communications earth & environment

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https://doi.org/10.1038/s43247-022-00497-4 OPEN

Historical patterns and sustainability implications of worldwide bicycle ownership and use

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Bicycles are widely recognized as an effective solution for reducing short-distance trip-related climate impacts and addressing sedentary lifestyle-caused chronic diseases. Yet, the historical patterns of global bicycle production, trade, stock, and use remain poorly characterized, preventing thorough investigation of its role in sustainable road transport transition. Here, based on a dynamic model and various data sources, we have compiled, to our knowledge, the first global dataset for bicycle ownership and use by country from 1962 to 2015. Our comparison between the historical development of per-capita bicycle ownership and car ownership reveals five varying types in an S-curve among different countries. High bicycle ownership does not necessarily lead to high bicycle use, which is instead still marginal in daily trips worldwide (<5% for most countries). A worldwide pro-bicycle policy and infrastructure development enabled modal shift like the Netherlands and Denmark can lead to significant untapped climate and health benefits.

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The transport sector accounts for one-quarter of global fuel-related greenhouse gas (GHG) emissions, and half of these emissions are from passenger cars[1]. The global demand for passenger road transport is anticipated to increase by approximately three times by 2050[2], further exacerbating the climate challenges. Technological mitigation strategies for passenger cars alone, such as electrification, lightweight, and fuel efficiency improvement[3–11], are insufficient to achieve corresponding climate target[12]. Travel behavior changes[13] and modal shifts from passenger cars to bicycles for short-distance trips that are too far for walking and too short to transit[14] are also necessary for a global sustainable transport transition.

Dating back to the early 19th century, bicycles have a longer history than motorized cars[15]. They have been used for multiples purposes, ranging from military operations in the first and second world wars[15] to being used for sport, recreation, and traveling purposes. Nonetheless, as of this writing, bicycles only play a marginal role in transport in most world countries[16,17]. In fact, most western countries still depend largely on cars for daily travel with a high motorization rate after the 1970s, with few notable exceptions of countries with pro-bicycle policies[18] such as the Netherlands and Denmark. These numbers indicate a substantial untapped potential of increasing cycling trip shares worldwide to reduce transport related GHG emissions, which deserves a close look facing the global climate urgency. On the one hand, the GHG emissions of trips on bicycles are almost negligible compared to car trips[19]. On the other hand, the frequent use of bicycles can change the car-based sedentary lifestyles[20,21], increase physical activity, and thus lead to a lower risk of all-cause mortality, especially chronic diseases like obesity and cardiovascular diseases[22–26].

The scientific understanding on the scale and impact of such long-discussed[27,28] modal shift from passenger cars to bicycles, however, is rather scattered, due largely to data gaps on bicycle stocks and use on a global scale. First, the bicycle stock data are difficult to obtain directly from statistics because most countries do not have bicycle registration system like that of cars. Even the bicycle production data are incomplete: Such production statistics exist only for some countries (e.g., in Europe) for the recent years, and longer time-series production data are not available for most countries across the world. The historical bicycle consumption and lifetime distribution data can be combined to estimate bicycle stocks based on a dynamic material flow analysis approach[29,30], but for deriving apparent consumption or sales, international trade data would be needed as well. Second, although the bicycle stocks provide basis for short-distance person mobility[31], the real relationship between the stock and use of bicycles on a large scale remains unknow. For example, in countries like the U.S., there is often a lack of correspondence between bicycle ownership and use for transportation. Third, from health to transport to environment and planning, the existing literature on bicycles and bicycle use is rich[14,27,32] but focuses only on a handful of cities and regions[24] (e.g., Stockholm in Sweden[33], Flanders in Belgium[25], London in the UK[34], and some cities in the U.S.[35]) and is mainly based on data from travel surveys. A recent study has combined the bicycle counter and bicycle lanes data for 106 European cities for 4 months in 2020[36]. However, a dynamic and systemic understanding of bicycle production, stock, and use across the world and their sustainability implications is still missing and requires further exploration, which we aim to address in this work.

Here we have compiled, the first to our own knowledge, global dataset for bicycle production, trade, stock, and ownership by country from 1962 to 2015, based on a dynamic material flow analysis model (see Methods) and a combination of bottom-up and top-down data collected from various sources (see Supplementary Tables 2–7). We have subsequently revealed the various national bicycle ownership patterns, vis-à-vis passenger car ownership, and subsequently identified five varying types among different countries in the global road transport transition. We have then discussed potential drivers and sustainability implications (e.g., GHG emission mitigation and prevented deaths) of increasing bicycle use.

Results and discussion

The global overview of bicycle production and stock. Global production of bicycles increased from 20.7 million units in 1962 to 123.3 million units in 2015, with a compound annual growth rate of 3.4% which is higher than that of global car production (3.0% from 14.0 million units to 68.6 million units) in the same period. The global bicycle production has particularly thrived since the 1970s, with a much higher growth rate than car production, and after a stagnating period in the 1990s, it revived after 2000 and leveled off at a high level of 111 million units in recent years. The aggregated amount of global bicycle production from 1962 to 2015 is 4.65 billion units, which is 2.4 times of the aggregated amount of global car production.

