Ecological Economics 200 (2022) 107511

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

How much infrastructure is required to support decent mobility for all? An exploratory assessment

Doris Virág [a,b], Dominik Wiedenhofer [a], André Baumgart [a], Sarah Matej [a], Fridolin Krausmann [a], Jihoon Min [b], Narasimha D. Rao [b,c], Helmut Haberl [a,*]

[a] Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna, Schottenfeldgasse 29, 1070 Vienna, Austria
[b] International Institute for Applied Systems Analysis, Laxenburg, Austria
[c] Yale School of the Environment, New Haven, CT, USA

ARTICLE INFO

Keywords:
Passenger transport
Well-being
Transport poverty
Decent living standards
Transport infrastructure
Stock-flow-service nexus

ABSTRACT

Decarbonizing transport is crucial for achieving climate targets, which is challenging because mobility is growing rapidly. Personal mobility is a key societal service and basic need, but currently not available to everyone with sufficient quality and quantity. The basis for mobility and accessibility of desired destinations is infrastructure, but its build-up and maintenance require a substantial fraction of global resource use. The question arises, how much mobility and how much infrastructure are required to deliver decent, sustainable mobility.

We explore the relations between mobility levels, mobility infrastructure and well-being. We synthesize definitions of decent mobility and assess mobility measurements and provide a novel estimate of mobility infrastructure stocks for 172 countries in the year ~2021. We then explore the relations between infrastructure, travelled distances, accessibility, economic activity and several 'beyond GDP' well-being indicators.

We find that travelled distances and mobility infrastructure levels are significantly correlated. Above levels of ~92–207 t/cap of mobility infrastructure no further significant gains in well-being can be expected from a further increase of infrastructure. We conclude that high mobility in terms of distances travelled as well as building up mobility infrastructure is only beneficial for well-being up to a certain point.

1. Introduction

Sustainable mobility requires universal access to affordable, safe and reliable mobility options, while minimizing the use of resources for infrastructure and mobility services, as well as rapidly reducing associated GHG emissions in absolute terms (UN, 2021; Wenz et al., 2020). The provision of sustainable mobility is central to achieving the 2030 Agenda for sustainable development, as well as for fulfilling the Paris Agreement on Climate Change (UN, 2021). The World Bank recognizes the mobility sector as highly important in fighting poverty, connecting people to essential services and combating climate change (World Bank, 2021). While personal transport, which we herein denote as 'mobility', is usually not per se regarded as ultimate goal, it is essential in enabling and providing access to participation in society.

However, the current transport system is not delivering on these targets. Transport is the third-largest source of CO_2 emissions globally (SLoCaT, 2018). Another 25–35% of global GHG-emissions are caused by industries processing materials, a significant share of which are used for the construction and maintenance of infrastructure stocks or for producing vehicles and other transport devices (Hertwich, 2021; Lamb et al., 2021). Measured as travelled distances, global mobility activity has expanded rapidly across the world throughout the last decades and is expected to grow further (International Transport Forum, 2021). Still, a large share of the global population is affected by 'transport poverty', i.e. the lack of sufficient and affordable mobility options (Lucas et al., 2016). Many people even lack basic access to reliable mobility infrastructure, for example as all-season roads (Iimi et al., 2016; Khandker et al., 2006). In the context of efforts to reduce climate heating in line with agreed-upon targets, e.g. the Paris Accord or the goal to end poverty, sufficiency and demand-side solutions are increasingly being debated. This applies especially to high-consumption settings where transport emissions are usually growing, despite policy statements calling for rapid emission reductions (Creutzig et al., 2020; Creutzig et al., 2018; Lamb et al., 2021). The question arises: How much mobility and how much (and which) infrastructure will be required for sustainable transport and climate-friendly development?

* Corresponding author.
E-mail address: helmut.haberl@boku.ac.at (H. Haberl).

https://doi.org/10.1016/j.ecolecon.2022.107511
Received 21 December 2021; Received in revised form 2 June 2022; Accepted 5 June 2022
Available online 23 June 2022

Progress towards safe, affordable, accessible, and sustainable mobility is indirectly called for in the Sustainable Development Goals (SDGs). While none of the main targets is directly concerned with sufficient mobility or the related infrastructure requirements, several aspects of mobility and transport are explicitly mentioned. SDG sub-target 11.2 demands safe, affordable, accessible, sustainable personal transport for all; however, the respective indicator measures local air pollution and user satisfaction. Sub-target 9.1 rates the quality of trade and transport-related infrastructure and its accessibility for the population, using a logistics performance index measure. Sub-target 3.6 is concerned with reducing deaths and injuries from road accidents (Sustainable Mobility for All, 2021; UN, 2021). So, even though adequate levels of transport infrastructure stocks are clearly central for enabling sustainable mobility, which are related to achieving a wider set of SDGs as well (Thacker et al., 2019), the sustainable development indicators do not provide concrete guidance on adequate mobility let alone the required infrastructure.

