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Review article

Comparison of air pollution exposures in active vs. passive travel modes in European cities: A quantitative review

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ABSTRACT

Background: Transport microenvironments tend to have higher air pollutant concentrations than other settings most people encounter in their daily lives. The choice of travel modes may affect significantly individuals' exposures; however such considerations are typically not accounted for in exposure assessment used in environmental health studies. In particular, with increasing interest in the promotion of active travel, health impact studies that attempt to estimate potential adverse consequences of potential increased pollutant inhalation during walking or cycling have emerged. Such studies require a quantification of relative exposures in travel modes.
Methods: The literature on air pollution exposures in travel microenvironments in Europe was reviewed. Studies which measured various travel modes including at least walking or cycling in a simultaneous or quasi-simultaneous design were selected. Data from these studies were harmonized to allow for a quantitative synthesis of the estimates. Ranges of ratios and 95% confidence interval (CI) of air pollution exposure between modes and between background and transportation modes were estimated.
Results: Ten studies measuring fine particulate matter ($PM_{2.5}$), black carbon (BC), ultrafine particles (UFP), and/or carbon monoxide (CO) in the walk, bicycle, car and/or bus modes were included in the analysis. Only three reported on CO and BC and results should be interpreted with caution. Pedestrians were shown to be the most consistently least exposed of all across studies, with the bus, bicycle and car modes on average 1.3 to 1.5 times higher for $PM_{2.5}$; 1.1 to 1.7 times higher for UFP; and 1.3 to 2.9 times higher for CO; however the 95% CI included 1 for the UFP walk to bus ratio. Only for BC were pedestrians more exposed than bus users on average (bus to walk ratio 0.8), but remained less exposed than those on bicycles or in cars. Car users tended to be the most exposed (from 2.9 times higher than pedestrians for BC down to similar exposures to cyclists for UFP on average). Bus exposures tended to be similar to that of cyclists (95% CI including 1 for $PM_{2.5}$, CO and BC), except for UFP where they were lower (ratio 0.7).
Conclusion: A quantitative method that synthesizes the literature on air pollution exposure in travel microenvironments for use in health impact assessments or potentially for epidemiology was conducted. Results relevant for the European context are presented, showing generally greatest exposures in car riders and lowest exposure in pedestrians.

Contents

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1. Introduction

Travel microenvironments may represent settings of greatest exposures to air pollutants throughout daily activities for many people. While a small portion of time may be spent commuting, this activity may lead to a substantial contribution to total daily exposures and inhalations of air pollutants. A study conducted in Barcelona for example found that respondents only spent 6% of their time traveling, but the activity contributed to 11% of their exposure to nitrogen dioxide (NO_2) and 24% of their inhalation of NO_2 (de Nazelle et al., 2013). These comparatively high peaks of exposure may have associated adverse health effects. For example, time spent in transportation modes (car, public transportation or bicycle) was shown to be associated with the onset of myocardial infarctions in a relatively large case-crossover study (1459 cases) (Peters et al., 2013). Experimental studies have shown sub-clinical effects of exposures while cycling, walking, or taking the bus in urban environments (Adar et al., 2007; McCreanor et al., 2007; Strak et al., 2009; Weichenthal et al., 2011).

Promoting walking and cycling for travel is seen as a promising solution to the physical inactivity pandemic, while also providing multiple co-benefits such as reductions in air pollution, noise, or traffic injuries (de Nazelle et al., 2011). Thus, health impact studies now attempt to estimate both positive and negative effects from being physically active while exposed to increased pollutant inhalation during walking or cycling (Mueller et al., 2015). Such studies require a quantification of relative exposures to pollutants in different travel modes. Data available locally or informal summaries of existing literature have typically been used (de Hartog et al., 2010; Rojas-Rueda et al., 2011).

Additionally, concerns are arising regarding air pollution epidemiologic research and the use of exposure assessments in which activity patterns are not fully accounted for, leading to bias in exposure-response estimates (Ragettli et al., 2015; Setton et al., 2011). While personal monitoring of air pollution exposure is currently too expensive to be used on the wide scale of entire cohorts in epidemiologic studies, future studies may be able to integrate information from daily activity patterns into their exposure assessments (de Nazelle et al., 2009; Dons et al., 2014). In particular, the development of smart phone and sensor technologies that allow seamless tracking of individuals renders such approaches much more feasible by potentially reducing costs and participant burden (de Nazelle et al., 2013; Nieuwenhuijsen et al., 2014). However, even when such detailed data of people's whereabouts and level of activity are possible, knowledge on the pollutant concentration and relative exposures in different travel modes are needed. This is particularly true when the combined effects of air pollution and physical activity are to be investigated (Andersen et al., 2015).

With the increasing numbers of studies on exposures in different travel modes, a few reviews have been published (Bigazzi and Figliozzi, 2014; Karanasiou et al., 2014), but none yet have attempted to provide a quantitative synthesis of findings from measurement studies. This paper summarizes the state of knowledge and provides quantitative estimates of relative exposures for different transportation modes in Europe.

2. Methods

A literature review on air pollution exposure for various modes of transport across Europe was completed. In this context, exposure refers to the concentration levels to which one is exposed to in a given environment, as opposed to time-weighted concentrations. Data from selected studies were harmonized to allow for a quantitative comparison. Ratios and 95% confidence interval (CI) of air pollution exposure between transportation modes and with respect to backgrounds concentrations were computed.