In 2015, China alone accounted for 65.7 % of global bicycle production, while the U.S. had been the world's largest bicycle producer until 1975. China became the largest producer after 2002 (Fig. 1 and Supplementary Fig. 5 in the supplementary material) and has produced over half of global bicycles since then. The other top countries for bicycle production after China were Brazil, India, Italy, and Germany, taking up 5%, 4%, 2%, and 2%, respectively, of the total global production.

The share of the top five countries in bicycle sales decreased from 67% in 1962 to 44% in 2015 because China's sale share decreased dramatically recently. China has overtaken the United States and dominated (22%) the global bicycle sales since 1980. Then China's share in global sales continued to increase to 45% in 1987 and remained at a high level of around 39% in China's golden time of bicycles from the early 1980s to the mid-1990s[29]. In contrast, the global sales shares of other major countries have not changed much. In 2015, the other three top countries in bicycle sales after China and the U.S. were Brazil, Japan, and Germany, taking up 4%, 4%, and 3%, respectively, of the global total. On a per capita level, however, the top countries are found in Europe (mostly Nordic countries), Japan, and the U.S.

The global bicycle stock and car stock growth from 1962 to 2015 showed varying patterns. The global bicycle stock continued to increase to 1.9 billion units in 2015. The top five countries in terms of bicycle stock (1.0 billion units and above) in 2015 were China, the U.S., India, Japan, and Germany, which add up to over 54% of the global total. This share increased significantly from 62% in 1980 to 68% in 1999 due to the cycling boom in China during this period, but decreased afterward as a result of the fast motorization in China. Nevertheless, China is still the country with the largest bicycle stock, accounting for 24% of the global total. Meanwhile, the global car stock increased from 0.1 billion units in 1962 to 1.1 billion units in 2015. The top five countries in terms of car stock in 2015 were sequentially the U.S., China, Japan, Germany, and Russia, which add up to 0.5 billion units or approximately 50% of the global total.

Historical patterns of bicycle ownership vis-à-vis car ownership in road transport. Generally, per-capita bicycle ownership is higher than per-capita car ownership in most countries, especially in industrialized countries (see Supplementary Fig. 10 and Supplementary Fig. 11). The global per-capita bicycle ownership continued increasing until 1995 and then remained around 0.29 unit percapita afterward (Supplementary Fig. 8). Nationally,

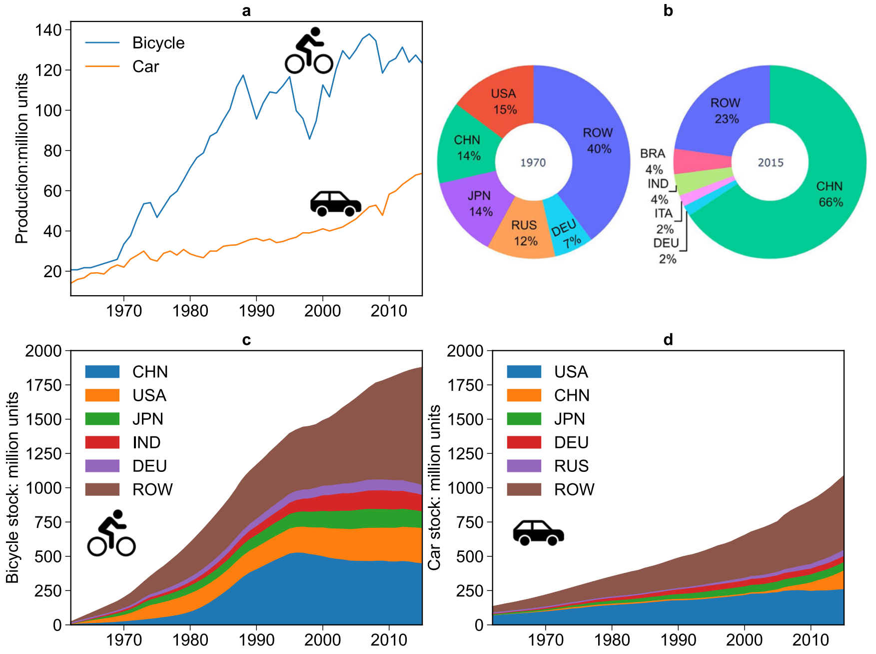

Fig. 1 Historical overview of global car and bicycle production and stock from 1962 to 2015. a Historical global production of car and bicycle from 1962 to 2015, **b** The share of global bicycle production in 1970 and 2015, **c** Bicycle stock from 1962 to 2015, **d** Car stock from 1962 to 2015. Bicycle refers to conventional human-powered ones only, while the car category includes all types of four-wheeled private vehicles such as small passenger cars, sports utility vehicles, and light trucks. The country codes are based on ISO 3166-1 alpha-3 code. ROW indicates the rest of world.

