Levels of ambient air pollution according to mode of transport: a systematic review

Magda Cepeda, Josje Schoufour, Rosanne Freak-Poli, Chantal M Koolhaas, Klodian Dhana, Wichor M Bramer, Oscar H Franco

Summary

Background Controversy exists about the differences in air pollution exposure and inhalation dose between mode of transport. We aimed to review air pollution exposure and inhaled dose according to mode of transport and pollutant and their effect in terms of years of life expectancy (YLE).

Methods In this systematic review, we searched ten online databases from inception to April 13, 2016, without language or temporal restrictions, for cohort, cross-sectional, and experimental studies that compared exposure to carbon monoxide, black carbon, nitrogen dioxide, and fine and coarse particles in active commuters (pedestrian or cyclist) and commuters using motorised transport (car, motorcycle, bus, or massive motorised transport [MMT—ie, train, subway, or metro]). We excluded studies that measured air pollution exposure exclusively with biomarkers or on the basis of simulated data, reviews, comments, consensuses, editorials, guidelines, in-vitro studies, meta-analyses, ecological studies, and protocols. We extracted average exposure and commuting time per mode of transport and pollutant to calculate inhaled doses. We calculated exposure and inhaled dose ratios using active commuters as the reference and summarised them with medians and IQRs. We also calculated differences in YLE due to fine particle inhaled dose and physical activity.

Findings We identified 4037 studies, of which 39 were included in the systematic review. Overall, car commuters had higher exposure to all pollutants than did active commuters in 30 (71%) of 42 comparisons (median ratio 1·22 [IQR 0·90–1·76]), followed by those who commuted by bus in 57 (52%) of 109 (1·0 [0·79–1·41]), by motorcycle in 16 (50%) of 32 (0·99 [0·86–1·38]), by a car with controlled ventilation settings in 39 (45%) of 86 (0·95 [0·66–1·54]), and by MMT in 21 (38%) of 55 (0·67 [0·49–1·13]). Overall, active commuters had higher inhalation doses than did commuters using motorised transport (median ratio car with controlled ventilation settings 0·16 [0·10–0·28]; car 0·22 [0·15–0·30]; motorcycle 0·38 [0·26–0·78]; MMT 0·49 [0·34–0·81]; bus 0·72 [IQR 0·50–0·99]). Commuters using motorised transport lost up to 1 year in YLE more than did cyclists.

Interpretation Proximity to traffic and high air interchange increased the exposure to air pollution of commuters using motorised transport. Larger inhalation rates and commuting time increased inhaled dose among active commuters. Benefits of active commuting from physical activity are larger than the risk from an increased inhaled dose of fine particles.

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Department of Epidemiology (M Cepeda MSc, J Schoufour PhD, R Freak-Poli PhD, C M Koolhaas MSc, K Dhana PhD, Prof O H Franco PhD), **and Medical Library** (W M Bramer), **Erasmus Medical Center, University Medical Center, Rotterdam, Netherlands; and Department of Epidemiology and Preventive Medicine, Monash University, Melbourne, VIC, Australia** (R Freak-Poli)

Correspondence to: Magda Cepeda, Department of Epidemiology, Erasmus Medical Center, University Medical Center, 3000 CA Rotterdam, Netherlands **m.cepedagil@erasmusmc.nl**

Introduction

Worldwide, air pollution exposure is a public health issue associated with various health effects, including cardiovascular and respiratory disease, cancer, pregnancy complications, and adverse birth outcomes.[1] Air pollution exposure can be considered a function of the concentration of pollutants in a microenvironment and the time spent by individuals in that microenvironment.[2] Traffic emissions contribute the major part of air pollution in traffic-related microenvironments.[3] Commuters are exposed to high levels of pollutants,[4] which often do not meet air quality standards.

Findings from two previous systematic reviews[5,6] suggested that commuters using motorised transport (ie, private or public car, train, metro, tram, bus, or subway) have a higher exposure to air pollution than do active commuters (ie, pedestrian or cyclist). However, if the higher breathing parameters and trip time of an active commute than of a motorised commute are considered, inhaled and deposited doses of pollutants become higher among cyclists and pedestrians than among commuters using motorised transport.[7–10] Authors of a systematic review[11] of health impact assessment studies concluded that consensus exists that despite the increased health risks associated with the higher inhaled dose of traffic-related pollutants among active commuters than among commuters using motorised transport, the benefits of physical activity from active commuting remain larger. Nevertheless, to our knowledge, no previous review of a modal comparison of air pollution exposure has systematically addressed the differences in inhaled dose of pollutant

Research in context

Evidence before this study

We did a systematic review of reviews published before June 18, 2014, without language or temporal restrictions. We used combinations of keywords related to "mode of transport" and "air pollution". We searched in Embase, MEDLINE, the Cochrane Library, Web of science, Scopus, and PubMed. We found 1887 references, among which we found three reviews. A non-systematic review published in 2007 addressed the evidence for the determinants of exposure to carbon monoxide and fine particles according to mode of transport. Additionally, a systematic review published in 2014 included only studies done in Europe of exposure in four modes of transport: car, bicycle, bus, and subway. On the basis of these two reviews, car, bus, and subway commuters have higher exposure than do cyclists and pedestrians to particulate matter, carbon monoxide, and black carbon. However, these reviews did not address the effect on the inhalation dose of the increased respiratory parameters among active commuters. Another non-systematic review published in 2010 assessed if the benefits of the modal shift from motorised to bicycle commuting outweigh the associated risks. Despite cyclists having increased inhaled doses of pollutants and a high risk of traffic injuries, these risks were found to be outweighed by the benefits of increased physical activity, by contrast with commuters using motorised transport. These findings were consistently supported by a systematic review published in 2016 that included studies that addressed the balance of the health risks and benefits of active commuting through health impact assessment.

