Exposure to Particulate Matter in Traffic: A Comparison of Cyclists and Car Passengers

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Exposure to particulate matter in traffic: A comparison of cyclists and car passengers

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A B S T R A C T

Emerging evidence suggests that short episodes of high exposure to air pollution occur while commuting. These events can result in potentially adverse health effects. We present a quantification of the exposure of car passengers and cyclists to particulate matter (PM). We have simultaneously measured concentrations (PNC, PM2.5 and PM10) and ventilatory parameters (minute ventilation (VE), breathing frequency and tidal volume) in three Belgian locations (Brussels, Louvain-la-Neuve and Mol) for 55 persons (38 male and 17 female). Subjects were first driven by car and then cycled along identical routes in a pairwise design. Concentrations and lung deposition of PNC and PM mass were compared between biking trips and car trips.

Mean bicycle/car ratios for PNC and PM are close to 1 and rarely significant. The size and magnitude of the differences in concentrations depend on the location which confirms similar inconsistencies reported in literature. On the other hand, the results from this study demonstrate that bicycle/car differences for inhaled quantities and lung deposited dose are large and consistent across locations. These differences are caused by increased VE in cyclists which significantly increases their exposure to traffic exhaust. The VE while riding a bicycle is 4.3 times higher compared to car passengers. This aspect has been ignored or severely underestimated in previous studies. Integrated health risk evaluations of transport modes or cycling policies should therefore use exposure estimates rather than concentrations.

1. Introduction

Adverse health effects of exposure to air pollution have traditionally and consistently been associated with ambient measurements at fixed monitoring stations in many different countries (Künzli et al., 2000; Nawrot et al., 2007; Pope et al., 2009). The exact contribution of different compounds and fractions of particulate matter (PM) to specific health endpoints has not been fully elicited but emissions of internal combustion engines and traffic have been suggested to be more toxic than the general mixture (Jerrett et al., 2005). Proximity of the residence to major roads has been used as a surrogate for exposure to traffic related air pollution (e.g. Beelen et al., 2007). Land-use regression models (LUR) therefore typically use road or traffic density as a predictor of local concentrations. Combined with other variables such as population density LUR provide a quick and accurate assessment of concentrations useful for exposure assessments (Briggs et al., 1997; Hoek et al., 2008). Other authors have used either measurements or models to demonstrate that exposure during commuting could make a significant contribution to total exposure (e.g. Fruin et al., 2004). Recent reviews of both approaches can be found in Boogaard et al. (2009) and Beckx et al. (2009a).

This increased exposure in traffic is a consequence of the fact that vehicles typically emit high quantities of pollutants under a limited number of specific driving conditions (Int Panis et al., 2006; Beusen et al., 2009). Close proximity to traffic therefore leads to peak exposure when trailing vehicles or cyclists cross the tailpipe plume. At this moment it is not clear what the health effects of short bursts of high exposure are relative to the effects of chronic exposure which are well known from epidemiological studies. Nevertheless some observations suggest that short episodes of

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high exposure can potentially account for some of the observed health effects (Pekkanen et al. 2002; McCreanor et al., 2007; Strak et al., 2010).

Recent advances in the field of exposure modelling have enabled the estimation of the time spent in traffic using different modes by using activity-based traffic models, a new class of transport demand models (Beckx et al., 2009b, 2009c). Similar work by Marshall (2008) used data from activity diaries to estimate exposure but neither approach has been fully validated (Beckx et al., 2009c). Hence accurate assessments of exposure in different vehicles are necessary to validate model predictions so that future studies can take dynamic exposure during commuting into account (Int Panis, 2010).

In this paper we present the results of measurements of concentrations of particulate matter inside a car and on a bicycle. Ventilatory parameters are simultaneously measured to assess the amount of pollutants actually inhaled during each trip. Only a few studies (van Wijnen et al., 1995; Rank et al., 2001; O'Donoghue et al., 2007; Zuurbier et al., 2009) have taken into account that cyclists have a variable and increased minute ventilation compared to other commuters, influencing their inhaled dose of air pollutants. For this study we also explicitly want to relate the lung deposited dose to cycling intensity.