European countries are among the highest. For example, Denmark, the Netherlands, and Norway all have over one bicycle per capita. The Netherlands and Denmark have always been the top two in terms of bicycle ownership after 1970. Around 95% of people in Denmark own at least one bicycle[37], and its per capita bicycle ownership exceeds that of the Netherlands and remains the world's highest after 1990, due mainly to education-cultivated cycling culture and well-developed cycling infrastructure[38]. Bicycle ownership in many low and middle-income countries (e.g., Africa and Asia), on the contrary, is less than the median per-capita bicycle ownership (0.3 unit per capita in 2015) of the 60 world major countries. Japan has the highest bicycle ownership per capita (0.95 unit per capita in 2015) in Asia.

Figure 2 portrays the evolutionary patterns of per capita bicycle ownership, vis-à-vis car ownership, of the 60 world major countries from 1962 to 2015. The comparison between the historical development of bicycle ownership and car ownership (see Supplementary Fig. 12) reveals five varying types (Supplementary Table 8) in an S-curve in the historical patterns of road passenger transport and socioeconomic development of countries.

The type 1 and type 2 countries are mainly low- and middle-income countries, in which bicycle ownership is higher than car ownership due to affordability. Their level of bicycle and car ownership is far less than the global median. The type 1 countries are at the extremely low levels for both bicycle and car ownership with an average value of 0.08 and 0.04 unit percapita, respectively, in 2015. As the countries continue to develop, the motorization rate gradually increases but remains still low in most type 1 countries (e.g., India and Bolivia). Type 2 countries have a relatively higher income level, and only 10% are in the lower middle income category. Compared with type 1 countries, the type 2 countries witnessed fast motorization with a rapid increase in car ownership over the past three decades. Their bicycle ownership, on the contrary, often levels off or even decreases (as shown by China, Chile, and Brazil) at the same time; and only a few countries (i.e., Korea, Romania, and Ukraine) resurged in bicycle ownership after their motorization rate gradually slows down.

Type 3, type 4, and type 5 countries are all high-income countries, reflecting that high-income countries tend to have more diverse road transport patterns. The type 3 countries, similar to type 2 countries, show an extremely rapid increase of car ownership and a slow increase of bicycle ownership, while both are on a higher level than that of the type 2 countries. For example, in Poland, Portugal, Italy, and Spain, car ownership in 2015 reached approximately 0.44 to 0.62 unit per capita, which is much higher than the global median in this year. Car ownership in Italy doubled (from 0.30 to 0.62 unit per capita) over the past 35 years, which is 131% higher than the global median value; however, its bicycle ownership was only 0.31 unit per capita in 2015, which is 3% below the global median level in 2015. The type 4 countries show the highest car ownership level and a high bicycle ownership level, which is 142% and 140%, respectively, higher than the global median in 2015. These countries (the U.S., Canada, Australia, and New Zealand) have vast land areas and cities with relatively low population densities, forcing residents into a car-centric lifestyle and resulting in unsustainable mobility patterns[39]. The type 5 countries show the highest level of bicycle ownership (which is 181% higher than the global median level) and a high but saturated level of car ownership (which is lower than that of the type 4 countries and falls into the range of the type 3 countries). These countries are industrialized countries in Europe where the basic transport needs are met already, and the pursuit for a more environmentally friendly and healthier life has driven the increase of bicycle ownership.

The global pattern of bicycle and car use. Figure 3 shows that, in comparison to cars, ownership for bicycles plays a less important role in their usage. Bicycle ownership in 2015 only explains 36% of the variation in bicycle use in that year. In other words, a higher bicycle ownership does not necessarily guarantee an increased bicycle use. To date, bicycle plays a marginal role in travel mode selection in most countries. Among the 60 countries