Added value of this study

Through a rigorous and comprehensive systematic review, we have addressed the evidence that compared air pollution exposure according to mode of transport. We provide estimations of the differences in exposure, but also in inhaled dose, which was not systematically addressed in previous reviews. We also calculated the potential trade-off in years of life expectancy (YLE) using fine particle exposure levels purposely measured to compare between mode of transport at specific study settings. We compared the effect on YLE of inhaled dose of pollutants, by contrast with physical activity levels, per mode of transport. We have addressed heterogeneity between studies by calculating ratios of exposure and inhaled dose within each study. Also, heterogeneity in YLE effect estimates was reduced by use of standard assumptions to calculate inhaled pollutant doses and levels of physical activity. Our study addresses transport microenvironments that were not consistently addressed in previous evidence, like motorcyclists and pedestrians. We also account for heterogeneous settings by including Asian and West Pacific cities

Implications of all the available evidence

The trade-off in health outcomes according to mode of transport depends largely on local context attributes. However, consensus exists that despite the harmful effects of air pollution exposure, physical activity from active commuting provides more gains in health outcomes than air pollution exposure provides losses. More research is required to account for other long-term and short-term risk factors associated with traffic. To stimulate a shift from motorised to active and public transport, policies should address traffic-related pollution of commuters' microenvironments. Large societal benefits can be obtained from environments that increase active and public transport commuting.

per mode of transport or the differential effect on years of life expectancy (YLE).

See Online for appendix

Therefore, we aimed to systematically review studies that compared air pollution exposure by mode of transport to examine differences in inhaled dose according to mode of transport and pollutant. Furthermore, we estimated the trade-off in YLE while taking into account the inhaled dose of fine particles and physical activity levels according to transportation.

Methods

Search strategy and selection criteria

In this systematic review, we searched ten databases (Embase, MEDLINE, Cinahl, the Cochrane Library, Web of Science, Scopus, PubMed, Google Scholar, ProQuest, and Scielo) in cooperation with a medical information specialist (WMB) to identify relevant studies that compared air pollution exposure between mode of transport among adult commuters from inception to April 13, 2016, with no language or temporal restrictions. We combined terms related to air pollution (eg, "air pollution") or specific air pollutants (eg, "PM_{10}", "$PM_{2\cdot5}$", or "CO") with terms related to mode of transport (eg, "traffic", "subway", "car", "bicycle", or "walk"). Full search strategies are provided in the appendix.

We included all studies (cohort, cross-sectional, and experimental) that measured personal air pollution exposure while commuting by at least one active and one motorised mode of transport. We excluded studies that measured air pollution exposure exclusively with biomarkers or on the basis of simulated data, reviews, comments, consensuses, editorials, guide-lines, in-vitro studies, meta-analyses, ecological studies, and protocols. We selected data only for carbon monoxide (CO), black carbon (BC), nitrogen dioxide (NO_2), fine (particulate matter of <2·5 μm) and coarse (particulate matter of 2·5–10 μm) particles, and six modes of transport: walking, cycling, bus, massive motorised transport (MMT—ie, subway, metro, and train), car (private or public), and motorcycle (motorcycle, scooter, and auto rickshaw). We stratified cars into two categories: cars that had controlled ventilation settings (windows closed, air conditioning on or off, or air recirculation modes on or off) and those without controlled ventilation settings.

Working in pairs, three authors (MC, CMK, and KD) reviewed titles and abstracts of the entire list of studies identified by the search to select those that fulfilled the selection criteria. After initial appraisal, we retrieved full texts of selected titles. Full texts were appraised independently by two authors (MC and RF-P) to select those that fulfilled the selection criteria. Disagreements were solved through discussion and with consultation with a third independent author (OHF). We reviewed reference lists of the retrieved articles and previous systematic reviews for additional publications. We contacted experts in the field to identify additional references that should be considered. Selection criteria and study selection procedures, data extraction, and quality assessment are described in detail in the appendix. The study protocol is available online.

Data analysis

We registered extracted data from each article in a purposely designed form, including for study design, measurement period, mode of transport, monitoring device, commuting time, and number of measurements. We extracted summary and dispersion measurements of exposure according to mode of transport and pollutant. If available, we extracted summary measurements stratified by season, day, period of monitoring, type of route, and city. If more than one summary measurement was reported for the same stratum, we preferably extracted arithmetic means, then geometric means, and, finally, medians. We extracted summary measurements of inhalation and uptake dose (per h or trip), the model, and the parameters used for the estimation. We used the most complete report when multiple papers of the same study were available. We addressed quality of the studies in terms of the comparability of the exposure measured between mode of transport (ie, time and route standards), external validity (ie, background and meteorological conditions and commuting standards), measurement standardisation, and data reporting. We used a modified version of the Newcastle-Ottawa Scale for assessing the quality of observational studies (appendix).

To uniformly summarise the exposure data extracted, we standardised the units of concentrations by applying standard conversion factors.[12] We calculated the median and IQR of averages of exposure concentration per mode of transport and pollutant and the percentage of exposure averages above the European Union ambient air quality standards[13] (except for BC because no standard has been defined). Within each study, we calculated the exposure ratio according to mode of transport using cyclists' exposure as the reference. We summarised exposure ratios as medians and IQRs per mode of transport and pollutant and calculated the percentages of ratios above 1. Also, we meta-analysed exposure ratios using random-effects models.[14] We assessed heterogeneity with I^2.[15] We assessed variability within studies by estimating the SE from the variance for ratios of the mean.[14] We visually inspected publication bias with funnel plots and used Egger's tests to assess asymmetry. All tests were two-tailed and we considered p values of 0·05 or less significant. For 13 studies that did not include cyclists, we used pedestrians' exposure as the reference (reported separately to the studies that included cyclists). For two additional studies, we used pedestrians' exposure as the reference because for some comparisons in these studies only comparisons with pedestrians were possible.

We calculated inhaled doses of pollutants (inhaled amount per trip) as the average exposure concentration (reported by authors) multiplied by minute ventilation (m^3/h) multiplied by trip time (min; reported by authors) multiplied by a conversion factor, if applicable. We used minute ventilation as suggested by the US Environmental Protection Agency[16] for each mode of

For the **study protocol** see http://www.erasmusage.com/wp-content/uploads/2016/10/Protocol_SR.pdf

