Supplementary Information for

Historical patterns and sustainability implications of worldwide bicycle ownership and use

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Supplementary Note1: System definition and scope

We considered only conventional human-powered bicycles in this study. The life cycle of bicycles includes stages such as production, use, and waste management (see Supplementary Fig. 1). While there is ample information about motor vehicle registration due to many purposes (e.g., tax and safety), the data on historical bicycle registration and sales are scarce. Instead, we used a lifetime delayed approach to model the in-use stocks of bicycles, as used in previous pieces of literature for products such as bicycles, refrigerants, and TVs [1–3].

There is scarce information on bicycle lifetime. Due to relatively good data on bicycle stock, production, and trade for China, we have validated the average lifetime and distribution of bicycles in China by comparing bottom-up and top-down estimates in our previous research [3]. We used the lifetime distribution from a survey-based product lifespan database [4].

We have tried to include as many as possible countries across all world regions. 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 region categorization and income group are based on the World Bank [5].

Supplementary Note 2: Production data sources and processing

The bicycle production data were mainly from the Industrial Commodity Statistics Database of United Nations. To address the inconsistency and gaps in this database, we have further sought national data sources as much as possible, particularly for major countries like China, Japan, the U.S., and most European countries (sources detailed in Table S2). We aimed to cover all historical years from as early as possible to 2015, and in case of missing data for a few years, linear interpolation was used. For a few small countries without any bicycle production data, such as Singapore, Switzerland, and Kuwait, we simply assumed the production as zero.
The global passenger car production data are from literature before 2005 [6] and from Organisation Internationale des Constructeurs d'Automobiles (OICA) after 2005 [7].

Supplementary Note 3: Trade data sources and processing

Trade data of bicycles were primarily from the United Nations Comtrade database [8] based on SITC classification. For major economies like China, a national data source was sought for data before 1985 [9]. To address the issues in the Comtrade database, such as missing physical values, temporal gaps, and inconsistencies of country codes (e.g., the code for the U.S. was 841 before 1981 and 842 after 1981), we have followed a cleaning and processing process similarly as used in our earlier work [10,11] as detailed below.

1) We unified the country code and merged those related trade flows for around 95 thousand datasets.
2) We found that all data in these datasets include trade monetary values ($). However, only 95% and 53% of data include physical weight values (kg) and physical quantity values (unit), respectively.
3) We filled the data gaps on the physical unit of bicycle trade and derived them through the world- and nation-level of average price and then validated the results under two price assumptions with the existing physical unit. We eventually used the national average price because the estimated values are more consistent with existing physical documentation.
4) For some countries (e.g., ARE) with available data only for the recent 10-20 years, we estimated the missing import values in earlier years based on changing population rate and linear interpolation.
5) For some countries still missing data in some years, we fill those missing data through linear interpolation.

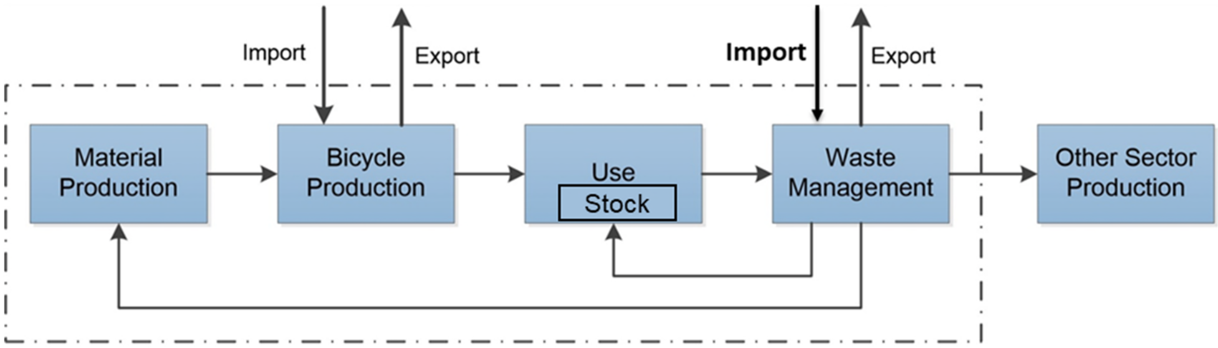
Supplementary Note 4: Bicycle and car use data processing

The bicycle and car use, which was reflected as the bicycle and car trip share, was collected from a wide range of literature with our best efforts. We have detailed the sources and results in Supplementary Fig. 2 and Supplementary Fig. 3. Supplementary Table 4 shows the detailed consumptions for each country. When the derived averages of trip modal share values on the city level were compared with those national values reported in the literature, they appear in line with each other for most countries. The only exception is China, for which the derived city average (23%) is much higher than the reported national average. We deem this is mainly because the sample cities for China were those with higher bicycle trip modal share (and thus not representative). As a compromise, we used reported national value for China and the mean city-level value for other co(see Supplementary Fig. 2 and Supplementary Fig. 3) in this research.

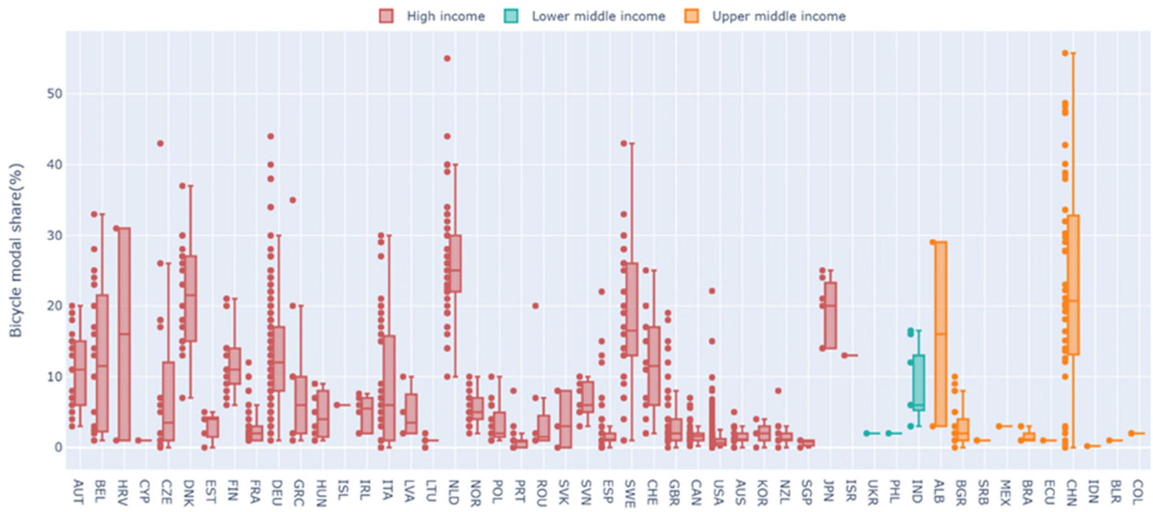
For countries without any data, an income similarity approach was used to estimate both their bicycle and car modal share. For low-income countries without any information, we assumed their trip modal share the same as that of the lower quarter quantile of lower-middle-income group countries. For countries in the other three income groups with data gaps, the same income group countries' median value was used.

Supplementary Note 5: Additional data sources for carbon and health benefits of increasing bicycle use

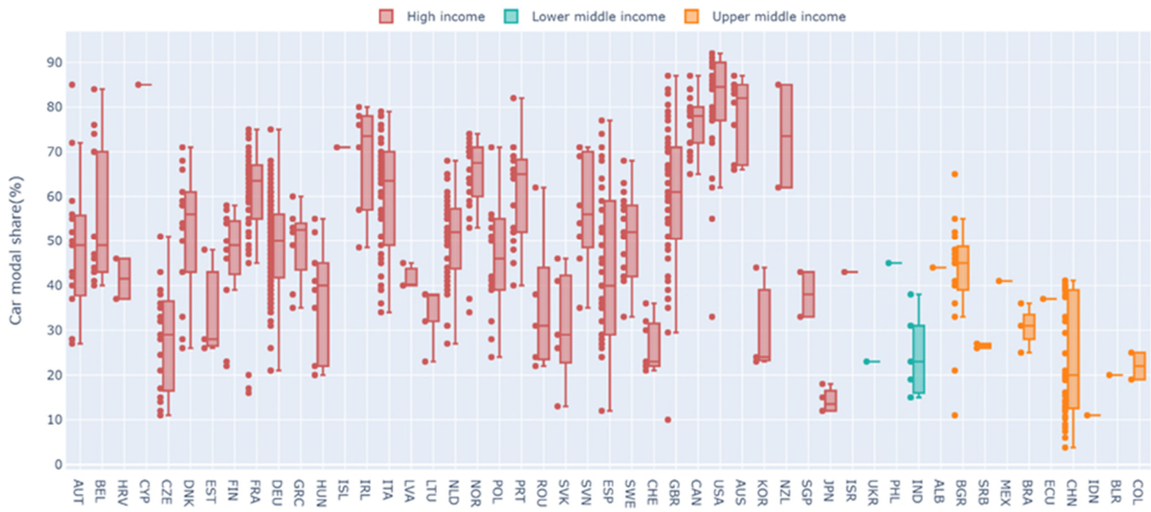
The carbon and health benefit in this study only cover adults (20-64 years old) based on the health economic assessment tool (HEAT) developed by World Health Organization [12].
The cycling distance of some countries has been collected from various literature with our best efforts [13–24]. Nonetheless, data on the average cycling distance by region/country are still lacking for some countries and regions compared to bicycle trip share. Therefore, we estimated the average daily cycling distance per person based on the identified positive correlation of trip share by bicycle and average daily cycling distance (as shown in Supplementary Fig. 4). The non-linear regression curve has an R^2 as 0.8459, as $y = 28.922\ x^2 + 1.1966\ x + 0.2413$, in which y indicates the average daily cycling distance per person and x indicates the national level of modal trip share by bicycle.



