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The long-term impact of restricting cycling and walking during high air pollution days on all-cause mortality: Health impact Assessment study

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ABSTRACT

Regular active commuting, such as cycling and walking to and from the workplace, is associated with lower all-cause mortality through increased physical activity (PA). However, active commuting may increase intake of fine particles ($PM_{2.5}$), causing negative health effects. The purpose of this study is to estimate the combined risk of PA and air pollution for all-cause mortality among active commuters who, on days with high $PM_{2.5}$ levels, switch to commuting by public transportation or work from home. Towards this purpose, we developed a Health Impact Assessment model for six cities (Helsinki, London, Sao Paulo, Warsaw, Beijing, New Delhi) using daily, city-specific $PM_{2.5}$ concentrations. For each city we estimated combined Relative Risk (RR) due to all-cause mortality for the PA benefits and $PM_{2.5}$ risks with different thresholds concentrations. Everyday cycling to work resulted in annual all-cause mortality risk reductions ranging from 28 averted deaths per 1000 cyclists (95% confidence interval (CI): 20–38) in Sao Paolo to 12 averted deaths per 1000 cyclists (95% CI: 5–19) in Beijing. Similarly, for everyday walking, the reductions in annual all-cause mortality ranged from 23 averted deaths per 1000 pedestrians (95 CI: 16–31) in Sao Paolo to 10 averted deaths per 1000 pedestrians (95%CI: 5–16) in Beijing. Restricting active commuting during days with $PM_{2.5}$ levels above specific air quality thresholds would not decrease all-cause mortality risk in any examined city. On the contrary, all-cause mortality risk would increase if walking and cycling are restricted in days with $PM_{2.5}$ concentrations below 150 μg/m^3 in highly polluted cities (Beijing, New Delhi). In all six cities, everyday active commuting reduced all-cause mortality when benefits of PA and risk or air pollution were combined. Switching to working from home or using public transport on days with high air pollution is not expected to lead to improved all-cause mortality risks.

1. Introduction

Physical inactivity increases the risk of developing cardiovascular disease (CVD), type II diabetes and cancer, causing approximately 9% of the global premature mortality (Lee et al., 2012). This indicates that policy recommendations promoting active commuting, such as cycling and walking to and from the workplace, could generate large health benefits at the individual and population level by incorporating physical activity to the daily life (Sahlqvist et al., 2012).

However, active commuting in the urban environment is in many places around the world characterised by elevated exposure to air pollution generated by stationary (e.g. power plants, industrial facilities, boilers) and mobile sources (e.g. cars, light and heavy duty trucks and motorcycles) (Ramos et al., 2016, WHO 2017). Cycling and walking near motorized traffic can lead to increased respiratory uptake (inhaled dose) and deposition of harmful air pollutants, such as fine particulate matter ($PM_{2.5}$), ozone and nitrogen dioxide (NO_2) (Pasqua et al., 2018, Ramos et al., 2016, Tan et al., 2017, Bigazzi and Figliozzi

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2014; Giles and Koehle 2014). $PM_{2.5}$, in particular, have been linked with increased cardiovascular, lung cancer and all-cause mortality (Burnett et al., 2014). Consequently, it is possible that active commuting, which combines higher ventilation rate along with likely higher concentration of $PM_{2.5}$ (de Nazelle et al 2011), could increase health risks.

Due to potential risks, several regulatory authorities, such as the UK Department of Environment, Food and Rural Affairs (DEFRA) and the US Environmental Protection Agency (EPA), recommend that the general population should limit outdoor physical activity (or any activity that makes breathing faster or deeper), including active commuting, on days when $PM_{2.5}$ levels exceed some pre-defined thresholds (Guide, 2017; Air, 2017). Some studies have concluded that individuals may refrain from participating in outdoor physical activity in days with high outdoor air pollution due to concerns regarding the negative health effects of high air pollution (Saberian et al 2017; An et al., 2017; Hu et al., 2017) and recent opinion articles and review papers have also suggested that limiting outdoor activity on high pollution days could minimize the health risks from exposure to air pollution (Laumbach et al., 2015; Zhang et al., 2016). These recommendations aim to decrease short-term risks of air pollution, as increases in daily $PM_{2.5}$ has been found to be associated with increased adverse events during the following days (Atkinson et al., 2014; Shang et al., 2013). However, the long-term health effects of limiting the outdoor physical activity in response to the air pollution is also characterised by a trade-off between physical activity and air pollution (Laumbach et al., 2015).

To address long-term risk-benefit balance of walking and cycling in polluted air, a previous Health Impact Assessment (HIA) study compared the health benefits of active commuting with the risks of air pollution across a wide range of possible $PM_{2.5}$ concentrations, and demonstrated that in most cases the health benefits outweigh risks (Tainio et al., 2016). The study by Tainio et al. was based on average annual concentration of $PM_{2.5}$, and did not consider daily variation of air pollution levels, which have been linked to negative health effects (Atkinson et al., 2014) and changes in commuters' behavior (Fan et al., 2014). Thus, Tainio et al. considered habitual cycling and walking that occurs every day of the year, regardless of the air pollution levels. However, individuals may make the decision not to actively commute based on the air quality of the specific day rather than based on overall pollution level of the city.

In this study, we extend Tainio et al., 2016 analysis by quantifying the long-term change in all-cause mortality risk among healthy (person without pre-existing conditions), adult active commuters who, on days with high $PM_{2.5}$ levels, switch to commuting to work by public transportation (buses, trams or surface trains) or work from home. We developed a HIA model using daily air pollution data from six cities in order to take into account the significant variability of air pollution levels across the world. We aim to examine (i) whether avoiding high air pollution days make substantive differences in annual all-cause mortality risk, (ii) how these benefits vary between different threshold concentrations, (iii) and examine how parameter and model uncertainties would impact these decisions. Questions (i) and (ii) aim to assess the effect of current recommendations, while question (iii) aims to guide further research by highlighting uncertainties that drive the results.

2. Materials and methods

2.1. Overview

A probabilistic model was developed to estimate the change in risk for all-cause mortality resulting from switching cycling and walking to commuting by public transportation, or working from home on days when $PM_{2.5}$ was greater than specific $PM_{2.5}$ thresholds. The $PM_{2.5}$ exposure differences under different thresholds were quantified by estimating the inhaled dose of $PM_{2.5}$ when time in different locations (e.g. home, travel) and ventilation rates of different activities (e.g. sleep, rest, cycling, walking) were taken into account. The change in all-cause mortality was estimated for both physical activity benefits and $PM_{2.5}$ risks and was used to calculate mortality rates per 1000 commuters at each city based on country specific adult mortality rates (15 – 60 years old) obtained from World Health Organization Global Health Observatory (WHO Global Health Observatory 2020). All-cause mortality was chosen as the main health indicator in this study as it has been found to be strongly associated with both physical activity (Schmid et al., 2015) and air pollution (Lepeule et al., 2012; Burnett et al., 2018). A diagram displaying the layout of the model is presented in Fig. 1.

