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Premature Mortality of 2050 High Bike Use Scenarios in 17 Countries

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Background: Biking plays a significant role in urban mobility and has been suggested as a tool to promote public health. A recent study has proposed 2050 global biking scenarios based on large shifts from motorized vehicles to bikes. No previous studies have estimated the health impacts of global cycling scenarios, either future car-bike shift substitutions.

Objectives: We aimed to quantify changes in premature mortality of 2050 global biking scenarios in urban populations from 17 countries.

Methods: Through a quantitative Health Impact Assessment, the mortality risks and benefits of replacing car trips by bike (mechanica bike and electric bike) in urban populations from 17 countries were estimated. Multiple bike scenarios were created based on current transport trends or large shifts from car trips to bike trips. We quantified the estimated change in the number of premature deaths (reduced or increased) concerning road traffic fatalities, air pollution, and physical activity. This study focuses on urban populations between 20 and 64 y old.

Results: We found that, among the urban populations (20–64 y old) of 17 countries, 205,424 annual premature deaths could be prevented if high bike-use scenarios are achieved by 2050 (assuming that 100% of bike trips replace car trips). If only 8% of bike trips replace car trips in a more conservative scenario, 18,589 annual premature deaths could be prevented by 2050 in the same population. In all the countries and scenarios, the mortality benefits related to bike use (rather than car use) outweighed the mortality risks.

Discussion: We found that global biking policies may provide important mortality benefits in 2050. Current and future bike- vs. car-trip policies should be considered key public health interventions for a healthy urban design. https://doi.org/10.1289/EHP9073

Introduction

In 2018, 55% of the total global population lived in an urban setting, and this percentage is expected to increase to 70%–80% within the next 20 y (United Nations Department of Economic and Social Affairs 2018). Urban development and transport planning have favored the use across the globe of private motorized vehicles, which occupy a significant part of public space (Nieuwenhuijsen et al. 2017). It is estimated that in modern cities, up to 70% of public space has been specifically designed to accommodate motor vehicles (Crawford 2002; Manville and Shoup 2005). Cities are places of innovation and wealth creation; however, many cities prioritize the use of private motorized vehicles, resulting in low levels of physical activity and high levels of environmental pollution (e.g., air pollution, noise, and anthropogenic heat) (Bettencourt et al. 2007; Nieuwenhuijsen and Khreis 2016).

Recent evidence has suggested that sustainable transport infrastructure (e.g., biking, walking, and access to public transit) can promote modes of active travel and health (Heath et al. 2006; Heinen et al. 2015; Mueller et al. 2020; Nieuwenhuijsen 2020; Panter et al. 2016). Investments in these modes of active transport could lead to climate mitigation through CO_2 emissions reduction from passenger travel by 40% in 2050 (Mason et al. 2015). Furthermore, sustainable transport policies can support equity by providing healthy and low-cost transport options to socially deprived communities that are in some cases highly affected by other environmental health inequities (Lindsay et al. 2011; Maas et al. 2006; Mitchell and Popham 2008).

Biking plays a significant role in personal mobility worldwide and can occupy a more important role across the globe if biking policies are widely implemented. Bicycles offer a convenient and affordable transportation option that could capture a higher proportion of urban transportation passengers than today when bicycles are compared to other modes of transportation (Mason et al. 2015).

A recent study has proposed future (by the year 2050) global transport scenarios, supporting large shifts from motorized transport to biking and estimating the climate benefits (Mason et al. 2015). Previous publications have assessed the health impacts of current local (Rojas-Rueda et al. 2012) or regional (Mueller et al. 2018b; Rabl and de Nazelle 2012) urban transport scenarios focused on replacing motorized transportation with active transport. To our knowledge, no study has estimated the health impacts related to premature mortality of future biking scenarios globally. This study aims to estimate the premature mortality changes (risks and benefits) of 2050 global bike scenarios.

Methodology

Study Design and Data Collection

A quantitative health impact assessment (HIA) was conducted, assessing future (2050) biking scenarios in urban populations from 17 countries. Transport data and future scenarios were collected from the Global High Shift Cycling study (Mason et al. 2015). The Global High Shift Cycling study forecast future biking scenarios [business as usual and high bike use (HBU)] for years 2030 and 2050, describing future transport patterns, such as trips per person per day, trip length, kilometers traveled by a person, and mode of transport, in all continents around the globe (Table 1). Methods and descriptions of the Global High Shift Cycling study have been reported elsewhere (Mason et al. 2015). This quantitative health impact assessment focused only on those countries from the Global High Shift Cycling study, where

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Table 1. Description of the 17 countries included in the analysis.

Country information	Brazil	Canada	China	Denmark	Egypt	France	Germany	India	Indonesia
Urban population in 2010 (20–64 y old)	100,205,138	16,704,130	455,230,100	2,804,582	17,755,391	27,905,877	37,409,144	205,931,904	70,812,326
Urban population in 2050 (20–64 y old)	127,964,526	23,958,250	711,957,631	3,403,568	36,403,098	35,587,345	36,526,649	449,744,804	134,235,428
Crude mortality rate per 100,000 people (2017)	378.15	239.56	293.25	253.03	427.09	243.03	275.91	475.42	426.57
Air pollution [$PM_{<2.5}$ annual mean concentration ($\mu g/m^3$)]	13.06	6.87	47.64	10.67	109.5	11.85	12.23	83.09	39
Traffic fatalities by bike per year	1,455	53	7,190	29	317	155	398	4,477	1,053
Traffic fatalities by car per year	7,568	1,433	16,590	113	5,175	2,021	1,851	21,693	1,545
Average trips per person/day									
LDV	0.32	2.18	0.29	1.62	0.33	2.06	2.06	0.32	0.32
Urban Bus	0.72	0.52	0.66	0.39	0.75	0.49	0.49	0.72	0.72
BRT	0.004	0.01	0.004	0.007	0.004	0.009	0.009	0.004	0.004
e-bike	0.0001	0.0001	0.1	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Bike	0.25	0.04	0.38	1	0.12	0.24	0.24	0.25	0.25
Walk	1.5	1	1.38	0.74	1.57	0.95	0.95	1.5	1.5
Total	2.79	3.75	2.81	3.76	2.78	3.75	3.75	2.79	2.79
Days traveled per year	252	244	243	199	254	217	195	250	243
Average levels of physical activity (METs/h/wk)									
Group 1	4.99	4.99	4.99	0	6.25	5	7.5	4.99	4.99
Group 2	17.5	17.5	17.5	12	18.75	17.5	18	17.5	17.5
Group 3	37.5	37.5	37.5	24	37.5	25	50.4	37.5	37.5
Group 4	30	—	—	—	—	—	—	—	—
Average levels of physical activity, population distribution (%)									
Group 1	30.4	13.7	6.9	5.8	24.9	33.3	33.3	23.4	27.2
Group 2	45	26.7	35.4	25.2	54.4	33.3	33.3	38.7	44.8
Group 3	24.6	59.6	57.7	58	20.7	33.3	33.3	37.9	28
Group 4	11	—	—	—	—	—	—	—	—
Bike trips per day (20–64 y old)									
BAU	25,051,285	668,165	172,987,438	2,804,582	2,130,647	6,697,411	8,978,195	51,482,976	17,703,082
BAU 2050	25,592,905	1,916,660	185,108,984	3,403,568	9,100,774	8,540,963	8,766,396	89,948,961	26,847,086
BAU e-bike	10,021	1,670	45,523,010	280	1,776	2,791	3,741	20,593	7,081
BAU e-bike 2050	2,559,291	239,582	142,391,526	34,036	728,062	355,873	365,266	8,994,896	2,684,709
HBU 2050	53,745,101	4,312,485	256,304,747	3,403,568	15,289,301	12,455,571	12,784,327	188,892,818	56,378,880
HBU e-bike 2050	25,592,905	2,395,825	177,989,408	510,535	7,280,620	5,338,102	5,478,997	89,948,961	26,847,086