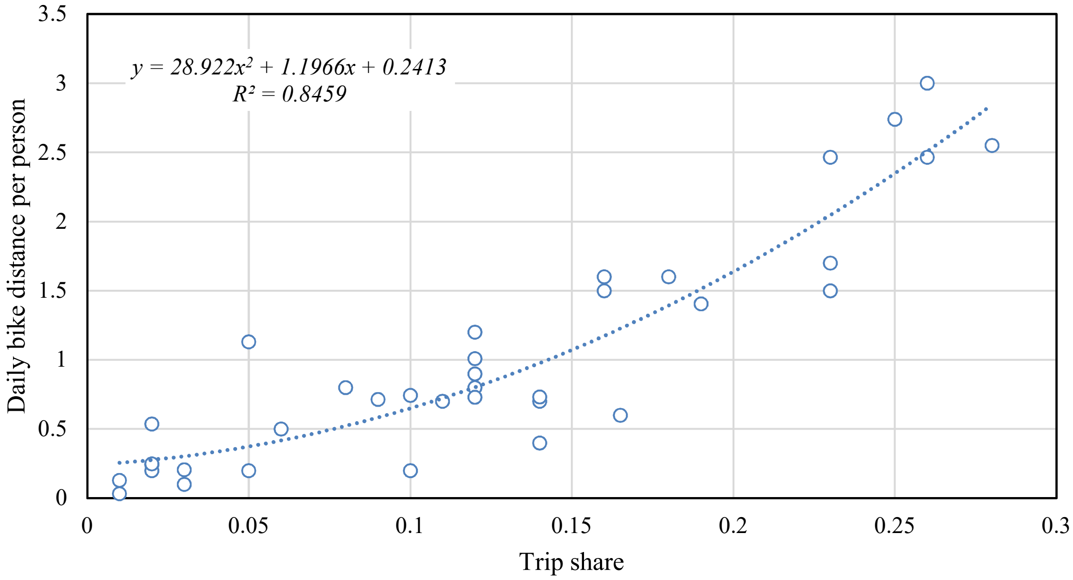
Supplementary Fig. 1. system definition for bicycle life cycle and stocks and flows.



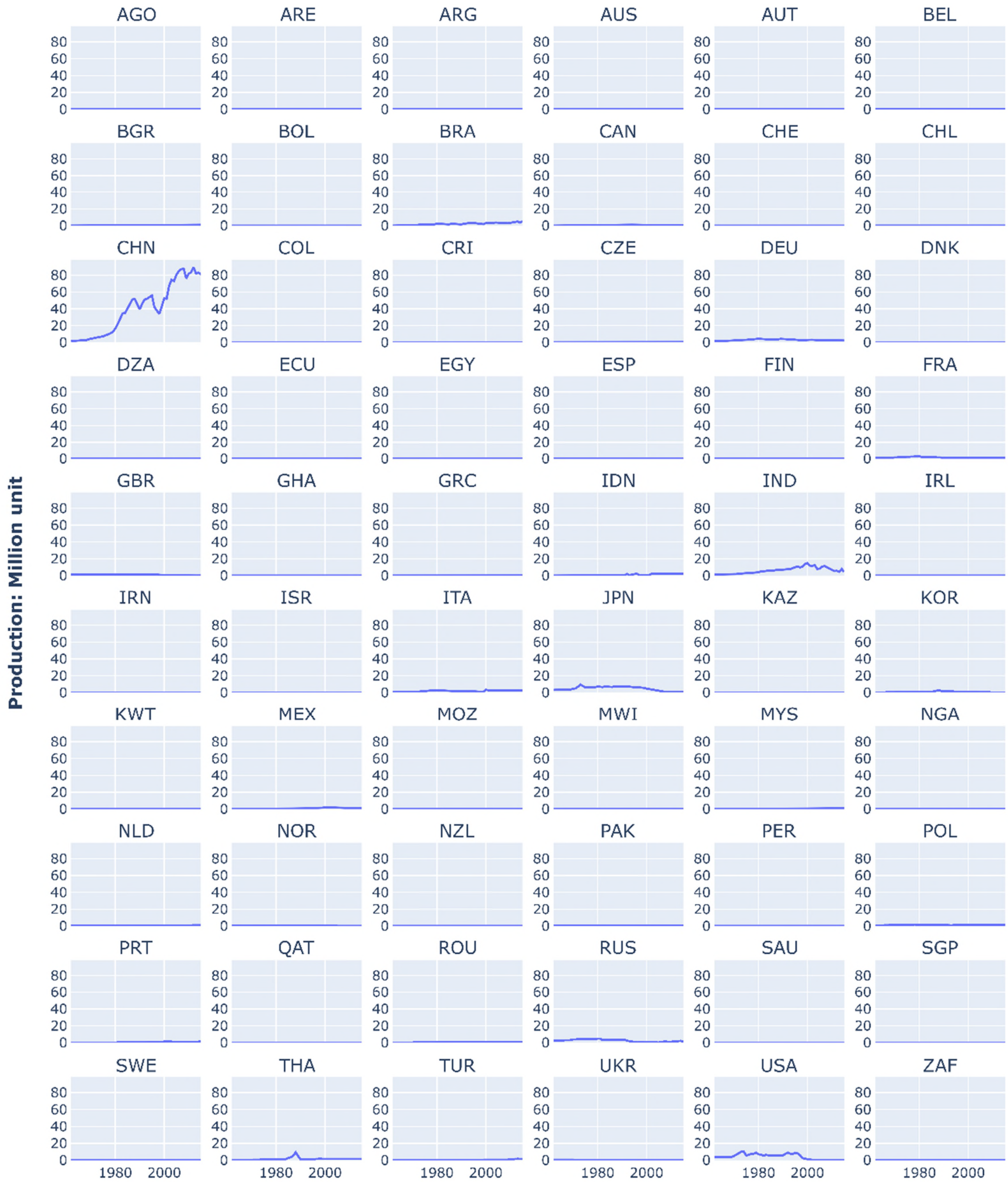
Supplementary Fig. 2. Transport trip modal share by bicycle in cities across the world, based on literature collected with the authors' best efforts [13–27]. The points in the figure represent the modal share by bicycle in the city. The candle bars next to the points show the maximum, higher quarter quantile, median, lower quarter quantile, and minimum values of the country.



Supplementary Fig. 3. Transport trip share by passenger car in the cities across the world, based on literature collected with the authors' best efforts [13,16–20,22,23,26]. The points in the figure represent the modal share by passenger car in the city. The candle bars next to the points show the maximum, higher quarter quantile, median, lower quarter quantile, and minimum values of the country.