2.1. Literature review

Articles published between the 1st January 2000 and 28th of June 2016 in peer-review journals were searched in PubMed, ISI web of knowledge, Google Scholar, and ScienceDirect, for a combination of search terms on travel modes and air pollutants (see Appendix A). Additionally, articles appearing in the "related citations" and "cited by" were checked. Articles were then selected according to the following criteria:

i) Monitoring studies of air pollution concentrations in transportation microenvironments in Europe;
ii) At least one active travel mode (walking or cycling) compared to one or more other modes or compared to background concentrations;
iii) An experimental design which includes a comparison between modes on the same or close to the same routes, with concomitant or near-concomitant sampling for selected modes;
iv) After inspection of most commonly measured pollutants, only articles reporting particulate matter of size less than 2.5 μm ($PM_{2.5}$), black carbon (BC), ultrafine particles of size less than 0.1 μm (UFP), or carbon monoxide (CO) were selected;
v) Articles with insufficient information to compute the parameter estimates (i.e. mean, standard deviation and sample size) for the lognormal distributions (geometric means and geometric standard deviations) were excluded.

2.2. Data harmonization and derivation of ratios

Monitoring studies of exposure concentrations are very diverse in study design and means of reporting the data. Many studies report and compute exposure to pollutants concentration assuming it follows a normal distribution, although it has been demonstrated to follow a log-normal distribution instead (Adams et al., 2001; Limpert et al., 2001). This makes meta-analyses challenging as such studies only report means and standard deviations. To derive meaningful ratios of exposures in various modes, which make sense statistically, the following choices and calculations briefly described here, and explained in more detail in Appendix B, were made:

i. When data were provided separately within a single study for various design options such as routes, seasons and cities, these data were kept separate (referred to as "study campaigns") rather than estimating a weighted mean for each study.
ii. Given that pollutant concentrations habitually follow lognormal distributions, when arithmetic means (AM) and standard deviations (SD) were provided these were back-transformed to estimate geometric means (GM) and geometric standard deviations (GSD). A 95.5% confidence interval for the geometric mean was also computed.
iii. The reported data did not permit computing concentration covariance between different modes of transportation in a same city. Thus, normalized results were calculated as the ratio of a mode A to a reference mode of transport (b), the latter being treated as a constant. The normalized ratios were computed for all possible combinations of (A) and (b = walk, bicycle, bus and car). Therefore, a "*bicycle to car*" ratio is the geometric mean of the bicycle mode divided by the geometric mean of the car mode, the car concentration being the constant of reference in this case.
iv. The 95.5% confidence interval for the ratios (to a constant) was also calculated considering a random sample of size *n*, and unknown population parameters.
v. Similar steps were made to estimate ratios of transport mode concentrations to background concentrations measured at fixed ambient monitoring stations. Some studies reported a single overall background concentrations value measured throughout the monitoring campaign, while others provided concomitant measurements at the background station with each mode separately (see mode-specific background concentration summary tables). Ratios between modes and background were estimated for each type of reporting.
vi. To compare similar ratios across cities (e.g. bicycle to car ratios), we computed the geometric mean of the ratios, considering the ratios in different studies as *n* multiple independent log-normally distributed random variables. Confidence intervals and percentiles were then estimated.

3. Results

Eight studies of $PM_{2.5}$ measurements which fulfilled the stated criteria were identified, seven articles were deemed suitable for UFP analyses, 3 for CO and 3 for BC (Tables 1, 2, 3 and 4, respectively). Details of study designs, including choice of travel routes, measurement periods, and type of instruments, reveal a large variety of designs, which can make direct comparison between studies highly challenging (Tables 1–4). As explained in the methods, each study was divided into "study campaigns", when appropriate. This subdivision led to a high number of campaigns for the car to bicycle ratio comparison (22 for $PM_{2.5}$ and 19 for UFP), due to the high number of cities sampled in Boogaard et al. (2009). All other ratios had at most 8 study campaigns

Table 1
Summary of $PM_{2.5}$ mode-comparison study designs.

Study	City	Measurement period	Study design	Routes	Instrument	Mode	Concentration arithmetic mean[a] (μg/m^3)	Fixed monitor arithmetic mean[a] (μg/m^3)	
								Roadside	Urban bkgd
Int Panis et al. (2010)	3 towns, Belgium	June 2009	Drive followed by cycle trip	1 loop/city mix of traffic and cycle lanes	TSI DustTrak (light scattering)	Car Cyclist	23.2 27.2	None available	
Boogaard et al. (2009)	11 cities, Netherlands	August–October 2006; 12h-19h.	Simultaneous bike/car on 12 routes in each city	Same origin and destination but not always same route/mode	TSI DustTrak (light scattering)	Car Cyclist	49.4 44.5	None available	
Kaur et al. (2005a)	London, UK	April–May 2003; morning, lunch & afternoon	4 volunteers at a time with simultaneous modes, 5 modes	2 routes: 1) heavy traffic; 2) congested + for ped. and bike mixed with backstreets	Adams' sampler (gravimetric)	Car Bus Cyclist Pedestrians	38.0 34.5 33.5 27.5	22.6	9.9
Zuurbier et al. (2010)	Arnhem, Netherlands	June 2007–June 2008; 8–10am	Simultaneous: diesel & petrol car/electric& diesel bus/hi-&lo-traffic cycling	Same high traffic route for car, bus and high traffic cycle; low traffic cycling route close by	DataRAM (pDR)1200 (light scattering)	Car Diesel bus Electric bus Cyclist	80.7 73.0 59.8 68.7	None available	22.8
McNabola et al. (2008b)	Dublin, Ireland	January 2005–June 2006; peak morning & evening	2 simultaneous modes on same route.	2 routes: 1) congested, with footpaths, bus lane and cycle lane; 2) less congested, with bus lane and cycle lane	Adams' sampler (gravimetric)	Car Bus Cyclist Pedestrians	85.8 115.8 80.5 64.8	None available	
de Nazelle et al. (2012)	Barcelona, Spain	May–June 2009; throughout the day	2 simultaneous modes on same route.	2 round trip routes, both mix of traffic & presence of bike lane	DustTrak (light scattering)	Car Bus Cyclist Pedestrians	35.5 25.9 35.0 21.6	None available	15.6
Gulliver and Briggs (2004)	Northampton, UK	Winter 1999–2000; morning & afternoon peak	Simultaneous car & walk.	2 routes: 1) hi-traffic, w/ some minor rds; 2) suburban less traffic, some congestion	OSIRIS (light scattering)	Car Pedestrians	15.5 15.1	None available	
Adams et al. (2001)	London, UK	July 1999 & February 2000; morning & afternoon	4 simultaneous sampling, multiple comparisons	3 routes: 1) highly congested + canyon effect; 2) mix; 3) some congestion but lower density	Adams' sampler (gravimetric)	Car Bus Cyclist	36.8 39.0 28.1	29.1	14.2

