) \qquad [1]$$

where k is the number of land-use categories (commercial, institutional, park, residential, street, vacant lot, and public utility), A_j is the area of the 20-metre buffer zone, and A_{ij} is the area of the ith land-use category within buffer zone j. The indicator varies from 0 to 1, that is, from perfect homogeneity (the buffer zone is covered by a single land-use category) to maximum heterogeneity (all $p_{ij} = 1\ /\ k$). Several hypotheses can be made regarding the effect of the land-use mix. Mixed land use is usually associated with a large number of users and a larger variety of uses in the urban environment. It may thus increase the levels of noise and pollution. On the other hand, several authors have shown that this type of land use encourages the choice of active modes of transportation (walking and bicycling) (Brown et al., 2009; Frank et al., 2004). So it could also lead to a decrease in the two measures of exposure.

For our choice of models, we preferred to use spatial regressions for two reasons. On the one hand, the ordinary least squares models calculated previously showed a problem of spatial dependence. Moreover, the values of the Lagrange Multiplier and Robust Lagrange Multiplier (LM and Robust LM) tests calculated using the residuals from the OLS models indicated that it was preferable to use a spatial lag model rather than a spatial error model (Anselin and Rey, 2014). On the other hand, the introduction of a lagged dependent variable was entirely logical. In fact, the level of noise or air pollution exposure could then be associated with the level observed during the previous and following minutes during the trip. The two spatial regressions were then calculated using a contiguity matrix generated from a program written in Python with the GDAL library. Each one-minute segment thus includes either two contiguous segments (the previous and following minutes) or a single contiguous segment (for the first or last minute of the trip). The spatial regressions were computed in R by using the spdep library (Bivand, 2013).

It should also be noted that we did not find any significant correlations between the residuals from the two OLS models ($R^2 = -0.05$, $p = 0.059$) and the two spatial regression models ($R^2 = -0.02$; $p = 0.469$) that might have justified the use of a seemingly unrelated regression model (Grene, 2011).

3. Results

3.1. Univariate statistics: levels of air pollution and road traffic noise exposure

The noise levels measured during the trips vary substantially from 54.6 to 87.6 dB(A) (Table 2). The World Health Organization (WHO) has set two guidelines for noise. The WHO considers noise levels above 55 dB(A) in outdoor living areas during the daytime and evening as a serious annoyance, and notes that noise levels of 70 dB(A) and over in a traffic area may have significant impacts on health (including hearing impairment) (Berglund et al., 1999). In addition, the Quebec Ministry of Transportation recommends that daily road noise levels should be kept under 65 dB(A) (MTQ, 2009). The levels of noise that we measured are therefore relatively high, with mean and median values above the

Table 2
Distribution of 1 min averages of road traffic noise and air pollution during cycling trips.

Exposure indicator	dB(A)	NO_2 (μg/m^3)
N	1494	1494
Minimum	54.6	0.0
Percentile		
5	61.7	26.0
10	63.6	35.0
25	67.0	52.0
50	70.3	81.7
75	73.6	111.0
90	76.3	137.0
95	78.0	151.0
99	82.6	172.0
Maximum	87.6	225.0
Mean	70.5	76.0
Standard deviation	4.933	39.165
Skewness	−0.015	0.181
Kurtosis	0.404	−0.409

70 dB(A) threshold. This means that during half the time the cyclist spent on the trip, the noise values exceeded the guideline value recommended by the World Health Organization in a traffic area.

NO_2 pollution varies from 0 to 225 μg/m^3, with mean and median values of 76 and 81.7 μg/m^3 respectively (Table 2). The pollution levels found are largely lower than 200 μg/m^3, the WHO short-term (1-hour) NO_2 guideline value (World Health Organization, 2006). Even the value of the 99th percentile (172 μg/m^3) is not above this threshold. However, the levels found greatly surpass the WHO annual mean guideline value of 40 μg/m^3. This is of course an annual mean, so that data are not really comparable.