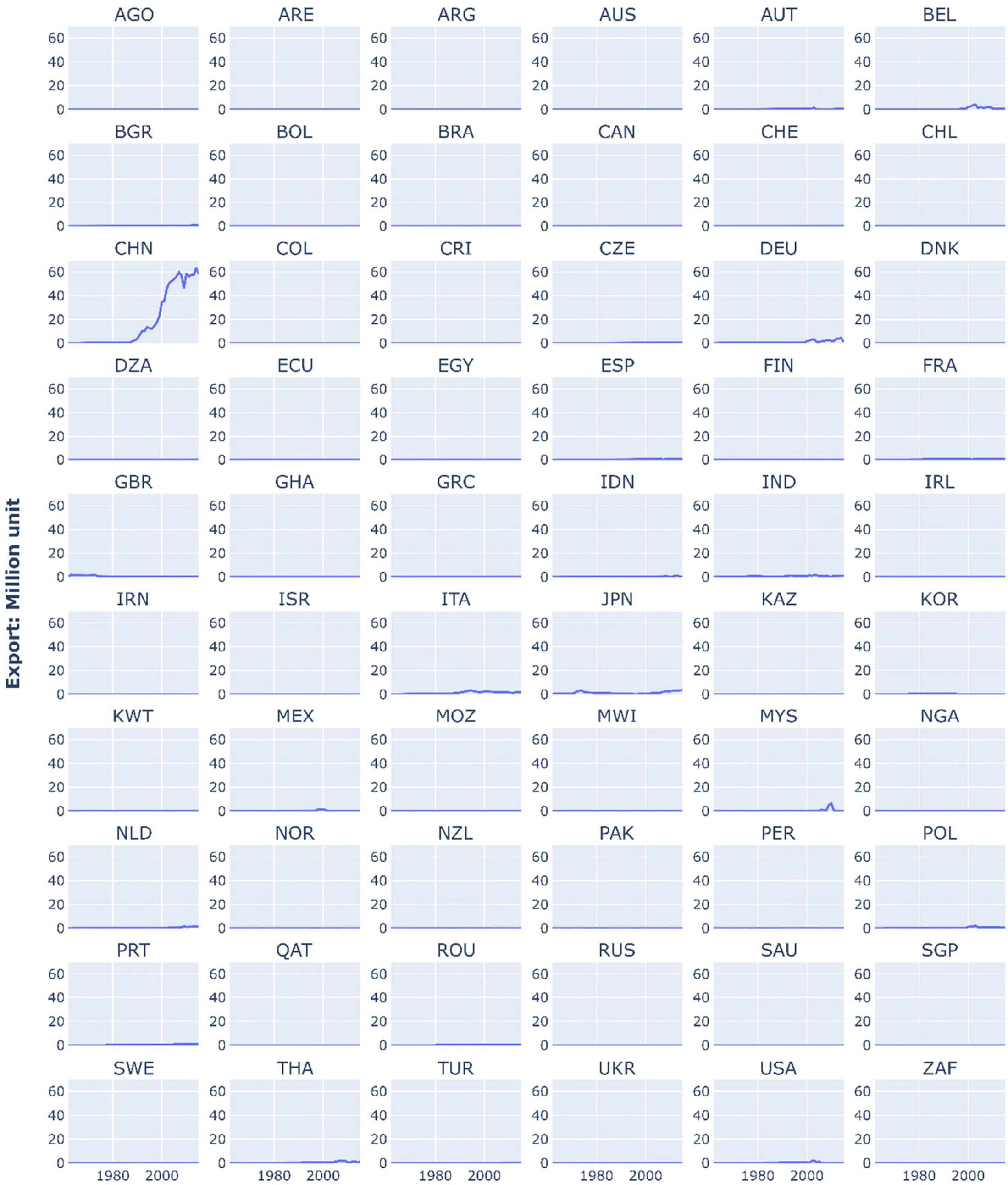


Supplementary Fig. 4. The relationship between bicycle trip modal share and cycling distance.

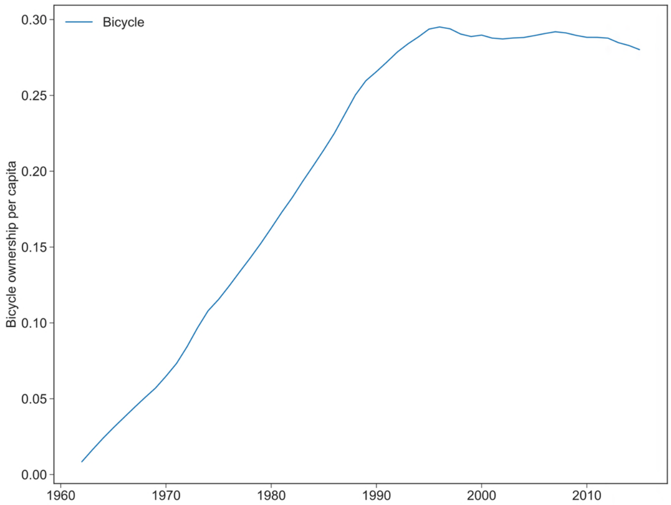


Supplementary Fig. 5. Bicycle production of selected countries from 1962 to 2015.

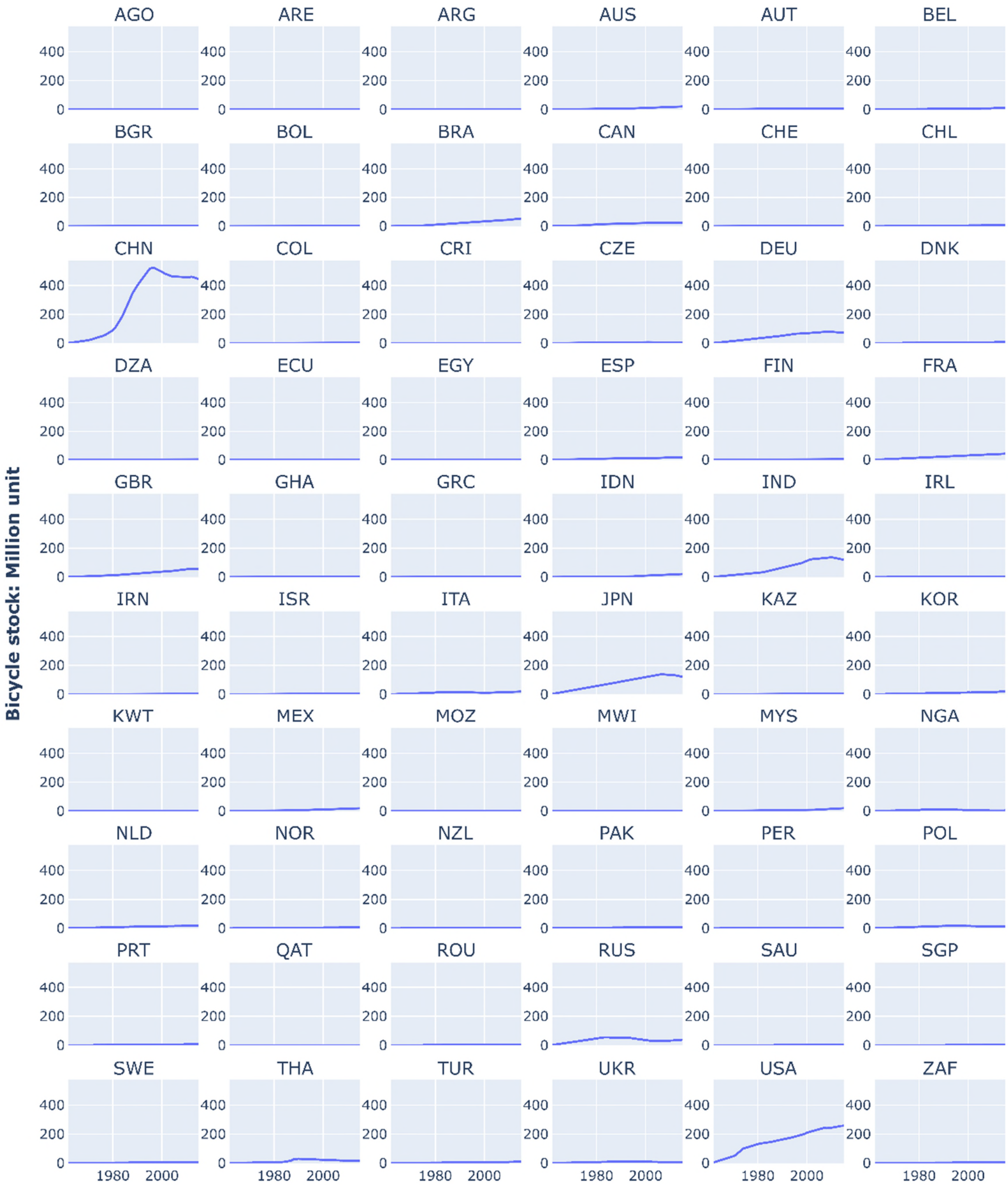
Supplementary Fig. 6. Bicycle import across the world from 1962 to 2015.



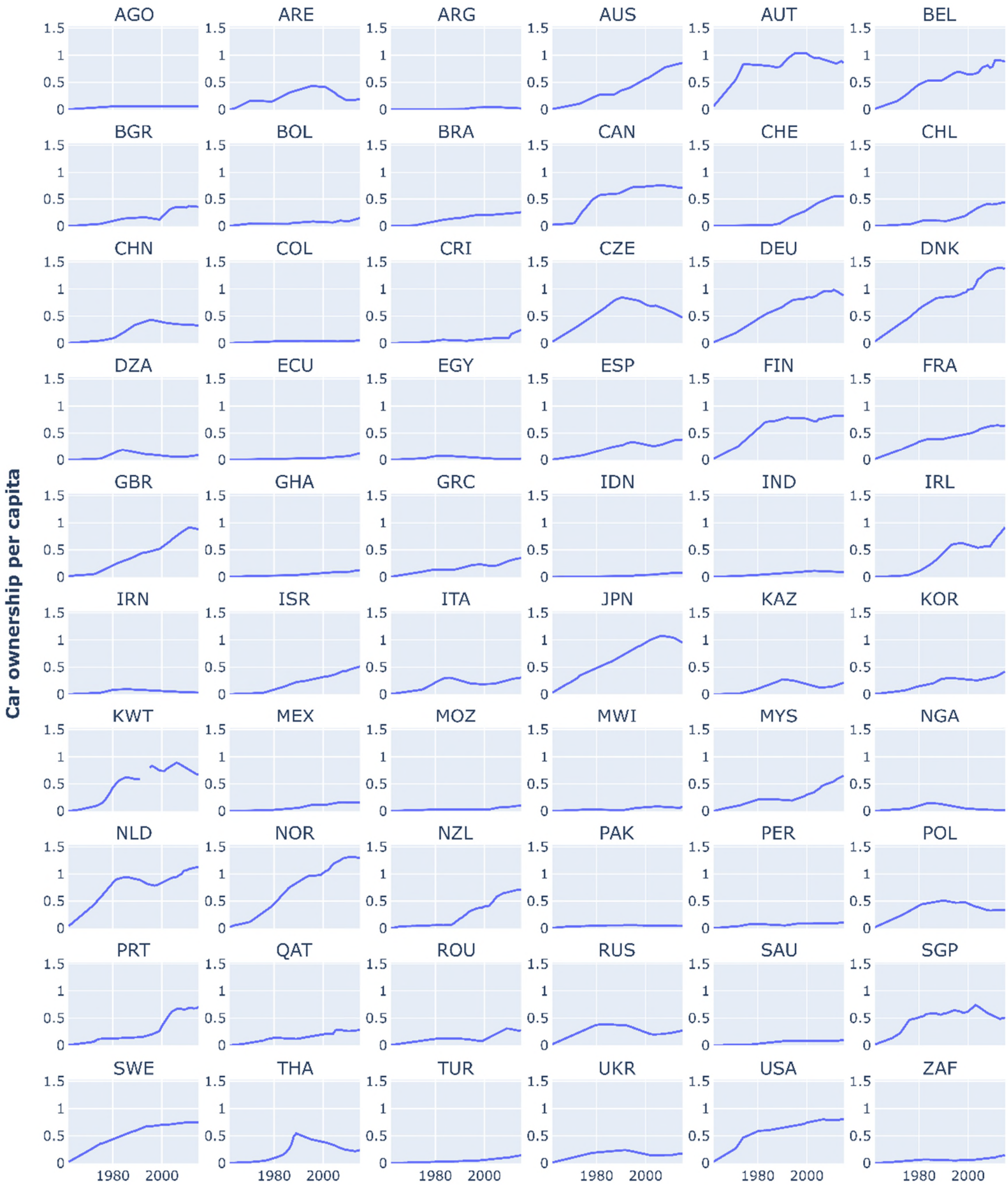
Supplementary Fig. 7. Bicycle export across the world from 1962 to 2015.