2. Methods

2.1. Study design and routes

The study described in this paper was conducted within the framework of the SHAPES project. The working hypothesis was that PM concentrations would be higher in the car than on the bicycle. This hypothesis was based on the results of a pilot study and published results from other studies (Kingham et al., 1998; Adams et al., 2001, 2002; Kaur et al., 2005, 2007). A similar result was expected for particle number concentrations (PNC) (Kaur et al., 2005; Boogaard et al., 2009). Three routes were chosen in three different Belgian regions (Fig. 1). Brussels (BxL) is the capital located in the centre of Belgium (pop. ~1.5 mil.), Louvain-la-Neuve (LLN) is a new university town (built between 1968 and 1975; ~10,000 inh. and 21,000 students) in Wallonia about 20 km southeast of Brussels. Mol, a small rural town (~34,000 inh) in Flanders, is an assembly of a dozen former hamlets about 70 km northeast of Brussels. Some attributes of the three routes, sampling dates and meteorological conditions are summarized in Table 1. All routes are in the form of loops so that all relative wind directions are included in each trip. All routes include sections with on-road cycling, cycle lanes marked on the road and grade separated cycling paths parallel to the lanes for motorized traffic.

The Brussels route loops through the European district. Its southern leg includes part of the Rue de la Loi, a busy 4 lane street canyon (N3; ~50000 vehicles day^{-1}). The routes that were chosen in Louvain-la-Neuve and Mol included very quiet residential areas as well as a busier street in the eastern section with mostly local traffic and few heavy duty vehicles (N4 and N18; ~15000 vehicles per day). The route in Louvain-la-Neuve includes some slopes, similar to the route in Brussels, whereas the route in Mol is flat. The Brussels route was cycled twice to obtain a similar sampling time and number of measurements as for the longer rural routes.

2.2. Selection of test persons

Participants were recruited through the 'SHAPES injury registration system'. Commuter cyclists were asked to report weekly on their bicycle usage and related traffic injuries. The SHAPES inclusion criteria are: (1) age between 18–65 years; (2) having a paid job outside the home; (3) cycling to work at least twice a week; (4) living in Belgium. All subjects who had filled out at least two week books ($N = 1048$) were sent an email. 281 subjects who

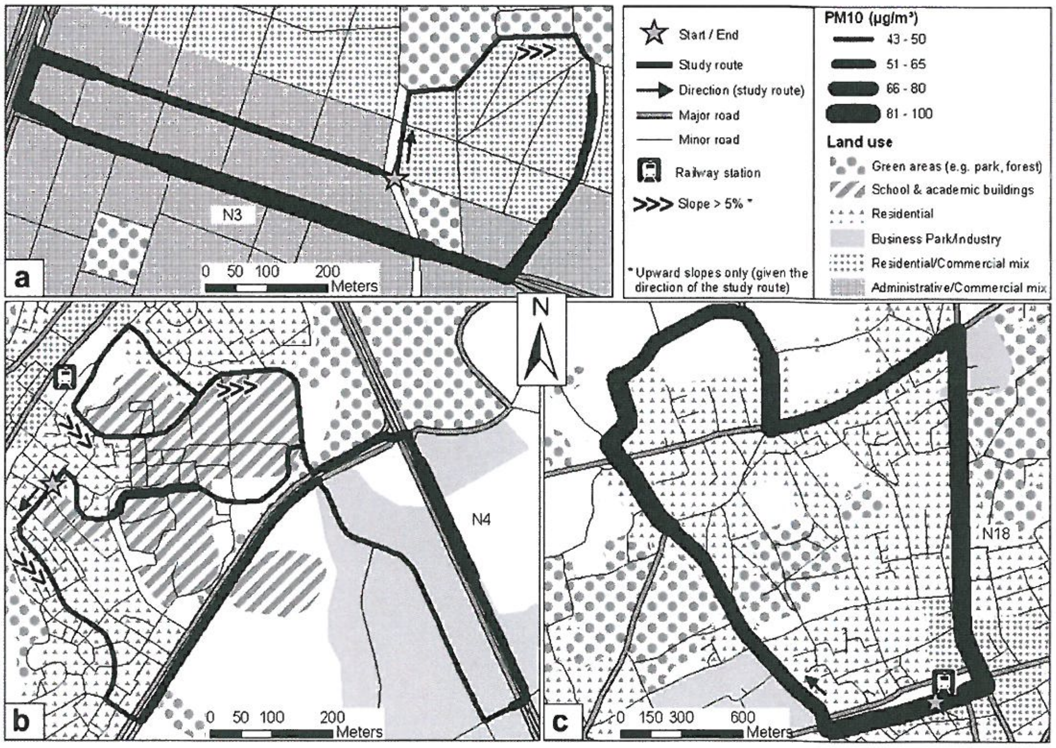

Fig. 1. Location of case-study routes in a. Brussels b. Louvain-la-Neuve and c. Mol.