[a] Arithmetic mean concentrations are provided here for illustrative purposes since they were the most commonly reported measures in the articles (geometric means and standard deviations are used in the analysis and can be found in Appendix C Tables). Where several campaigns (seasons, routes, cities) were presented in the study, the weighted arithmetic mean concentrations are shown.

Table 2
Summary of UFP mode-comparison study designs.

Study	City	Measurement period	Study design	Routes	Instrument	Mode	Concentration arithmetic mean[a] (cm^{-3})	Urban bkgd (cm^{-3})
Boogaard et al. (2009)	11 cities, Netherlands	August–October 2006; 12 h–19 h.	Simultaneous bike/car on 12 routes in each city	Same origin and destination but not always same route/mode	TSI CPC Model 3007	Car Cyclist	25,322.6 24,338.7	None available
de Nazelle et al. (2012)	Barcelona, Spain	May–June 2009; throughout the day	2 simultaneous modes on same route.	2 round trip routes, both mix of traffic & presence of bike lane	TSI CPC Model 3007	Car Cyclist Pedestrian Bus	129,601.1 77,495.3 52,714.6 55,204.2	19,190
Int Panis et al. (2010)	3 towns, Belgium	June 2009	Drive followed by cycle trip	1 loop/city mix of traffic and cycle lanes	TSI P-Trak Model 8525	Car Cyclist	23,478.9 20,931.4	None available
Kaur et al. (2005a)	London, UK	April–May 2003; morning, lunch & afternoon	4 volunteers at a time with simultaneous modes, 5 modes	2 Routes: 1) heavy traffic; 2) congested + for ped and bike mixed with backstreets	TSI P-Trak	Car Cyclist Pedestrian Bus	99,736.0 93,968.0 67,773.0 101,364.0	88,101
Moreno et al. (2015)	Barcelona, Spain	October–November 2014	2 simultaneous modes on same route.	1 round trip route on main urban arterial	Philips Aerasense Nano Tracer	Pedestrian Bus	48,000.0 54,000.0	None available
Ragettli et al. (2013)	Basel, Switzerland	March–May 2010 & September 2011	Walk, bike and bus trips consecutive, car on the day following or preceding. Similar meteorological conditions	Main road in Basel, twice in each direction per sample (Appendix A)	MiniDiSC CPC	Car Cyclist Pedestrian Bus	31,784.0 22,660.0 19,481.0 14,055.0	12609[b]
Zuurbier et al. (2010)	Arnhem, Netherlands	June 2007–June 2008; 8–10 am	Simultaneous: diesel & petrol car/electric& diesel bus/ Hi-&lo-traffic cycling	Same high traffic route for car, bus and high traffic cycle; low traffic cycling route close by	TSI CPC Model 3007	Car Cyclist Diesel bus Electric bus	38,827.5 44,257.5 43,235.0 28,602.0	21,776.8

[a] Arithmetic mean concentrations are provided here for illustrative purposes since they were the most commonly reported measures in the articles (geometric means and standard deviations are used in the analysis and can be found in Appendix C tables). Where several campaigns (seasons, routes, cities) were presented in the study, the weighted arithmetic mean concentrations are shown.
[b] The background given is from a suburban, not urban, monitoring station in Basel.

($PM_{2.5}$ bus to bicycle ratio); all BC and CO comparisons only had 1 to 3 data points to rely on.

Walking is consistently the least exposed mode of transport for $PM_{2.5}$ across all study campaigns when compared to other modes (Fig. 1 and Appendix Table C1). Bicycle, car and bus users are exposed to respectively 30, 40 and 50% greater $PM_{2.5}$ concentrations than pedestrians on average. Pedestrian exposures are also consistently lower than those for cyclists and car users for all pollutants, with average ratios ranging from 1.3 for the UFP bicycle to walk ratio, 2.9 for the CO car to walk ratio, and 2.9 for the BC car to walk ratio. The lower bound of the 95% confidence interval is well above the equality factor 1 (at least 1.2) for all these pedestrian-related ratios. (Fig. 1 and Appendix Tables C1–C4)

When comparing pedestrians to bus users, however, a study in Basel (Ragettli et al., 2013) found lower UFP concentrations for bus users (GM 12233 particles/cm^3 vs. 16,699 particles/cm^3 for pedestrians), and one study in Barcelona (Moreno et al., 2015) found lower concentrations for BC in buses (GM 3.6 μg/m3 vs. 7.7 μg/m3 for pedestrians) and similar levels for CO (0.9 ppm) (Tables C5–C20). As a result, average ratios for buses vs. pedestrians are low and inconsistent across pollutants: 0.8 for BC (95% CI 0.7–0.8), 1.1 for UFP (95% CI 1.0–1.1), 1.3 for CO (95% CI 1.2–1.4) and 1.5 for $PM_{2.5}$ (95% CI 1.5–1.6).

Cyclists have higher exposures than pedestrians but inconsistent relationships with other modes, within and across pollutants (Fig. 2 and Appendix Tables C1–C4). On average, car users are 20% more exposed

Table 3
Summary of CO mode-comparison study designs.