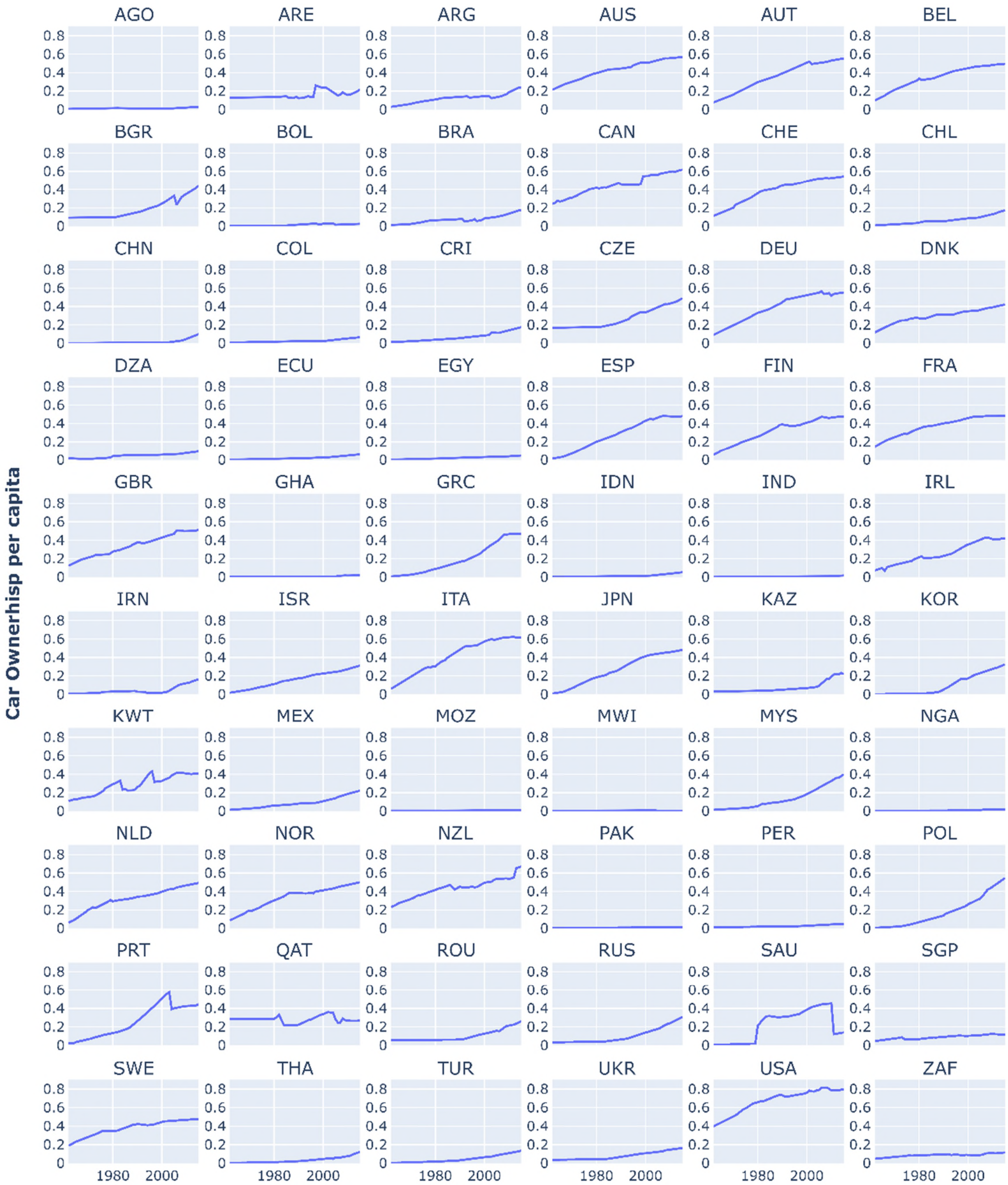
Supplementary Fig. 8. Global per capita bicycle ownership from 1962 to 2015.



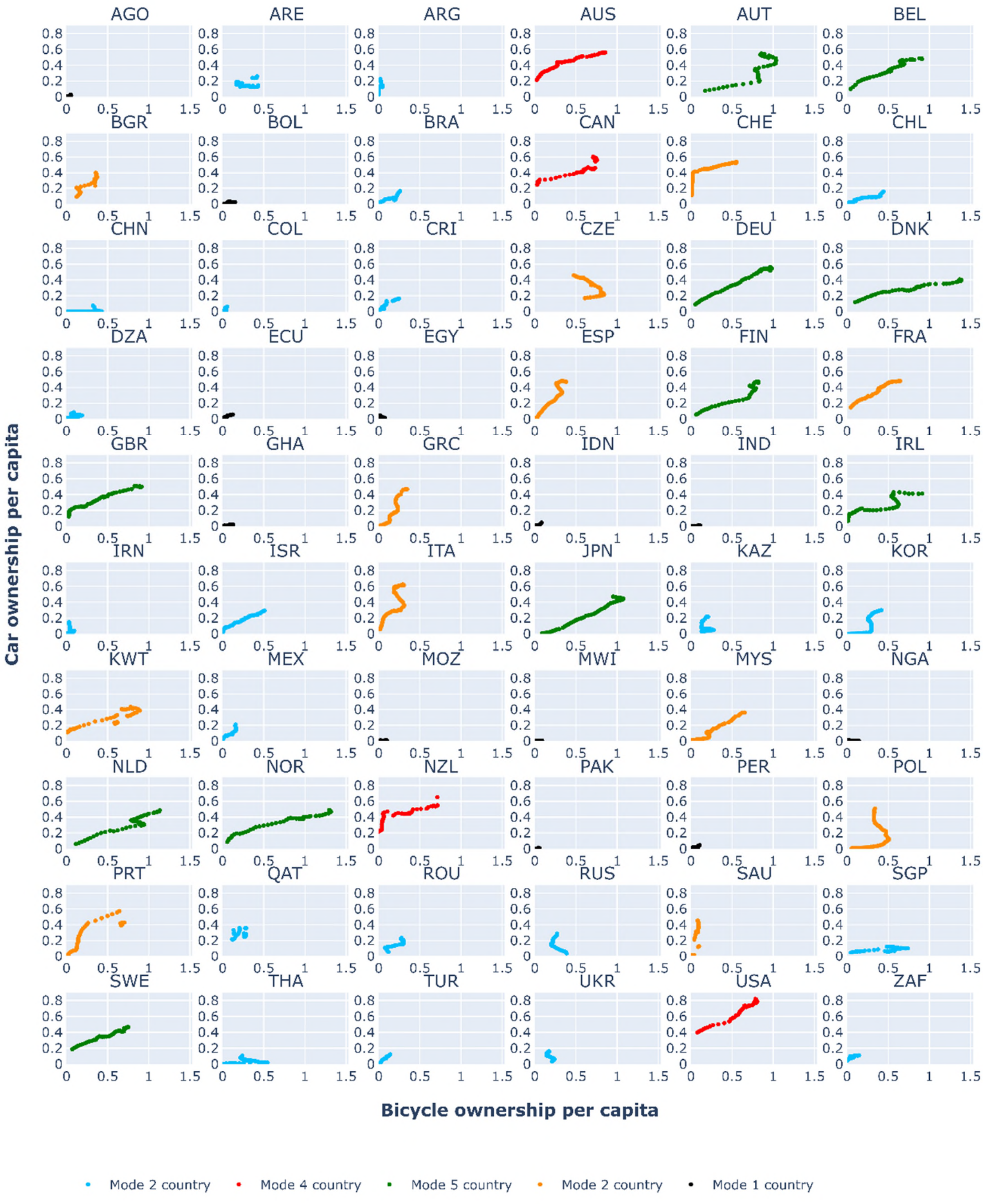
Supplementary Fig. 9. Bicycle stock across the world, 1962-2015.