Country information	Italy	Japan	Mexico	Netherlands	Russia	South Africa	United Kingdom	United States
Urban population in 2010 (20–64 y old)	24,562,968	63,644,276	51,718,756	8,562,350	66,935,164	18,572,212	29,721,081	149,095,840
Urban population in 2050 (20–64 y old)	27,709,385	58,400,561	76,005,629	9,650,920	62,009,331	28,487,796	38,184,184	207,104,946
Mortality rate per 100,000 people (2017)	185.09	189.19	369.36	220.33	693.02	828.28	230.47	369.92
Air pollution [$PM_{<2.5}$ annual mean concentration ($\mu g/m^3$)]	16.4	15	23.38	11.31	14	28.17	10.22	8.05
Traffic fatalities by bike per year	272	799	301	160	474	410	111	744
Traffic fatalities by car per year	1,762	1,542	4,704	266	15,891	8,221	988	19,487
Average trips per person/day								
LDV	2.06	2.12	2.18	1.62	0.32	0.33	2.06	2.18
Urban Bus	0.49	0.5	0.52	0.39	0.72	0.75	0.49	0.52
BRT	0.009	0.01	0.01	0.007	0.004	0.004	0.009	0.01
e-bike	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Bike	0.24	0.15	0.04	1	0.25	0.12	0.24	0.04
Walk	0.95	0.97	1	0.74	1.5	1.57	0.95	1
Total	3.75	3.75	3.75	3.76	2.79	2.78	3.75	3.75
Days traveled per year	246	240	307	205	282	250	220	255

Table 1. (*Continued.*)

Country information	Italy	Japan	Mexico	Netherlands	Russia	South Africa	United Kingdom	United States
Average levels of physical activity (METs/h/wk)								
Group 1	2	4.99	8.95	4.99	6.25	4.99	4.99	4.99
Group 2	5.97	17.5	26.85	17.5	27.5	17.5	17.5	17.5
Group 3	10	37.5	35.8	37.5		37.5	37.5	37.5
Group 4	—	—	—	—	—	—	—	—
Average levels of physical activity, population distribution (%)								
Group 1	33.3	43.4	19.4	16	18	6.4	27	15.9
Group 2	33.3	35.4	28.8	28	82	20.85	41	22.1
Group 3	33.3	21.2	51.8	56		72.75	32	62
Group 4	—	—	—	—	—	—	—	—
Bike trips per day (20–64 y old)								
BAU	5,895,112	9,546,641	2,068,750	8,562,350	16,733,791	2,228,665	7,133,059	5,963,834
BAU 2050	6,650,252	10,512,101	6,080,450	9,650,920	12,401,866	7,121,949	9,164,204	16,568,396
BAU e-bike	2,456	6,364	5,172	856	6,694	1,857	2,972	14,910
BAU e-bike 2050	277,094	584,006	760,056	96,509	1,240,187	569,756	381,842	2,071,049
HSC 2050	9,698,285	14,016,135	13,681,013	9,650,920	26,043,919	11,964,874	13,364,464	37,278,890
HSC e-bike 2050	4,156,408	8,760,084	11,400,844	1,447,638	12,401,866	5,697,559	5,727,628	20,710,495

Note: —, no data available; BAU, business as usual; BRT, bus rapid transit; HBU, high bike use; HSC, LDV, light duty vehicles; MET, metabolic equivalent of task; $PM_{2.5}$, particulate matter with a diameter ≤2.5 μm.

transport (trip characteristics and volume), environment (air quality concentrations), and health data (mortality rates, traffic fatalities, and physical activity levels) were available at a national level from national and international public records and scientific publications. Only year 2050 data and results are presented in the main text herein; however, analyses were also performed for the year 2030. Data and results for the year 2030 are displayed in the supplemental material (see Tables S1, S2, and S9–S30).

National population data for 2050 was obtained from the United Nations population forecast (United Nations Department of Economic and Social Affairs 2018). Age-specific mortality rates by country were collected from the year 2017 from the Global Burden of Disease (GBD) project (IHME n.d.). Air pollution was included by estimating the exposure to particulate matter with aerodynamic diameter less than or equal to 2.5 μm of ($PM_{2.5}$). $PM_{2.5}$ data was collected in annual average national concentration from the World Health Organization (WHO) Global Ambient Air Quality Database (WHO 2019). Annual traffic fatalities by mode of transport and country were collected from the Road Safety Annual Reports for the year 2018 (International Transport Forum 2019) and the global observatory data from the World Health Organization from 2009 to 2018 (WHO 2009, 2013, 2015, 2018). Physical activity data was collected in metabolic equivalent of task (MET) at the national level from scientific publications (Bauman et al. 2009; Ding et al. 2016; Dugas et al. 2014; Khusun et al. 2015; Krasnov and Bokhan 2015; Loyen et al. 2016; Medina et al. 2013; Otero et al. 2018; Rojas-Rueda et al. 2016). Dose–response functions used in this HIA for physical activity, $PM_{2.5}$, and all-cause mortality were collected from the published meta-analysis (Hoek et al. 2013; Woodcock et al. 2011).