Study	City	Measurement period	Study design	Routes	Instrument	Mode	Concentration arithmetic mean[a] (ppm)	Fixed monitor arithmetic mean[a](ppm)	
								Roadside	Urban bkgd
Kaur et al. (2005a)	London, UK	April–May 2003; Morning, lunch, afternoon	4 volunteers at a time with simultaneous modes, 5 modes	2 Routes: 1) heavy traffic; 2) congested + for ped and bike mixed with backstreets	Langan (T15 & T15v)	Car Bus Cyclist Pedestrians	1.3 0.8 1.1 0.9	1.5	0.3
de Nazelle et al. (2012)	Barcelona, Spain	May–June 2009; throughout the day	2 simultaneous modes on same route.	2 round trip routes, both mix of traffic & presence of bike lane	TSI Q-Trak Model 7565	Car Bus Cyclist Pedestrians	7.3 2.1 1.6 1.3	None available	0.2
Moreno et al. (2015)	Barcelona, Spain	October–November 2014	2 simultaneous modes on same route.	1 round trip route on main urban arterial	TSI IAQ-Calc Model 7545	Bus Pedestrians	0.9 0.9	None available	

[a] Arithmetic mean concentrations are provided here for illustrative purposes since they were the most commonly reported measures in the articles (geometric means and standard deviations are used in the analysis and can be found in Appendix C Tables). Where several campaigns (seasons, routes, cities) were presented in the study, the weighted arithmetic mean concentrations are shown.

Table 4
Summary of BC mode-comparison study designs.

Study	City	Measurement period	Study design	Routes	Instrument	Mode	Concentration arithmetic mean (see note on units[a])[b]	Fixed urban bkgd monitor arithmetic mean (see note on units[a])[b]
Zuurbier et al. (2010)[c]	Arnhem, Netherlands	June 2007–June 2008. 8–10 am	Simultaneous: diesel & petrol car/electric& diesel bus/ Hi-&lo-traffic cycling	Same high traffic route for car, bus and high traffic cycle; low traffic cycling route close by	Smoke Stain Reflectometer Model M43D	Car Diesel bus Electric bus Cyclist	8.8 9.0 5.1 6.0	2.8
de Nazelle et al. (2012)	Barcelona, Spain	May–June 2009. throughout the day	2 simultaneous modes on same route.	2 round trip routes, both mix of traffic & presence of bike lane	Magee Scientific Micro-aethalometer Model AE51	Car Bus Cyclist Pedestrians	19.5 7.6 9.5 6.3	1.7
Moreno et al. (2015)	Barcelona, Spain	October–November 2014 10 am	2 simultaneous modes on same route.	1 round trip route on main urban arterial	Magee Scientific Micro-aethalometer Model AE51	bus pedestrians	5.5 6.5	1.6[d]

[a] Zuurbier uses units of 10-5/m whereas de Nazelle and Moreno both use μg/m3. As such, the values should not be directly compared and are given here only for illustrative purposes.
[b] Arithmetic mean concentrations are provided here for illustrative purposes since they were the most commonly reported measures in the articles (geometric means and standard deviations are used in the analysis and can be found in Appendix C Tables). Where several campaigns (seasons, routes, cities) were presented in the study, the weighted arithmetic mean concentrations are shown.
[c] Zuurbier reports data on soot of which black carbon is the primary constituent, hence ratios calculated in subsequent analysis are broadly comparable despite the small difference in what was actually measured.
[d] Background is the average for the year 2014, not over the study and so no comparison to the background is made in subsequent analysis.

than cyclists for $PM_{2.5}$, 70% more for BC, 90% for CO, and suffer similar exposures for UFP. Again we find inconsistent results for cyclists compared to buses, with a variety of studies finding alternately higher and lower concentrations. As a result, the 95% CI for ratios between the bus and bicycles modes include 1 for all pollutants except for UFP, for which the 95% CI is (1.3–1.4).

In all but one study, background concentrations measured at fixed monitoring stations are consistently lower than in walking and cycling microenvironments (Fig. 3 and Tables C1–C4). However, in London (Kaur et al., 2005a) measured lower UFP concentrations for pedestrians than what was observed at the background station (64,861 vs. 82,819 particles/cm^3) (Fig. 3, and Appendix Tables C1–C20). Average active mode to background ratios range from 1.4 (UFP walk to background ratio) to 4.5 (CO bicycle to background ratio), with all lower bound 95% CI well above 1 (lowest being 1.4 for UFP walk to background ratio).

4. Discussion

A quantitative method was used to estimate ratios of concentrations between active and passive modes (walk, bicycle, bus, car) based on available evidence collected in European studies for the most commonly studied pollutants - $PM_{2.5}$, BC, UFP and CO. With the exception of BC bus exposures, we found pedestrians to be on average the least exposed of all. Car drivers were the most exposed across modes and pollutants, although the average car to bicycle ratio was 1 for UFP. Cyclists and bus users were roughly equivalent on average, with study findings alternating on which is more exposed. The greatest contrasts were found between cars and pedestrians, with BC, CO and UFP mean ratios of 2.9, 2.9 and 1.7, respectively. Transport microenvironments were shown to experience exposures from 40% to more than 4-fold higher than urban background sites.

4.1. Variations within- and across-studies

Synthesizing the literature on travel mode exposure contrasts is complex given the disparate study designs, settings and reporting methods. There is a relatively clear signal of a pedestrian advantage over other modes, although even there, some individual studies present 95% CI that include the equality factor (1) for at least one pollutant-mode contrast (de Nazelle et al., 2012; Gulliver and Briggs, 2004; Kaur et al., 2005a; McNabola et al., 2008b; Moreno et al., 2015), and two of five studies found lower bus exposures (Moreno et al., 2015; Ragettli et al., 2013). For cyclists compared to car and bus users, results diverge within and across individual studies (albeit higher exposures in cars on average for all pollutants). Most individual studies display 95% CIs which include the equality factor, and, exceptionally, Int Panis et al. (2010)'s Belgian study found lower exposures in cars than for cyclists in all 3 study campaigns reported. Reasons for such discrepancies may range from study design (sample number, day time, weather, seasons, type of sensor), to urban design and local vehicle fleet characteristics.