Supplementary Fig. 10. Bicycle ownership across the world, 1962-2015.

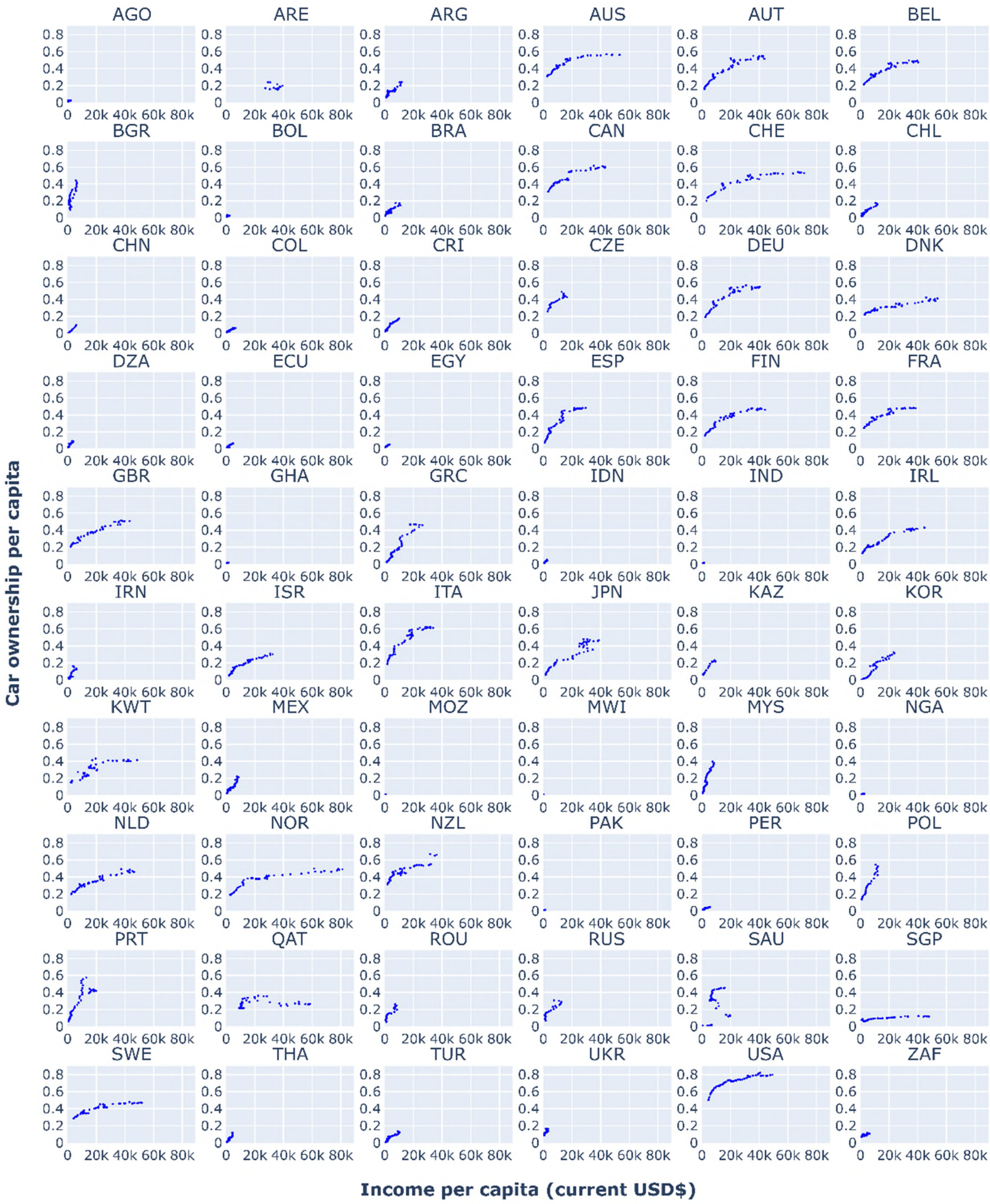


Supplementary Fig. 11. Car ownership across the world, 1962-2015.

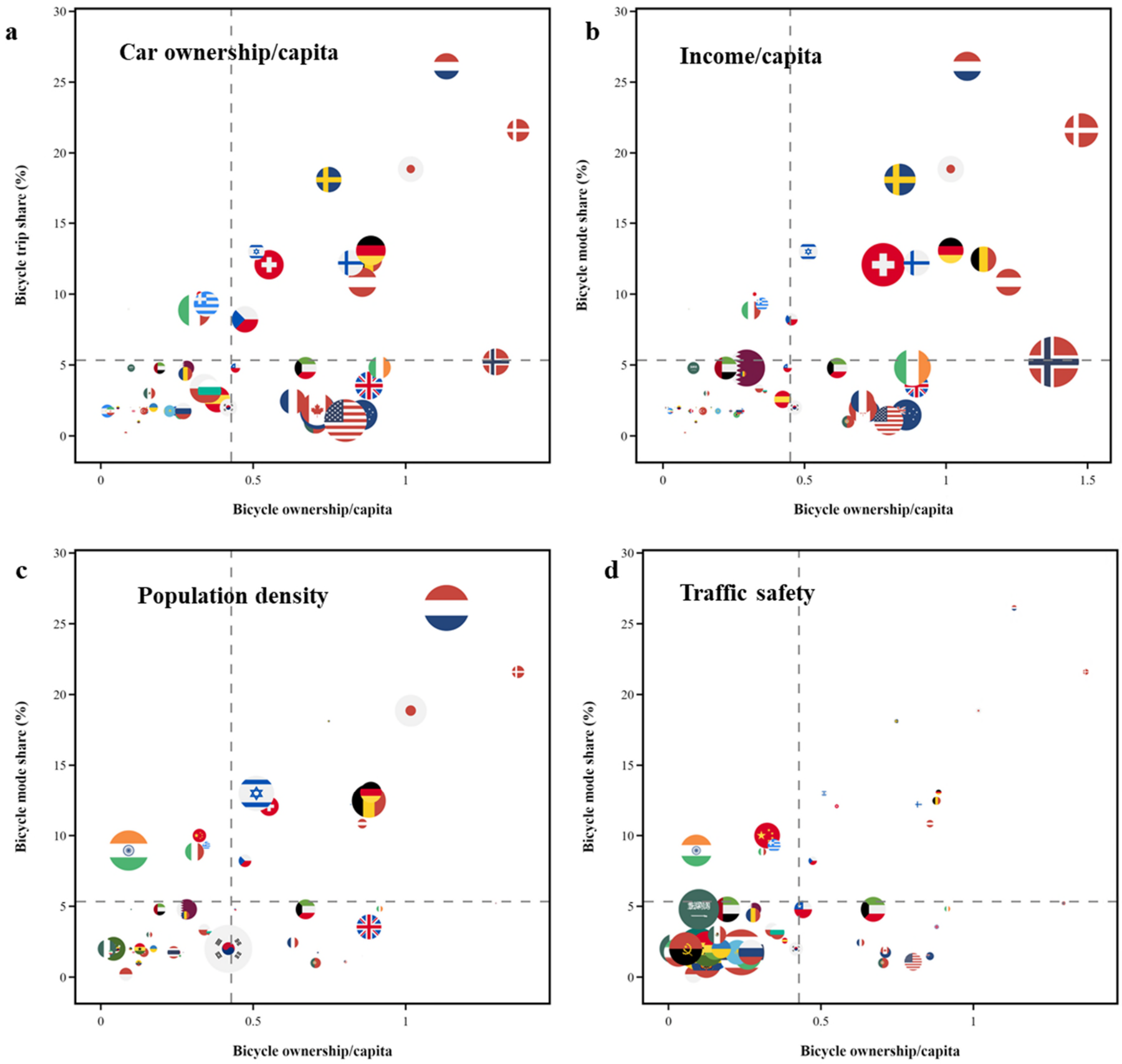


Supplementary Fig. 12. Per-capita bicycle ownership vis-à-vis per-capita car ownership on the country level, 1962-2015.