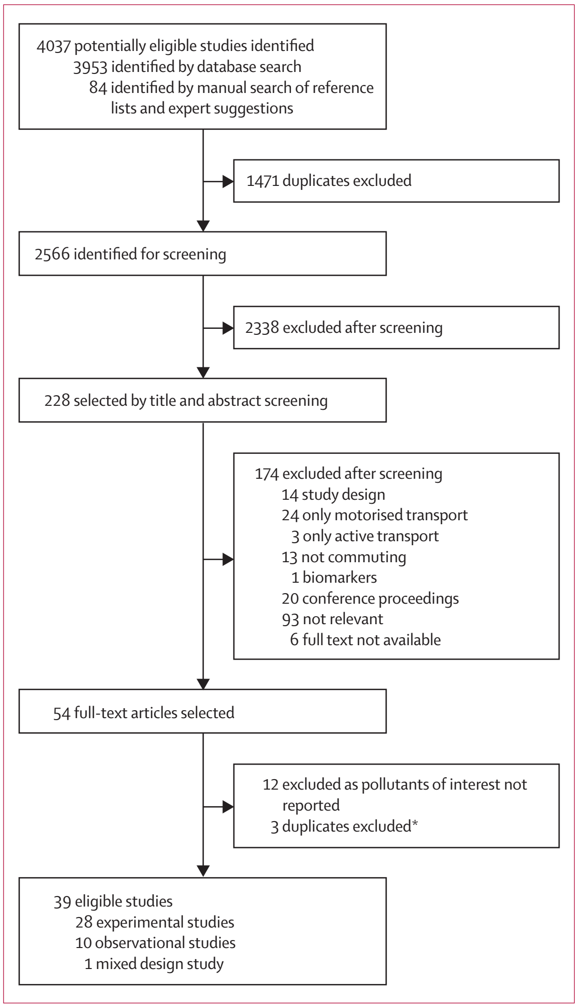

Figure 1: **Study selection**
*We included these three duplicate studies in the table of study characteristics.

	Pollutants	Method of measurement	Mode of transport		Monitoring period	Location
			Active	Motorised		
Adams et al (2001)[18]; Adams et al (2002)[19]*	$PM_{2·5}$	Gravimetric analysis	Cyclist	Car, bus, and MMT	3 week measurements in July, 1999, and February, 2000	London, UK
Boogaard et al (2009)[20]	$PM_{2·5}$	Light scattering	Cyclist	Car	11 days (except Fridays) between late August and October, 2006	Apeldoorn, Delft, Den Bosch, Eindhoven, Groningen, Haarlem, Maastricht, Nijmegen, The Hague, Utrecht, and Zwolle (Netherlands)
Brauer et al (1999)[21]	Particle concentration (≥1 to <5 μg; ≥5 μg)	Light scattering	Cyclist and pedestrian	Car, bus and seabus, and MMT	May to October, 1999	Vancouver, Canada
Briggs et al (2008)[22]	$PM_{≥1 \text{ to } <2·5}$; $PM_{≥2·5 \text{ to } <10}$	Light scattering	Pedestrian	Car	7 weekdays during May and June, 2005	London, UK
Chertok et al (2004)[23]	NO_2	NS	Cyclist and pedestrian	Car, bus, and MMT	13–27 Sept, 2002	Sydney, Australia
Bruinen de Bruin et al (2004)[24]	CO	Electrochemical sensor	Pedestrian	Car, MMT, and motorcycle	1997–98 (1 year period)	Milan, Italy
de Nazelle et al (2012)[25]	$PM_{2·5}$; CO; BC	$PM_{2·5}$: light scattering and gravimetric analysis; CO: electrochemical monitor; BC: optical sensor (aethalometer)	Cyclist and pedestrian	Car and bus	4 weeks beginning May 28, 2009	Barcelona, Spain
Dirks et al (2012)[26]	CO	Electrochemical monitor	Cyclist and pedestrian	Car, bus, MMT, and motorcycle	Nov 8–Dec 17, 2010	Auckland, New Zealand
Dons et al (2011)[27]*; Dons et al (2012)[28]	BC	Aethalometer	Cyclist and pedestrian	Car (driver and passenger), MMT (train, light rail, and metro), and bus	16 participants only during summer of 2010; 8 of them plus 38 new volunteers were measured during winter 2010–11	Mol, Belgium
Dor et al (1995)[29]	CO	Electrochemical monitor	Pedestrian	Car and MMT	October, 1991, to September, 1992	Paris, France
Duci et al (2003)[30]	CO	Electrochemical monitor	Pedestrian	Car, bus, and MMT (rail)	Summer of 1998 and November, 1998, to February, 1999	Athens, Greece
Farrar et al (2001)[31]	NO_2	Adsorbance (spectrophotometer)	Cyclist	Car and bus	August to September, 2000	Perth, Australia
Gee and Raper (1999)[32]	$PM_{4·0}$	Gravimetric analysis	Cyclist	Bus	NS	Manchester, UK
Georgoulis et al (2002)[33]	CO	Electrochemical monitor	Cyclist and pedestrian	Car, MMT, and motorcycle	February, 1997, to January, 1998; February, 1997, to March, 1998; June, 1997, to June, 1998; March, 1997, to January, 1998; October, 1996, to December, 1997	Basel, Switzerland; Athens, Greece; Prague, Czech Republic; Milan, Italy; Helsinki, Finland
Goel et al (2015)[34]	$PM_{2·5}$	Light scattering	Cyclist and pedestrian	Car (open and closed windows), bus (open and closed windows), MMT, auto rickshaw, and motorised two-wheeler	41 days between January and May, 2014	Delhi, India
Gulliver and Briggs (2004)[35]	PM_{10}; $PM_{2·5}$	Light scattering	Pedestrian	Car	Pilot: July, 1999; Route 1: November, 1999, to March, 2000; Route 2: April 2000	Northampton, UK
Gulliver and Briggs (2007)[36]	$PM_{1–2·5}$; $PM_{2·5–10}$; PM_{10} to TSP	Light scattering	Pedestrian	Car	10 different days between January and March, 2005	Leicester, UK
Huang et al (2012)[37]	$PM_{2·5}$; CO	$PM_{2·5}$: spectrometer and gravimetric analysis; CO: electrochemical sensor	Cyclist	Car and bus	December, 2010, and February, 2011	Beijing, China
Int Panis et al (2010)[7]	PM_{10}; $PM_{2·5}$	Light scattering	Cyclist	Car	8 days in June, 2009	Brussels, Louvain-la-Neuve, and Mol (Belgium)
Kaur et al (2005)[38]; Kaur and Nieuwenhuijsen (2009)[39]*	$PM_{2·5}$; CO	$PM_{2·5}$: gravimetric analysis; CO: electrochemical monitor	Cyclist and pedestrian	Car and bus	4 week field campaign from April 28 to May 23, 2003	London, UK

(Table continues on next page)