Scenarios

The Global High Shift Cycling study described transport projections for 2030 and 2050 in a "business as usual" (BAU) scenario based on current biking and transport trends and an HBU scenario based on future projections on modal share assuming a high bicycle use. The BAU 2050 scenario described the likely future if the current trajectories for transportation and development policies continue (Mason et al. 2015). The BAU scenario assumed that those Organization for Economic Co-operation and Development (OECD) countries (Canada, Denmark, France, Germany, Italy, Japan, Mexico, Netherlands, the United Kingdom, and the United States) could expect an increased bike share by 0.2 percentage points per year (1 percentage point every 5 y), though also subject to a maximum 2% change vs. the previous year to avoid excessive changes in countries with low mode shares; in non-OECD countries was assumed a declining rate of the same magnitude as reported in international transport data (Mason et al. 2015). The BAU e-bike scenario was based on the trends in e-bike sales reported by different countries (Mason et al. 2015). Sales were expected to increase from 2015 to 2030 by the same percentage increase seen in recent history, with a maximum increase of 5% yearly (Mason et al. 2015). From 2030 to 2050, the e-bike scenario assumed a sales growth cap of 2.5% annually, assuming that most of those interested in e-biking already possess electric bikes (e-bikes), and e-bikes sales are primarily for replacing existing e-bikes (Mason et al. 2015).

The HBU scenario represents the upper limits of a plausible future of cycling: To reach cycling and e-bike riding levels that are well above current levels or the projected increase in the cycling BAU scenario. The HBU scenario was based on three general considerations: *a*) that the average city in 2050 can reach or approach the current biking level of the best performing city in the country; *b*) that a certain percentage of trips are "cyclable" based on trip distance (5 – 10 km); and *c*) that the future increase will not exceed a

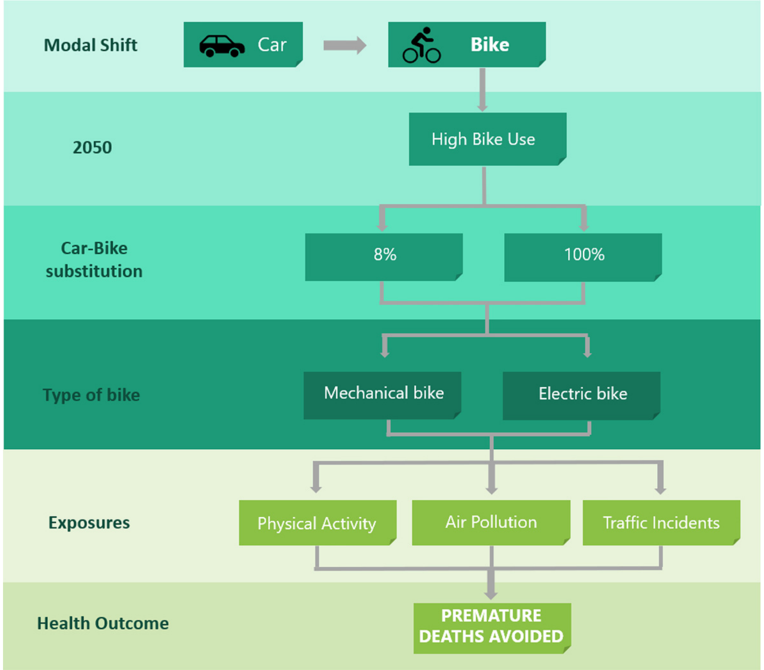

Figure 1. Conceptual framework of the "2050 high bike use scenarios" quantitative health impact assessment.

maximum rate of change in a 5-y period, based on previous increases (Mason et al. 2015). Both scenarios (BAU and HBU) provide bike use projections for mechanical bikes and e-bikes for 2050.

In addition to this, to measure the health opportunity of urban cycling, we created four subscenarios: *1*) a conservative scenario assuming that only 8% of all future bike trips will replace car trips, based on a car–bike shift reported from 26 cities from China (Ma et al. 2019), Europe (Bjørnarå et al. 2019; Oakil et al. 2016; Otero et al. 2018; Scheepers et al. 2014), and the United States (Scheepers et al. 2014) (see Table S16); and *2*) an ambitious scenario assuming that 100% of the future bike trips will replace car trips (Figure 1); additional scenarios were created to estimate alternative assumptions regarding the percentages of car trips that could be substituted for future bike trips. These additional scenarios assumed *3*) "what if" 35% of future bike trips replace car trips (as the maximum substitution reported among the 26 cities analyzed), or *4*) "what if" only 0.46% of future bike trips replace car (as the minimum substitution reported among the 26 cities analyzed). All scenarios were modeled for the BAU, HBU, mechanical bikes and e-bikes, in 2050 (see Tables S1, S3, S16–S18).

Quantitative Health Impact Assessment Model

This study followed a quantitative HIA approach to estimate the change in annual premature deaths related to each health determinant and scenario. Three different health determinants [physical activity, road traffic fatalities, and air pollution ($PM_{2.5}$)] were considered to estimate the impacts on all-cause mortality. The "TAPAS tool" developed and used in previous HIA was applied to estimate the change in premature mortality in this study (Otero et al. 2018; Rojas-Rueda et al. 2012, 2016). A detailed description of the TAPAS tool methods has been reported elsewhere (Rojas-Rueda et al. 2012, 2016). The TAPAS tool is a quantitative HIA run on Microsoft Excel for Office 365, version 1908 (Microsoft, Inc.). The dose–response functions (DRF) included in the TAPAS tool (for the relationship between $PM_{2.5}$, physical activity, and all-cause mortality) were obtained from published meta-analyses of cohort studies from adult populations (20–64 y old). The risk of traffic fatalities was estimated based on the kilometers traveled by mode of transport. Traffic fatality data were obtained from national transport and health data sources. Levels of each exposure were estimated for each country and scenario. Relative risks (RR) for all-cause mortality were estimated for each health determinant, scenario, and country, and then the RR was transformed into a population attributable fraction (PAF). Country mortality rates for adults (20–64 y old) were multiplied in each scenario by the number of new cyclists scaled from each national urban adult population (20–64 y old) to obtain the number of expected premature deaths for the country and scenario. The last step in this process was the multiplication of the expected number of premature deaths by the corresponding PAF from each scenario and country to estimate the final number of attributable premature deaths. We also calculated the expected number of premature deaths per 100,000 bicyclists in each scenario and country. Additionally, we ran two sensitivity analyses using 2050 (instead of 2017) mortality rates for those 20–64 y old and for those 20 y old and older to assess the impacts of the epidemiological transition and aging process in future years (IHME 2020). These 2050 mortality rates focused on the top four countries regarding the number of premature deaths avoided (China, India, Indonesia, and Russia). We have also assessed the uncertainty of our estimates by providing uncertainty intervals (UI). These UIs were composed by the variability of the input data, using *a*) the changes "maximum and minimum" of the estimated traffic fatalities per billion of kilometer traveled and speed and *b*) the confidence intervals (CIs) from the DRF from air pollution and physical activity.