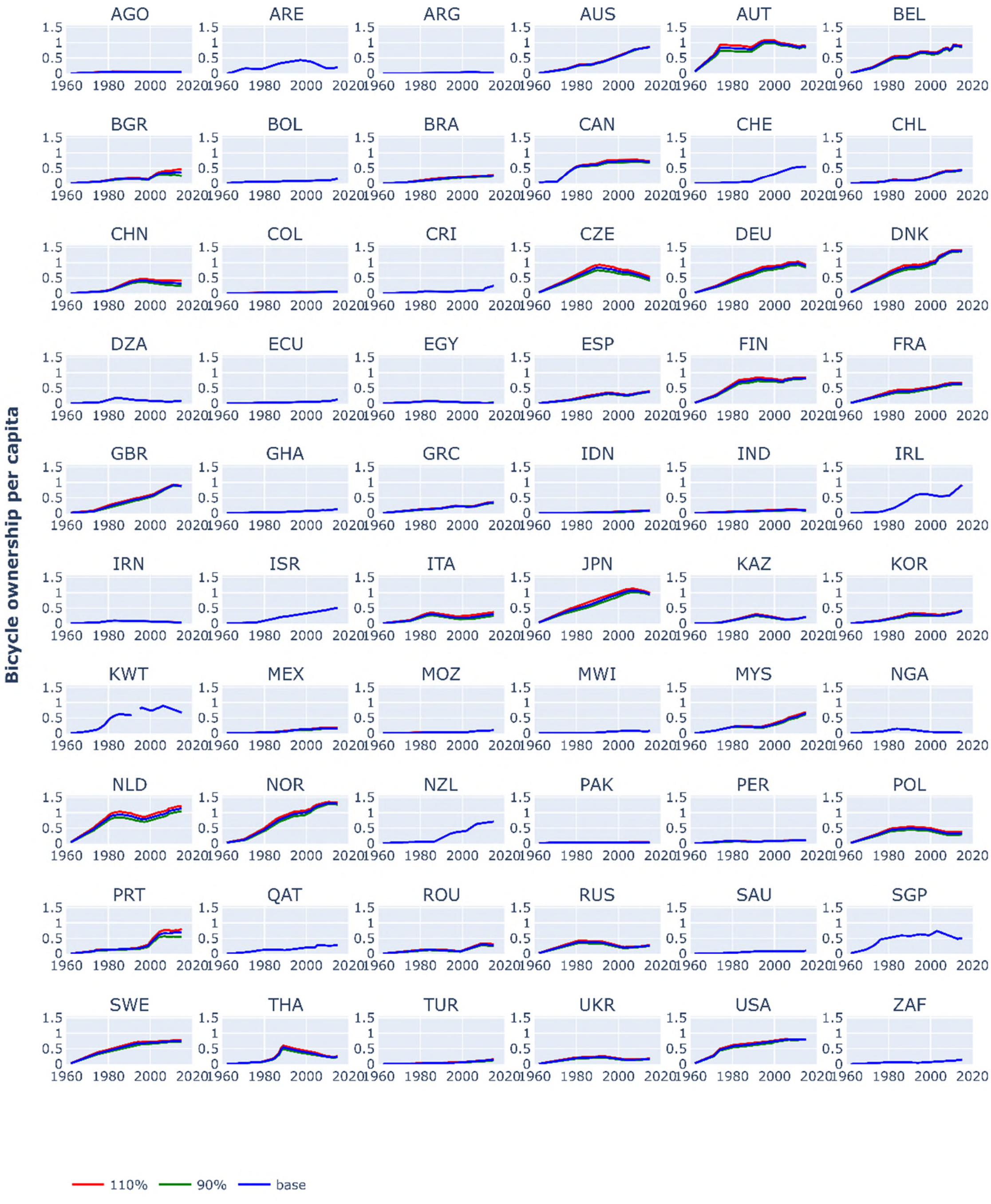
Supplementary Fig. 13. The correlation between per-capita income level and per-capita bicycle ownership. X and Y axis indicate per-capita income level and per-capita Bicycle ownership.



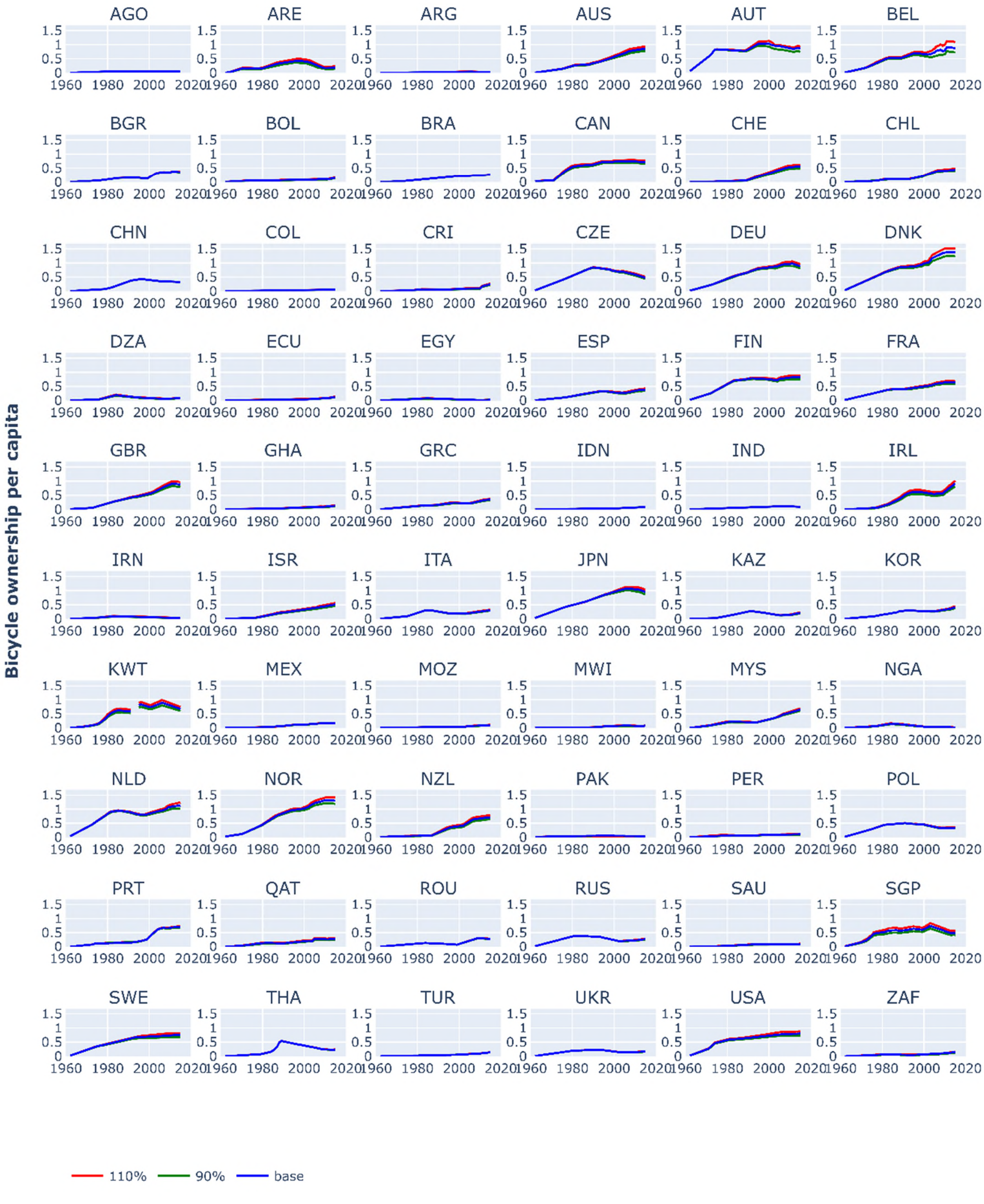
Supplementary Fig. 14. The correlation between per-capita income level and per-capita car ownership. X and Y axis indicate per-capita income level and per-capita car ownership.



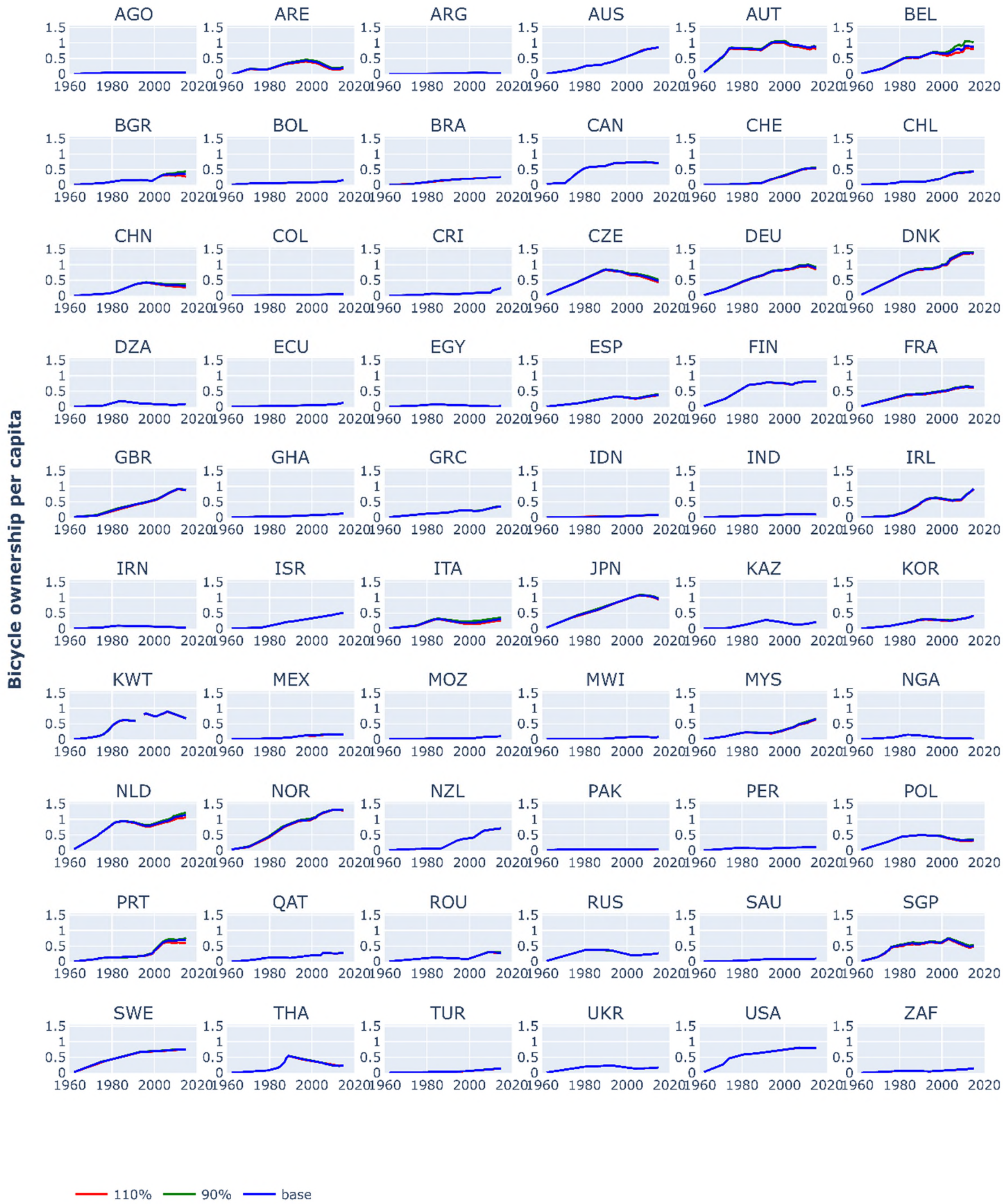
Supplementary Fig. 15. The correlation between four selected parameters with bicycle use (per-capita car ownership (a), per-capita income (current USD$) (b), population density (c), and traffic safety as reflected by road traffic death rate (d)). The bubble size in (a), (b), (c), and (d) are proportional to the values of per-capita car ownership, per-capita income, population density, and traffic safety respectively. The dashed lines indicate the median values of the x-axis and y-axis, which splits the figures into four quadrants.