	Pollutants	Method of measurement	Mode of transport		Monitoring period	Location
			Active	Motorised		
(Continued from previous page)						
Kingham et al (2013)[40]	PM_{10}; $PM_{2·5}$; CO	PM_{10} and $PM_{2·5}$: spectrometer; CO: electrochemical monitor	Cyclist	Car and bus	Weekdays between Feb 26 and March 26, 2009	Christchurch, New Zealand
Li et al (2015)[41]	BC	Optical sensor (aethalometer)	Cyclist and pedestrian	Car, bus, and MMT	6 non-rainy working days during August, 2014	Shangai, China
Liu et al (2015)[42]	PM_{10}; $PM_{2·5}$	Light scattering	Pedestrian	Car, bus, and MMT	January to March between 2012 and 2014	Taipei, Taiwan
McNabola et al (2008)[8]	$PM_{2·5}$	Gravimetric analysis	Cyclist and pedestrian	Car and bus	January, 2005, to June, 2006	Dublin, Ireland
Morabia et al (2009)[43]	$PM_{2·5}$	Light scattering	Pedestrian	Car and MMT	October, 2007, to February, 2008	New York, USA
Moreno et al (2015)[44]	BC; $PM_{2·5}$; CO	BC: optical sensor (aethalometer); $PM_{2·5}$: gravimetric analysis and light scattering; CO: electrochemical monitor	Pedestrian	MMT (subway) and bus	39 weekdays between October and November, 2014	Barcelona, Spain
Nyhan et al (2014)[9]	PM_{10}; $PM_{2·5}$	Light scattering	Cyclist and pedestrian	Bus and MMT	NS	Dublin, Ireland
Onat and Stakeeva (2013)[45]	$PM_{2·5}$	Light scattering	Pedestrian	Bus, MMT, car (A/C on or off), and metrobus	Oct 8 and Nov 16, 2008	Istambul, Turkey
Ramos et al (2016)[46]	PM_{10}; PM_{4}; $PM_{2·5}$; PM_{1}; CO	PM: light scattering; CO: electrochemical monitor	Cyclist	Car, bus, MMT, and motorcyclist	15 non-rainy days during December, 2013, to March, 2014	Lisbon, Portugal
Rank et al (2001)[47]	Particles	Gravimetric analysis	Cyclist	Car	June 18 and Aug 3, 1998	Copenhagen, Denmark
Saksena et al (2008)[48]	PM_{10}; CO	PM_{10}: nephelometer (light scattering); CO: electrochemical monitor	Pedestrian	Car, bus, and motorcyclist (Mobi bike)	October, 2006	Hanoi, Vietnam
Suárez et al (2014)[49]	$PM_{2·5}$	Light scattering	Cyclist	Car, bus, and MMT	Winter to spring, 2011, and summer to autumn, 2012	Santiago de Chile, Chile
van Wijnen et al (1995)[10]	CO; NO_2	CO: gas chromatography; NO_2: adsorbance (spectrophotometer)	Cyclist and pedestrian	Car	January, May, and August, 1990	Amsterdam, Netherlands
Vellopolou and Ashmore (1998)[50]	CO	Electrochemical sensor	Pedestrian	Car, bus, and motorcyclist	5 month period beginning December, 1992	Athens, Greece
Vouitsis et al (2014)[51]	PM_{10}; $PM_{2·5}$; BC	PM: light scattering; BC: optical sensor (aethalometer)	Cyclist	Bus and car (windows open and closed)	April, 2011	Thessaloniki, Greece
Williams and Knibbs (2016)[52]	BC	Aethalometer	Cyclist and pedestrian	Car (windows open and closed), bus, and MMT	April, 2016, to October, 2016	Brisbane and Eden, Australia
Wu et al (2013)[53]	$PM_{2·5}$	Light scattering	Cyclist and pedestrian	Car, bus, MMT, and motorcylist	March 5–10, 2011, March 28–April 3, 2011, and July 5–11, 2011	Foshan, China
Yan et al (2015)[54]	$PM_{2·5}$	Light scattering	Pedestrian	Bus and MMT (A/C on and off)	Dec 10–23, 2011	Beijing, China
Zuurbier et al (2010)[55]	PM_{10}; $PM_{2·5}$	PM_{10}: gravimetric analysis; $PM_{2·5}$: light scattering	Cyclist (low-traffic and high-traffic route)	Bus, MMT (diesel and electric), and car (diesel and petrol)	June, 2007, to June, 2008	Arnhem, Netherlands

PM=particulate matter. MMT=massive motorised transport. NO_2=nitrogen dioxide. NS=not specified. CO=carbon monoxide. BC=black carbon. TSP=total suspended particles. A/C=air conditioning. *Duplicate studies used to extract study characteristics but excluded from systematic review.

Table: **General characteristics of the studies**

transport (appendix). Then, we calculated the inhalation dose ratio between mode of transport using the inhaled dose of cyclists (or pedestrians, accordingly) as the reference. We summarised ratios as medians and IQRs.

Finally, we estimated the trade-off in YLE due to fine particle inhaled dose and physical activity, according to mode of transport. We used fine particles because it has the most consistent evidence for all-cause mortality risk.[17] We calculated the loss or gain of YLE due to fine particle inhaled dose and physical activity levels for a person commuting by a given mode of transport. We based calculations on fine particle exposure and a set of assumptions regarding weekly levels of physical activity per mode of transport (appendix). We built the assumptions for a given scenario where one hypothetical person spends 7 days in four microenvironments: at work, at home, sleeping, and commuting by one of the modes of transport over a 7 km route twice a day. We did a sensitivity analysis