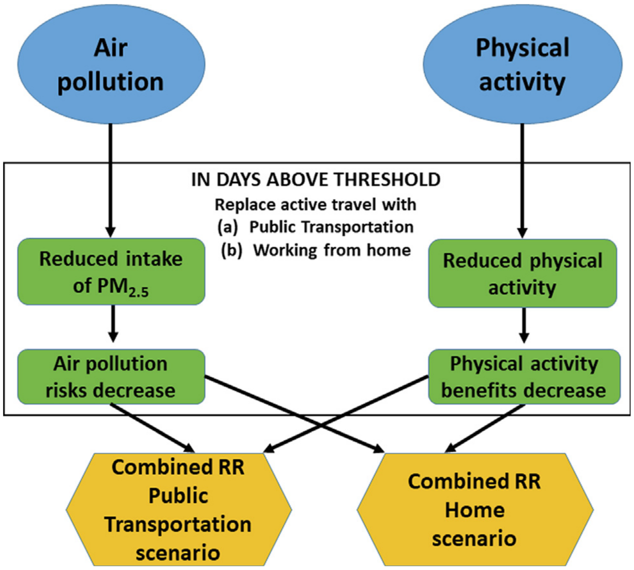


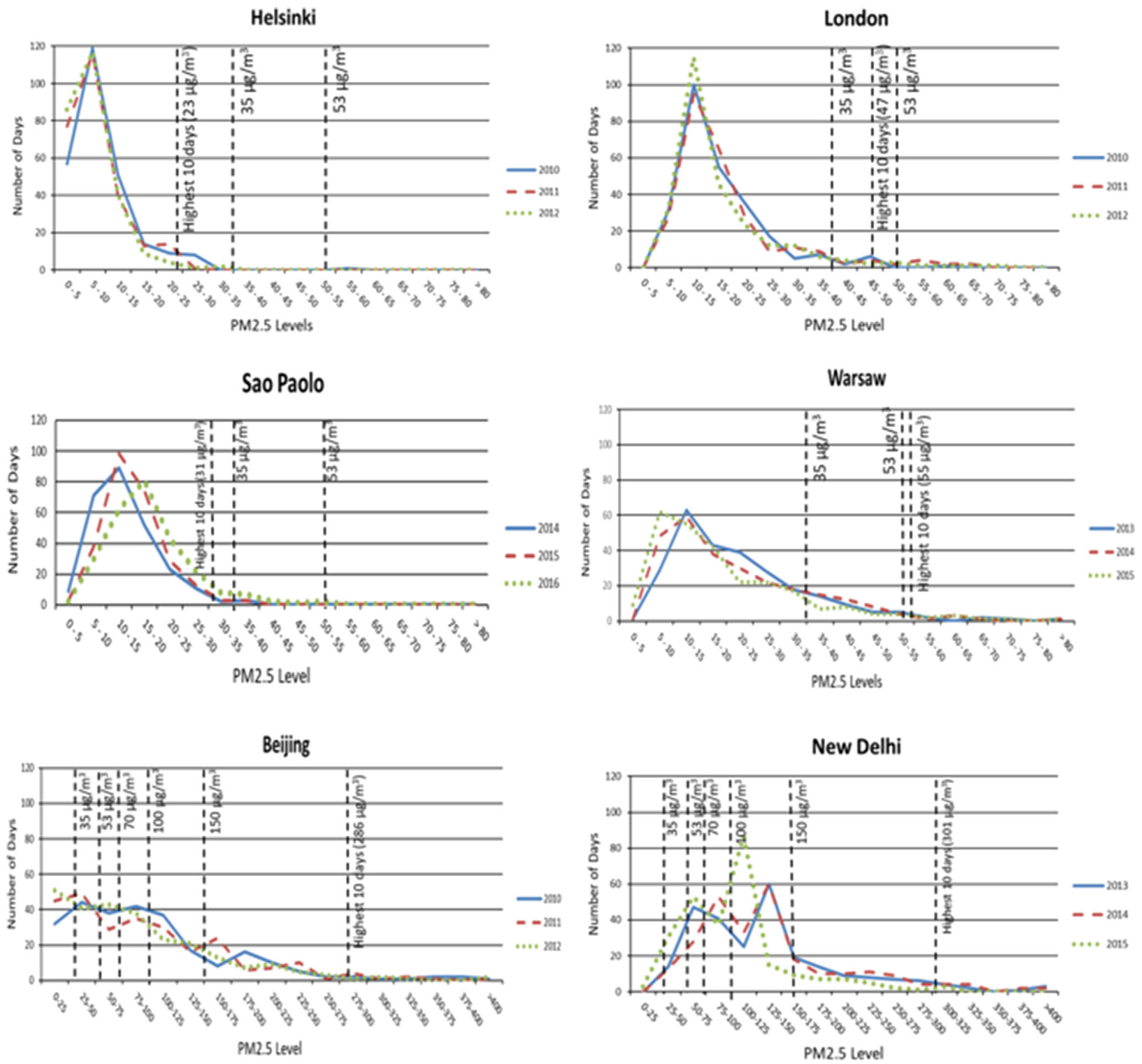
Fig. 1. Model Layout. Diagram displaying the simultaneous assessment of the positive effect of physical activity and the negative effect of air pollution in different counterfactual scenarios for active commuting.

$PM_{2.5}$ was selected to represent air pollution risks for active commuters as it is has been estimated to cause the largest health burden compared to other classes of air pollutants (Fann et al., 2012; Pascal et al., 2013; Tainio et al., 2015), it is strongly associated with increased all-cause mortality (Franklin et al., 2007), and has been frequently used in other active commuting HIA studies (Mueller et al., 2015).

2.2. Air pollution data and scenarios

City-center hourly $PM_{2.5}$ concentration data were obtained for three consecutive years for the cities of Helsinki (Finland), London (United Kingdom), Sao Paolo (Brazil), Warsaw (Poland), Beijing (China) and New Delhi (India). These cities were selected as they are representative of the wide spectrum of urban air pollution conditions around the world with Helsinki having low air pollution levels (2014 annual average of 9 $\mu g/m^3$), London, Sao Paolo and Warsaw characterized by moderate levels (2013 annual averages of 15 $\mu g/m^3$, 19 $\mu g/m^3$ and 26 $\mu g/m^3$ respectively) and Beijing and New Delhi characterized by high levels (2012 annual averages of 85 $\mu g/m^3$ and 122 $\mu g/m^3$ respectively) (WHO 2017).