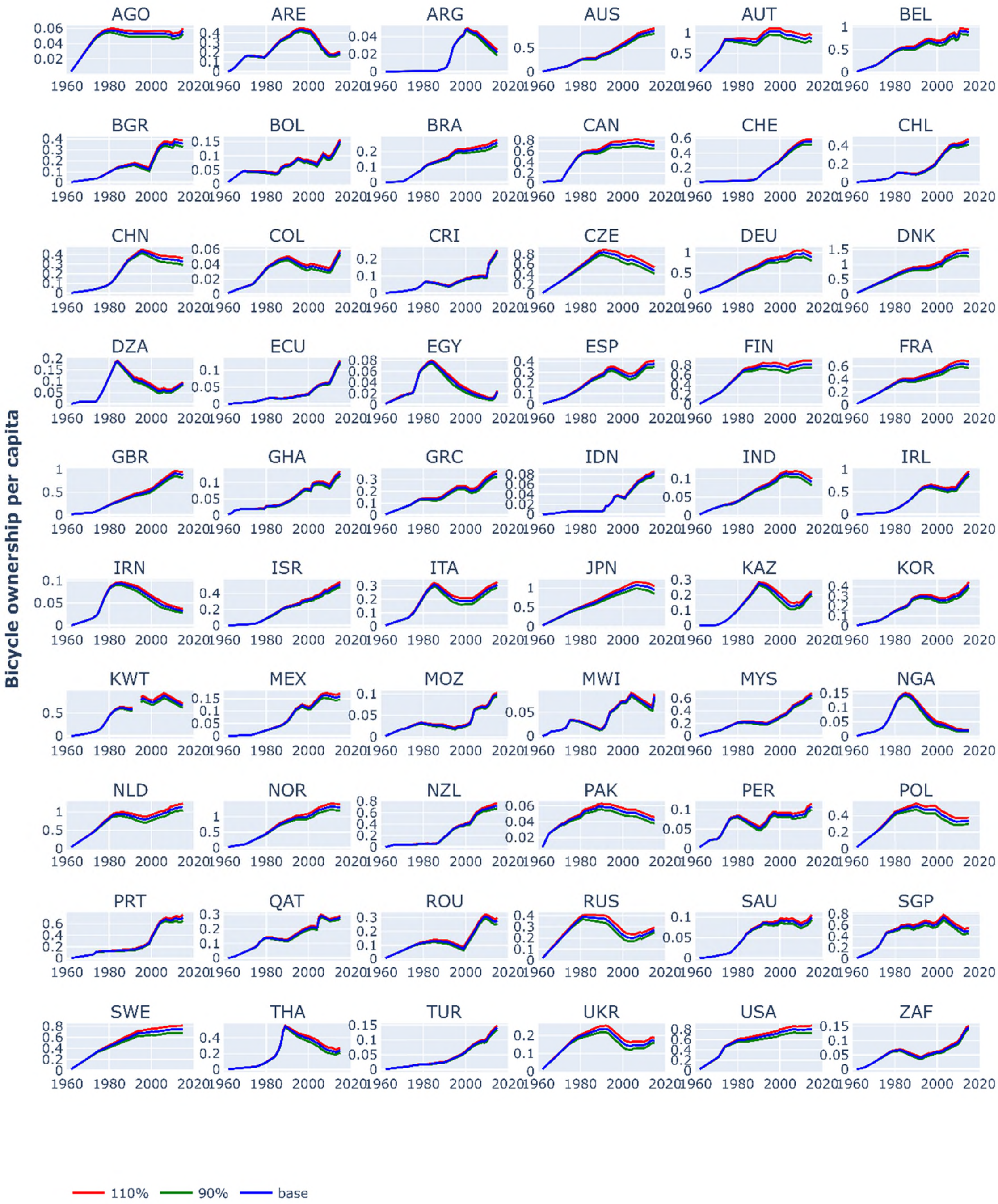
Supplementary Fig. 16. The sensitivity of bicycle production change on bicycle ownership.



Supplementary Fig. 17. The sensitivity of bicycle import change on bicycle ownership.



Supplementary Fig. 18. The sensitivity of bicycle export change on bicycle ownership.



Supplementary Fig. 19. The sensitivity of bicycle lifetime change on bicycle ownership.

Supplementary Table 1. The country name, code, region, and income group classification of the selected 60 countries. Data is also available in the repository[28].

Country Code	Country Name	Region	Income Group
AGO	Angola	Sub-Saharan Africa	Lower middle income
ARE	United Arab Emirates	Middle East & North Africa	High income
ARG	Argentina	Latin America & Caribbean	Upper middle income
AUS	Australia	East Asia & Pacific	High income
AUT	Austria	Europe & Central Asia	High income
BEL	Belgium	Europe & Central Asia	High income
BGR	Bulgaria	Europe & Central Asia	Upper middle income
BOL	Bolivia	Latin America & Caribbean	Lower middle income
BRA	Brazil	Latin America & Caribbean	Upper middle income
CAN	Canada	North America	High income
CHE	Switzerland	Europe & Central Asia	High income
CHL	Chile	Latin America & Caribbean	High income
CHN	China	East Asia & Pacific	Upper middle income
COL	Colombia	Latin America & Caribbean	Upper middle income
CRI	Costa Rica	Latin America & Caribbean	Upper middle income
CZE	Czech Republic	Europe & Central Asia	High income
DEU	Germany	Europe & Central Asia	High income
DNK	Denmark	Europe & Central Asia	High income
DZA	Algeria	Middle East & North Africa	Lower middle income
ECU	Ecuador	Latin America & Caribbean	Upper middle income
EGY	Egypt, Arab Rep.	Middle East & North Africa	Lower middle income
ESP	Spain	Europe & Central Asia	High income
FIN	Finland	Europe & Central Asia	High income
FRA	France	Europe & Central Asia	High income
GBR	United Kingdom	Europe & Central Asia	High income
GHA	Ghana	Sub-Saharan Africa	Lower middle income
GRC	Greece	Europe & Central Asia	High income
IDN	Indonesia	East Asia & Pacific	Upper middle income
IND	India	South Asia	Lower middle income
IRL	Ireland	Europe & Central Asia	High income
IRN	Iran, Islamic Rep.	Middle East & North Africa	Upper middle income
ISR	Israel	Middle East & North Africa	High income
ITA	Italy	Europe & Central Asia	High income
JPN	Japan	East Asia & Pacific	High income
KAZ	Kazakhstan	Europe & Central Asia	Upper middle income

KOR	Korea, Rep.	East Asia & Pacific	High income
KWT	Kuwait	Middle East & North Africa	High income
MEX	Mexico	Latin America & Caribbean	Upper middle income
MOZ	Mozambique	Sub-Saharan Africa	Low income
MWI	Malawi	Sub-Saharan Africa	Low income
MYS	Malaysia	East Asia & Pacific	Upper middle income
NGA	Nigeria	Sub-Saharan Africa	Lower middle income
NLD	Netherlands	Europe & Central Asia	High income
NOR	Norway	Europe & Central Asia	High income
NZL	New Zealand	East Asia & Pacific	High income
PAK	Pakistan	South Asia	Lower middle income
PER	Peru	Latin America & Caribbean	Upper middle income
POL	Poland	Europe & Central Asia	High income
PRT	Portugal	Europe & Central Asia	High income
QAT	Qatar	Middle East & North Africa	High income
ROU	Romania	Europe & Central Asia	High income
RUS	Russian Federation	Europe & Central Asia	Upper middle income
SAU	Saudi Arabia	Middle East & North Africa	High income
SGP	Singapore	East Asia & Pacific	High income
SWE	Sweden	Europe & Central Asia	High income
THA	Thailand	East Asia & Pacific	Upper middle income
TUR	Turkey	Europe & Central Asia	Upper middle income
UKR	Ukraine	Europe & Central Asia	Lower middle income
USA	United States	North America	High income
ZAF	South Africa	Sub-Saharan Africa	Upper middle income

Supplementary Table 2. Data sources of production and trade for 60 countries.