In addition, the two measures of exposure are strongly spatially autocorrelated with Moran's I statistic values of 0.57 ($p = 0.000$) for the dB(A) and 0.91 for the NO_2 ($p = 0.000$) levels, obtained with the contiguity matrix described above. Finally, a very weak negative correlation was found between the two measures of exposure (Pearson's correlation coefficient = −0.07, $p = 0.005$). At first sight, this may seem surprising. However, as pointed out by Boogaard et al. (2009), "congestion and vehicle speed have opposite effects on air pollution and noise emissions." Indeed, traffic density is generally associated with high NO_2 values, but not necessarily with high levels of noise. For example, in a peak hour traffic jam, NO_2 emissions are high because of the large number of vehicles involved. On the other hand, there may be less noise than outside rush hours as the vehicles are moving very slowly.

3.2. Spatial regression

The results of the spatial regression models show that temperature, humidity and wind are negatively associated with air pollution (Table 3). This corroborates the findings of Dekoninck et al. (2013) in Ghent (Belgium) which showed that the wind speed significantly reduced the cyclists' exposure to black carbon. On the other hand, the wind speed is not significantly associated with the level of exposure to noise.

Table 3
Spatial lag regressions.

Dependent variable	NO_2 (μg/m3) Coef.	Z	Pr	dB(A) Coef.	Z	Pr
Intercept	36.133	6.66	0.000	47.431	29.06	0.000
Rho (Wy)	0.823	91.13	0.000	0.316	14.28	0.000
Temperature (Celsius)	−0.404	−2.07	0.038	–		
Humidity (%)	−0.185	−4.06	0.000	–		
Wind (km/h)	−0.345	−4.08	0.000	0.028	1.24	0.214
Monday	Ref.			Ref.		
Tuesday	1.391	1.15	0.249	0.393	1.19	0.233
Wednesday	2.567	1.09	0.275	0.152	0.34	0.732
Thursday	2.597	1.11	0.269	0.451	1.07	0.286
Friday	3.280	1.21	0.228	0.475	0.99	0.324
Night-time hours (7 pm–6 am)	Ref.			Ref.		
Morning peak hour (7 am–9 am)	3.949	3.16	0.002	2.224	6.47	0.000
Daytime hours (10 am–3 pm)	2.530	2.06	0.039	2.328	6.94	0.000
Evening peak hour (4 pm–6 pm)	1.596	1.25	0.212	1.105	3.28	0.001
Number of intersections crossed	−0.078	−0.36	0.720	−0.157	−2.58	0.010
Collector road (min)	Ref.			Ref.		
Arterial road (min)	−3.761	−4.05	0.000	1.801	6.91	0.000
Local street (min)	−1.924	−1.57	0.116	−2.402	−6.88	0.000
Bike lane and shared bike lane (min)	−1.019	−1.08	0.280	−0.430	−1.62	0.105
On-street bicycle path (min)	−2.621	−2.03	0.043	−1.053	−2.90	0.004
Off-street bicycle path (min)	−3.790	−1.76	0.078	0.210	0.35	0.726
Off-street bicycle path (min) * proximity to the street section (m)	−0.086	−1.01	0.311	−0.050	−2.10	0.036
Number of trees per metre	0.472	1.93	0.054	−0.045	−0.66	0.509
Buildings (%)	0.000	−0.01	0.992	−0.047	−4.77	0.000
Park (%)	0.044	1.12	0.262	−0.021	−1.92	0.055
Land-use mix (entropy)	2.739	0.71	0.475	−1.507	−1.40	0.162
AIC	12,724			8236		
AIC (difference from OLS)	−2042			−181		
Nagelkerke pseudo R^2	0.815			0.419		

The day that the trip was made has no significant impact on the two indicators of exposure. But several interesting associations are found in regard to the time of day of the trip. In comparison with the night-time period (7 pm to 6 am), cycling during the morning peak period is strongly associated with a higher level of air pollution (B = 3.949, $p = 0.002$) and noise exposure (B = 2.224, $p = 0.000$). But, surprisingly, the evening peak period does not have a significant impact on the level of air pollution exposure. Daytime hours are associated with a higher level of noise (B = 2.328, $p = 0.000$) than rush hours (morning, B = 2.224, $p = 0.000$; evening, B = 1.105, $p = 0.001$). This may be explained by the fact that there are fewer cars during daytime hours, but they are driving faster than during peak hours. There are also more delivery trucks and more roadwork during daytime hours. Consequently, the noise level is higher.