Physical activity. The level of physical activity was estimated in metabolic equivalent of task (MET), using the intensity of physical activity, trip duration, and frequency (Table 1 and Table S5). We defined the physical activity in bikes as 6.8 METs, in e-bikes as 6.12 METs (assuming standard assistance for e-bikes), and 2 METs for car travelers. All-cause mortality RR was based on DRF for those 20–64 y old, as reported in a meta-analysis of cohort studies (Woodcock et al. 2011), assuming a nonlinear

DRF. The nonlinear DRF for physical activity considers as the baseline the average levels of physical activity in each population to calculate the RR for each scenario before being translated into a PAF and then to the estimated attributable premature deaths (see Figure S1). In other words, the nonlinear DRF takes into account that individuals who already were physically active would gain fewer mortality benefits compared with those who are less physically active.

Air pollution. This assessment included only the trip exposure to $PM_{2.5}$, which has shown a strong association with all-cause mortality (Laden et al. 2000; Pope et al. 2007). The annual average $PM_{2.5}$ concentrations from each country was obtained from the WHO database of air quality (WHO 2019) (Table 1). We then estimated the $PM_{2.5}$ concentration in each transport microenvironment (car and bike), using corresponding background/car or background/bike ratios provided from a published meta-analysis (de Nazelle et al. 2017), following a similar approach as reported in previous studies (Otero et al. 2018; Rojas-Rueda et al. 2012, 2011, 2016). We estimated the inhaled dose was based on the $PM_{2.5}$ concentration in each transport microenvironment (car or bike), the minute ventilation was based on the intensity of physical activity according to the mode of transport (bike, e-bike, and car), and trip duration (Rojas-Rueda et al. 2013, 2011, 2016). The DRF used for $PM_{<2.5}$ and all-cause mortality was obtained from a published meta-analysis [RR = 1.06 (95% CI: 1.04, 1.08)] for each increment of ($10\ \mu g/m^3$ of $PM_{2.5}$) (Hoek et al. 2013). The last steps in the air pollution assessment were the estimation of the RR, PAF, and the corresponding attributable number of premature deaths by country and each scenario, as described before (see Figure S2). We also ran a sensitivity analysis comparing a more recent DRF for $PM_{2.5}$ and all-cause mortality (RR = 1.08) (Chen and Hoek 2020) to the DRF reported from Hoek et al. (RR = 1.06) (Hoek et al. 2013) among the top five countries with the largest number of bike trips (India, China, Indonesia, Brazil, and Russia).

Road traffic fatalities. The annual traffic fatalities reported between 2009 and 2018 at the country level were used to estimate the road traffic fatalities in each scenario, country, and mode of transport (see Table S4). For each scenario and country, we first estimated the expected number of kilometers traveled by mode of transport (car, bike, and e-bike) among the adult population (20–64 y old). Then the expected annual traffic fatalities by each mode of transport were calculated based on the distance traveled in each mode and country, and the corresponding traffic fatalities per billion kilometers traveled (Johan de Hartog et al. 2010; Rojas-Rueda et al. 2011). Then we estimated the RR of traffic fatalities for bike or e-bike trips compared with those of car trips. The RR was then translated to a PAF and to an estimated number of premature deaths in each country and scenario (see Figure S3). We also ran a sensitivity analysis using the "estimated" country traffic fatalities instead of the "reported" country traffic fatalities both presented by the Global Status Reports on Road Safety from the WHO (WHO 2009, 2013, 2015, 2018).

E-Bikes

The TAPAS tool estimates the impacts related to mechanical bikes and e-bikes (Otero et al. 2018). For this analysis, a "standard assistance" from the e-bike was assumed. The e-bike analysis in the TAPAS tool includes specific ratios to estimate the corresponding physical activity (METs), inhalation rates, traffic fatalities, and speed in comparison with those of mechanical bikes (Otero et al. 2018) (see Tables S6–S8). For physical activity, we assumed that the e-bikes' standard assistance requires 90% of the physical activity compared with the physical activity of a mechanical bike (Gojanovic et al. 2011; Louis et al. 2012; Otero et al. 2018; Simons et al. 2009), 21% more speed than that of a mechanical bike, and an odds ratio (OR) of 1.92 (95% CI: 1.48, 2.48) for e-bike traffic fatalities was assumed compared with those associated with mechanical bikes (Otero et al. 2018; Schepers et al. 2014).

Results

This study included 17 countries from 5 different continents (Brazil, Canada, China, Denmark, Egypt, France, Germany, India, Indonesia, Italy, Japan, Mexico, Netherlands, Russia, South Africa, United Kingdom, and the United States) (Figure 2). The country-level urban adult populations included in this study ranged from 3,403,568 people in Denmark to 711,957,631 people in China in 2050 (Table 1). The number of bike trips per day (combining mechanical bikes and e-bikes) ranged from 3,914,103 trips in Denmark to 434,294,155 trips in China in 2050 (Table 1). In all the situations (countries and scenarios), the benefits in preventable deaths of physical activity related to biking outweighed the mortality risks associated with traffic fatalities and air pollution inhalation (Figure 3).