A total of six different threshold scenarios were modeled. As baseline scenario (no threshold), it is assumed that active commuting takes place every weekday (Monday to Friday) during the day (06:00–22:00), regardless of the air pollution concentration. In the threshold scenarios high air pollution days were defined for each city to be days where $PM_{2.5}$ concentration exceeds 35 $\mu g/m^3$, 53 $\mu g/m^3$, 70 $\mu g/m^3$, 100 $\mu g/m^3$ or 150 $\mu g/m^3$, while a 6th, city-specific, scenario assumed that the 10 most polluted days in each year and city were considered as high air pollution days. Threshold values of less than 100 $\mu g/m^3$ were based on


Helsinki

London

Sao Paolo

Warsaw

Beijing

New Delhi

Fig. 2. Daily PM2.5 levels and threshold values. The distribution of daily PM2.5 levels displayed for all cities and across all years and threshold values. See Table S1 in supplementary material for numerical values.

DEFRA bands, and thresholds of 100 µg/m^3 and 150 µg/m^3, that are not based on DEFRA AQI, were selected to account for cities with frequent episodes of PM$_{2.5}$ pollution > 100 µg/m^3. The city specific scenario was selected to reflect the effect of threshold that was not arbitrary defined, but is driven by the actual PM$_{2.5}$ levels at each city. Table S1 displays the average PM$_{2.5}$ levels during the three-year period, and the number of days above each threshold for each city is displayed in Fig. 2.

On days with high air pollution, active commuters were either assumed to commute by public transportation or work from home. During these days, active commuters do not gain benefits from physical activity while at the same time they experience less intake of PM$_{2.5}$ due to reduced exposure to roadside air pollution and lower ventilation rates. The calculation is done for each day, and then averaged over the year (PM$_{2.5}$) or per week (physical activity) to calculate health effects. The application of thresholds was assumed to reduce active commuting only during weekdays. This resulted us to estimate %change in all-cause mortality risk due to active commuting for 260 or 261 days per year, depending on a year.

2.3. Modelling physical activity and PM$_{2.5}$ impact for all-cause mortality

The model inputs for the cycling and walking times are based on UK national census estimations regarding daily commuting distance for cyclists (mean: 12.4 km) and walkers (mean: 6.2 km) (Census Analysis - Cycling to Work 2011) and Danish estimates regarding cycling (mean: 15 km/h) and walking (mean: 5 km/h) speed (Bicycle statistics 2016). Based on these assumptions, commuting by bicycle takes, on average, 0.8 h/day, while walking to and from the workplace requires 1.2 h per day. In order to account for the variability regarding daily commuting distance, the calculations were repeated assuming a “low” and a “high” distance using values equal to 50% and 200% of UK commuting distance estimates. The comparison of the distance data from the six cities (when such data was available) indicate that the distances between cities were similar for cycling, but varied more substantially for walking

(Table S2).

The total time spent cycling or walking was converted to the metabolically equivalent of task (MET) using a mean estimate of 4.0 MET for walking and mean estimate of 6.8 MET for cycling, based on the Compendium of Physical Activities (Ainsworth et al., 2011). Same values were used in the Health Economic Assessment Tool (HEAT) (WHO/Europe HEAT 2018). For the purposes of this study, we considered cycling and walking for commuting to work as the only physical activity involving cycling or walking. The reduction in all-cause mortality risk resulting from physical activity in active commuters was calculated using several approaches based on the *meta*-analysis derived dose response functions from Kelly et al. (2014). Based on studies following healthy individuals only, Kelly et al. reported six different dose-response functions (DRF) for both cycling and walking, adjusted for other physical activities (other than cycling and walking). In this study, we calculated reduction in all-cause mortality with all six of them and then averaged relative risks (RRs) over these six DRFs (main analysis). The reduction in all-cause mortality based on the most linear and non-linear DRF were also calculated and reported separately (sensitivity analysis). The METs due to cycling and walking were converted to RRs using equations reported in Table S3.

2.4. Exposure to $PM_{2.5}$: Increase in all-cause mortality risk

The health risks of air pollution were calculated by taking into account daily inhaled dose by combining inhaled dose while (i) commuting to and from work, (ii) during sedentary and light activity, and (iii) during night time (sleep). The inhaled dose was calculated separately for each day of the year, and for each threshold scenario, and was combined to estimate long-term (chronic) exposure to air pollution. We relied on a long term, instead on a short term, exposure response relationship for $PM_{2.5}$, given that the best evidence for the association of $PM_{2.5}$ with all-cause mortality is derived from long term cohort studies (Pope and Dockery, 2006). Thus, our assumption is that daily changes in exposure to $PM_{2.5}$ will contribute to all-cause mortality risk through changes in long term exposure to $PM_{2.5}$. For each individual sleep time was 8 h, and sedentary and light activity time was 16 h minus time spend commuting to and from work. Thus, we assumed that people are not doing any other PA which would increase ventilation rates (see below). For the sleep and sedentary and light activity time we assumed that exposure equals daily background PM2.5 concentrations during night and day, respectively.

The exposure concentrations for each transport mode (walking, cycling or public transportation) were estimated by combining two distinct methods. In the first method the transport mode specific concentration of $PM_{2.5}$ (exposure) was calculated based on de Nazelle et al. quantitative synthesis of eight European studies which reported pooled ratios of transport mode concentrations to background concentrations for several transport modes (de Nazelle et al., 2017). A ratio of 1.9 (95% CI: 1.7–2.0) was used for walking, a ratio of 2.0 (95%CI: 1.9–2.1) was used for cycling, and a ratio of 1.9 (95%CI: 1.8–2.0) was used for public transportation (buses). The second method relied on the exposure relationship derived by Goel et al. (2015) for on vehicle exposure in New Delhi, India. This method assumes that the relationship between background concentration and traffic exposure concentration varies with background air pollution levels so that under condition of high background air pollution, traffic exposure concentration approach the level of background concentrations. The relationship is given by the formula (Goel et al., 2015):

$$Ratio = 3.216 - 0.379 ln(Ambient \quad PM_{2.5})$$

Thus, with the background concentration of 346 μg/m^3 the relationship between background concentration and on traffic exposure is 1. For the case of the lowest threshold used in the study (35 μg/m^3) the relationship between background and traffic is 1.87 while for the highest non city specific threshold (150 μg/m^3) the relationship is 1.32. In the main analysis we show the result of the average over these two methods and in a sensitivity analysis we examine the effect of each of these methods in estimated risk for all-cause mortality.