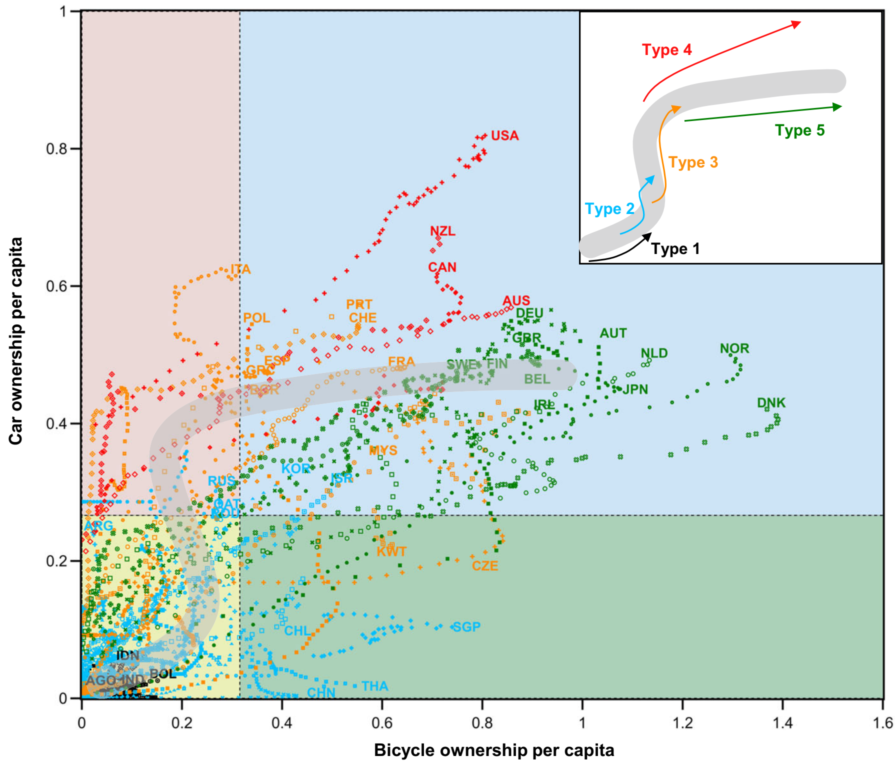

Fig. 2 Historical per-capita bicycle ownership versus per-capita car ownership from 1962 to 2015. The figure is divided into four quadrants with color by median values of the two in 2015 (the dashed lines in the figure). The first (blue), second (pink), third (yellow), and fourth (green) quandrants thus indicate combinations of high bicycle ownership & high car ownership, low bicycle ownership & high car ownership, low bicycle ownership & low car ownership, and high bicyle ownership & low car ownership. The black, blue, orange, red, and green dots, letters, or lines in both inner and outer figures indicate Type 1, Type 2, Type 3, Type 4, and Type 5 countries respectively, which are further detailed in Table 1, Supplementary Table 8, and Supplementary Fig. 12. The country codes are based on ISO 3166-1 alpha-3 code. The indicative grey belts in both outer and inner figures summarize the evolutionary pattern with five varying types among different countries.

Table 1 The five varying types in historical development of per capita car and bicycle ownership.

Types	Characteristics	The share of countries at different income levels (based on income classification defined by the World Bank)
Type 1	Low bicycle ownership and low car ownership	Low income (17%), Lower middle income (58%), Upper middle income (25%)
Type 2	Rapid motorization with increasing car ownership and decreasing or resurging bicycle ownership in recent years	Lower middle income (10%), Upper middle income (57%), High income (33%)
Type 3	Further rapid motorization with both high car and high bicycle ownership	Upper middle income (17%), High income (83%)
Type 4	The highest car ownership and high bicycle ownership	High income (100%)
Type 5	The highest bicycle ownership and high but saturated car ownership	High income (100%)

included in our dataset, the average bicycle modal share accounts for less than 5%. Intuitively, countries with low bicycle ownership (mainly in the third quadrant, predominantly low-income countries) also have low bicycle modal share because they lack access to a bicycle. Further, countries with high bicycle ownership (especially type 4 and type 5 countries in the fourth quadrant) but with similarly low bicycle modal share deserve a closer look. Instead, countries in the first quadrant have high ownership and high modal share (both are much higher than the global median level). In particular, the Netherlands and Denmark represent the top level of the bicycle modal share (higher than 20%) and bicycle ownership (over 1 unit percapita) in the world. Comparing to these countries, the countries in the lower part of the first quadrant and in the fourth quadrant either have special climate and terrain conditions (e.g., in cold and hilly Norway and dry and hot Kuwait where bicycle use is challenging) or dependence on cars (e.g., in the U.S. and Australia where bicycle use is more seen as a leisure activity).

Car ownership and car modal share are well correlated ($R^2 = 0.57$, $p = 0.000$). The car modal share is relatively low (25–38%) in countries with low car ownership (in the third quadrant), and it increases to 40% or higher as car ownership increases, reaching as high as 74% for type 4 countries. The few exceptions where car modal share remains low and car ownership is relatively high, such as Switzerland, Japan, and the Czech Republic, have well-developed and efficient public transportation systems (e.g., public buses and subways) to satisfy their main mobility demand.

To explore other factors that influence bicycle modal share, we tested the correlation between bike use patterns and potential influence factors. Previous studies have identified built environment[40,41], individual behavior[14,42], and trip