Table 1
Route characteristics and meteorological and environmental conditions during the experiments.

Average[a] Date	Route	Route length (m)	Avg. temp. (°C)	Avg. wind speed (km h^{-1})	Wind direction	Avg. Ozone (µg m^{-3})	Avg. relative humidity (%)	Avg. air pressure (hPA)	Avg. PM10 (µg m^{-3})
4/06/2009	Brussels	4800	13.5	12.9	NW	92.8	49.5	1005.8	22.6
5/06/2009	Brussels	4800	13.5	7.3	W	70.4	64.7	999.0	26.9
8/06/2009	Brussels	4800	16.5	9.1	S	94.9	53.3	996.4	16.1
9/06/2009	Brussels	4800	17.8	21.2	S	77.9	71.9	994.3	19.0
11/06/2009	LLN	5450	15.5	17.1	WSW	72.7	80.7	1004.7	12.3
12/06/2009	LLN	5450	18.2	9.5	W	90.3	53.7	1009.9	21.8
30/06/2009	Mol	6800	28.1	12.2	WNW	140.8	47.8	1020.0	14.6
1/07/2009	Mol	6800	25.3	8.9	NE	113.9	55.8	1021.0	18.3

[a] Averages in the nearest station of the automatic monitoring networks (ISSeP; BIM; VMM): For PM10 and O_3, stations Uccle/Ukkel, Corroy-le Grand and Dessel were used for Bxl, LLN and Mol respectively. For meteorological data, station Uccle-Ukkel was used for Brussels and LLN and station Luchtbal was used for Mol. There was no precipitation.

volunteered to participate were contacted by telephone. During this phone call, we tested additional exclusion criteria (e.g. use of anti-platelet medication). Finally 55 healthy non-smokers were randomly selected (stratified by their place of residence relative to one of the three case-study locations). None were rejected based on a medical pre-participation screening. Some descriptive statistics of the 55 test subjects are summarized in Table 2. During the experiment, each test person was first driven over the route as a passenger in a car. Immediately after the car trip the subjects were asked to ride the same route by bike. The time between the car trip and the bike trip was kept to a minimum (range 3–8 min). This pairwise design was chosen to minimise the effect of the timing on the analysis (e.g. because of intraday variation in concentrations due to changes in traffic, wind speed and direction). The bike trip always followed the car trip to avoid an effect of the bike ride on the ventilation and heart rate during the car ride. The same car (Citroën Jumpy, model year 2007) was used for all tests. The car was always driven with the windows closed, air conditioning off and the fanned ventilation system in mode 1. The same P-Trak and DustTrak instruments were used for each pair of trips to sample air within the breathing zone (i.e. approximately 30 cm from the mouth).

2.3. Measurements of particle numbers, PM10 and PM2.5

A bicycle equipped with different instruments was used to measure particulate concentrations in the ambient environment (Berghmans et al., 2009). Only the TSI P-TRAK, TSI DustTrak, and a commercial GPS were used in this study. A GRIMM 1.108 spectrometer (Grimm Technologies Inc, USA) was added for calibration purposes, but only the results of the calibrated DustTrak were used because second-by-second data is necessary for the synchronization with the other instruments. The TSI DustTrak DRX model 8534 (TSI Inc, USA), a portable optical dust monitor, was used to simultaneously measure PM2.5 and PM10. Calibrations were performed in dry conditions for 5 days in an urban background site versus a Partisol Plus model 2025 filter sampler (Thermo Fisher Scientific Inc, USA), which is an equivalent sampler for PM10 dust according to standard EN 12341. Particle number concentrations (PNC) at 1-s resolution were made using P-Trak UFP Counters (TSI Model 8525, USA), for particles in the size range 0.02–1 µm (maximum 500,000 cm^{-3}).

2.4. Respiratory measurements

Simultaneous respiratory measurements were made during each trip (one while driving and another while cycling) and synchronized with the P-Trak, DustTrak and GPS datasets. During the field tests, breathing frequency, tidal volume and oxygen uptake were measured using a portable cardiopulmonary indirect breath-by-breath calorimetry system (MetaMax 3B, Cortex Biophysik, Germany) fixed into a chest harness. A flexible facemask covered the mouth and nose. Before each test, gas and volume calibration took place and ambient air was measured before each test according to the manufacturer's guidelines. Heart rate was recorded via a Polar X-Trainer Plus system (Polar Electro OY, Finland). During the field tests, subjects were asked to cycle at the same average speed as during their trips to and from work which were recorded in weekly web-based diaries for approximately 1 year prior to this experiment.