The number of intersections crossed had a negative impact on the noise level (B = −0.157, $p = 0.010$), but no significant impact on the level of air pollution. For the type of road, cycling on an arterial road significantly reduces the exposure to air pollution (B = −3.761, $p = 0.000$), but increases the level of exposure to noise (B = 1.801, $p = 0.000$), compared with cycling on a collector road. Local streets are significantly less noisy (B = −2.402, $p = 0.000$) than collector roads, but we did not find any significant reduction in exposure to air pollution. In regard to air pollution, our results are consistent are those obtained by Dons et al. (2013) who showed that cyclists's exposure tends to be higher on local street than on major roads in Flanders (Belgium).

The type of bicycle path or lane used also has an impact on the levels of exposure to air pollution and noise. The coefficients obtained for bike lanes and shared bike lanes are not significant. This means that, all other things being equal, the levels of exposure for the two indicators do not differ from those seen for collector roads (the reference variable). In other words, exposure is therefore high on these types of bike lanes. However, cycling on an on-street bicycle path significantly reduces the levels of exposure to air pollution (B = −2.621, $p = 0.043$) and noise (B = −1.053, $p = 0.004$). Also, the coefficient obtained for off-street bicycle paths for the model of air pollution exposure is by far the strongest (B = −3.790, $p = 0.078$), but off-street bicycle paths are not significantly less noisy than collector roads. This may be explained by the fact that some of these paths are close to particularly noisy sections of street. Indeed, when we place the off-street bicycle path (min) in interaction with proximity to the street section (m), we obtain a significant negative coefficient (B = −0.050, $p = 0.036$). This means that the more the cyclist travels on an off-street bicycle path that is far from the street, the lower the noise level is. This result is due to the fact that off-street bicycle paths in the central neighbourhoods of Montreal are mainly located along major traffic arteries, and, therefore, the further the cyclist is from the road, the lower the noise level is.

Finally, there is no significant association (at 5% level) between the predictors of the surrounding environment—trees, buildings, a park and the land-use mix—and air pollution exposure. These results contrast with the study of MacNaughton et al. (2014) in Boston, which found a negative association between vegetation density and exposure to BC and NO_2. The presence of a park along the path reduces the noise level because this open space allows noise to disperse (B = −0.021, $p = 0.055$).

4. Discussion

4.1. The importance of measuring the two pollutants simultaneously

We found almost no correlation between the measures of exposure to noise and air pollution ($R^2 = -0.07$), whereas previous studies had obtained much higher correlations (Boogaard et al., 2009; Davies et al., 2009). It should however be pointed out that, in a study on eleven Dutch cities (Boogaard et al., 2009), the correlations varied considerably from one city to another between noise and particle number concentration (from 0.21 to 0.60) and $PM_{2.5}$ (from −0.17 to 0.38) pollution. These results are important in terms of public health. They show that a high level of exposure to air pollution does not necessarily mean that the level of exposure to noise is equally high. It is therefore appropriate to measure exposure to air pollution and noise simultaneously, in order to evaluate their combined effects on the health of urban populations. This also means that in urban planning, different solutions need to be developed to reduce each of these two nuisances.