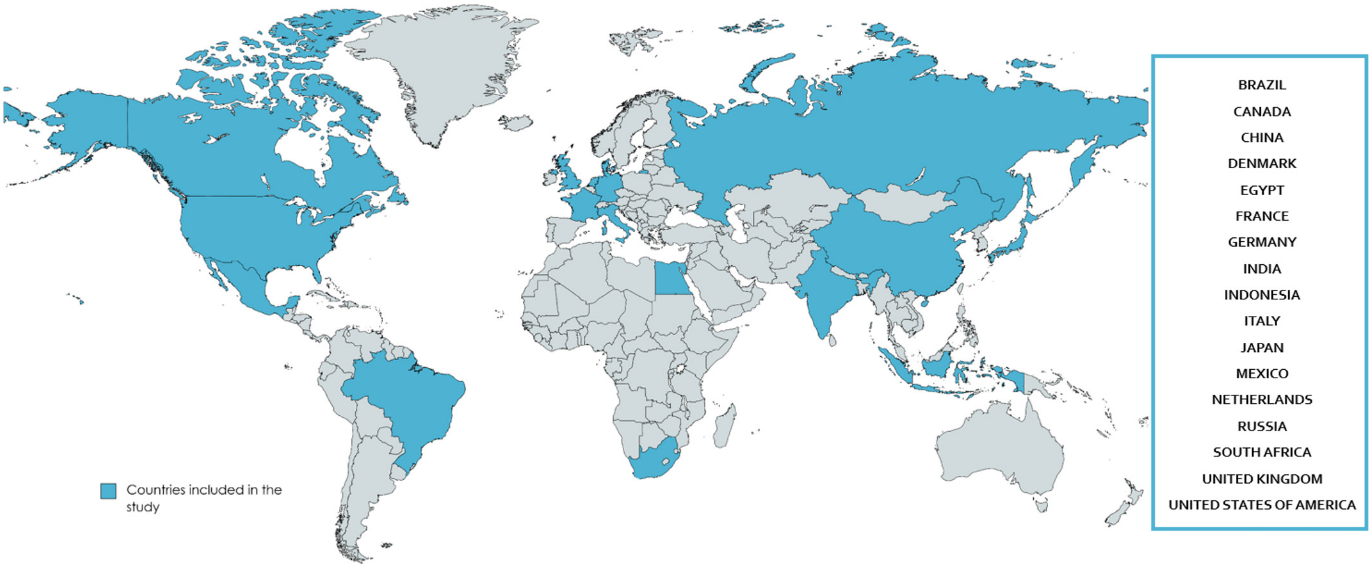

Figure 2. Countries included in the study ($N = 17$).

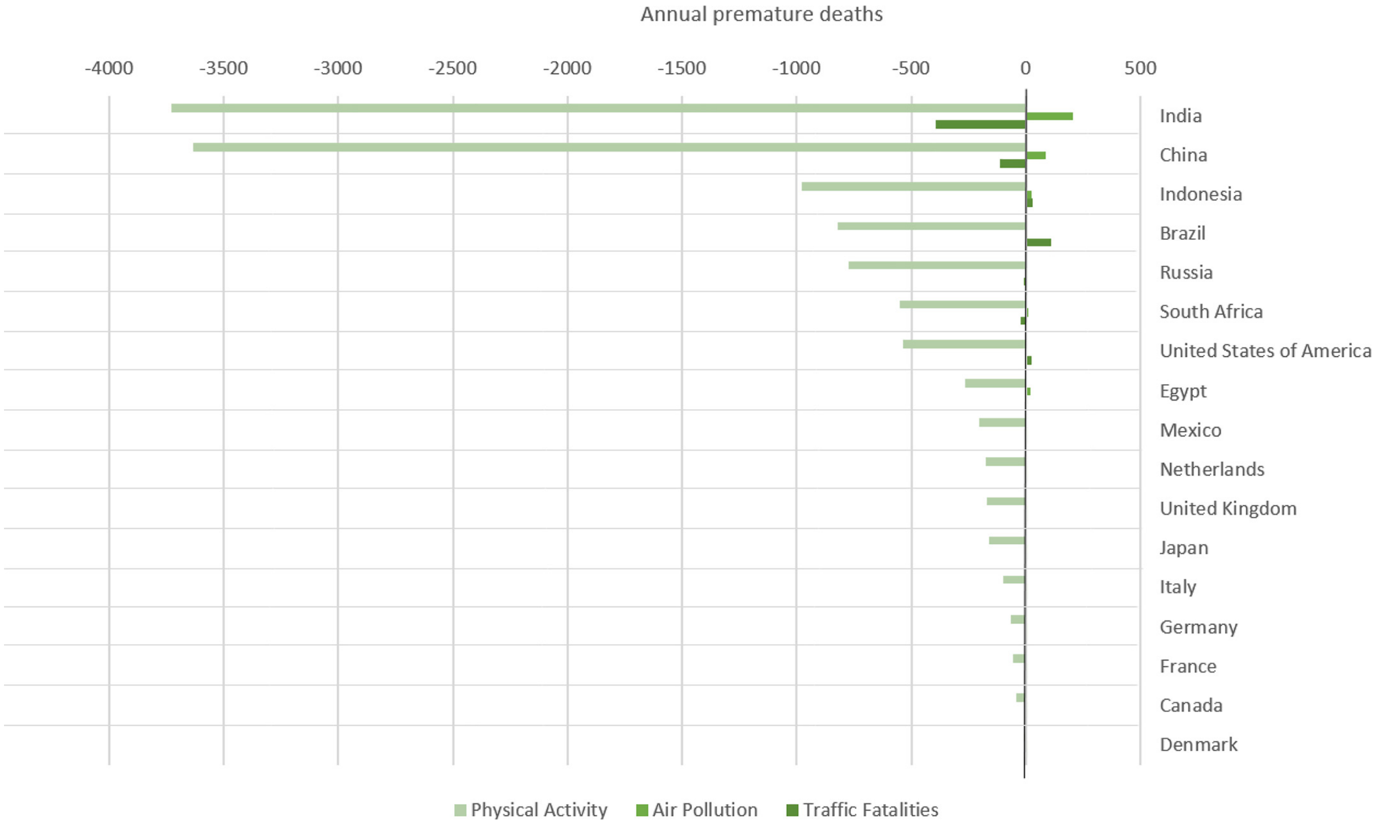

Figure 3. Annual premature deaths in 2050 by country and health determinant (Scenario 1).