2.5. Lung deposited dose calculation

Minute ventilation (VE) was calculated by the MetaSoft software (VE = breathing frequency × tidal volume). Inhaled amounts were calculated by multiplying PNC and PM2.5 and PM10 mass with VE. The lung deposited fraction was determined based on published deposition factors (DF) which decrease strongly with particle size and increase with tidal volume (Jaques and Kim, 2000). To relate the lung deposited dose to cycling intensity we used the data presented in Daigle et al. (2003) who report that DF strongly increases with exercise. An average PNC DF at rest of 0.63 ± 0.03 was used in our calculation of dose for car trips compared to 0.83 ± 0.04 for cycling (although their reported VE (38.1 ± 9.5 L min^{-1}) is lower than in our measurements; Table 3). Chalupa et al. (2004) reported fractional UFP deposition as a linear function of tidal volume. For comparison this function was evaluated for each breath

Table 2
Descriptive statistics of the routes by location and gender (mean and standard deviation (SD)).

Route	# of Test persons	Mean age, years (SD)	Mean BMI, kg m^{-2} (SD)	Average speed time based, km h^{-1} (SD)	Average speed GPS based,[a] km h^{-1} (SD)	Total cycling time, min	Total driving time, min
BxL	Male $N = 21$	42.9 (9.4)	23.7 (2.0)	18.8 (1.5)	20.6 (1.8)	15.4 (1.3)	16.9 (2.5)
	Female $N = 10$	40.9 (11.1)	24.3 (4.2)	16.5 (1.8)	17.9 (1.9)	17.6 (1.9)	16.2 (3.6)
LLN	Male $N = 8$	41.5 (11.0)	23.8 (2.2)	20.1 (1.5)	20.9 (1.8)	16.3 (1.2)	10.6 (0.3)
	Female $N = 1$	29.0 (.)	20.7 (.)	22.2 (.)	24.6 (.)	14.7 (.)	10.8 (.)
Mol	Male $N = 9$	44.7 (8.1)	24.3 (2.6)	22.1 (3.0)	22.1 (3.7)	18.8 (2.8)	9.5 (1.0)
	Female $N = 6$	49.8 (3.2)	22.5 (3.1)	19.4 (1.8)	20.1 (1.7)	21.1 (2.0)	10.2 (1.24)

[a] Distance based average speed while cycling (excluding zero speeds during stops at intersections etc.).

Table 3
Average respiratory parameters. Values are mean (SD).

	# of Test persons	Breathing frequency (breaths min^{-1})	Tidal volume per breath (L)	Minute ventilation (VE) (L min^{-1})	Heart rate (beats min^{-1})	Total inhaled volume during trip (L)
Bike	Male $N = 21$	27.9 (4.2)	2.2 (0.4)	59.1 (13.7)	129.6 (12.8)	924.8 (182.3)
	Female $N = 10$	32.7 (7.0)	1.4 (0.3)	46.2 (10.6)	140.0 (13.6)	801.4 (98.2)
Car	Male $N = 8$	18.3 (3.0)	0.8 (0.2)	13.4 (1.7)	71.9 (9.7)	176.8 (55.8)
	Female $N = 1$	21.3 (4.8)	0.6 (0.1)	11.3 (1.8)	74.8 (9.0)	153.4 (62.7)
Bike/car ratio	Male $N = 9$	1.6 (0.3)	2.8 (0.6)	4.5 (1.1)	1.8 (0.2)	5.8 (2.3)
	Female $N = 6$	1.6 (0.2)	2.6 (0.4)	4.1 (0.6)	1.9 (0.3)	5.9 (2.0)

taken during the car trips (only car trips, because it was only defined at tidal volumes <1 liter which was exceeded during all the cycling trips). We took a similar approach for the calculation of PM2.5 and PM10 doses based on Löndahl et al. (2009) who report slightly higher DF for traffic exhaust particles relative to general curb side particles. Mass based DF (0.23 ± 0.03) are much lower than number based DF. We were unable to find peer-reviewed data on the effect of exercise on mass based fractional deposition of particles.