In the literature review in Section 2, we identify the following research gaps and subsequent research questions tackled in this article: (1) There is a lack of cross-national to global insights on the existing levels of mobility, infrastructure stocks and infrastructure requirements for sufficient or decent mobility standards. (2) These issues are not straightforward to address because there are different perspectives on how to define and measure the desired mobility services (e.g. as distances travelled or rather through measures of accessibility or affordability), and on possible thresholds required for providing decent mobility standards. (3) The assessment of infrastructure stocks for mobility and their relationship to mobility services for need satisfaction is still in its infancy (Carmona et al., 2017; Haberl et al., 2017; Tanikawa et al., 2020; Whiting et al., 2020). Due to their large resource requirements and associated environmental impacts, it is crucial to understand infrastructure stock requirements that serve as a basis for accessibility of different services and thus enable decent mobility (see Section 2.2 for a discussion of this concept). Striking a balance between providing an adequate level of mobility, limiting resource requirements and environmental impacts requires understanding the connections between material stocks, (decent) mobility services and well-being. We hence pose the following research questions:

(1) How is sufficient or decent mobility defined in the literature, and with what quantifiable indicators at a macro-scale?
(2) What is the current size and mass of global mobility infrastructure stocks?
(3) What are the relations between mobility, mobility infrastructure stocks, economic activity and well-being? In particular, (3.1) are high levels of travelled distances associated with high levels of development and well-being, measured by widely used indicators (SPI, HDI, SDGs or GDP)? (3.2) How does mobility infrastructure relate to development and well-being, as measured by these indicators? (3.3) Is well-being related to accessibility, measured as Rural Access (RAI)?

To tackle these questions, we conceptually and empirically explore the relations between different parameters of mobility and well-being in a global cross-country analysis. We present a literature review (Section 2), followed by the description of methods and data (Section 3) and the presentation of results on infrastructure stocks and analyses of cross-country patterns of their relations to the mobility system, accessibility, and well-being (Section 4). Section 5 summarizes how travelled distances, infrastructure stock levels and accessibility of road infrastructure relate with well-being, and Section 6 concludes.

2. Literature review

2.1. Concepts relating mobility, infrastructure and well-being

A number of concepts have been developed to investigate the relation between service provision, social well-being and environmental limits (Table 1). These concepts revolve around minimum and maximum levels of consumption and service provision for sustainability. However, none of them have deeply investigated decent mobility in a sustainability context (see also Subsection 2.2).

Mobility infrastructure is central to understanding transport energy use and GHG emissions, as well as for the provision of mobility services in a more resource-efficient and low-carbon manner (Creutzig et al., 2015). While there is a long-standing debate on the role of urban form (s), spatial planning and infrastructure configurations for sustainable urbanization across many cities and regions (Kenworthy, 2020; Kenworthy and Laube, 1999; Newman and Kenworthy, 1996), little research has been conducted so far on the more general relation between the required mobility infrastructure stocks and sufficient or decent mobility for all (Wenz et al., 2020). Recently, the material and energy resources required for delivering well-being have been analysed (Brand-Correa et al., 2018; Kikstra et al., 2021; Mayer et al., 2017; Millward-Hopkins, 2020; Steinberger and Roberts, 2010), only a few of which explicitly include mobility. However, while the importance of infrastructures for mobility is generally acknowledged, so far no comprehensive global database exists that would quantify mobility-related material stocks at the national level (Lanau et al., 2019).

Material use has been growing rapidly throughout the last decades and a large – and increasing – part of the materials extracted globally are used to build up and maintain material stocks, which are expected to grow further (Krausmann et al., 2020a). Various country-level studies have found that a substantial share of total societal material stocks is used to build mobility infrastructures, which require significant flows of material and energy for their construction and maintenance (Haberl et al., 2021; Schiller et al., 2017; Shi et al., 2012; Tanikawa et al., 2015; Wiedenhofer et al., 2015). Material stocks in infrastructures are a key sustainability challenge, not only due to the resources needed to build and maintain them, but also because their patterns create path dependencies for future use (Baiocchi et al., 2015; Pauliuk and Müller, 2014). Mobility infrastructures, their spatial patterns (density, distribution), types (e.g., road vs. rail) and quality (road surface and drainage, accessibility of different locations by public transport) influence future mobility patterns and thus future resource use and environmental impacts from mobility (Barrington-Leigh and Millard-Ball, 2015; Seto et al., 2016). Following a stock-flow-service nexus perspective (Haberl et al., 2017), stocks of mobility infrastructures are a core element of providing mobility services. This recognition calls for the exploration of both elements of the nexus and their connection to desired outcomes, such as well-being, to understand pathways towards more sustainable resource use.