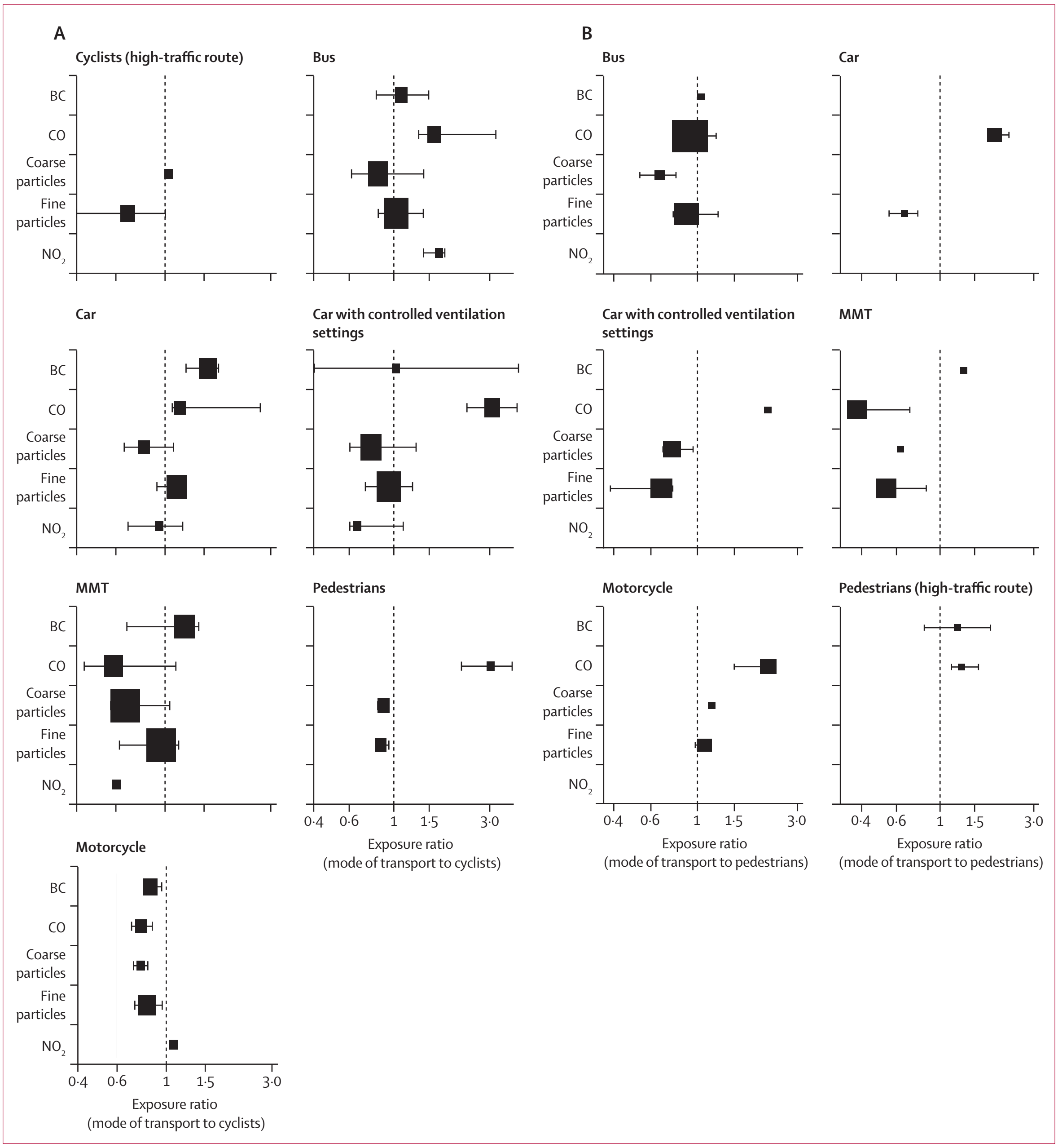

Figure 2: **Distribution of ratio of pollutant exposure level among different modes of transport to (A) cyclists' or (B) pedestrians' exposure**
The squares size is weighted according to the number of comparisons used to calculate the median. The exact medians and IQRs are provided in the appendix. BC=black carbon. CO=carbon monoxide. MMT=massive motorised transport.

for the person commuting over a 3·5 km route. We calculated the net gains or losses by comparing each mode of transport to a reference scenario (cyclists or pedestrians, accordingly) and summarising them as medians and IQRs. A detailed description of the procedures is provided in the appendix. We did all analyses in Stata (version 14.0).

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

After screening 4037 potentially relevant studies, we retrieved and assessed 228 full texts, of which 54 fulfilled the initial selection criteria and 39 reported on exposure to the pollutants of interests and were included in the systematic review (figure 1, table; we excluded three duplicate studies from the systematic review but included them in the table of study characteristics). The studies were done in European (n=24), west Pacific (n=11), American (n=3), and southeast Asian (n=1) countries. Further characteristics are provided in the appendix.

Irrespective of pollutant, car commuters had higher air pollution exposure than did active commuters in 30 (71%) of 42 comparisons (median 1·22 [IQR 0·90–1·76]), followed by those who commuted by bus in 57 (52%) of 109 (1·0 [0·79–1·41]), by motorcycle in 16 (50%) of 32 (0·99 [0·86–1·38]), by a car with controlled ventilation settings in 39 (45%) of 86 (0·95 [0·66–1·54]), and by MMT in 21 (38%) of 55 (0·67 [0·49–1·13]). We observed differences in exposure ratio per mode of transport and pollutant (figure 2). We obtained similar estimations by meta-analysing the exposure ratios, but we identified a large heterogeneity (higher than 90% in most comparisons; appendix). We did not find evidence of publication bias (appendix).

Inhalation or uptake pollutant dose was available in 12 of the studies included in the systematic review (appendix). Cyclists followed by pedestrians had the highest uptake dose of pollutants. Minute ventilation as a breathing parameter was heterogeneous across studies. Five studies[7,9,10,25,55] used surrogates of activity intensity to derive minute ventilation, whereas the remaining studies[8,26,28,37,41,46,51] used published parameters. In Figure 3, we compare the distribution of exposure and inhaled dose ratios on the basis of our calculation of inhalation dose. For all motorised modes of transport, the median of the inhaled dose ratio was lower than the exposure ratio. Active commuters had a higher inhalation dose of pollutants than did commuters who used motorised transport (median ratio car with controlled ventilation settings 0·16 [IQR 0·10–0·28]; car 0·22 [0·15–0·30]; motorcycle 0·38 [0·26–0·78]); MMT 0·49 [0·34–0·81]; bus 0·72 [0·50–0·99]) due to increased respiratory parameters. A ratio of inhaled dose lower than the ratio of exposure, with respect to the y axis, suggests that the relative inhaled dose of pollutant among cyclists, in the denominator, is higher than their relative exposure. We observed small differences between exposure and inhaled dose ratios for the comparison of pedestrians with cyclists.