3. Results

3.1. General results

Table 2 summarizes some descriptive statistics about the tested persons and their performance during the experiments. Mean age (*F*-test, $p = 0.1899$) and mean BMI (*F*-test, $p = 0.8642$) were similar in all 3 locations. Mean age and sex ratio were similar to those of frequent commuter cyclists in Belgium (mean age ± SD = 39.7 ± 10; 68.2% Men, 31.8% Women; $N = 932$). Time based cycling speeds recorded in Brussels were somewhat lower than in both rural towns because of traffic lights and pedestrians. Otherwise average (self-selected) cycling speeds were similar for both rural locations but slightly lower for women (*t*-test, $p = 0.0098$). The cycling speed during the experiment was comparable to the average commuting speed that was reported in the weekly diaries (men: 19.5 ± 4.8 km h^{-1}, women: 15.5 ± 3.8 km h^{-1}).

3.2. Concentrations

Data were first checked for unreliable measurements and outliers. Ventilation or PM data were missing on some trips due to equipment failure, especially in Mol. Whenever there were anomalies in the measurements of one trip, both trips were excluded from the analysis (since we use a pairwise design, the associated car or bike trip was also excluded). Only subjects with valid concentration and respiration data for both trips were taken into account. After applying these cleaning criteria, the final dataset included 24 cyclists in Brussels (Male = 15, Female = 9), 6 in LLN (M = 5, F = 1) and 13 in Mol (M = 8, F = 5).

PNC values in traffic were more chaotic on the bicycle and peak values are frequently above 100,000 particles cm^{-3} whereas numbers inside the car are more stable. Fig. 2 shows all measurements taken in Brussels on 4th June 2009. Fig. 3 shows a summary of all measurements for the three locations. PNC were approximately three times higher in Brussels than in both other locations. Levels of PM were elevated in Mol (Fig. 1) due to specific meteorological conditions which did not occur at the other locations. High temperatures, combined with sunny weather and low relative humidity caused an increase in both ozone and PM concentrations (Table 1). PNC were significantly higher inside the car than on the bicycle in Mol whereas differences at similar levels in LLN and at much higher levels in Brussels were not significant. The opposite result was found for particulate mass. Average PM2.5 and PM10 levels were significantly lower inside the car in Brussels and LLN, but not in Mol.

3.3. Respiratory parameters

A summary of the respiratory data is shown in Table 3. Women breathed significantly more frequently and had lower tidal volumes than men (*t*-test $p < 0.01$; $p < 0.0001$). As a result men inhaled about 17% more air while cycling ($p < 0.01$). Ventilation frequency was 1.6 times higher and tidal volume increased by a factor of 2.6 while cycling. VE increased by a factor of 4.1 in women and 4.5 in men. Differences between the three routes were not significant.

3.4. Inhaled quantities and lung deposited dose

Inhaled quantities shown in Table 4 were computed by multiplying the concentration of pollutants with tidal volume. The inhaled amount was calculated for each breath and then summed

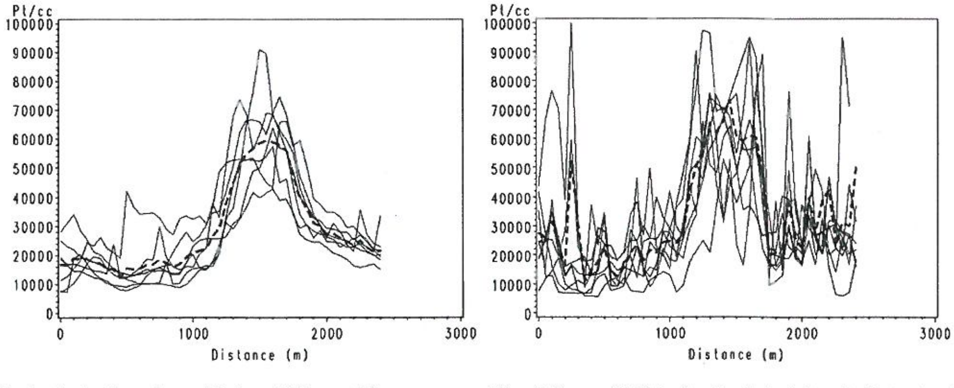

Fig. 2. PNC for all individual trips in Brussels on 4th June 2009; spatial average over 50 m (left car, right bicycle; the dashed lines indicate the daily average). Number of particles/cm^3 (Pt cc^{-1}).