Scenario 1

If HBU levels are achieved by 2050, and 8% of these future bike trips replace car trips, the estimated premature annual deaths avoided based on the model assumptions could be 18,589 (95% UI: 11,396, 28,969) among the 17 countries (conservative scenario) (Table 2). This means that 112% more annual premature deaths will be avoided due to bike use in the HBU in comparison with the current 2050 bike trends (assuming 8% of car–bike substitution). In absolute numbers, the top five countries with the largest benefits will be India [6,987 annual premature deaths avoided (95% UI: 4,349, 10,787)], China [4,127 annual premature deaths avoided (95% UI: 2,694, 6,332)], Indonesia [1,437 annual premature deaths avoided (95% UI: 737, 2,376)], Russia [1,302 annual premature deaths avoided (95% UI 900,1,940)] and the United States [1,227 annual premature deaths avoided (95% UI: 816, 1,865)]. When this result was adjusted by 100,000 bicyclists, it was estimated that 17.67 annual premature deaths could be avoided among the urban populations from the 17 countries, ranging from 2.35 in Denmark to 38.82 in South Africa (see Table S22). We also found in Scenario 1 that e-bike use in 2050 could prevent 7,639 annual premature deaths, whereas 10,950 premature deaths could be prevented from use of mechanical bikes among the urban populations from the 17 countries. In the $PM_{2.5}$ sensitivity analysis, when we used an alternative DRF for $PM_{2.5}$ and all-cause mortality (Chen and Hoek 2020), we estimated between 1.6% (in India) and 0.2% (in Russia) fewer premature deaths could be avoided. In the traffic incident sensitivity analysis, using the "estimated" country traffic fatalities (as reported by the WHO) (WHO 2018) instead of the reported data, we found that the overall health impacts (physical activity, air pollution, and traffic fatalities) were 12,001 expected premature deaths that could be avoided in China (using the estimated data), and 12,641 expected premature deaths could be avoided in India (using the estimated data) (see Table S31). In the sensitivity analysis using a 2050 mortality rate (instead of 2017) for those 20–64 y old, we found in China 3,543 annual premature deaths avoided; 3,666 in India; 892 in Indonesia; and 635 in Russia (see Table S32). When we use a 2050 mortality rate but include people age 20 y and older, we found 34,896 annual premature deaths prevented in China; 10,161 in India; 3,327 in Indonesia; and 2,241 in Russia (see Table S32).

Scenario 2

If HBU levels are achieved by 2050, and 100% of these future bike trips replace car trips, the estimated premature annual deaths avoided, based on the model assumptions, could be 205,424 (95% UI: 123,592, 322,850) among the 17 countries (ambitious scenario) (Table 2). This means 89% more annual premature deaths avoided due to bike use in the HBU in comparison with the current 2050 bike trends (assuming 100% of car–bike substitution). In absolute numbers, the top 5 countries with the largest benefits will be India [87,337 annual premature deaths avoided (95% UI: 54,350, 134,832)], China [25,153 annual premature deaths avoided (95% UI: 15,209, 40,530)], Indonesia [17,968 annual premature deaths avoided (95% UI: 9,211, 29,071)], Russia [16,274 annual premature deaths avoided (95% UI: 11,246, 24,262)] and the United States [15,309 annual premature deaths avoided (95% UI: 10,199, 23,308)].

Discussion

This study found that HBU in urban populations across 17 countries by 2050 could prevent up to 205,424 annual premature deaths if 100% of these future bike trips replace car trips. In a conservative scenario, if only 8% of these future bike trips replace car trips, HBU could prevent 18,589 annual premature

Table 2. Changes in annual premature deaths of 2050 high bike use scenarios in 17 countries (Scenario 1 and 2).

	2050							
	Scenario 1. Conservative high bike use (only 8% of all future bike trips will replace car trips)				Scenario 2. Ambitious high bike use (100% of all future bike trips will replace car trips)			
Country	Annual premature deaths	LUI	UUI	Percentage of change between 2050 trends vs. high bike use (%)	Annual premature deaths	LUI	UUI	Percentage of change between 2050 trends vs. high bike use (%)
Brazil	−859	−379	−1,571	114%	−10,747	−4,732	−19,633	114%
Canada	−96	−65	−144	218%	−1,205	−807	−1,794	224%
China	−4,127	−2,694	−6,332	57%	−25,153	−15,209	−40,530	24%
Denmark	−17	−13	−25	283%	−144	−102	−214	17%
Egypt	−399	−180	−710	153%	−4,241	−1,796	−7,702	106%
France	−160	−108	−241	276%	−2,132	−1,452	−3,195	106%
Germany	−206	−145	−301	282%	−2,749	−1,941	−4,008	109%
India	−6,987	−4,349	−10,787	162%	−87,337	−54,350	−134,832	162%
Indonesia	−1,437	−737	−2,326	143%	−17,968	−9,211	−29,071	143%
Italy	−100	−63	−146	100%	−1,257	−788	−1,814	101%
Japan	−181	−122	−274	113%	−2,271	−1,520	−3,435	113%
Mexico	−571	−204	−944	268%	−7,133	−2,554	−12,037	268%
Netherlands	−28	−20	−44	16%	−357	−247	−536	17%
Russia	−1,302	−900	−1,940	153%	−16,274	−11,246	−24,262	153%
South Africa	−707	−473	−1,045	117%	−8,839	−5,836	−13,058	117%
United Kingdom	−185	−128	−274	107%	−2,308	−1,602	−3,421	107%
United States of America	−1,227	−816	−1,865	218%	−15,309	−10,199	−23,308	218%
Total	−18,589	−11,396	−28,969	112%	−205,424	−123,592	−322,850	89%

Note: HUI, high uncertainty interval; LUI, low uncertainty interval.

deaths by 2050 among the urban populations of 17 countries. In all the countries and scenarios, the reductions of premature mortality (due to physical activity) related to bike use outweighed the increments of premature mortality due to air pollution inhalation and traffic incidents, with an average benefit:risk ratio among the 17 countries of 32:1.

To our knowledge, this is the first study assessing the health impacts of future and global biking scenarios. This study included urban populations from 17 countries (Brazil, Canada, China, Denmark, Egypt, France, Germany, India, Indonesia, Italy, Japan, Mexico, Netherlands, Russia, South Africa, United Kingdom, and the United States) across 5 continents and considered mechanical and e-bikes. This study provides a systematic assessment comparing biking trends and HBU scenarios for 2050.

The results of this study are in accordance with findings from previous biking HIAs using similar health exposures (physical activity, air pollution, and traffic fatalities) (Mueller et al. 2018a; Otero et al. 2018; Rojas-Rueda et al. 2012, 2013, 2011, 2016; Stevenson 2017; Woodcock et al. 2014; Zapata-Diomedi et al. 2017). Unlike previous studies that have been focused on single cities (Rojas-Rueda et al. 2012, 2016; Woodcock et al. 2014; Zapata-Diomedi et al. 2017) or a comparison of few cities (Stevenson 2017), our study focused on the national urban populations in comparing 17 countries, providing a global perspective of similar biking scenarios in the future (2050), including the health impacts in low- and middle-income countries. Like previous studies, this HIA focused on car trip replacement, considering that shifting car trips to active transportation could have larger health benefits, in addition to other important climate and environmental co-benefits (Rojas-Rueda et al. 2013, 2016).