Figure 4 shows the difference in YLE due to fine particle exposure and physical activity per mode of transport. Median losses in YLE were up to 1 year larger among commuters using motorised transport than among cyclists because of less physical activity, despite the lower inhaled dose of fine particles (appendix). Losses were larger among people commuting by car, by a car with controlled ventilation settings, and by motorcycle than among bus and MMT commuters because of the active stages attributed to public transport commuters. Losses of commuters using motorised transport compared with pedestrians were larger than of those using motorised transport compared with cyclists because of the longer commuting time of pedestrians than of cyclists. In a sensitivity analysis, we tested varying commuting times and consistently observed YLE gains in favour of active transport (appendix), as the difference between life-years lost due to fine particle exposure and life-years gained due to physical activity remained roughly the same for a 3·5 km route as for a 7 km route with the relative risk of physical activity of 0·80[56] (age 20–30 years: median –1·50 years [IQR –1·69 to –1·08]; age 40–64 years: –1·26 [–1·44 to –0·77]; age ≥65 years: –0·59 [–0·82 to –0·26]).

Regarding quality of studies, comparability of exposure between mode of transport was high (at least three stars according to the Newcastle-Ottawa Scale) in 16 experimental studies (appendix). We noted a very low comparability in 13 experimental studies (two or fewer stars). Ten studies were observational, which aimed to measure rather than compare exposure between mode of transport. Irrespective of pollutant, exposure levels to CO, NO_2, and fine and coarse particles were above ambient air quality standards[13] among cyclists in 50 (56%) of 89 exposure averages, among pedestrians in 22 (46%) of 48, among those who commuted by car in 22 (55%) of 40, among those who commuted by a car with controlled ventilation settings in 45 (52%) of 87, among those who commuted by MMT in 25 (48%) of 52, and among those who commuted by motorcycle in 24 (65%) of 37. The distribution of pollutant exposure level per mode of transport is shown in the appendix. Fine particles were more frequently above ambient air quality standards than were the other pollutants (155 [83%]) of 187 exposure averages). Detailed information about ascertainment of air pollution exposure was provided in 33 (85%) studies. Sample size or dispersion measurements were not reported in four (10%) studies. Complete reporting of background and meteorological conditions was found in 21 (54%) studies. Standardisation of all modes of transport measured and reporting of it was found in 20 (51%) studies.

Discussion

Car and bus commuters had the highest levels of air pollution exposure, followed by those commuting by a car with controlled ventilation settings, cyclists, and pedestrians, whereas the lowest was experienced by MMT commuters and motorcylists. Cyclists, followed by pedestrians, had the highest inhalation and uptake dose of pollutants because of increased minute ventilation and trip time. Compared with people commuting by car, by a car with controlled ventilation settings, and by motorcycle, the negative effect on YLE of increased inhaled dose did not overcome the positive effect of physical activity when commuting actively. Commuter exposure can be reduced by increasing the distance from traffic emissions, reducing air exchange with use of ventilation settings in motorised mode of transport, and choice of routes with

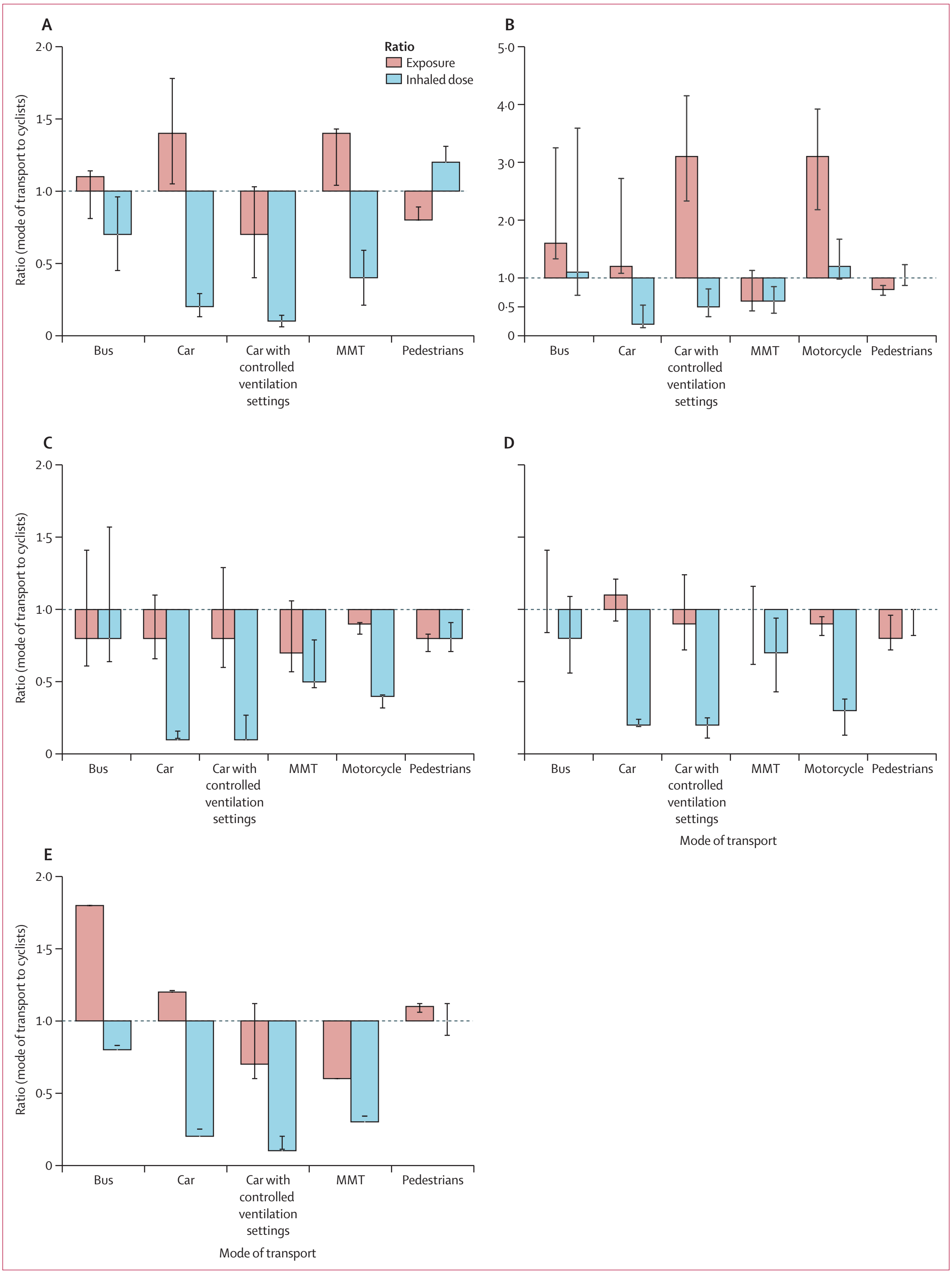

Figure 3: **Comparison of ratio of exposure to pollutants with ratio of inhaled dose of pollutants according to mode of transport and pollutant to that of cyclists**
(A) Black carbon. (B) Carbon monoxide. (C) Coarse particles. (D) Fine particles. (E) NO_2. MMT=massive motorised transport.

low emissions and high dispersion of pollutants (eg, parks), as well as efforts to reduce local and regional emissions. We observed a large heterogeneity across the evidence. Further research should consider inhaled and uptake dose while commuting to address air pollution effects on health.