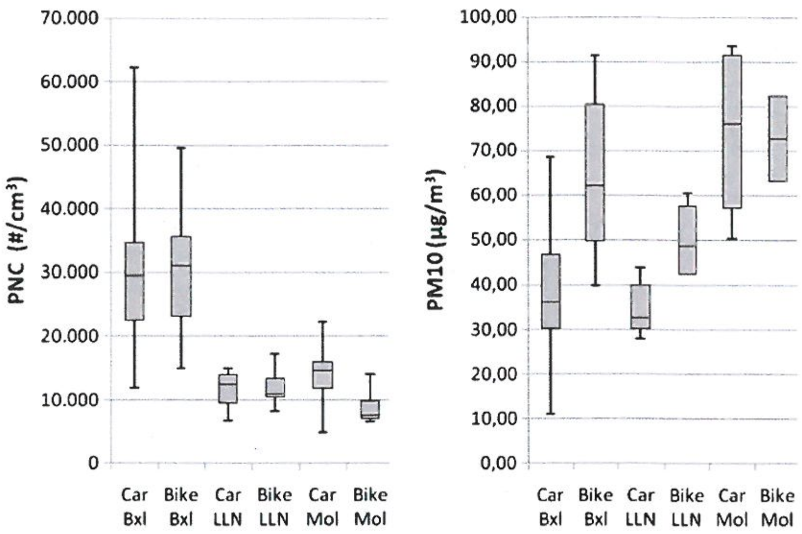

Fig. 3. Median, quartiles and range of PNC (left, #/cm^3) and PM10 measurements (right, µg m^{-3}).

over the entire trip. The fraction of particles that is estimated to stay in the respiratory tract after being inhaled (dose) is the inhaled amount multiplied by the relevant DF. Relative differences between inhaled amounts and dose are higher for PNC than for PM10 and PM2.5 because the DF for UFP is higher when performing physical exercise. There is little difference whether the Daigle et al. (2003) average DF is used or a specific DF for each breath is calculated based on Chalupa et al. (2004). Quantities of particles inhaled by cyclists were between 400 and 900% higher compared to car passengers on the same route. The longer duration of the cycling trip also increased the inhaled doses.

4. Discussion

In general, observed PNC for Brussels are similar to published numbers for cities such as Aberdeen (Dennekamp et al., 2002), Copenhagen (Vinzents et al., 2005) and a number of Dutch cities (Boogaard et al., 2009).

We have identified an apparent inconsistency in the measured average PNC values which are significantly higher in the car in Mol, but not in Brussels (at relatively higher concentrations) or LLN (with lower concentrations). This inconsistency indicates that there are differences between locations or the time at which they were sampled, which remain unexplained. Similar findings can be found in Boogaard et al. (2009) who concluded that the overall mean PNC in the car is 5% higher than the overall mean PNC of cyclists in 11 Dutch cities. Their general conclusion ignores the fact that they did find important differences in either direction. Mean PNC and mean PM2.5 were higher in the car in 4 and 6 Dutch cities respectively. Mean PNC and mean PM2.5 were higher on the bicycle in 4 and 3 Dutch cities respectively and small differences were reported in the other locations (Boogaard et al., 2009). Earlier studies also found higher UFP concentrations in cars compared to cyclists. Kaur et al. (2005) reported a car/bicycle PNC ratio of 1.06. Both ratios are very similar to the result for Brussels (1.05).

We have also found inconsistencies in the mass based measurements of PM2.5 and PM10. Although a pilot study had indicated that in car concentrations were higher than on the bike in Mol, this difference was not found to be significant in this study despite the much larger sample size. In Brussels and LLN the opposite was even observed: lower concentrations in the car. In contrast with our results, most other studies (van Wijnen et al., 1995; Kingham et al., 1998; Adams et al., 2001, 2002; Rank et al., 2001; Kaur et al., 2005) reported higher PM concentrations for car drivers, confirming similar findings for organic pollutants (O'Donoghue et al., 2007). Also when comparing car drivers with pedestrians Kaur et al. (2005) reported lower concentrations for the latter. Gulliver and Briggs (2007) however reported results which are in line with our results for cyclists in Brussels and LLN. A number of explanations for these differences, mostly related to the proximity of (traffic) sources, have been suggested (Gee and Raper, 1999; Briggs et al., 2008) although

Table 4
Average inhaled quantities of PNC, PM10 and PM2.5. PNC m^{-1} and µg km^{-1}; mean (SD).