To estimate the inhaled dose of $PM_{2.5}$, the ventilation rate during different activity periods was taken into account. For ventilation rates we used the same values as in the HEAT that correspond to the values used for METs (6.8 for cycling and 4.0 for walking). Namely, the ventilation rates used were 0.27, 0.609, 1.37 and 2.55 m^3/h for sleep, sedentary and light activity, walking, and cycling, respectively (WHO/Europe HEAT 2018). The ventilation rate for the counterfactual scenarios of working from home or commuting by public transportation was considered equal to the sedentary and light activity ventilation rate. In the case of public transportation scenario, cyclists were assumed to cycle for 5 min and pedestrians to walk for 15 min every day to and from the public transportation station (Sallis et al., 2016; Rissel et al., 2012) and the corresponding physical activity benefits and ventilation rates for cycling and walking were included in the calculations. Resulting inhaled doses of $PM_{2.5}$ in different scenarios were compared to baseline inhaled dose by assuming that population would cycle or walk every week day, every week of the year. Thus, we calculated changes in active commuting related risks of PM2.5, not overall health risks of $PM_{2.5}$.

The change in RR for all-cause mortality due to air pollution was calculated with two methods. First, using a linear Exposure Response Function (ERF), with a RR of 1.062 (95%CI: 1.040–1.083) per 10 μg/m^3 increase in long term average $PM_{2.5}$ (Héroux et al., 2015), and, second, using a non-linear Exposure Response Function (ERF) from Burnett et al. (2018). We used nonlinear ERF to account potential non-linear nature of ERF in high concentrations, especially in New Delhi and Beijing. However, since this could potentially underestimate the risks of small changes in $PM_{2.5}$ exposures, the final RR for $PM_{2.5}$ was average between linear and non-linear RRs.

2.5. Sensitivity analysis

The uncertainty in exact numerical form of input parameters and model structure were taken into account during the model development. Parameter uncertainties were represented with probability distribution reflecting uncertainty around the best estimate. The parameters that were modeled as uncertain and the derived probability distributions are presented in Table 1. Monte Carlo sampling performed at 5000 iterations allowed the uncertainty of model parameters to be propagated throughout the model and 95% confidence intervals (CI, 2.5th–97.5th percentile) were calculated for model outputs. To address the impact of each uncertain input to the total uncertainty of the output, we performed importance analysis which calculates the absolute rank-order correlation between each input sample and the output sample. The high correlation indicates that the input parameter uncertainties have large impact to the output parameter uncertainty, meaning that model is sensitive to that parameter. The model was developed in Analytica Professional edition (Lumina Decision Systems, CA, United States). Model is available as Supplementary File 1 and can be assessed using Analytica Free 101 (http://www.lumina.com/products/free101/). A simplified spreadsheet model (only for London for one year) is available online.

3. Results

Cycling to work in all weekdays resulted in reductions in annual all-cause mortality, which ranged between 28 averted deaths per 1000 cyclists (95% CI: 20–38) in Sao Paolo and 12 averted deaths per 1000 cyclists (95% CI: 5–19) in Beijing, when effects of $PM_{2.5}$ and physical activity were combined (Fig. 3). Similarly, walking to work every day, resulted in reductions in annual all-cause mortality which ranged between 23 averted deaths per 1000 pedestrians (95%CI: 16–31) in Sao Paolo and 10 averted deaths per 1000 pedestrians (95%CI: 5–16) in

Table 1
Input Parameter Description.

Input parameter	Parameter Description	Best Estimate	Probability Distribution	Source Reference
CyclAverage_Comm_Spe	Cycling Average Commuting Speed (km/hour)	15	Triangular (9,15,24)	Bicycle Statistics 2016
WalkAverage_Comm_Spe	Walking Average Commuting Speed(km/hour)	5	Normal(5,0.66)	Bicycle Statistics 2016
CyclingMET	MET for 1 h of cycling	6.8	Triangular(5.1,6.8,8.5)	Ainsworth et al. (2011)
WalkingMET	MET for 1 h of walking	4.0	Triangular(2.9,4.0,4.9)	
Dose_Response_Shape	All-cause mortality Relative Risk Dose response shape for walking and cycling	RR for Cycling (power 0.50): 0.87 RR for Walking (power 0.50): 0.9	Cycling: Normal (0.87, 0.0204) Walking: Normal(0.9, 0.0204)	Kelly et al. (2014)
Public_transport_spe	Average traffic speed for street transport in London (2014–2017) (km/hour)	28.2	Normal(28.2,1.39)	Census Analysis - Cycling to Work 2011
Cycling_Background_t	Rate for Background $PM_{2.5}$ exposure to Cycling exposure (ratio)	2	Triangular(1.9,2,2.1)	de Nazelle et al. (2011)
WalkBackground_to_tr	Rate for Background $PM_{2.5}$ exposure to Cycling exposure (ratio)	1.9	Triangular(1.7,1.9,2.0)	
Public_Transport_Coe	Rate for Background $PM_{2.5}$ exposure to vehicle exposure (ratio)	2.5	Triangular(2.4,2.5,2.6)	
Ventilation_rate	Ventilation rates (m^3/hour) for sedentary and light activity, Sleep, Walking, Cycling, Public Transport	Sedentary and light activity, Public Transport: 0.609 Walking: 1.37 Cycling: 2.55 Sleep: 0.27	Constants	Health economic assessment tool (HEAT) (2018)
RR_for_PM2_5	Linear increase of RR for all-cause mortality for a 10 μg/m3 increase of $PM_{2.5}$	1.062	Normal(1.062,0.01097)	Héroux et al. (2015)
RR_non_linear_Air_Po	Non Linear curve of the increase in RR for all-cause mortality with a unit increase of $PM_{2.5}$	Specific. See text for details.	Specific. See text for details.	Burnett et al. (2018)

Beijing (Fig. 4).

Under the counterfactual scenarios of switching to public transportation or working from home when $PM_{2.5}$ levels are above specific thresholds, there was little or no change in all-cause mortality in cities with relatively low levels of air pollution such as Helsinki, London and Sao Paolo (Figs. 3 and 4). In Warsaw, applying the lowest threshold (35 μg/m^3), reduced annual averted mortality for cyclists, indicating that restricting cycling on days with $PM_{2.5}$ concentrations above 35 μg/m^3 would decrease PA benefits more than it would decrease air pollution risks. In Beijing and New Delhi, the change in all-cause mortality varied greatly depending on the $PM_{2.5}$ threshold applied. Using thresholds values less then < 150 μg/m^3, walking and cycling would increase the combined risk of PA and air pollution (Figs. 3 and 4). In high threshold value (150 μg/m^3) combined reduction in mortality was same as in baseline, indicating that replacing active commuting only on days with very high levels of $PM_{2.5}$ would decrease PA benefits as much as it would decrease air pollutions risks. Under the last counterfactual scenario, assuming that switching to public transportation or working from home during the ten most polluted days per year, per city, there were no additional reductions in mortality compared to everyday cycling or walking (Figs. 3 and 4). Numeric results for main analysis for all cities and threshold scenarios are summarized in Table S4.