In agreement with previous systematic reviews,[5,6] the differences in air pollution exposure between mode of transport in this study can be explained mainly by the position of the commuter with respect to the gradient of pollutant concentration[8,18,20,25,28,38,41,49] and the commuter's microenvironment sensitivity to surrounding pollutant concentration. The gradient of pollutant concentration depends on the rate of emissions and the dispersion and decay of pollutants in the air,[1,57] which is influenced, among others, by meteorological[58,59] and route[25,39,41] attributes. The close contact of commuters using motorised transport to the traffic line explains their higher levels of air pollution exposure than those for active commuters.[5,6,46] Indeed, bus commuters and cyclists have lower exposure when they travel via separated bus lanes or cycle routes or travel close to kerb than when they do not.[2,5,25,38,46] Also, pedestrians, who usually travel on the pavement, have a lower exposure than do cyclists.[6,38] We observed the lowest exposure among MMT commuters, except for exposure to BC, most probably because they often travel on railways or through tunnels separated from ground traffic.[26] The main sources of exposure for MMT commuters involve walking stages, when approaching the stations,[49] and while waiting inside the stations.[5,41,53] Commuters using ground motorised transport (ie, car and bus) on overcongested routes with high emission levels had high pollutant exposure because of high emissions, long trip time, and frequent idling.[5,6,37] Additionally, canyon-like street configuration reduces the dispersive and catalytic action of environmental and meteorological factors, thus trapping the pollutants.[8,31,41]

Commuters' microenvironment sensitivity to surrounding pollutants depends on the rate of air interchange of the microenvironment. Active commuters, and commuters using motorised transport with open windows, have a high rate of air interchange, increasing their exposure to high pollutant concentrations[41,36,53] and pollutant hotspots like intersections and traffic lights.[26,36,41,45,54,59] This leads to a pattern of concentration peaks in active commuters' exposure, whereas commuters using motorised transport have a constant concentration exposure. Physical barriers like controlled ventilation settings in cars help to extract and filter fine and coarse particles from the vehicle microenvironment.[22,36,48,53] Moreover, physical barriers make a large difference in highly contaminated environments,[37]

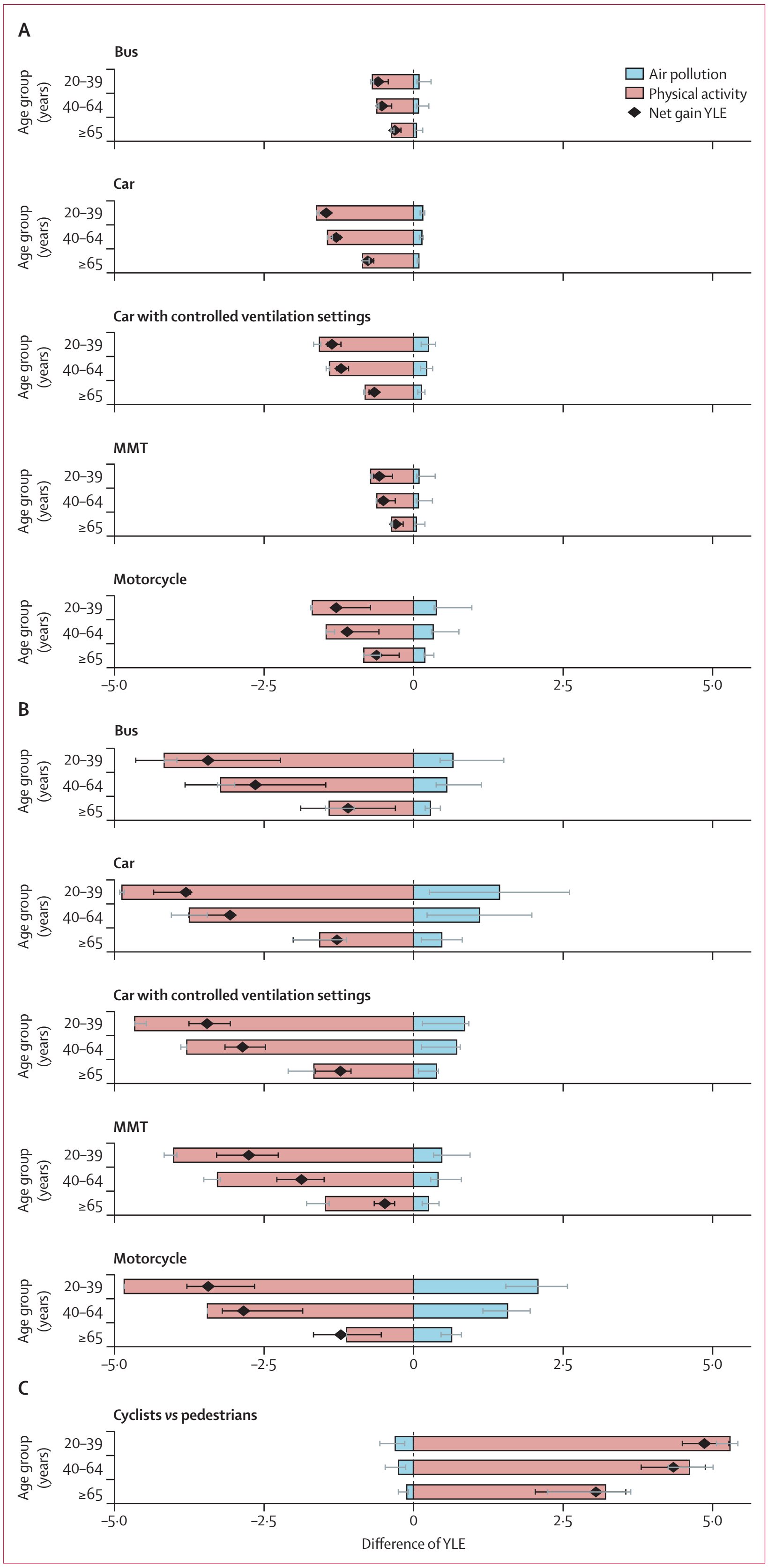

Figure 4: **Gains of YLE per age group due to air pollution exposure and physical activity compared between any mode of transport and (A) cyclists or (B) pedestrians or (C) between cyclists and pedestrians commuting a 7 km route per week**