		PNC (SD) #inhaled per meter	PNC #dose per meter	µg PM10 (SD) inhaled km^{-1}	µg PM10 dose km^{-1}	µg PM2.5 (SD) inhaled km^{-1}	µg PM2.5 dose km^{-1}
Brussels	Bike	5,580,195 (1,924,800)	4,631,562[a]	11.5 (4.5)	2.6	3.4 (1.3)	0.8
	Car	1,335,467 (83,365)	841,344[b] 965,696[c]	1.6 (0.6)	0.4	0.6 (0.2)	0.1
	Bike/car ratio	4.50 (2.17)		7.3 (3.0)		5.9 (2.1)	
LLN	Bike	2,023,702 (594,881)	1,679,673[a]	8.4 (1.6)	1.9	3.8 (0.8)	0.9
	Car	305,095 (83,365)	192,210[b] 214,045[c]	0.9 (0.1)	0.2	0.5 (0.1)	0.1
	Bike/car ratio	6.83 (1.68)		9.0 (1.0)		8.0 (0.8)	
Mol	Bike	1,135,046 (435,493)	942,088[a]	8.5 (0.2)	1.9	5.2 (0.2)	1.2
	Car	216,768 (75,832)	136,564[b] 135,956[c]	1.2 (0.2)	0.3	0.7 (0.1)	0.1
	Bike/car ratio	6.05 (3.46)		6.6 (0.3)		7.4 (0.6)	

[a] Avg DF = 0.83, Daigle et al. 2003.
[b] Avg DF = 0.63, Daigle et al. 2003.
[c] Variable DF, Chalupa et al. 2004.

uncontrolled effects of relative humidity on measurements cannot be excluded.

The results of this study suggest that the discussion on which transport mode is associated with the highest concentrations may not be entirely relevant. Comparative studies should focus on exposure and associated risk in order to come up with a valid comparison as is the case with accidents risks for example (Vandenbulcke et al., 2009). Although there are obvious differences in exposure between cyclists and car drivers, this aspect has often been ignored for lack of measured data. Three differences influence the exposure of cyclists to air pollution. The most important one is a large increase in breathing frequency and tidal volume which increases the total inhaled volume. Secondly, for the same inhaled quantity, the amount of particles that remains in the respiratory tract is higher while exercising because of increased deposition. Finally, the time needed to complete the route is often (but not always) longer for the cyclist. Nevertheless it is mainly the differences in ventilation (and associated deposition) that matter. The difference between the results based on concentration measurements only (Fig. 3) and those including both the tidal volume and deposition fraction (Table 4) clearly demonstrates how important it is to take the physical effort that cyclists make into account. Nevertheless, to our knowledge no other project has ever designed such simultaneous measurements of concentrations and respiration. The scant attention for differences in respiration rates contrasts sharply with our assessment which suggests that increased ventilation is often seriously underestimated even for non-sloping routes cycled at low wind speeds. Most authors have either used rough estimates to account for the higher tidal volume of cyclists or ignored differences in tidal volume (Hertel et al., 2007; Kaur et al., 2005).

Rank et al. (2001) used a correction of 2.3 for the ventilation of all cyclists (referring to van Wijnen et al., 1995 but actually based on an unpublished study (Vrijkotte, 1990)). O'Donoghue et al. (2007) estimated the ratio at 2.6 based on laboratory measurements by averaging the results of two subjects at rest and while cycling on a cycling ergometer. Zuurbier et al. (2009) recently suggested a slightly lower value of 2.09. Minute ventilation levels in that study were estimated using a relation with heart rate measurements that was established in the laboratory. Their low cycling speed ($\sim 12\ \mathrm{km\ h^{-1}}$) was caused by the use of a three wheeled delivery bike to carry the particle counters and PM instruments. One laboratory study (Bernmark et al., 2006) found a ratio between rest and cycling of 5, in bicycle messengers based on the individual relationship between heart rate and VE. An average factor of 4.3 is our present best estimate based on field measurements for commuter cyclists. Even if a correction for ventilation rate is made, the inhaled dose of air pollutants is not only influenced by minute ventilation, but deposition of particles is also influenced by the amount of nasal and oral breathing and by depth of inhalation. More oral breathing and deeper inhalation will occur during exercise, both leading to higher deposition of pollutants. Daigle et al. (2003) found that a 3.3-fold increase in minute ventilation led to a more than 4.5-fold increase in total ultrafine particle lung deposition.

We hypothesize that the bike/car exposure ratio, calculated in this study is much higher than in previously published studies because VE and HR were directly and continuously measured, rather than by extrapolating the measured heart rates from laboratory based respiration and HR measurements (Samet et al., 1993). Also most other studies were conducted at much lower cycling speeds than the normal cycling speeds in a population of commuters used in this study (e.g. Strak et al., 2010).