4.1.1. Urban design

Urban design, and in particular the amount of separation between cyclists or pedestrians and vehicle exhausts, may contribute to inconsistencies in the contrasts found across cities. For example while cyclists rode on separate cycle lanes in most of the routes sampled in Barcelona by de Nazelle et al. (2012), Kaur et al.'s (2005a) London cyclists shared a lane with buses, thus being more directly exposed to exhaust fumes and explaining the more uniform mode exposures between cyclists and other modes across pollutant found in this study. Other studies have confirmed how specific route choice might influence cyclists' exposures considerably. For example studies reviewed by Bigazzi and Figliozzi (2014) show that cyclists experience increased exposures in high vs. low traffic routes, with a median 26% increase for $PM_{2.5}$, 39% for BC, 47% for CO and 70% for UFP. A study assessing impacts of infrastructure on exposures found cycle lanes shared with buses led to BC exposures 33% higher than on paths separated from traffic, after controlling for traffic, background concentrations and intersections (MacNaughton et al., 2014). The presence of vegetation as a buffer between cyclists and vehicles also led to additional protection of cyclists (MacNaughton et al., 2014).

While pedestrians were shown to be consistently the least exposed in our analysis, it is noteworthy that street characteristics also affect their exposures, especially in street canyons. Kaur et al. (2005b) for example found significant differences depending on the side of the road for $PM_{2.5}$, and walking position (by the kerb or the buildings) for BC, UFP and $PM_{2.5}$. McNabola et al. (2008a) found close to a three-fold difference between two sides of a low-level wall separating two footpaths.

More generally, factors which affect exposures such as meteorology, traffic density, and time of day (Karanasiou et al., 2014), will also affect mode contrasts due to their effect on pollutant dispersion, explaining in part variations within and across studies.

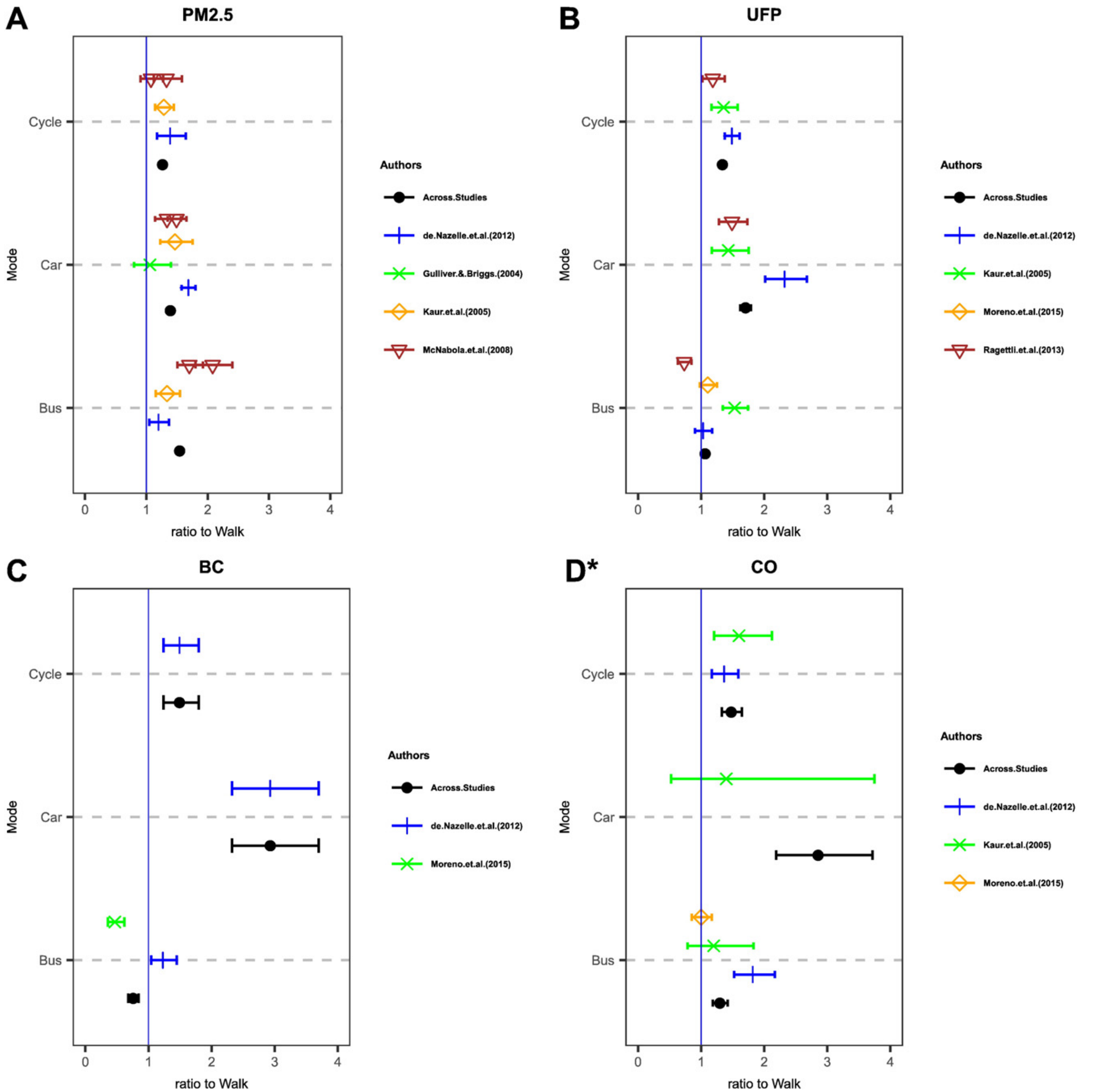

Fig. 1. Transport modes ratios of exposure to pollutant concentrations (fine particulate matter ($PM_{2.5}$), ultrafine particles (UFP), black carbon (BC) and carbon monoxide (CO)) and their 95.5% confidence intervals: bicycle, car, and bus modes vs. walk. Multiple marks along the same line indicate the different ratios for separate study campaigns reported within the article. *Note that for CO de Nazelle et al.'s car to walk ratio fell outside the range shown in this graph, see Table C1–4 for full results.