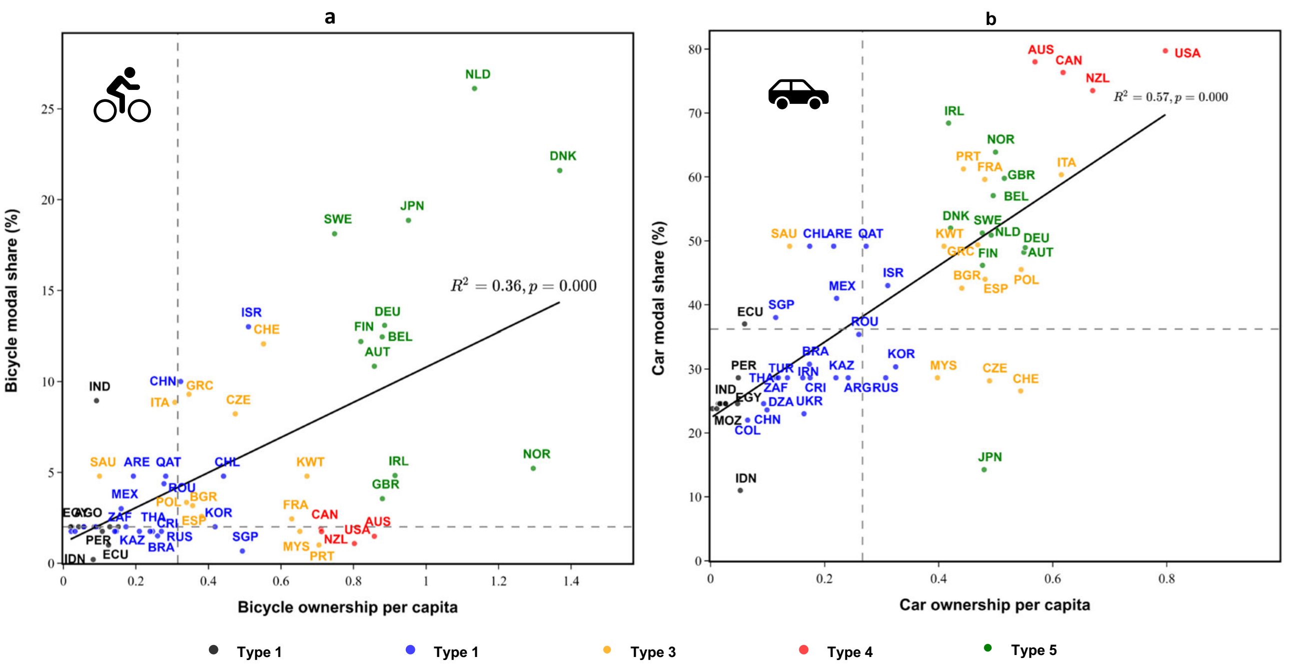

Fig. 3 The patterns of the car and bicycle use in 2015. a Bicycle modal share against bicycle ownership per capita, and **b** car modal share against car ownership per capita. The dashed lines indicate the median values of the x-axis and y-axis, which splits the figures into four quadrants. The solid lines in **a** and **b** show results of the linear regression fitting. See details of regression results in Supplementary Table 9 and Supplementary Table 10.

characteristics[14,16,43,44] as important factors underlying the use patterns of bicycles. Based on this, we collected data and tested the influences of four key parameters (car ownership, income level, population density, and traffic safety) to bicycle use patterns in various countries (see Supplementary Fig. 15). For countries with relatively high car ownership (especially type 4 countries in Fig. 2), higher car ownership and thus car addiction would negatively impact bicycle modal share. We also noticed that countries with extremely high income level and bicycle ownership (e.g., the Netherlands and Denmark) tend to increase bicycle use, likely due to some special country characteristics, such as a cycling culture, high environmental awareness, well-developed cycling infrastructure, and flat terrains. It is also shown that, among countries with a similar level of bicycle ownership, population density positively affects bicycle use on a daily trip because lower population density often makes driving a necessity (e.g., type 4 countries). Countries with high traffic death rates (e.g., Thailand, Brazil, and Russia) tend to have relatively low bicycle use because cycling can be perceived as dangerous. This finding echoes earlier research that bicycle infrastructure expansion (e.g., separate bicycle lanes) could increase the bicycle modal share[36,45]. For example, the provisional redistribution of street space during the COVID-19 crisis has induced large, rapid increase in cycling[36].

Potential climate and health benefits of increasing bicycle use. Using the bicycle use patterns from the Netherlands and Denmark, the two countries with the highest bicycle modal share (Supplementary Fig. 2), as two reference scenarios, we provided an order-of-magnitude estimate on the health and climate benefits if other countries follow the Dutch and Danish patterns (detailed in Methods). Results (in Fig. 4a) show that approximately 414 million metric tons of carbon emission could be reduced if everyone in the world cycles 1.6 kilometers every day like the Danes[46], which is approximately the same (98%) as the national carbon emissions of the UK in 2015[47]. This climate benefit could be increased to 686 million metric tons if the Dutch cycling pattern was followed with daily cycling distance of 2.6 kilometers; this saving is approximately 86% of the national carbon emissions of Germany in 2015[47], or around 20% of carbon emissions from the global passenger car fleet in 2015[48].

Furthermore, countries with higher cycling modal share tend to have a lower rate of adult obesity[26]. For example, the prevalence of adult obesity in type 5 countries is much lower than that in type 4 countries (see Fig. 4c). Although the prevalence of obesity is a factor of many other socioeconomic, behavioral, cultural, and environmental factors[24,49,50] (which deserve further quantitative and causality analysis in the future), the negative correlation between the prevalence of adult obesity and bicycle modal share sheds light on the potential health benefits of increasing bicycle use.