From our measurements, we conclude that exposure to traffic related PM is up to an order of magnitude higher for cyclists than for car passengers. The remaining question however is whether this difference, which occurs only for relatively short periods during the journey to work, entails any significant health risks? Most of the epidemiological evidence of the health risks related to near-traffic pollution gradients is derived indirectly through PM2.5. UFP is considered to be a likely candidate to contribute to cardiovascular health effects, due to its characteristics and potential to induce inflammation. UFP is a part of diesel exhaust, that is labeled likely carcinogenic by the US-EPA. An interesting study in Copenhagen backs this hypothesis, where it is shown that cyclists in traffic have more oxidative DNA damage (Vinzents et al., 2005). Observations by Peters et al. (2004) suggest that short episodes of high exposure can potentially account for some of the cardiovascular effects while exposure chamber studies also indicate inflammatory and cardiovascular effects of short exposure during mild exercise (Ghio et al., 2000; Gong et al., 2003; Stenfors et al., 2004). But Brugge et al. (2007) conclude that "while the evidence is considerable, it is not overwhelming and weak in some areas". Although dedicated epidemiological evidence is limited there is some direct evidence of the effect of UFP on clinical or sub clinical effects linked to cardiovascular and respiratory illness (Pekkanen et al., 2002; Riediker et al., 2004; Huang and Ghio, 2009), but some evidence is still circumstantial and there is a need for more targeted research to unequivocally link UFP from traffic to health endpoints (HEI, 2009). According to Delfino et al. (2005) poor exposure assessment and misclassification is one of the reasons that UFP effects are still not well defined – a conclusion that can be extended to most pollutants (Int Panis, 2010).

On the other hand there is strong evidence that regular physical activity contributes to the prevention of chronic conditions (including cardiovascular disease) and that it is associated with a reduced risk of premature death (Andersen et al., 2000; Brown et al., 2007; de Geus et al., 2007, 2008, 2009). Commuter cycling seems a convenient way to incorporate exercise into the daily schedule.

5. Conclusion and further research

The aim of the present study was to objectively compare the exposure to traffic exhaust for car passengers and cyclists. PNC, PM2.5 and PM10 and ventilatory parameters were therefore continuously measured in the field, using portable devices. From the results, we conclude that the size and magnitude of differences in concentrations depend on the location, confirming similar inconsistencies reported in literature. In Brussels and LLN, the PM2.5 and PM10 concentration was significantly higher for the bicycle compared to the car. In Mol PNC were higher for the car. Minute ventilation while cycling is on average 4.3 times higher compared to driving a car. Inhaled μg PM2.5 $\mathrm{km^{-1}}$ and μg PM10 $\mathrm{km^{-1}}$ is significantly higher while cycling compared to driving in a car. The bicycle/car ratio ranges between 5.92 (2.06)–8.99 (1.03). Hence it is necessary that future exposure measurements use realistic cycling speeds that reflect the physical activity and respiration associated with typical speeds in commuter cycling (in line with self-selected speed over a long period of time). Likewise it is important to take minute ventilation and deposition fraction into account.

Nevertheless the study presented here also has some limitations. It is hard to obtain complete datasets for a car trip and a cycling trip using the P-Trak and DustTrak in combination with the MetaMax. The TSI instruments were chosen for this study because they are hand-held and have a fast response time. Although they had a relatively robust performance while in motion they occasionally stopped measuring during bike trips following a shock. We have excluded each dataset with one or more missing values. The number of complete observations (pairs) in LLN and Mol is therefore relatively small and the analysis of our results is subject to caution. Further research should be performed on larger samples, in more locations and during other seasons in order to confirm the results. Given that the results for concentrations are apparently inconsistent, care should also be taken to include in-car measurements of relative humidity in future studies. Other factors that could potentially affect measured concentrations of PNC are the 20 nm cut-off point and the 5×10^5 maximum of the P-Trak which make it impossible to account for freshly emitted nucleation mode particles (Zhu et al., 2006).

The results presented in this paper should be seen as an opportunity to improve cycling conditions. Given the fact that people who choose to cycle contribute to better air quality, policies and measures should first target the motorized traffic that is a cause of air pollution and focus on reducing exposure (rather than concentrations) to prevent unwanted health effects. In a forthcoming paper we will disaggregate the measurements along the routes to study the effects of small scale attributes of the road layout on exposure and use the dataset to derive individual optimised cycling speeds. The results of this study will likely have interesting implications for the planning of cycling infrastructure. Any measure that increases the distance between cyclists and tail-pipes will help to reduce exposure. Identifying and implementing separated and dedicated routes for cyclists and motorized traffic will go a long way in decreasing exposure but will likely not offset the entire exposure difference. However we hypothesize that it is unlikely that this would completely offset the health benefits of cycling.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2010.04.028.

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