The results of sensitivity analysis (importance analysis) for cycling scenarios are presented in Fig. 5 and for walking scenarios in Fig. S1. For cycling, in all cities, but especially in cities with low (Helsinki) and moderate (London, Sao Paolo, Warsaw) levels of air pollution, the biggest sources to the uncertainty were physical activity related parameters, such as commuting distance, cycling speed, cycling METs/hour and the shape of the physical activity and all-cause mortality dose response function. On the contrary, in cities with high $PM_{2.5}$ levels (Beijing and New Delhi) parameters relating to the health impact of air pollution such as the shape of the $PM_{2.5}$ ERF and change in RR per 10 mg/m^3 increase in $PM_{2.5}$, had also a large impact for the uncertainty.

When examining, in more detail, three of the uncertainties (choice of DRF for cycling and walking; choice of ERF for $PM_{2.5}$ air pollution; estimation of transport mode specific exposure), the results vary greatly regarding which method was used. For example, with a linear DRF for cycling and walking (Table S5), reduction in annual mortality risk was larger in all cities (e.g. for everyday cycling in New Delhi, a mean reduction of 31 deaths per 1000 cyclists was estimated, as compared to a mean reduction of 26 deaths per 1000 cyclists that was estimated for everyday cycling in the main analysis, Table S4). Using the most non-linear DRF for walking and cycling (Table S6) resulted in the lower reduction of annual mortality in all cities (e.g. for everyday cycling in New Delhi, mean reduction of 12 deaths per 1000 cyclists, as compared to the mean reduction of 26 deaths per 1000 cyclists that was estimated for everyday cycling in the main analysis, Table S4). This also had an impact for the threshold analysis so that in in Beijing and in New Delhi switching to public transportation or working from home when $PM_{2.5} > 100$ μg/m^3 resulted in increased health benefits when using most non-linear DRF for walking and cycling (Table S6).

The choice between linear and non-linear ERF for $PM_{2.5}$ had noticeable impact for the combined all-cause mortality risk in Beijing and New Delhi, but almost no impact in other examined cities. Still, even in Beijing and New Delhi using the linear ERF for $PM_{2.5}$, which predicted larger risks due to air pollution, provided no benefits in any of the counterfactual threshold scenarios. Figure S2 presents how the choice of ERF for $PM_{2.5}$ affects the results for cycling and in Figure S3 for walking, in all cities. Numeric results for a linear ERF for $PM_{2.5}$ are summarized in Table S7 and for a non-linear ERF for $PM_{2.5}$ in Table S8.

Similarly, in Beijing and New Delhi, the choice of value for the ratio between background and mode specific concentration of $PM_{2.5}$ had large impact on the results. Using the ratios from de Nazelle et al. (2017), commuting by public transportation or working from home in days when $PM_{2.5}$ concentrations are above 150 μg/m^3 was marginally more beneficial than cycling every day (see Fig. S4). On the contrary,

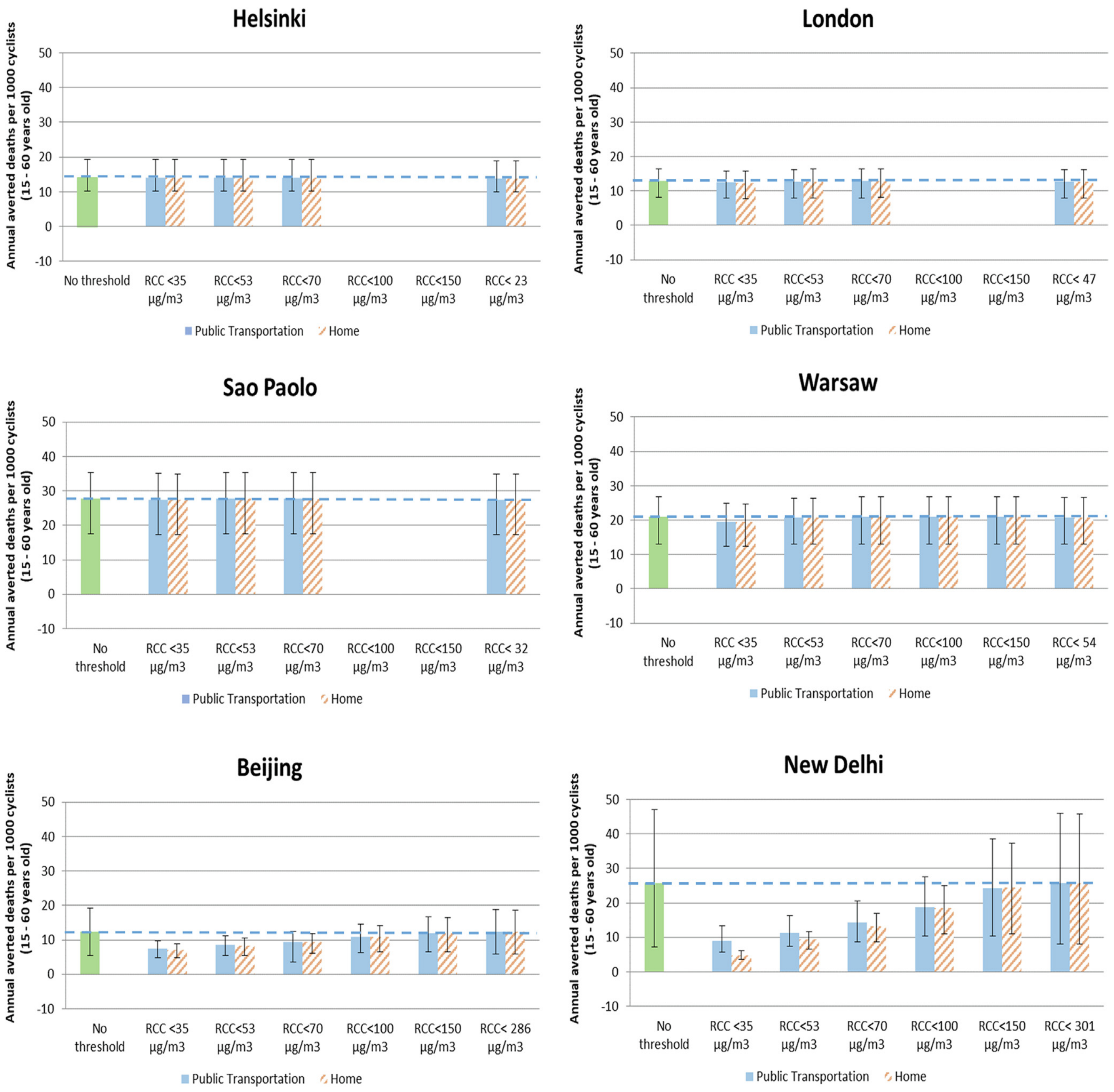


Fig. 3. Averted all-cause mortality per 1000 cyclists in different cities. The change in all-cause mortality is presented across different $PM_{2.5}$ thresholds above which cyclists choose not to cycle to work but rather use public transportation to commute to work or work from home. Error bars represent 95% confidence intervals. The dotted line represents the mortality reduction for everyday cycling.

using the ratios from the Goel et al. (Goel et al., 2015), the mean reduction in all-cause mortality risk for every day cycling and walking in all cities was greater than any counterfactual scenario, and there were no reductions in all-cause mortality risk observed by commuting by public transportation or working from home. Ratio from de Nazelle et al. (2017) was based on review on several studies from Europe, while ratio from Goel et al. (2015) was based on results from New Delhi. Until further studies from high air pollution environment becomes available, it will be difficult to generalise which ratios will represent long-term average situation better in high air pollution environment.