We quantified the positive and negative health impact based on the health economic assessment tool (HEAT) model developed by World Health Organization. Figure 4b shows that approximately 0.17 million deaths were prevented due to the current level of bicycle use. Compared to this baseline in 2015, another 0.43 million or 0.78 million deaths, respectively, could be potentially prevented in the two thought-experiment scenarios. Meanwhile, the increasing cycling activity will lead to 0.09 and 0.16 million deaths under the current situation of traffic safety in the two scenarios. In the end, 0.34 and 0.62 million deaths could be prevented if the Danish and Dutch cycling patterns were followed globally. Realizing such cycling patterns globally in reality, however, would be challenging. Thus lessons learned from successful experiences in countries like Denmark and the Netherlands, particularly on the city level such as Copenhagen and Amsterdam[51–53], would be essential. These include but are not limited to, for example, proper bicycle lanes planning and constructuion, pro-bicycle education and culture, and policies to discourage car use through tax[45,54–56].

Limitation and outlook. The global bicycle ownership and use data we compiled, as a first estimate, bear unavoidable uncertainties. The drivers and impact analysis are mainly based on the

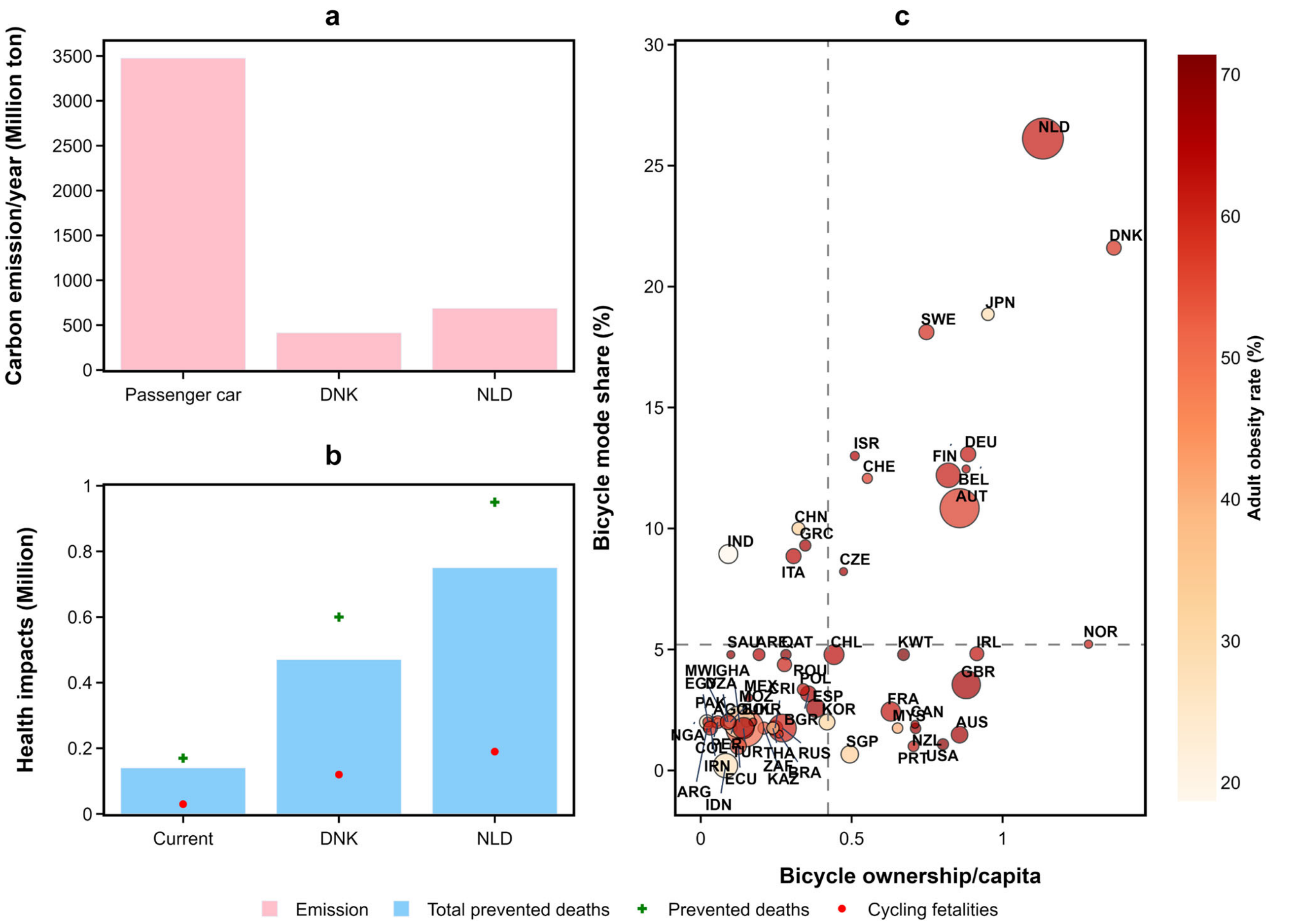

Fig. 4 The potential benefit of increasing bicycle use in two thought-experiment scenarios. a The carbon emissions saving and **b** health benefit (measured as prevented deaths) used in the scenarios assuming the current bicycle use patterns in Denmark and the Netherlands were followed globally. **c** The current bicycle ownership, modal share, and the obesity rate across countries in 2015. The bubble sizes in **c** indicate the stock efficiency of bicycles (defined as km service per bicycle) and the color indicates the rate of obesity across the country.