Country	Bicycle production	Passenger car production	Trade
CHN	[9,29*]	-	1950-1992[29], 1992-2015[8]
JPN	1970-2015[30]	-	[8]
USA	1970-1986[30], 1990-2000[13], 2001-2015[31,32]	-	[8]
FRA, DEU, GBR, ITA, NLD, BGR, ESP, GRC, SWE, ROU, POL, PRT, HUN, DNK, FIN, CZE, BEL, LTU, SVK, AUT, SVN, HRV, CYP, EST, LVA, MLT, LUX	1970-2000[30], 2000-2015[33–37]	-	[8]
Other countries	[13,30]	-	[8]
world	1950-2007 [6], 2007-2015 [30]	[6,7]	-

*The production data is mainly based on the China Light Industry Yearbook. The production data is from the China Industry Statistical Yearbook for some years without data.

Supplementary Table 3. Data sources for bicycle survival rate.

Description	Parameter	Source
The bicycle survival rate for China	SR	[3]
The bicycle survival rate for other countries excluding China	SR	[4]

Supplementary Table 4. The modal share of bicycle and car*. Data is also available in the repository[28].

Country	Income Group	Bicycle trip share (%)	Car trip share (%)	Assumptions
AGO	Lower middle income	2	25	The median value of lower middle income group countries
ARE	High income	5	49	The median value of High income group country with value
ARG	Upper middle income	2	29	The median value of upper middle income group countries with value
AUS	High income	1	78	The mean value of city-level trip share
AUT	High income	11	48	The mean value of city-level trip share
BEL	High income	12	57	The mean value of city-level trip share
BGR	Upper middle income	3	43	The mean value of city-level trip share
BOL	Lower middle income	2	25	The median value of lower middle income group countries
BRA	Upper middle income	2	31	The mean value of city-level trip share
CAN	High income	2	76	The mean value of city-level trip share
CHE	High income	12	27	The mean value of city-level trip share
CHL	High income	5	49	The median value of High income group country with value
CHN	Upper middle income	10	24	The car modal share is the mean value of city-level trip share. The bicycle modal share is based on the national data[27].
COL	Upper middle income	2	22	The mean value of city-level trip share
CRI	Upper middle income	2	29	The median value of upper middle income group countries with value
CZE	High income	8	28	The mean value of city-level trip share
DEU	High income	13	49	The mean value of city-level trip share
DNK	High income	22	52	The mean value of city-level trip share
DZA	Lower middle income	2	25	The median value of lower middle income group countries
ECU	Upper middle income	1	37	The mean value of city-level trip share

EGY	Lower middle income	2	25	The median value of lower middle income group countries
ESP	High income	3	44	The mean value of city-level trip share
FIN	High income	12	46	The mean value of city-level trip share
FRA	High income	2	60	The mean value of city-level trip share
GBR	High income	4	60	The mean value of city-level trip share
GHA	Lower middle income	2	25	The median value of lower middle income group countries
GRC	High income	9	49	The mean value of city-level trip share
IDN	Upper middle income	0	11	The mean value of city-level trip share
IND	Lower middle income	9	25	The mean value of city-level trip share
IRL	High income	5	68	The mean value of city-level trip share
IRN	Upper middle income	2	29	The median value of upper middle income group countries with value
ISR	High income	13	43	The mean value of city-level trip share
ITA	High income	9	60	The mean value of city-level trip share
JPN	High income	19	14	The mean value of city-level trip share
KAZ	Upper middle income	2	29	The median value of upper middle income group countries with value
KOR	High income	2	30	The mean value of city-level trip share
KWT	High income	5	49	The median value of High income group country with value
MEX	Upper middle income	3	41	The mean value of city-level trip share
MOZ	Low income	2	24	The lower quantile value of lower middle income group countries
MWI	Low income	2	24	The lower quantile value of lower middle income group countries
MYS	Upper middle income	2	29	The median value of upper middle income group countries with value
NGA	Lower middle income	2	25	The median value of lower middle income group countries
NLD	High income	26	51	The mean value of city-level trip share
NOR	High income	5	64	The mean value of city-level trip share
NZL	High income	2	74	The mean value of city-level trip share
PAK	Lower middle income	2	25	The median value of lower middle income group countries
PER	Upper middle income	2	29	The median value of upper middle income group countries with value
POL	High income	3	46	The mean value of city-level trip share

PRT	High income	1	61	The mean value of city-level trip share
QAT	High income	5	49	The median value of High income group country with value
ROU	High income	4	35	The mean value of city-level trip share
RUS	Upper middle income	2	29	The median value of upper middle income group countries with value
SAU	High income	5	49	The median value of High income group country with value
SGP	High income	1	38	The mean value of city-level trip share
SWE	High income	18	51	The mean value of city-level trip share
THA	Upper middle income	2	29	The median value of upper middle income group countries with value
TUR	Upper middle income	2	29	The median value of upper middle income group countries with value
UKR	Lower middle income	2	23	The mean value of city-level trip share
USA	High income	1	80	The mean value of city-level trip share
ZAF	Upper middle income	2	29	The median value of upper middle income group countries with value

* This table only show the final modal share for 60 countries used in this study. Detailed information of bicycle modal share and car modal share from various sources could be find in Supplementary Fig. S2 and Supplemenrtary Fig. S3.

Supplementary Table 5. Typical distance of trips by Car and Bicycle.

Mode	Typical distance	Source
Car	1-20+ km	[38]
Bicycle	1-5km	[38]

Supplementary Table 6. Data sources of other factors behind bicycle use (used in Figure S15).

Description	Source
Passenger car stock	[7,29,39,40]
Adjusted income per capita (current US$)	[41]
Population density (people per square km of land area)	[42]
Road traffic death rates per 100000 people	[43,44]

Supplementary Table 7. Data sources for other background data for the health and climate quantification.

Description	Parameter	Source
Population	PO	[45]
The share of short-distance car trips	γ	[17,19,21,24,46–49]
All-cause population deaths aged 20 to 64 years old	AD	[50]
Cycling fatalities aged 20 to 64 years old	R	[50]
Average carbon emission per km for conventional bicycle by country	$C_{bicycle,c}$	[51,52]
Average carbon emission per km for car by country	$C_{car,c}$	[53]
Relative risk of all-cause mortality rate	R	[12,54,55]
Reference biking time	RS	[12]
Reference biking speed	RT	[12]
Traffic fatalities from cycling for country c in year t	$BI_{c,t}$	[50]

Supplementary Table 8. The countries, codes, and characteristics of the five evolutionary modes of historical patterns of per capita car and bicycle ownership.

Modes	Countries and country codes	Characteristics
1	Mozambique (MOZ), Malawi (MWI), Angola (AGO), Bolivia (BOL), Egypt, Arab Rep. (EGY), Ecuador (ECU), Ghana (GHA), Nigeria (NGA), India (IND), Indonesia (IDN), Pakistan (PAK), Peru (PER),	Low bicycle ownership and low car ownership
2	Argentina (ARG), (ARE), Brazil (BRA), China (CHN), Colombia (COL), Costa Rica (CRI), Algeria (DZA), Iran, Islamic Rep. (IRN), Kazakhstan (KAZ), Korea, Rep. (KOR), Mexico (MEX), Qatar (QAT), Romania (ROU), Russian Federation (RUS), Turkey (TUR), Ukraine (UKR), Chile (CHL), Thailand (THA), Israel (ISR), Singapore (SGP), South Africa (ZAF)	Rapid motorization with increasing car ownership and decreasing or resurging bicycle ownership in recent years
3	Bulgaria (BGR), Switzerland (CHE), Czech Republic (CZE), Greece (GRC), Ireland (IRL), France (FRA), Italy (ITA), Malaysia (MYS), Poland (POL), Portugal (PRT), Saudi Arabia (SAU), Kuwait (KWT), Austria (AUT), Spain (ESP)	Further rapid motorization with both high car and high bicycle ownership
4	Australia (AUS), Canada (CAN), New Zealand (NZL), United States (USA)	The highest car ownership and high bicycle ownership
5	Belgium (BEL), Germany (DEU), Denmark (DNK), Finland (FIN), United Kingdom (GBR), Japan (JPN), Netherlands (NLD), Norway (NOR), Sweden (SWE), Austria (AUT), Ireland (IRL)	The highest bicycle ownership and high but saturated car ownership

Supplementary Table 9. The statiscs description of the bicycle use pattern.

VARIABLES	bicycle_ownership
bicycle_modal_share	0.037***
	(7.48)
Constant	0.228***
	(4.72)
Observations	60
R-squared	0.361

Robust t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Supplementary Table 10. The statiscs description of the car use pattern.

VARIABLES	car_ownership
car_modal_share	0.010***
	(8.99)
Constant	-0.086
	(-1.66)
Observations	60
R-squared	0.570

Robust t-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Supplementary References.

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