2.2. State of the art of mobility measures and sufficiency thresholds

In this subsection we summarize concepts and literature discussing definitions of basic mobility needs, (decent) mobility services and their operationalization. Various approaches aim to capture the basic need of mobility, some of them coming from broader conceptualizations of societal services (Kalt et al., 2019), 'universal basic services' (Coote, 2021), or 'decent living standards' (Rao and Min, 2018a) and some of them directly developed to describe personal transport (mobility), such as 'transport poverty' (Lucas et al., 2016), 'sustainable transport' (Zhao et al., 2020) or 'mobility needs' (Mattioli, 2016). Between those strands of literature, definitions and common terms vary, as they focus on different aspects of mobility.

A part of the literature explicitly focuses on mobility and minimum boundaries of sufficiency and decency above poverty. The Decent Living

Table 1
Concepts of the relation between service provision, social well-being and environmental limits.

Concept	Core messages	Core references
'Doughnut' - a safe and just space for humanity	Raworth (2012) complemented the planetary boundaries concept of Rockström et al. (2009) with social foundations, i.e. minimum requirements for a good life. In between both there is a safe and just operating space, which has been subsequently operationalized and investigated globally by O'Neill et al. (2018).	O'Neill et al., 2018; Raworth, 2012; Rockström et al., 2009
Sustainable development target space'	A sustainable future for all is to be achieved by reaching a set of targets based on the UN 2030 Agenda. Target values are not always concrete but the target space considers non-linearities and interdependences.	van Vuuren et al., 2021
Sustainable consumption corridors	Sustainable individual consumption levels lie between minimum and maximum standards and allow sufficient access to resources for others in the present and in the future. Theories to link natural and social resources to human needs are needed for their definition and implementation.	Di Giulio and Fuchs, 2014; Gough, 2020; Sahakian et al., 2021
Universal basic services (UBS)	As an alternative to the proposal for universal basic income, UBS are a contribution to establishing sustainable consumption corridors, i.e. ensuring a good quality of life for all. Public and shared consumption as opposed to just private consumption is put into focus.	Coote, 2021; Gough, 2019
'Buen vivir' or 'good life'	Collectively defined social boundaries of self-limitation have the potential to guide a just social-ecological transformation towards a sustainable future.	Brand et al., 2021
Provisioning systems	A set of related elements such as households, markets, the commons, the states, techniques and material stocks, work together as a provisioning system to transform resources for the satisfaction of a human need. It mediates the relationship between biophysical resource use and social outcomes.	Fanning et al., 2020; Gough, 2019; Lamb and Steinberger, 2017; Plank et al., 2021; Schaffartzik et al., 2021
The stock-flow-service nexus	The stock-flow-service nexus concept emphasises the pivotal role of societal material stocks of buildings, infrastructure and machinery, together with the resource flows required for their construction, maintenance and operation, in providing material and energy services essential for social well-being.	Carmona et al., 2017; Haberl et al., 2017; Pauliuk et al., 2021; Tanikawa et al., 2020; Whiting et al., 2020
Decent living standards (DLS)	DLS are a comprehensive set of generalizable dimensions, building on previous work on 'subsistence emissions' (Shue, 1993) and 'decent living emissions' (Rao and Baer, 2012) for a decent life for all.	Rao et al., 2018; Rao and Min, 2018a; Rao and Pachauri, 2017

Standards (DLS) framework provides a first set of indicators and minimum thresholds, enabling the estimation of materials, energy and GHG implications for achieving them (Rao et al., 2018; Rao and Min, 2018a; Rao and Pachauri, 2017).

Recent reviews of the literature on transport poverty (Lowans et al., 2021; Lucas et al., 2016) identified several dimensions of mobility that have to be fulfilled to prevent mobility deprivation ('transport poverty'). One key aspect is accessibility of desired locations and basic services in a specific geographic context. However, it remains unclear how much mobility and infrastructure provision would be required to prevent transport poverty, and what indicators and thresholds should guide a transition to a mobility system for a world with high well-being.