This study found that the health impacts of biking vary among countries. In the most realistic of our scenarios, Scenario 1, using the average (8%) reported car–bike substitution related to multiple bike interventions among 26 cities in China, Europe, and North America, we estimated that in 2050 an HBU scenario could result in the avoidance of 18,589 annual premature deaths, ranging from 2.35 annual premature deaths per 100,000 bicyclists in Denmark to 38.82 in South Africa. The estimated differences, comparing a similar number of bicyclists across countries, could be explained by the difference between trip distances, speed, days traveled per year, average levels of physical activity, air quality, traffic fatalities, and baseline mortality rate in each country. If national and local stakeholders could improve traffic safety, air quality, and bike usability, larger reductions in premature mortality related to biking scenarios could be expected in the future. In addition, we found that if more bike trips replaced car trips in each country, benefits could increase by 1,105% (comparing Scenario 1, 18,589 annual premature deaths avoided vs. Scenario 2, 205,424 annual premature deaths avoided). This scenario comparison highlights the importance of car-trip substitution policies for health, and the combination of bike policies (e.g., bike lanes, bike parking, bike-sharing systems, etc.) with policies aiming to reduce car use (e.g., parking pricing and reduction, congestion pricing, etc.).

We performed our analysis distinguishing between e-bikes and mechanical bikes. E-bikes offer different levels of electric assistance (Otero et al. 2018). In our analysis was assumed that e-bikes were used in a "standard assistance" function. "Standard assistance" e-bikes consider 90% of the physical activity needed to ride a bike compared with that needed to ride a mechanical bike (e-bikes' 6.12 METs vs. 6.8 METs of mechanical bikes) (Otero et al. 2018). In addition, we also assumed a higher traffic fatality for kilometers traveled by e-bike compared with mechanical bikes (Otero et al. 2018). Fewer mortality benefits have been found among e-bikes in previous studies (Otero et al. 2018), mainly due to the lower number of expected trips compared with mechanical bikes. In our study, e-bikes had the largest estimated increment of avoided premature deaths compared with mechanical bikes by 2050 (173% vs. 90%) due to the expected increase in future e-bike sales. We also found that in all countries and scenarios, the reductions in premature mortality from e-bike use related to physical activity outweigh the increments of premature mortality due to traffic fatalities and air pollution inhalation, similar to findings for mechanical bikes.

Physical activity resulted in the largest health impacts in our analysis. Physical activity can prevent several noncommunicable diseases, such as cardiovascular disease, diabetes mellitus, colon and breast cancers, and dementia, among others, which can also reduce the overall mortality (Rojas-Rueda et al. 2013). This study focused on all-cause mortality as a health outcome because it has been suggested as the outcome with the largest health impacts, in comparison with morbidity, in previous HIAs of active transportation (Mueller et al. 2015; Otero et al. 2018; Rojas-Rueda et al. 2013). The TAPAS tool for biking estimated the health impacts of physical activity using a nonlinear DRF from a meta-analysis of cohort studies (Woodcock et al. 2011) and calibrated with the corresponding physical activity levels reported by the adult population in each country and applied to the exposure levels by each scenario and country assessed. The nonlinear function considers that people who already were physically active would gain fewer reductions in premature mortality in comparison with those who are more sedentary. This nonlinear approach results in fewer mortality benefits compared with using a linear DRF (Rojas-Rueda et al. 2016).

The air pollution assessment included in this study was based only on $PM_{2.5}$ inhalation during the trip. Although changes in modal share, especially shifts from car to bike, are expected to produce changes in air pollution emissions and concentrations at the city and regional levels (Rojas-Rueda et al. 2012), these air quality and health-related impacts were not in the scope of this study, and we focused only on the $PM_{2.5}$ biking exposure during the trip. $PM_{2.5}$ was chosen because it was expected to produce the largest health burden in comparison with other air pollutants, such as NO_2 or black carbon (Rojas-Rueda et al. 2013). We also decided not to include these other pollutants in the analysis because these are highly correlated and produce similar health outcomes (Otero et al. 2018). We found differences between the health impacts associated with $PM_{2.5}$ among the urban populations from 17 countries and scenarios. These differences can be explained by the variability in air pollution levels, trip characteristics (duration and frequency), and physical activity among the countries and scenarios. Annual average $PM_{2,5}$ concentrations among the 17 countries included ranged from $109.5\ \mu g/m^3$ in Egypt to $6.87\ \mu g/m^3$ in Canada (WHO 2019). If national and local authorities implement and promote policies to improve air quality to those levels recommended by the WHO ($PM_{2.5}$ annual average concentrations $<10\ \mu g/m^3$ (WHO 2006), the expected reductions in premature mortality in our scenarios could be larger.

The traffic fatality assessment quantified fatal traffic incidents per billion kilometers traveled. To create this model, we used the reported national road safety estimates provided by the WHO in each country (WHO 2009, 2013, 2015, 2018). This study only took into account the traffic fatality risk by mode of transport (car, bike, and e-bike) but did not assess the impacts related to other traffic risk factors, such as traffic route, traveler age, or sex, due to the lack of data on these specific characteristics from traffic safety records from each country. From the 17 countries included, 13 reported a higher risk of traffic fatalities per kilometers traveled by bike compared with travel in a car (WHO 2009, 2013, 2015, 2018). China, India, Russia, and South Africa reported a higher risk for traffic fatalities per kilometer traveled in a car compared with travel by bike (WHO 2009, 2013, 2015, 2018). These greater traffic risks in cars vs. on bikes in China, India, Russia, and South Africa could be explained by the low traffic safety levels in those countries, resulting from having fewer national car safety policies in comparison with high-income countries, in addition to having older vehicle fleets and poorer transport infrastructure (Vinand and Reich 2014). Another explanation could be the possibility of an incomplete record of traffic safety data (WHO 2018). To provide a better estimation of the traffic fatalities in these countries, we ran a sensitivity analysis using the estimated traffic fatalities records instead of the reported national data, both provided by the WHO (WHO 2009, 2013, 2015, 2018).

The results of our analysis are consistent with previous studies assessing car–bike trip substitution. Otero et al. found a reduction in premature deaths in multiple bike-sharing systems across European cities. According to this study, the 12 largest bike-sharing systems in Europe could avoid up to 73 annual premature deaths with an economic value of 225 million Euros if 100% of bike trips replaced car trips (Otero et al. 2018). Furthermore, it has been suggested that the health impacts of car–bike trip substitution on mortality should be considered in the long term, after 3 or 4 years of achieving the specific car–bike substitution level (Otero et al. 2018). These effects on mortality would be mainly due to the impacts of physical activity and air pollution, which have to be maintained over time before the effects would be perceptible (Rojas-Rueda et al. 2013).