Values of medians and IQRs are provided in the appendix. MMT=massive motorised transport. YLE=years of life expectancy.

where both commuters using motorised transport and active commuters have similar exposure levels to fine and coarse particles.[22,35,37] Nevertheless, people commuting with a car with controlled ventilation settings had an increased exposure to CO,[10,29,37,38,46,48] attributed to self-pollution due to filtration of surrounding emissions and products from engine combustion.

Commuters' microenvironment sensitivity to traffic-related air pollution is largely determined by built environment attributes that increase their proximity to traffic emissions, by an absence of physical barriers like ventilation settings, and by increased respiratory parameters leading to increased airway deposition of pollutants. Therefore, active commuters might benefit from air pollution forecasting and on-road advice to actively protect themselves from exposure—eg, by choosing uncongested routes. Incentives to shift from private motorised to active and public transport should be accompanied by urban planning standards and policies, such as dedicated lanes, separated cycle routes and pavements, improved ventilation in vehicles and at stops and stations for public transport, a boosted transition to environmentally friendly vehicles, and other efforts aimed to reduce both combustive and non-combustive traffic-related emissions.[3] Moreover, large societal benefits are obtained from an active commuter-friendly environment, which affects additional traffic-related risk factors, like noise, traffic injuries, quality of life, and social cohesion, among others.[60,61]

By contrast with overall exposure, the inhaled dose of pollutants was higher among active commuters than among commuters using motorised transport. This finding is mainly explained by the increased minute ventilation, leading to increased air volume and frequency of breathing, deeper inhalation, and larger inhalation of pollutants in active commuters than in commuters using motorised transport.[7] Active commuters, especially pedestrians, also have a longer trip time than do commuters using motorised transport and thereby have increased exposure time.[7,8,22,37,55]

In agreement with previous studies,[11] the large losses in YLE among commuters using motorised transport due to less physical activity than in active commuters were not offset by the modest gains due to lower inhaled fine particles. YLE losses of commuting by car, by a car with controlled ventilation settings, and by motorcycle were larger than were the losses observed among public transport commuters (bus and MMT). This finding can be explained by the contribution of physical activity during the active stages of the trip, like when approaching stations or stops, despite additional sources of air pollution inhalation.[9,25,55,62]

To our knowledge, this study is the first systematic review of air pollution exposure and inhaled dose according to mode of transport. Our findings are in agreement with the systematic review by Mueller and colleagues,[11] which included 30 studies that assessed the net health benefits of active transport through health impact assessment, 17 of which addressed the negative effect of air pollution exposure. Nevertheless, none of the studies included by Mueller and colleagues[11] were included in our study as they did not comply with our selection criteria and research question. Also, all but one study analysed by Mueller and colleagues[11] were done with data from European countries, the USA, New Zealand, and Australia, with mostly indirect air pollution exposure levels, and with heterogeneous assumptions and modelling frameworks. By contrast, we used fine particle exposure levels purposely measured for modal comparison in 23 studies and applied standard assumptions for inhaled and physical activity doses. Also, because of our selection criteria, we included further settings, also adding Asian and west Pacific cities, with higher ambient air pollution than in the USA and most European countries. Under very high air pollution concentrations, the trade-off between air pollution exposure risks and active transport benefits has been suggested to not benefit active transport anymore.[63] Yet, our findings are consistently in favour of active transport.

Limitations of our analyses deserve attention. First, the external validity of the studies included in this report was affected by the heterogeneity of settings and methodological approaches. Nevertheless, on the basis of the observed heterogeneity, this systematic review encompasses various environmental conditions and makes our findings generalisable. Second, despite our comprehensive search, only eight studies were done in countries other than European and North American countries (China,[37,41,53,54] India,[34] Taiwan,[42] Vietnam,[48] and Chile[49]). Although we did not find evidence of publication bias, these regions are under-represented in our review. Third, we did not take into account the additional toxicity of other pollutants. However, fine particle levels are a strong marker of traffic-related air pollution, and we found that fine particles were more frequently above ambient air quality standards than were the other pollutants. Fourth, we assumed a rather unlikely scenario of pedestrians commuting daily for longer than 2 h. Walking is an important source of physical activity, and a large proportion of active commuters are pedestrians.[64] With a sensitivity analysis, we tested varying commuting times and consistently observed YLE gains in favour of active transport. Fifth, we focused on the long-term mortality effect of physical activity and fine particle exposure. However, examination of other short-term and long-term health effects would be beneficial, as well as other exposures, like noise and traffic injuries. Findings from previous studies suggest that regardless of the expected increment of traffic injuries along the shift from motorised to active commuting, the reduction in motorised traffic volume and the increment of an active commuter-friendly environment would contribute to a reduction of the burden of traffic incidents.[11] Finally, we assumed a total replacement of mode of transport at each scenario modelled and a linear association of fine particle exposure and physical activity with mortality, by contrast with previous findings.[11,60,56] However, our approximation is intended to build on previous efforts to summarise air pollution exposure according to mode of transport to examine the effect of commuting parameters on inhaled doses and potential population-level effects. Health benefits strongly depend on specific local attributes,[11,60] such as the offer of mode of transport, apportionment of emissions, and built environment attributes, besides local policies and normative behaviour. Decision making based on health impact assessment should take into account such local attributes.

Contributors

MC and OHF conceived and designed the study. MC was involved in the search process, study selection, quality assessment, data extraction, and data analysis, and wrote the manuscript. CMK, KD, RF-P, and WMB were involved in the search process and study selection and commented on the manuscript. JS and OHF were involved in data analysis, study selection and data handling, and figure preparation, helped to develop the methods, supervised the work, and commented on drafts of the manuscript.

Declaration of interests

We declare no competing interests.

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