4.1.2. Fleet characteristics

The specificities of vehicles used in the mode comparison studies also influence results, in particular fuel use and ventilation settings (Karanasiou et al., 2014). This is especially apparent for bus users compared to cyclists and pedestrians, which displayed inconsistent results across studies. Electric buses in particular have the ability to eliminate self-pollution, otherwise contributing significantly to in-vehicle bus concentrations (Adar et al., 2008). Zuurbier et al. (2010)'s study, included in this meta-analysis, for example found $PM_{2.5}$, BC and UFP concentrations respectively 41%, 34% and 22%, higher in diesel buses compared to electric buses. A relatively modern bus fleet in Barcelona would also explain lower concentrations found there (de Nazelle et al., 2012) compared to Dublin (McNabola et al., 2008b), and explain the overall lower exposures in bus riders compared to pedestrians for BC, as the estimate was only based on Barcelona measurement studies (de Nazelle et al., 2012; Moreno et al., 2015). Open windows would explain the higher concentrations found in cars relative to other modes in de Nazelle et al.'s (2012) study in Barcelona compared to many other studies. Indeed, Hudda and Fruin (2013) determined that ventilation settings were the greatest determinant of indoor/outdoor ratios in vehicles, with as small as a 2 in. gap in the window preventing any protection from roadway concentrations

4.1.3. Instrument types

Choice of monitoring instrument can also affect measured exposure contrasts. For example, for UFP, the P-Trak (used in 2 of 7 studies, Table 2) only detects ultrafine particles greater than 20 nm diameter while instruments used in the other studies count particles as small as 10 nm.

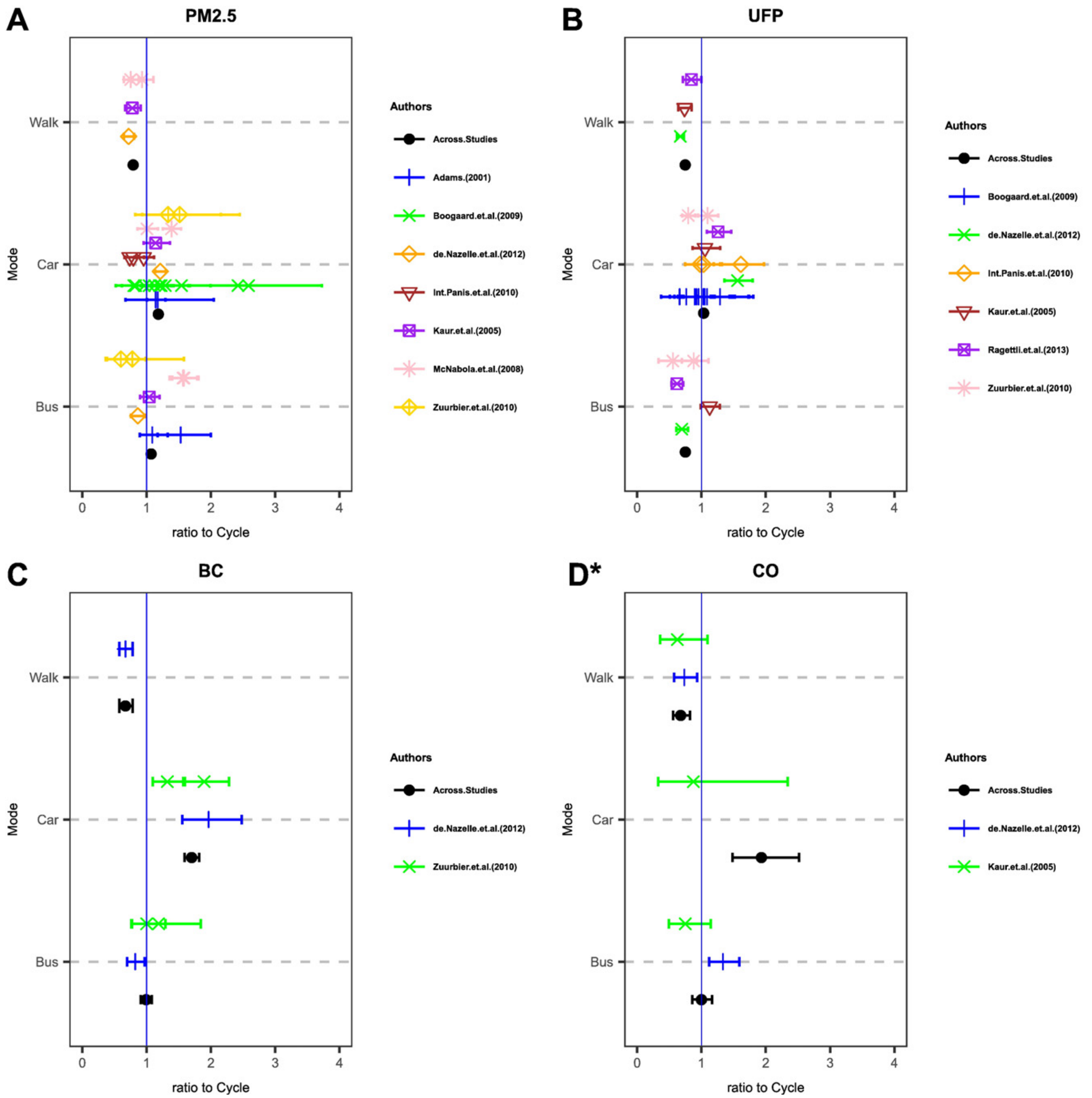

Fig. 2. Transport modes ratios of exposure to pollutant concentrations (fine particulate matter ($PM_{2.5}$), ultrafine particles (UFP), black carbon (BC) and carbon monoxide (CO)) and their 95.5% confidence intervals: walk, car, and bus modes vs. bicycle. Multiple marks along the same line indicate the different ratios for separate study campaigns reported within the article. *Note that for CO de Nazelle et al.'s car to bicycle ratio fell outside the range shown in this graph, see Table C1–4 for full results.