Moreover, to improve health in cities, other urban interventions in addition to bike interventions should also be considered. In Barcelona, Spain, the Superblock model has been implemented to promote sustainable mobility and an active lifestyle (Mueller et al. 2020). It has been suggested that this built environment intervention could also help prevent premature mortality (Mueller et al. 2020). Overall, each city has unique geographic, environmental, and sociocultural characteristics that influence the health status of its inhabitants. Identifying and improving these characteristics may help promote healthier cities (Mueller et al. 2018b).

As in all quantitative HIAs, our study was limited by the availability of data and the necessity to make assumptions to model likely scenarios. In terms of the scenarios modeled, the forecast for 2050 was based on a previously published report from the Global High Shift Cycling study that estimated the bike use scenarios for several countries and all regions around the world (Mason et al. 2015). Due to the lack of transport and health data to perform the assessment in all the countries reported by the Global High Shift Cycling study, we could include only 17 countries from those reported in this study (Mason et al. 2015). The lack of data was particularly common in low- and middle-income countries, such as countries in Africa and the Middle East (WHO 2018). The Global High Shift Cycling study forecast biking and transport scenarios based on modal share predictions estimating the number of trips per person per day, distance traveled per mode, and the urban population projections for 2050 (Mason et al. 2015). The Global High Shift Cycling study was limited by the availability of transport estimations at the national level and the need to include transport assumptions in their analysis, such as the use of constant average trip lengths and speed across modeled years (Mason et al. 2015).

Another limitation was the lack of specific modal shift data from car to bike in the Global High Shift Cycling study (Mason et al. 2015). For this reason, in addition to the 2050 HBU scenario provided by the Global High Shift Cycling study, we created additional subscenarios to capture the variability in the expected car–bike substitution levels in the future years in all the countries (Scenarios 1–4). These car–bike substitution scenarios were based on data available from 26 cities from China (Ma et al. 2019), Europe (Bjørnarå et al. 2019; Oakil et al. 2016; Otero et al. 2018; Scheepers et al. 2014), and the United States (Scheepers et al. 2014), where previous studies reported the car–bike substitution levels of multiple urban bike interventions, such as the implementation of bike-sharing systems, bike infrastructure, and bike promotion and education. Although this data combined different cities, we acknowledge that these estimations could not reflect the reality of car–bike substitution across the globe, mainly because this data comes primarily from high-income countries, with only three cities coming from China (Ma et al. 2019). Based on the data for these 26 cities, we estimated that on average multiple bike interventions could support an average 8%

car–bike substitution, which we used in Scenario 1. We also used the maximum (35%) and minimum (0.46%) reported car–bike substitution among the 26 cities and used these as a reference for our Scenarios 3 and 4, respectively. We also estimated the health impacts of a hypothetical scenario, based on "what if" 100% of the future bike trips were to replace cars trips, to provide an overall picture of the health opportunities related to large biking interventions (Scenario 2).

In the sensitivity analysis using a 2050 mortality rate (instead of 2017) for those 20–64 y old, in Scenario 1, we found a slightly lower number of premature deaths avoided. This finding can be explained because mortality rates in the countries analyzed (similarly to the global trend) are expected to improve by 2050 (IHME 2020).

When we use a 2050 mortality rate but include people age 20 y and older, assuming that an aging population will also affect the cyclist population, we found that the number of annual premature deaths prevented increased importantly. This finding can be explained because including older age groups (such as 65 y and older) will increase the mortality rates and affect the number of premature deaths that could be prevented if bike use increases by 2050. These sensitivity analyses, considering those age 20 y and older, also highlight the importance of promoting and implement active transportation policies to support older age groups. In addition, in this study, we assessed the uncertainty of our estimates, providing UIs that were composed by the variability of the input data, using the changes (maximum and minimum) and the CIs from the DRF from air pollution and physical activity.

To achieve HBU among the urban population, the following policies have shown to bring a quick increase in biking levels: retrofitting biking infrastructure onto existing roads to create backbone networks in arterial streets, small residential streets, and intercity roads; implementation of bike-share systems in large cities; laws and enforcement practices to better protect active transport; investment in walking facilities and public transport to offer transport options that can be combined with bike trips; elimination of policies that support additional motorized vehicle use, such as free parking and fuel subsidies; and establishment of congestion pricing, vehicle-kilometers traveled fees, and development impact fees to charge a price for driving (Mason et al. 2015). In our analysis, we have also quantified an intermediate year (2030) to provide a vision of the health opportunities that HBU scenarios could provide if those are achieved sooner (see Tables S19–S30).

General recommendations can be extracted from this study for national and local authorities, health practitioners, and researchers. Regarding local and national transport authorities, this study supports the implementation of strong bike and car substitution policies as key interventions for healthy and sustainable development. Furthermore, transport authorities should consider systematic data collection through travel surveys and traffic counts at national and local levels, prioritizing data on modal share, number of trips per person/mode/day, trip frequency, duration, length, and transport mode shifts. These data will help policymakers and stakeholders to understand travel behavior and plan for specific transport interventions. Also, these data should be harmonized among cities, countries, and regions and published in an open-access format. We also found a lack of needed transport and health data from low- and middle-income countries that authorities and researchers could help collect and harmonize. The need for such data is especially important because low- and middle-income countries face a faster population growth (IHME 2020), increasing epidemiological transition to noncommunicable diseases (IHME n.d.), and rapid urbanization (Stevenson 2017). For health practitioners, these study supports the prioritization of interdisciplinary collaborations among urban and transport planners and health practitioners, considering current and future active transport policies for health promotion and prevention, improving collaborations on road traffic safety, air quality, physical activity, and transport and health equity.

Conclusions

We found that global bike use may provide important reductions in premature mortality by 2050. If biking trips above current trends (high bike use scenario) are achieved by 2050, 205,424 annual premature deaths could be prevented among Brazil, Canada, China, Denmark, Egypt, France, Germany, India, Indonesia, Italy, Japan, Mexico, Netherlands, Russia, South Africa, the United Kingdom, and the United States. The mortality benefits of physical activity drive the health impacts estimated in this study. In all countries and scenarios analyzed, the benefits of physical activity outweighed the mortality risks related to air pollution inhalation and road traffic fatalities. Future reductions in premature mortality of bike use will depend on current and future transport and built environment policies, promoting active transportation, car–bike substitution, air quality, and traffic safety. Implementing ambitious urban policies supporting biking and car–bike substitution should be considered key public health interventions for a healthy urban design.

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