interpretation of correlation analysis because sufficient bottom-up data (especially at the sub-national and city level) for further causality analysis is not available yet. More city-level data collection via advanced technologies and emerging types of urban big data (e.g., mobile phone or sensor based data and GPS based mobility patterns) in the future could facilitate better understanding of drivers (e.g., behavioral factors[19,57–60]) of bicycle use. Furthermore, the temporal (until 2015 only) and spatial coverage (for 60 world major countries) of our data can be further extended in future analysis. For example, the bicycle sharing scheme which popped up in some countries in the recent years (after 2015) may change the patterns of bicycle stocks and use and deserve a special focus[29]. Nevertheless, we believe our resulst still provide a good basis to elaborate our global history on bicycles, particularly the role of bicycles in sustainable road transport transition. The significant untapped climate and health benefits of increasing bicycle use call for further data collection and quantitative analysis along this line[19,57–60] and suggest an urgent need to promote sustainable bicycle use via supporting policy, planning, and infrastructure development.

Methods

Historical bicycle stock and ownership estimation. We considered only conventional human-powered bicycles in this analysis. We tried to include as many countries as possible across different world regions based on data availability. This eventually adds up to 60 countries or regions covering 95% of the world's GDP, bicycle production, import, and export in 2015 (see Supplementary Table 1).

The statistics and reported data in the literature on bicycle stocks and ownership are often scarce, inconsistent, and generally based on (small-scale) travel surveys. Here, we filled this gap and quantified the historical in-use stocks of bicycles using a dynamic material flow analysis (MFA) and multiple data sources from 1962 to 2015 across the world (Supplementary Tables 2–7).

The apparent consumption of bicycles $I_{c,t}$ that equals to production $P_{c,t}$ plus import $IM_{c,t}$ and minus export $EX_{c,t}$ of bicycles in country c, year t (shown in Eq. 1), is used for bicycle inflows into society due to the unavailable long time-series bicycle sale data by country. Then we used a top-down lifetime delayed method[30,61] to simulate the historical in-use stocks $ST_{c,t}$ for country c in year t (shown in equation2). The final bicycle stock ($ST_{c,t}$) is determined by the initial stock ($ST_{c,0}$) and the accumulated stock from t_0 to t year (as shown in Eq. 2). The initial stock is assumed as zero due to lack of lacking bike stock data before 1961. The accumulated stock is based on the apparent consumption of bicycles from the year t_0 to year t and their associated survival rate $SR_{c,t-a}$ after $t-a$ years step-by-step (see Supplementary Table 3). The bicycle ownership $OW_{c,t}$ is then determined by bicycle stock $ST_{c,t}$ and population $PO_{c,t}$ for country c in year t.

$$I_{c,t} = P_{c,t} + IM_{c,t} - EX_{c,t} \quad (1)$$

$$ST_{c,t} = ST_{c,0} + \sum_{a=t_0}^{t} (I_{c,a} \times SR_{c,t-a}) \quad (2)$$

$$OW_{c,t} = \frac{ST_{c,t}}{PO_{c,t}} \quad (3)$$

Potential carbon and health benefit of increasing bicycle use. We used the Netherlands and Denmark, the two countries with the highest bicycle modal share as two references (Scenario 1 and Scenario 2, respectively), to simulate the potential carbon and health benefits of increasing bicycle use globally. The Netherlands reports the world's highest cycling level, with approximately 2.6 km per cap per day, followed by Denmark (1.6 km per cap per day or 584 km per cap per year). Therefore, the two scenarios are based on assumptions that global travel mode would follow the present levels in the Netherlands and Denmark, respectively. The increased cycling distance L is then determined by the respective national population P, the present ($B_{j=0,c}$), the target daily cycling distance ($B_{j,c}$) in two scenarios, and annual cycling days (D).

Therefore, the climate benefit in terms of carbon emission savings is determined by the increased cycling distance and the difference in emission intensity between passenger cars and bicycles, as shown in Eqs. 4–6 below.

$$L_{j,c} = PO_c \times \left(B_{j,c} - B_{j=0,c}\right) \times D \quad (4)$$

$$\triangle E = \sum_c \left(L_{j,c} \times \alpha \times \left(C_{car,c} - C_{bicycle,c}\right)\right) \quad (5)$$

$$\alpha = \begin{cases} 1, V_c \times \gamma \geq B_{j,c} \\ \frac{V_c \times \gamma}{B_{j,c}}, V_c \times \gamma < B_{j,c} \end{cases} \quad (6)$$

where PO_c indicate population for country c, $L_{j,c}$ indicate increased cycling distance for country c in scenario j, $B_{j=0,c} and\ B_{j,c}$ indicate the present and the target cycling distance for country c, D indicates annual cycling days (here extremely assumed as 365 days), V_c indicate driving distance for country c, $C_{car,c}$ and $C_{bicycle,c}$ indicate per km carbon emission intensity for car and bicycle for country c, α indicates the efficient rate of shifting passenger car trips to bicycle trips, and γ indicates the share of short-distance passenger car trips (see Supplementary Table 7).