4.2. The planning and development of bicycle paths and bike lanes: an important issue in terms of cyclists' exposure to air pollution and noise

The results of this study show that, all other things being equal, cyclists who use bike lanes and shared bike lanes are not exposed to significantly less pollution than if the cyclists use collector roads with no additional cycling space or signage. This corroborates the findings of the study by MacNaughton et al. (2014) on cyclists' exposure to BC and NO_2 pollutants in Boston. Over the past ten years, boroughs in the City of Montreal have largely developed these types of bike lanes because of their low cost. It has however been widely shown that the risks of accidents involving cyclists are greater on these types of bike lanes because cyclists share the road with motor vehicles (Teschke et al., 2012), in addition to the fact that they are exposed to higher levels of air and noise pollution than they would be on on- or off-street bicycle paths. So it would be preferable to place less emphasis on the development of bike lanes and shared bike lanes.

For off-street bicycle paths, we found that the closer they are to major traffic arteries the greater their exposure to noise is. Surprisingly, however, off-street bicycle paths are no less noisy than collector roads. These off-street paths should therefore be developed as far away from major traffic arteries as possible. For the existing network, vegetation barriers (especially hedges) could be set up between sections of the off-street bicycle path and the road in order to reduce cyclists' exposure to noise.

The results of the regression modeling also showed that levels of exposure to NO_2 and noise were significantly higher during the morning peak period. This poses a considerable challenge for the development of a cycling network serving central city neighbourhoods. Certain streets could perhaps be reserved for cyclists during rush hours, particularly along a north-south and an east-west axis, in order to rapidly connect outlying neighbourhoods with downtown areas where many jobs and higher education institutions are located. These streets, exclusively reserved for cyclists either all day or during rush hours only, would thus represent "veritable cycling expressways," with a rapid flow and large volume of cyclists, while substantially reducing the risk of accidents and the levels of exposure to pollutants. And they would undoubtedly encourage many people to bicycle to work or school and thus reduce the modal share of cars in peak hour commuting.

4.3. Research limitations

We did not include any direct measure of real-time traffic density in this study. This study has only compared people traveling by bicycle on different types of routes. In order, to more reasonably make inferences about health it would also be of value to simultaneously compare exposure to air pollution and noise for other modes of peak-hour transportation such as travel by car, public transit or walking.

The assessment of cyclists' exposure to air pollutants could be improved in future studies. As mentioned by Schepers et al. (2015), the cyclist's inhaled dose of pollutants is the result of three factors: the air pollutant concentration, the duration of exposure and the ventilation rate. We could then estimate the cyclist's inhaled dose every minute by taking into account of the average NO_2 value recorded by the Aeroqual device and the average ventilation rate every minute. A relatively precise estimate of ventilation could be obtained in two ways. The first option would be to have all the participants perform a cycling exercise test in the laboratory to simultaneously measure their heart rate and ventilation rate. These data could then be used to estimate the cyclists' ventilation rate during their bicycle trips by having them wear a watch with a heart rate monitoring strap. The second option would be to have the cyclists wear biometric t-shirts (e.g. Hexoskin) that measure ventilation in real time.

5. Conclusion

Cyclists' levels of exposure to air and noise pollution in central city neighbourhoods on the Island of Montreal are relatively high. A weak correlation was found between the exposure to noise and air pollution. The morning peak hour and the types of roads and bicycle paths or lanes used by cyclists have significant impacts on their exposure to both air and noise pollution. For example, bike lanes and shared bike lanes are associated with higher levels of exposure to both air and noise pollution, while the proximity of the off-street bicycle path to the closest road increases the level of exposure to noise. On the other hand, some factors are only significant for one or the other of the two types of exposure. The number of intersections crossed, the distance of the off-street bicycle path from the main road, and the presence of a park, for example, significantly reduce the level of exposure to noise, but have no impact on the level of air pollution. For example, off-street bicycle paths are associated with lower levels of air pollution but have no significant impact on noise. Finally, mixed land use does not have any impact on the two measures of exposure.

As recommended by MacNaughton et al. (2014) in Boston, in Boston, our results suggest that, where possible, the City of Montreal should not prioritize bike lanes or shared bike lanes, but should instead develop on-street bicycle paths on streets with little traffic or, better still, off-street paths that are far from major roads.

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