Fresh emissions from vehicular traffic can have a large fraction of particle number below 20 nm in close proximity to the emission source (Westerdahl et al., 2005), suggesting that using the P-Trak might lead to lower contrasts between measurements made close to the source and further away, as we observed in general.

For $PM_{2.5}$ measurements, light scattering devices (used in 5 of 8 studies) are known to be affected by factors such as particle composition and size and relative humidity, in contrast to the more stable gravimetric approach(Zhu et al., 2011). It is unclear, however, whether the contrasts in such factors between different travel microenvironments are sufficiently large to affect results.

The choice of instruments is perhaps even more problematic for contrasting exposures with background concentrations, given that all comparisons except Zuurbier et al.'s (2010) are based on different monitoring devices at fixed monitoring stations.

4.2. Study limitations

4.2.1. Route choice

Most studies that compare travel mode exposures measure concentrations on the same routes. Some will argue that in fact it is unrealistic to assume similar routes as cyclists and pedestrians have the ability to choose routes with less traffic, and thus reduce their exposures, as discussed in Section 4.1.1 (Bigazzi and Figliozzi, 2014; Knibbs et al., 2011). There is evidence, for example, that cyclists will deviate up to 10% from their most direct route if they can ride on a bicycle facility,

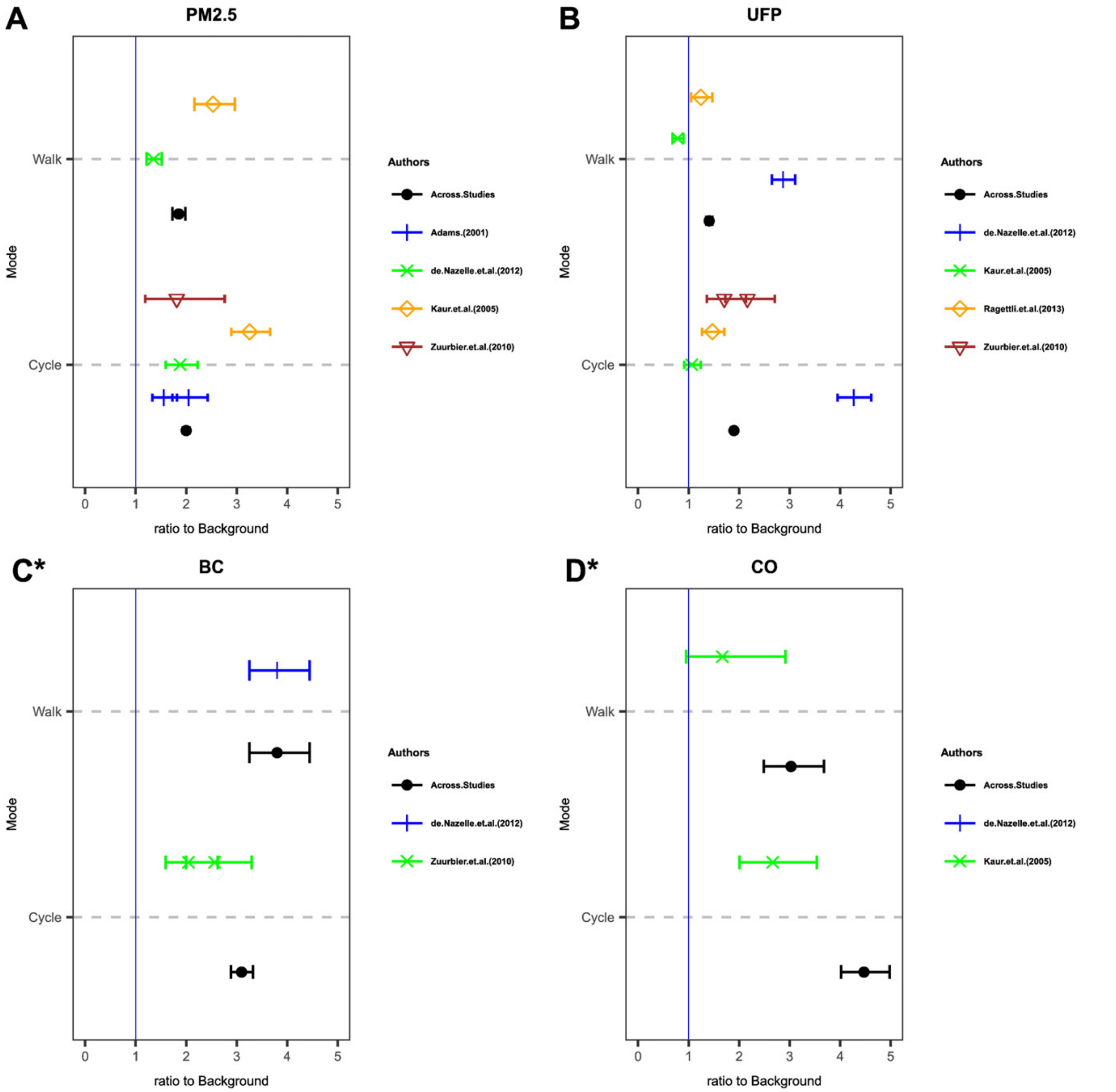

Fig. 3. Walk or bike vs. background ratios of exposure to pollutant concentrations (fine particulate matter ($PM_{2.5}$), ultrafine particles (UFP), black carbon (BC) and carbon monoxide (CO)) and their 95.5% confidence intervals. Multiple marks along the same line indicate the different ratios for separate study campaigns reported within the article. * Note that for BC and CO, some of de Nazelle et al.'s ratios fell outside the range shown in this graph, see Table C1–4 for full results.

for example (Broach et al., 2012). The same route comparison, however, is useful in terms of standardizing exposure studies and is relevant in many cities where indeed cyclists tend to travel on the same (usually "most direct") routes as other modes, and to inform policies that promote cycle lanes on major roads (e.g. typically in Barcelona or in the London "cycle super highways").