Building on conceptualizations of material and energy services as a cascade from resources to functions, services, and well-being contributions (Kalt et al., 2019; Whiting et al., 2021), it is useful to define mobility services in terms of the mobility's purpose, such as having access to have goods or products available at a specific place, visit other places or participate in social life (work, family, etc.). Therefore, mobility services can for example be expressed as reaching places to fulfil other needs, such as social participation (Virág et al., 2021). In the logic of the 'energy service cascade,' popular mobility indicators such as distances travelled are measures of mobility 'functions' that satisfy context-specific needs for the actual underlying mobility services. Travel distances depend on a number of context-specific socio-economic and structural conditions and may therefore vary substantially for the same 'service' of reaching a particular type of destination. Developing widely applicable definitions of these needs is itself complex, because, among other things, mobility needs change considerably during people's life course (Rau and Sattlegger, 2018; Scheiner and Rau, 2020). Moreover, mobility patterns are strongly shaped by prevalent mobility practices (Røpke, 2009) characterized by materials and infrastructures (e.g. road or rail networks), meaning and skills as well as competences, all of which are deeply embedded in social structures and even 'mobility cultures' (Mögele and Rau, 2020). This interwoven bundles of social practices (Shove and Walker, 2014) may explain mobility better than perspectives limited to trip distances.

Despite these challenges in defining mobility needs, some studies propose universal standards for mobility. For example, Coote (2021) proposes 'universal basic services' of mobility, a well-functioning, co-ordinated and sufficiently funded scheme that encourages active (walking, cycling) mobility and affordable or free public transit over car travel. This scheme would encourage sustainable consumption by also reducing GHG emissions and air pollution.

The 'Decent Living Standards' (DLS) Framework defines and quantifies universal minimum conditions for well-being based on human needs (Doyal and Gough, 1984) and capabilities (Gough, 2020; Nussbaum, 2003). DLS provide concrete indicators and thresholds, enabling the estimation of materials, energy and GHG implications of achieving them. In the mobility dimension of DLS, about 8,500–10,000 p-km/year are assumed to be necessary for decent living, depending on population density and urbanization (Kikstra et al., 2021; Millward-Hopkins, 2020; Rao and Min, 2018a). While this literature provides important first insights into minimum levels for decent mobility for all, these values may be interpreted as coarse approximations that might need to be substantially higher or lower, depending on the respective context. It also remains unclear how much infrastructure is required to enable these travelled distances for everyone, and whether the suggested threshold provides the guidance needed to move towards a safe, sustainability and just mobility system.

Lucas et al. (2016) provide a thorough review of different conceptualizations of mobility requirements. They introduce 'transport poverty' as an overarching notion to describe insufficient mobility levels at the individual, rather than at the household level to acknowledge gender differences. Their concept of 'transport poverty' combines the following parameters: transport affordability – the ability to purchase basic mobility within one's limited budget (Litman, 2021), mobility poverty – the systemic lack of transport services or infrastructure (Moore et al., 2013), accessibility poverty – the ability to get to key services (Social Exclusion Unit, 2003) and exposure to transport externalities – negative effects such as casualties or chronic diseases (Barter, 1999). It remains unclear, if a deficiency in transport supply, a minimum level of mobility and/or a minimum level of accessibility of goods, services and activities are suited best to define 'transport poverty' (Lucas et al., 2016).

One key aspect of the definitions of transport poverty is accessibility of desired locations and basic services in a specific geographic context. In high-income nations it has been shown that socio-economic inequality, affordability of mobility modes and availability of alternatives to the car seem to intersect in producing transport poverty (Mattioli, 2016). In lower-income countries, limited connectivity and the lacking availability of reliable mobility infrastructure have been identified as critical constraints. Moreover, limited affordability of mobility can result in social exclusion (Jaramillo et al., 2012; Peng et al., 2008; Wenz et al., 2020). In recent studies, a minimum threshold of all-season road access within a 2-km-distance of each household has been proposed, which leaves two thirds of the global rural population without sufficient access to the mobility network (Iimi et al., 2016; Khandker et al., 2006).

Another term frequently used to describe decent mobility within environmental limits is 'sustainable transport', meanwhile a fast growing research topic (Zhao et al., 2020). An agreed-upon definition of sustainable transport is still lacking, despite useful efforts towards that end (Banister, 2008; Janic, 2006; Zhou, 2012). The Centre for Sustainable Transportation's definition of 'sustainable transport' includes the fulfilment of basic and development needs of current and successive generations equally and safely and in a manner consistent with human and ecosystem health, affordability including external costs, support of a vibrant economy, efficiency, limiting the emissions of pollutants, GHGs and noise, minimizing the consumption of non-renewable resources and land use and involving relevant stakeholders in all parts of society (Bongardt et al., 2011; Gilbert et al., 2002). A high proportion of the literature on sustainable transport published throughout the last years focused on GHG emissions and environmental sustainability (Zhao et al., 2020). While economic and environmental impacts of different transport strategies are modelled rather frequently, understanding the social outcomes of transport remains a key issue (Lucas et al., 2007).