Lastly, the choice of commuting distance had no impact on the results. In all cities, change in all-cause mortality under every counterfactual threshold scenario, assuming either “low” or “high” commuting distance was analogous to the change observed under the assumption of “medium” commuting distance. Fig. S5 summarizes results of the sensitivity analysis for the impact of three possible levels of commuting distance (“low”, “medium”, “high”) on the reduction of all-cause mortality risk for cycling in Helsinki and New Delhi.

4. Discussion

We estimated that overall active commuting (walking, cycling) reduces all-cause mortality even under high air pollution environment for 15–60 years old adults. Switching to public transportation or working from home on days with high $PM_{2.5}$ concentrations had no effect on the long-term risk for all-cause mortality in cities with low or moderate air pollution, but in cities with high air pollution health combined benefits would decrease if cycling and walking would be restricted in days with

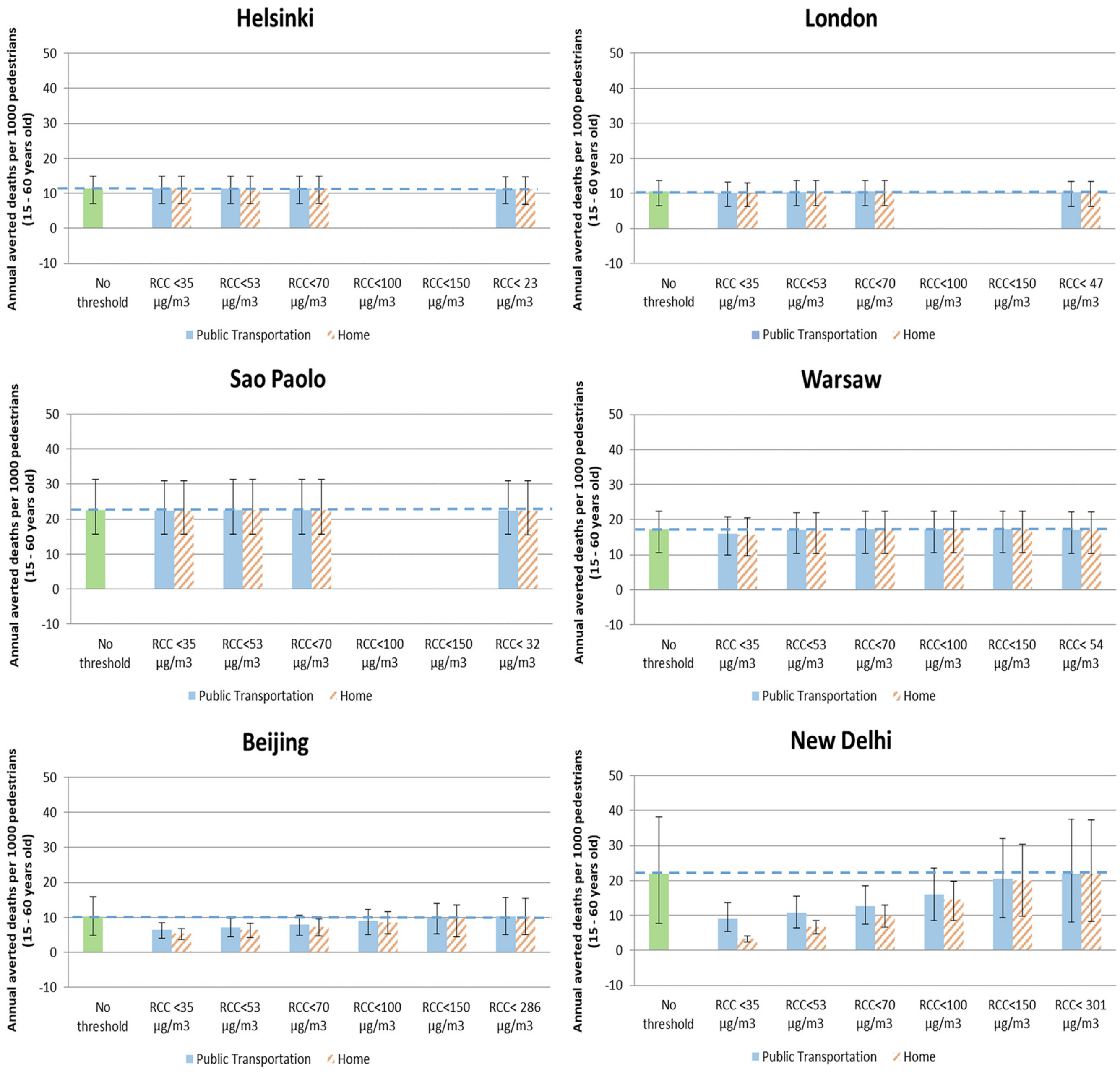


Fig. 4. Averted all-cause mortality per 1000 pedestrians in different cities. The change in all-cause mortality is presented across different $PM_{2.5}$ thresholds above which pedestrians choose not to walk to work but rather use public transportation to commute to work or work from home. Error bars represent 95% confidence intervals. The dotted line represents the mortality reduction for everyday walking.

$PM_{2.5}$ air pollution levels less than 150 μg/m^3. These results indicate that benefits of avoiding air pollution are smaller than risk caused by physical inactivity, even in most polluted cities of the world.

Our study was based on changes in long-term $PM_{2.5}$ exposures. However, as short-term exposure to air pollution is also associated with adverse health effects (Atkinson et al., 2014; Shang et al., 2013), recent reports (Laumbach et al 2015; Zhang et al., 2016) as well as public health recommendations, recommend that the general population should limit outdoor physical activity during air pollution episodes (Review of the UK Air Quality Index 2018). Not surprisingly, recent studies demonstrated that, to some extent, individuals do refrain from participating in outdoor physical activity in days with high outdoor air pollution (An et al., 2017; Hu et al., 2017). In addition, several studies have already provided information on the combined effects of exercising in polluted air and on the potential biological mechanisms involved (Bigazzi and Figliozzi, 2014; Giles and Koehle, 2014). For example, it has been observed that physical activity attenuated the adverse impacts of traffic related air pollution on cardiovascular morbidity through protective effects on blood pressure (Kubesch et al., 2015), systemic inflammation (Zhang et al., 2018) and parasympathetic modulation (Cole-Hunter et al., 2016), although the relationship between physical activity and physiological parameters may vary depending on levels of air pollution exposure (Cole-Hunter et al., 2016; Weichenthal et al., 2014). Nevertheless, as high pollutant concentrations may also influence disease process that may become obvious after several months or years (Review of the UK Air Quality Index 2018), and as active commuting has been found to be protective for human health (Celis-Morales et al., 2017), the evaluation of the long-term effects of any intervention that involves such risk trade-off is useful for public health professionals and policymakers.