4.2.2. Inhalation rates

We only considered exposure contrasts in our analysis, however it is well known that active transport such as walking and cycling lead to higher pollutant intake, due to higher ventilation rates compared to sedentary modes such as driving and sitting in a bus. Bigazzi and Figliozzi (2014) for example estimated 3-folds greater intakes for cyclists compared to cars for $PM_{2.5}$, and 5-fold for UFP, per unit of time. Physical exertion will also affect particle deposition in the lungs (Daigle et al., 2003). We chose to provide ratios between modes, so readers may develop their own estimates of intake (Bigazzi and Figliozzi, 2014; de Nazelle and Rodríguez, 2009; de Nazelle et al., 2009).

4.2.3. Experimental designs

Another limitation is that we are constrained by the number of studies that have evaluated a specific contrast, and not all studies evaluate all the same contrasts. The numbers of studies for each combination affects the overall results. Our approach to keep individual campaigns within each study as separate entries in the analysis also may introduce a bias by giving more weight to studies with multiple campaigns (e.g. Boogaard et al., 2009). For example, for $PM_{2.5}$ car to bicycle ratios for $PM_{2.5}$ are bases on as many as 22 data points, and only 5 for car to walk ratios. Studies contrasting travel mode exposures to background concentrations were particularly scarce, with the walk mode ratios relying on 1 to 3 data point for the four pollutants, and bike mode ratios on 1 to 6 data points. CO and BC were only measured in only 3 studies, and most exposure contrasts for these pollutants were based on one or two data points (Tables Appendix C); hence results should be interpreted with caution especially for these pollutants. We provide, however, 95% confidence interval or the interquartile range of variability (25th and 75th percentiles), thus taking into account the variability of estimates found in the literature. Researchers who would like to apply these ratios to estimate exposures in a cohort study or for health impact assessment (HIA) applications can thus develop uncertainty or sensitivity analyses to reflect a variety of conditions likely present in their study area.

4.2.4. Other pollutants

We chose to focus on modes and pollutants that are most widely studied in active travel microenvironments. However pollutants such as NOx are increasingly shown to be health relevant (WHO, 2013), and subways and trains are common forms of urban transport with potentially high exposure levels (but large variations from city to city or within systems) (Karanasiou et al., 2014). Future measurement studies should therefore strive to incorporate such contrasts.

4.2.5. Global literature review

Finally, only European studies were chosen for this review, although examples exist from across the world (Knibbs et al., 2011). In Latin America for example, Suárez et al. (2014) explore personal exposure to PM in different transport modes in Chile, but most private cars in Santiago use petrol instead of diesel and public transport emission standards are not comparable to current EU standards. Similarly in China, Huang et al. (2012) carried out their research in petrol taxis and diesel buses with Euro III engines representing common practice in Beijing. As expected, both studies result in relatively high cycle/car ratios. In North America results are variable depending on the city where the measurements are taken. Jarjour et al. (2013) for example, show results for the City of Berkeley within the San Francisco Metropolitan Area, city where strong winds from the Pacific Ocean result in low background pollution. Their results show PM averages well below any of the ones included in this study. The impact of urban design and urban sprawl in air pollution exposure levels has also been subject of study (Schindler and Caruso, 2014). Given the heterogeneity not only in study designs but also in real-world conditions (urban designs, fuel use, engine types), it was deemed more reliable to provide results from only one continent.

5. Conclusion

Previous literature reviews on travel microenvironments have been limited to qualitative assessments; we provide for the first time a quantitative synthesis of exposure contrasts between walking, cycling, and other modes and background concentrations. While such synthesis is challenging given the disparity of study designs and urban settings, we provide central estimates with 95% confidence intervals for the corresponding distribution to give a range of likely exposure ratios in travel modes for $PM_{2.5}$, BC, CO and UFP. We recommend caution, however, in interpreting some of these contrasts based on only few data points, such as CO and BC for which there were only three studies available. To ensure better comparability across studies, future work must strive to follow a uniform protocol with simultaneous measurements in different travel modes, methods that account for temporal patterns and differences in instrumentation, and reporting of parameters of the logarithmic distributions.

Results reported in this paper can be useful for exposure analyses and may inform planners and decision makers on urban policies. Of particular interest to the health and planning communities, these ratios can feed into health impact assessments of active travel policies such as the WHO Health Economic Assessment Tool (HEAT) for walking and cycling (Kahlmeier et al., 2011). While travel contributes substantially to overall pollutant intake and can lead to detrimental health impact, studies to date have revealed clear net health benefits from active travel due to increased physical activity despite increased pollutant intake in most areas of the world (Mueller et al., 2015; Tainio et al., 2016). This has also been supported at the individual level by recent epidemiologic analysis, although more work is needed in this area to disentangle effects of physical activity and air pollution inhalations (Andersen et al., 2015; Jarjour et al., 2013; Kubesch et al., 2015a; Kubesch et al., 2015b). Policy makers need to recognize the issue of travel-related exposures and help address air pollution while promoting active travel to yield substantial health benefits in the population.

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Appendix A–C. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2016.12.023.

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