We estimated the potential positive health impact based on the health economic assessment tool (HEAT) developed by the World Health Organization[62]. Air pollution is ignored because air quality levels in more than 90% of the cities around the world require cycling more than one and a half hours per day to justify any reduction in health benefits from physical activity[63]. The negative health impact of traffic crashes was ignored. The prevented deaths (positive health impacts) in the scenario year 2015 for each country are estimated by all-cause mortality adult death (20-64 years old) AD_c, relative-risk of all-mortality R, the cycling distance in country $D\times B_{j,c}$, and reference cycling distance (that is determined by reference cycling speed and reference cycling time) (shown in Eq. 7). The negative health impact (or increased road fatalities from cycling) in the scenario year 2015 for each country are estimated by the current traffic fatalities from cycling for each country $BI_{c,t}$, the current cycling distance $B_{j=0,c}$, and the target cycling distance in the scenario $B_{j,c}$ (shown in Eq. 7).

$$D_c = AD_{c,t} \times (1-R) \times \left(\frac{D\times B_{j,c}}{RS\times RT}\right) - BI_{c,t} \times \frac{B_{j,c}}{B_{j=0,c}} \quad (7)$$

where $AD_{c,t}$ indicate the adult death in year t, RS and RT indicate reference cycling speed and reference cycling time, $BI_{c,t}$ indicates the traffic fatalities from cycling for country c in year t.

Data collection, cleaning, and processing. The bicycle production data for the selected 60 countries were mainly from the Industrial Commodity Statistics Database of United Nations[64] and other national data sources[65–69] for major countries like China, Japan, the U.S., and most European countries (Table S2). We used linear interpolation for countries with missing data for a few years. For a few small countries (e.g., Singapore, Switzerland, and Kuwait) without any bicycle production data, we simply assumed their production as zero.

The United Nations Comtrade database[70] provides data for bicycle trade for most countries. However, these trade data have some issues, for example, missing physical unit of bicycles, varying temporal coverage, and inconsistent country codes. We followed a cleaning and processing process similar to our earlier work[71–73]. Inconsistent country codes are unified first (e.g., the numeric code for the U.S. was 841 before 1981 and 842 after 1981) to merge those related trade flows. We then addressed data gaps for missing physical units of bicycle, based on the trade monetary values (US dollars) and estimated average price (values at both global and national levels were calculated, while the national average prices were deemed more consistent with existing physical documentation and thus eventually used). For some countries with missing data for only a few years, we filled the data gaps through linear interpolation.

The bicycle and car use data, reflected as the bicycle and car trip shares, were collected from a wide range of literature (e.g., travel surveys, journal articles, and industry reports) with our best efforts (detailed in Supplementary Fig. 2 and Supplementary Fig. 3 for bicycle and car trip shares, respectively). Since the bicycle and car trip shares from travel surveys are mainly for cities, we used the mean of city-level values as the corresponding national trip share, because the derived values appear in line with national values from other sources (see detailed assumptions in Supplementary Table 4). The only exception is China, for which the derived city average (23%) is much higher than the reported national average because of higher bicycle trip modal share (and thus not representative) in the sample cities for China in related literature. For countries without any data, we assumed their bicycle and car modal shares the same as countries with similar income levels. Specifically, for low-income countries without any information, we assumed their trip modal share the same as that of the lower quarter quantile of lower-middle-income group countries; while for countries in the other three income groups with data gaps, the median value of the same income group countries was used.

Sensitivity analysis. Sensitivity analysis was conducted by adjusting key data values compiled from various sources such as bicycle production (eight different sources in Supplementary Table 2) and trade (two different sources in Supplementary Table 2) and key parameters such as the bicycle lifetime by ±10%. Results of sensitivity analysis are presented for per capita bicycle ownership in Supplementary Figs. 16–19. The sensitivity analysis results show that our estimated bicycle ownership of the selected 60 countries is relatively robust and the bicycle ownership is slightly more sensitive to bicycle lifetime compared with other parameters.

Data availability

The datasets generated and analysed in this study are further elaborated in the supplementary information and available in the public repository[74].

Code availability

The mathematical algorithm used in this study is available from the corresponding author upon reasonable request.

Received: 21 January 2022; Accepted: 7 July 2022;
Published online: 18 August 2022

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Acknowledgements

We acknowledge financial support from Natural Sciences Foundation of China (71991484, 72088101, and 71991480), China Scholarship Council (201708510095), and Independent Research Fund Denmark (ReCAP).

Author contributions

G.L. conceived the original idea and designed the research. W.C. collected the data and run the simulation. G.L. and W.C. analyzed the results and prepared the figures. T.A.C., R.W., S.D., D.R.R., and M.J.N. enhanced the discussion. G.L. and W.C. drafted the paper, and all authors contributed to writing this paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-022-00497-4.

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Peer review information *Communications Earth & Environment* thanks Fanran Meng and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editor: Joe Aslin