Another framework on transport needs in a climate-constrained world by Mattioli (2016) integrates human needs theory and structuration theory to break down several transport needs and their context-specific need satisfiers, using an industrialized setting (the UK) as an example. Mattioli (2016) describes mobility needs as universal, objective, satiable and universally valid, but usually vaguely defined and quite general. While needs are seen as invariant, their satisfiers are context-dependent and socio-ecologically variable (Lamb and Steinberger, 2017). Several hierarchical orders of satisfiers for transport needs can be distinguished (Mattioli, 2016): (1) the societal level of required systems, such as the system of employment or food production, (2) the existence of paid employment or shopping facilities (3) travel and (4) a car. The perceived necessity of different orders of satisfiers can change over time. For example, the percentage of the British population who think of a car as a necessity for their life doubled between 1983 and 2012, which Mattioli interprets as a side-effect of increased motorization and growing distances between private settlements and destinations that need to be reached, in combination with cuts on public transport funding by the British government. This example illustrates how need satisfiers can become more travel- and carbon-intensive over time through structuration processes, which makes the satisfaction of basic needs dependent on unsustainable, carbon-intensive need satisfiers (Mattioli, 2016).

Across these strands of literature, definitions and operationalizations of minimum levels or basic needs vary substantially, and are usually without explicit reference to the required infrastructure. In general, the authors aim at identifying the part of societal services, such as personal mobility, that can be assigned to the level needed to avoid serious harm such as disabled social participation, i.e. that can be defined as 'needs', in contrast to 'wants' (Doyal and Gough, 1984). There is a clear consensus in the literature that such minimum levels are "not only about food, clothing, and shelter; they are about having the opportunities and choices necessary to participate effectively in society" (Gough, 2020), which necessarily requires a certain amount of mobility enabling the participation in society, as all activities are organized across space and time (Wiedenhofer et al., 2018). It is important to recognize, however, that definitions of 'decency' and the related distinction between 'needs' and 'wants' require normative judgments, which raises difficult questions of who has the power to draw such lines. Recent discourses inspired by experiences during the Covid pandemic suggest that 'voluntary immobility' could foster well-being, help reduce inequalities, improve people's work-life balance and address gender imbalances. Such considerations hint at the need to rethink mobility at an even deeper level (Adey et al., 2022; Adey et al., 2021), e.g. by including active modes of mobility, such as walking and cycling (Spinney, 2021).

Several approaches to measuring mobility have developed different indicators for assessing specific dimensions of mobility (see Table S1), but hardly any of them can be rolled out for a cross-national or global analysis. A comparison of projects for collecting data on sustainable transport shows that so far no scheme enables the assessment of sustainable transport on a global scale, as most concepts focus on specific aspects (Bongardt et al., 2011). At the macro-scale, data on mobility are only available in terms of travelled distances, which does not represent the actual need or service of mobility but only 'functions' (Kalt et al., 2019) or 'satisfiers' (Mattioli, 2016) for mobility. However, a number of transport models rely on travelled distances: MESSAGE-Transport (Agnew et al., 1979; McCollum et al., 2017), the ITF model (International Transport Forum, 2021) and the IEA Mobility Model (Fulton et al., 2009). This seems practical but implicitly equates increased mobility activity with better fulfilment of mobility needs or a contribution to well-being. As discussed above, the travelled distance may not reflect the desired outcome of mobility (i.e. the service itself). Social participation (in family life, work life, etc.) and access to vital goods/services such as education, health care etc. can be possible with very little travel in physical space if most or all destinations are available in a person's vicinity. Hence, a decent life or high well-being may also be possible while travelling very short distances. However, as travelled distances, usually measured in person-kilometres (p-km), are the most widely available and used measure for mobility with good data availability, we explore their relationship with well-being in Section 4.2.

3. Methods and data

For the empirical analyses, we calculate the mass of global mobility infrastructure stocks and draw upon a number of published databases for statistical analyses.

3.1. Sources of mobility data and well-being indicators

We compiled a broad set of socio-economic indicators on sustainable development for cross-sectional statistical analyses, which are available for a differing number of countries and years (Table 2). Data on travelled distances are available mostly for industrialized countries and different periods from (European Commission, 2020; ICCT, I.C. on C.T, 2017; ITF, 2021; Worldbank/UIC, 2021). We used the most recent datapoint after

Table 2
Data on mobility and socio-economic indicators on well-being and economic activity.