This study built upon the findings of the study by Tainio et al. (2016), that calculated the combined health effect of active commuting

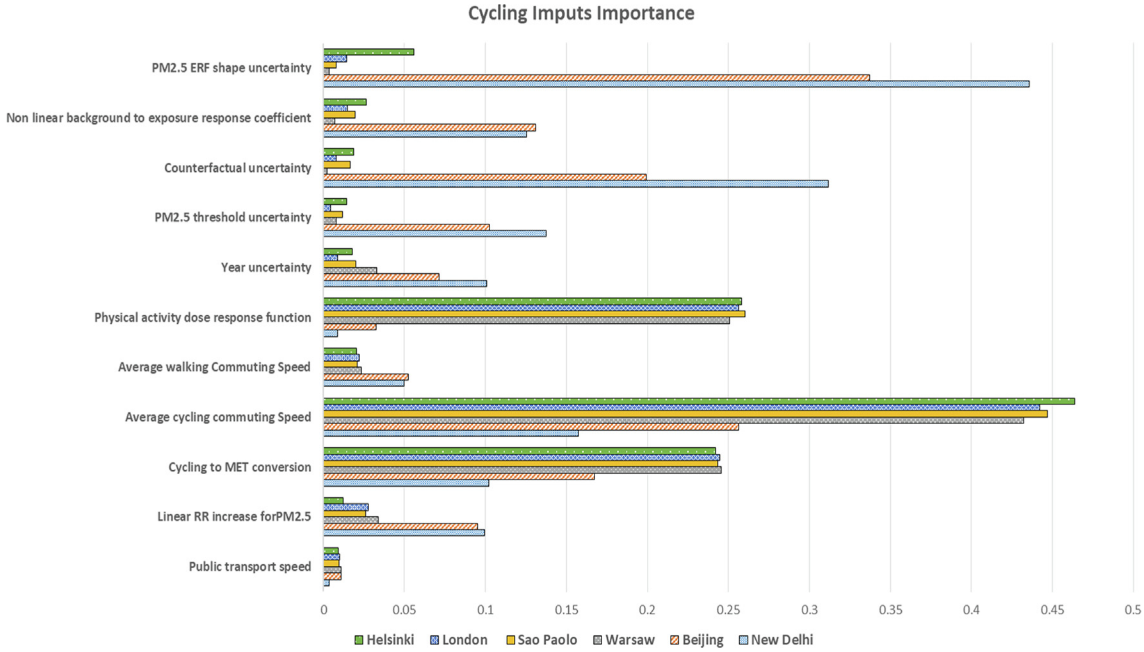


Fig. 5. Cycling to work-Importance Analysis. The absolute rank-order correlation between each uncertain parameter and the final result for cycling, presented separately for each city. High correlation means that input parameter have high impact for the uncertainty of the final results.

and air pollution across a wide range of possible air pollution concentrations and active commuting durations. However, in that study the authors did not consider the daily variation in air pollution, did not consider the uncertainty in model parameters and did not examine the impact of daily commuting choices for combined benefits. The present study takes into account the daily and the within the day variation of air pollution levels, takes into account the uncertainty in model inputs and propagates the uncertainty throughout the model, and addresses how switching to commuting via public transportation or working from home may affect the risk for all-cause mortality. Furthermore, in comparison to Tainio et al., we also improved the estimation of ratios between background $PM_{2.5}$ concentrations and travel mode (roadside) $PM_{2.5}$ concentrations to reflect a potential non-linear relationship between traffic related-air pollution and ambient air pollution in high-polluted urban areas outside Europe (Goel et al., 2015).

Overall, the results presented here are in agreement with the previous findings that even in areas with high $PM_{2.5}$ concentrations (annual average $PM_{2.5} \approx 100$ μg/m^3), a net reduction in all-cause mortality is expected following up to 1.2 h/day of cycling or up to 10.5 h/day of walking (Tainio et al., 2016). However, this study assumed higher reduction in all-cause mortality risk for everyday cycling and walking in the case of Beijing and New Delhi as a result of the improved methodology employed here. Considering the annual average city specific concentrations (for Beijing: 95 μg/m^3, for New Delhi: 120 μg/m^3) and assuming approximately 3.5 h of cycling to work per week, the resulting reduction in mortality risk for cycling and all-cause mortality in Beijing was 8% (reported as RR equal to 0.92) in Tainio et al. while in our revised model is higher at 15%. For New Delhi, the corresponding reduction in mortality risk in the original model was 5% (reported as RR equal to 0.95) as opposed to 14% in the revised model used here. The differences in results are explained by the differences in the models, especially the use of non-linear ERFs for $PM_{2.5}$ and background to exposure concentration rate in the present study.

Besides modeling, only few epidemiological studies have examined the risk-benefit tradeoffs between air pollution and physical activity with similar results as in the present study. In a large prospective study involving a Danish elderly population, Andersen et al, used NO_2 as the primary air pollutant examined, reported that traffic related air pollution may moderate but not reverse the health effect of outdoor physical activity (Andersen et al., 2015). Similarly, in urban Shanghai (China) where average background concentrations of $PM_{2.5}$ (2014 average: 52 μg/m3) are much higher, a protective effect of physical activity has been described for different types of outdoor physical activity such as walking, exercising and commuting to work via bicycle (Matthews et al., 2007). More recently, a large prospective cohort study involving elderly subjects ($>$ 65 years) in Hong Kong, demonstrated that habitual physical activity decreased cardiovascular and respiratory mortality regardless of the individual level of long term $PM_{2.5}$ exposures (Sun et al., 2019).

Nevertheless, our study suffers from some limitations. Active commuting data was based on average distances and speed data from UK and Denmark, respectively, and these could be different in different cities (see Table S2). To account for this variability in distance, we calculated the results for low and high travel distances. The results for Helsinki and New Delhi (Figure S5) indicated that the change in all-cause mortality for different threshold values is similar for low, medium and high distances, indicating that our results are not sensitive for distance of the travel. Additionally, it is possible that associations observed in western settings, namely the DRF for physical activity and ERF for air pollution may not be representative of populations in New Delhi and Beijing. To address these limitations, the uncertainty around model parameters and DRFs was incorporated in the parameter definition and propagated through the model. The resulting sensitivity analysis revealed that parameters relating to physical activity, such as the DRF for physical activity and cycling speed, were modifying the magnitude of the all-cause mortality results for cities with lower air pollution levels, while parameters relating to air pollution, such as the background to transport mode exposure coefficient and the $PM_{2.5}$ thresholds, were modifying the magnitude of the all-cause mortality results for cities with high air pollution. Another factor that could modify the magnitude of all-cause mortality risk in cities with high air pollution would be the decision of individuals to compensate missed active commuting with indoor exercise in a climate controlled environment, such as a gym. Nevertheless, we did not take into account this factor as previous studies have indicated low correlation between changes in active commuting and recreational physical activity (Foley et al., 2019; Sahlqvist et al., 2013; Panik et al., 2019).

We also did not take into account the possible short-term (daily variation) impact of air pollution to mortality. Although it is known that short term variation in air pollution is associated with changes in daily mortality (Shi et al., 2016) and morbidity (Atkinson et al., 2014), the air pollution exposure associations with mortality reported by long-term exposure studies are of considerably higher magnitude (Beverland et al., 2012; Pope III et al., 2007) and therefore it is recommended that HIAs should rely primarily on evidence from cohort studies (Krzyzanowski et al., 2002). Consequently, in this study, the use of evidence from cohort studies produced the largest plausible estimates of air pollution impacts during active commuting. Given that our results suggest that net health effects of active commuting were positive even in cities with very high $PM_{2.5}$ levels, it can be inferred that the use of evidence from short-term studies would result in even greater estimates of the net reduction in all-cause mortality risk of active commuting. Finally, the risk due to exposure to other harmful traffic-related pollutants during active commuting, such as nitrogen dioxide (NO_2), was not taken into account (Faustini et al., 2014).

The sensitivity analyses that were included in this study, underscore the need for further research on the relationship between $PM_{2.5}$ and all-cause mortality, especially in cities with high background air pollution concentrations, as well as the need for additional research towards reducing the uncertainty around the dose response relationship between physical activity and all-cause mortality. Furthermore, our scenarios relied on active commuting characteristics (travelling distance, cycling/walking intensity) that were derived from European studies (Census Analysis - Cycling to Work 2011; Bicycle statistics 2016). Although, these estimates, especially for cycling, may hold elsewhere (Table S2), better access to travel surveys from non-European settings could allow for a more precise characterization of active commuting across the world and as a result, better informed HIA models. Similar to travel distance and speed, the energy expenditure during active commuting could also vary between individuals and cities as a result of e.g. hilliness. Although, the METs used in our study were similar to the objectively measured activity in UK (Costa et al., 2015) (4.6 for walking and 6.4 for cycling), additional studies from other geographical settings could further improve our understanding of energy expenditure of active commuting.

In this study, we also did not account for the use of protective face masks during active commuting, primarily due to the fact that their effectiveness may depend on personal factors (Cherrie et al., 2018) and due to the lack of adequate quality data regarding their use and effectiveness to inform a HIA model. The effectiveness of masks was also recently challenged by the French Agency for Food, Environmental and Occupational Health and Safety opinion report, in which it was concluded that the current evidence do not support the use of face masks in population level (French Agency for Food, Environmental and Occupational Health & Safety 2018). Nevertheless, highly efficient industrial dust respirators do have the potential to limit personal exposure to air pollution (Langrish et al., 2009; Langrish et al., 2012), although use of some models may require additional breathing effort during physical activity. Overall, as new data regarding face masks use and effectiveness become available, future HIA studies could include this parameter in the calculation of air pollution intake.

Our study focused on mortality risks and did not evaluate the possible morbidity effects (Samoli et al., 2016; Delfino et al., 2014). Inclusion of morbidity outcomes in the future, could help to estimate the full health burden of these scenarios e.g. to estimate economic consequences of the scenarios through healthcare costs. Similarly, our study did not take into account the mortality and morbidity risk from road traffic injuries. Although the risk from traffic injury has been found to be considerably lower compared to the health benefits of cycling and walking, it still depends on city characteristics (Rojas-Rueda et al., 2016) and a future analysis including local accident rates could further clarify this relationship. Finally, our study did not address the health effect of active commuting on pre-existing medical conditions such as people suffering from cardiovascular disease, asthma or Chronic Obstructive Pulmonary Disease (COPD) and thus our results should not be generalized for populations with pre-existing diseases. Sensitive subpopulations have been found to walk and cycle less than healthy individuals (van Lummel et al., 2015) and light physical activity interventions have been proposed to reduce symptoms (Russell et al., 2017). However, regulatory authorities (EPA, DEFRA) recommend that sensitive subpopulations should refrain from physical activity under conditions of urban air pollution as pollutants may increase exercise-induced bronchoconstriction as well as decrease lung function and increase exacerbations (Gautier et al., 2017). Future studies focusing on the interaction of air pollutants concentrations with the effect of physical activity in cardiovascular disease, asthma and COPD patients are required.

5. Conclusion

We modelled the health risks and benefits of walking and cycling in six different cities by taking into account long-term health benefits of physical activity and long-term risks of $PM_{2.5}$ air pollution for healthy adults. We estimated that in in all cities everyday walking and cycling is beneficial for health. Avoiding walking and cycling on high air pollution days did not lead to better combined health in any cities. In contrary, in Beijing and New Delhi avoiding walking and cycling on high air pollution days could decrease physical activity benefits more than it would decrease air pollution risks, leading to net health loss. These estimates are sensitive to number of model assumptions and uncertain parameters, and more empirical evidence is welcomed, especially from high air pollution environment, to qualify our assumptions. Current Air Quality Indexes recommend avoiding waking and cycling on high air pollution days, and our results indicate that there could be a need to re-evaluate the long-term risk-benefit balance of these recommendations, especially for healthy adult population.

CRediT authorship contribution statement

Giorgos Giallouros: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Panayiotis Kouis:** Conceptualization, Methodology, Data curation, Visualization, Writing - original draft. **Stefania I. Papatheodorou:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **James Woodcock:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Marko Tainio:** Conceptualization, Methodology, Software, Validation, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions

All authors made substantial contributions to the conception and design of the study. GY had the original idea of the study. GY and PK extracted relevant data from the published literature, developed the HIA model and drafted the first version of the manuscript. SIP. contributed to the model development, and interpretation of findings. JW contributed to model development and interpretation of the findings. MT supervised data extraction, model development, and contributed towards the interpretation of findings and the final version of the manuscript. All authors drafted and critically revised the manuscript.

Declaration of Competing Interests

All authors wish to declare that they have no competing interests.

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Appendix A. Supplementary material

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