	Units	Years available	Countries covered	Sources
Travelled distances (road and rail)	Person-km per year	1970–2019	Any year: 118 countries; >2015: 37 countries	European Commission, 2020; ICCT, I.C. on C.T, 2017; ITF, 2021; Worldbank/UIC, 2021
Economic Activity (GDP)	2019 prices at market exchange rates, US$	2019	200 countries and territories	World Bank, 2019
Human Development Index (HDI)	Index: 0–1	2020	186 countries	UNDP, 2020b
Sustainable Development Goals reached (SDGs)	% of SDGs (incl. all sub-targets) reached	Latest: 2021	165 countries	Sachs et al., 2021
Social Thresholds passed	Count: 0–11	2011	151 countries	O'Neill et al., 2018; Raworth, 2012
Social Progress Index (SPI)	Index: 0–100	2011–2021	168 countries	The Social Progress Imperative, 2021
Rural Access Index (RAI) geospatial	% of households within a country	2016	183 countries	World Bank et al., 2016

the year 2015, which results in all datapoints for annual p-km in the final dataset being from the years 2018 or 2019. Data preparation is explained in detail in the SI.

To measure economic activity, we used GDP at market prices of 2019, sourced from World Bank (2019), because values from 2020 are expected to be less representative due to the economic recession following the COVID pandemic. As there are strong arguments against equating well-being or human flourishing with economic activity (Cassiers and Thiry, 2014; Kubiszewski et al., 2013; Stiglitz et al., 2010), we included a number of 'beyond GDP' indicators which are not, or at least less directly, dependent on measures of economic activity. The most well-known alternative is the 'Human Development Index' (HDI), which includes a measure of economic activity (Gross National Income per capita and year) and additionally considers life expectancy at birth and expected years of schooling (to represent human capabilities) but omits ecological and environmental dimensions (UNDP, 2020a). Another prominent framework to assess progress towards eradicating poverty and sustainable development are the Sustainable Development Goals (SDGs). Within its 17 main targets, 169 sub-targets and 304 indicators, three dimensions are covered: economic, social and environmental progress (UN, 2015). While this framework has undoubtedly had an impact on the global sustainability discourse (Sachs et al., 2019), critics highlight that the lack of systemic conceptualization of trade-offs and synergies across the various SDGs and the explicit target on economic growth (SDG 8) might undermine the SDGs targets on ecological integrity (Bengtsson et al., 2018; Eisenmenger et al., 2020). To represent social progress, we used the 'Social Progress Index' (SPI). It is composed of 51 sub-indicators reflecting the dimensions of basic human needs, the foundations of well-being and opportunities for people (The Social Progress Imperative, 2021). We compared results of all analyses using SPI also with results on the main three SPI-modules (basic needs, foundations for well-being and opportunity). Furthermore, we included the quantification of 11 minimum 'social thresholds' by O'Neill et al. (2018). These are based on the extension of the concept of planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) to the concept of a 'safe and just space' that also considers social foundations (Raworth, 2012), and quantifies both upper and lower thresholds for >150 nations (Fanning et al., 2021; O'Neill et al., 2018).

To our knowledge, no macro-scale indicator of accessibility of basic services is available that could be applied to our cross-country analysis (see Table S 1). Instead, we used the Rural Access Index (RAI), i.e. the SDG-indicator associated with accessibility of (road) transport infrastructure. The RAI measures the accessibility of adequate roads from households (Iimi et al., 2016; Roberts et al., 2006). For reasons explained in the SI, we used the geospatial version of the RAI (World Bank et al., 2016).

3.2. Calculation of material stocks of global mobility infrastructures

We calculated global mobility infrastructure stocks for 172 countries/country-groups in terms of network lengths and material stocks. To estimate infrastructure stocks by country, we combined information on network lengths from OpenStreetMaps (OSM) with material intensities for 17 road- and rail-based infrastructure types for different countries and regions, following a stock-driven modelling procedure established previously (Frantz et al., in prep.; Haberl et al., 2021; Wiedenhofer et al., 2021). OSM has been shown to be the most complete global map of mobility infrastructure globally available (Barrington-Leigh and Millard-Ball, 2017). For this estimation, OSM categories identified as most important mobility infrastructure in previous work (Haberl et al., 2021) were aggregated into six road and four rail-based infrastructure types, for which data on infrastructure network lengths (L) for all countries were processed from Geofabrik (2021) (see supplementary information for details). Based on literature on the composition and dimensions of mobility infrastructure types, average widths (W) and material intensity (MI) factors were developed for each stock type (see supplementary information for data and further detail). Eq. (1) shows a standard equation for stock-driven 'bottom-up' estimations (Lanau et al., 2019; Virág et al., 2021; Wiedenhofer et al., 2019; Wiedenhofer et al., 2015) and was used to estimate material stocks per infrastructure type. In this equation, *st* denotes stock type, *m* represents the respective material, *c* the respective country, *L* the length of the stock type and *W* its width.

$$Stock_{st,m,c} = L_{st,c} * W_{st} * MI_{st,m} \tag{1}$$

The material intensity factors used to calculate global mobility stocks as described in Eq. (1) are listed in Table 3. Material intensity factors may vary regionally due to different building standards, as well as locally due to specific on-site conditions and requirements. A complete assessment of differences in material intensities in all countries analysed is not possible due to studies lacking for most regions, an effort which was out of scope for this article. Herein, we draw on country-specific data from several nationally specific studies, while for the rest of the world a global average of material intensity factors was used. Qualitative differences are accounted for, for example by separating different types of roads. However, qualitative differences within subtypes may vary in its quality from region to region and cannot be captured in detail.

4. Results

4.1. The mass of infrastructures and their relation to travelled distances

Global material stocks of transport and mobility infrastructure amount to 312 Gt in the year 2021, of which road infrastructure makes up 294 Gt and rail-based infrastructure (including subways, trams and other light rails) 18 Gt (Fig. 1A). Paved high-class roads (e.g. motorways, primary, secondary, and tertiary roads) make up 49% (144 Gt) of the total mass of road infrastructure, even though they account for only 12% of the global road network in terms of length, which is due to their significantly higher material intensity compared to other types of infrastructure. Low-class roads, mostly gravel or dirt roads with minor

Table 3
Overview of total material intensity factors for individual countries and global average for roads and rails.

Stock group	Stock type	Total MI of asphalt, concrete, sand and gravel, timber and steel [t/m^2]							
		USA	CHN[3]	AUT	DEU	SVK	JPN	GBR/IRL	Global average
Roads	Motorway	1.22	1.58	1.76	1.76	1.76	1.99	1.50	1.73
	Primary	1.07	1.49	1.37	1.37	1.37	1.74	1.48	1.42
	Secondary	0.97	0.79	1.27	1.27	1.27	1.36	1.60	1.30
	Tertiary	0.82	0.79	1.15	1.15	1.15	1.04	1.55	1.12
	Local[1]	0.43	0.36	0.61	0.61	0.61	0.22	0.84	0.50
	Rural[1]	0.34	0.19	0.24	0.31	0.23	0.28	0.74	0.30
	Motorway bridges[2]	1.32	1.32	1.65	1.65	1.65	1.10	1.32	1.32
	Motorway tunnels[2]	2.92	2.92	2.65	4.73	3.65	2.87	2.92	2.92
	Other road bridges[2]	1.15	1.15	1.43	1.43	1.43	1.10	1.15	1.15
	Other road tunnels[2]	2.92	2.92	2.65	4.73	3.65	2.87	2.92	2.92
Rails	Railway	0.85	0.48	0.33	0.35	0.33	0.55	0.41	0.41
	Railway bridges[2]	1.62	1.62	1.58	1.58	1.58	1.77	1.62	1.62
	Railway tunnels[2]	4.26	4.26	4.22	4.22	3.50	5.09	4.26	4.26
	Subway underground	11.19	11.19	13.83	13.83	13.83	3.27	11.19	11.19
	Subway elevated	4.24	4.24	5.39	5.39	5.39	0.80	4.24	4.24
	Subway ground-level	2.46	2.46	3.01	3.01	3.01	0.80	2.46	2.46
	Tram and other rails	0.47	0.47	0.61	0.61	0.61	0.03	0.47	0.47
References		Frantz et al., in prep.	Bai et al., 2019; Chen et al., 2017	Haberl et al., 2021			Journal Article; Tanikawa et al., 2015	Wiedenhofer et al., 2021	AUT, DEU, SVK, JPN, GBR/IRL, and additional sources: ARE: (Alzard et al., 2019; Department of Municipal Affairs and Transport, 2016); NPL: (Department of Roads, 2014); TUR: (Alzaim et al., 2020; Özgenel, 2016), ZAF: (CSIR, 2000; Henderson and Van Zyl, 2017)

[1] Assumptions on the shares of paved, unpaved and compacted local earth roads considered in factors.
[2] Only bridge or tunnel structure itself is considered in this factor, excluding corresponding road surface or rail track, which are covered in the respective road/rail intensity.
[3] Missing country-specific data supplemented by global average.

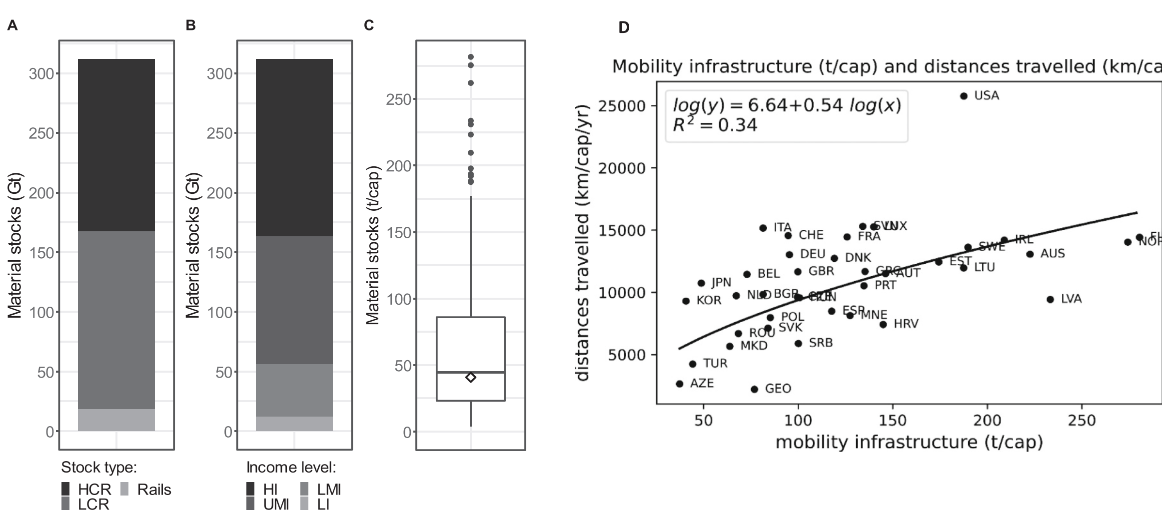

Fig. 1. Global material stocks in road- and rail-based infrastructure per main stock type (A), by income-group (B) and as a global distribution and population-weighted average (C). *HCR* denotes high-class roads (motorways, primary, secondary and tertiary roads). *LCR* denotes low-class roads (local and rural roads). Income level groups: *HI* = High income, *UMI* = Upper-middle income, *LMI* = Lower-middle income, *LI* = Low income. (Median = line, population-weighted average = square). Note that the boxplot (C) excludes one outlier (ISL). Regression analysis of mobility infrastructure levels per capita and travelled distances per capita per year (D).

asphalt sections (e.g. local and rural roads) make up 149 Gt.

Distinct regional stock levels are observed along income differences, as countries with higher income levels usually have larger mobility infrastructure stocks (Fig. 1B). With 48% (149 Gt), the majority of mobility infrastructure stocks are located in high-income countries. By contrast, in low-income countries we find <4% (12 Gt) of total mobility infrastructure stocks. Average global mobility infrastructure stocks are estimated at 44.3 t/cap (median) or 40.7 t/cap (population-weighted average), with countries between the 25th and 75th percentile ranging between 23.1 t/cap and 86.1 t/cap (Fig. 1C). The country with the highest per capita infrastructure level is Iceland (outside of scale in Fig. 1C) with 494 t/cap, Bangladesh has the lowest mobility infrastructure level with 3.6 t/cap.

Across all countries for which mobility data are available, we find that mobility infrastructure stocks per capita are significantly correlated with annual travelled distances per capita (see Fig. 1D, Table S3 in the SI for details). This may only reflect that higher car dependence in wealthier countries drives both greater investments in roads and more travel-intensive lifestyles. However, it is noteworthy that no country (for which we had data) has average travel demand of >10,000 km/capita with <48 tons of mobility infrastructure per capita. This may suggest that present structural patterns of the built environment demand this amount of material to support contemporary (largely Western) lifestyles.

4.2. The relationship of travelled distances, economic activity and well-being

We continue our empirical explorations with a cross-sectional analysis of the relationships between travelled distances per capita and well-being indicators (see Table 2 for an overview). We note that this correlation may reflect a bidirectional relationship: better travel opportunities enable more economic activity and potentially greater well-being as much as the latter can drive more travel-intensive lifestyles. We use a

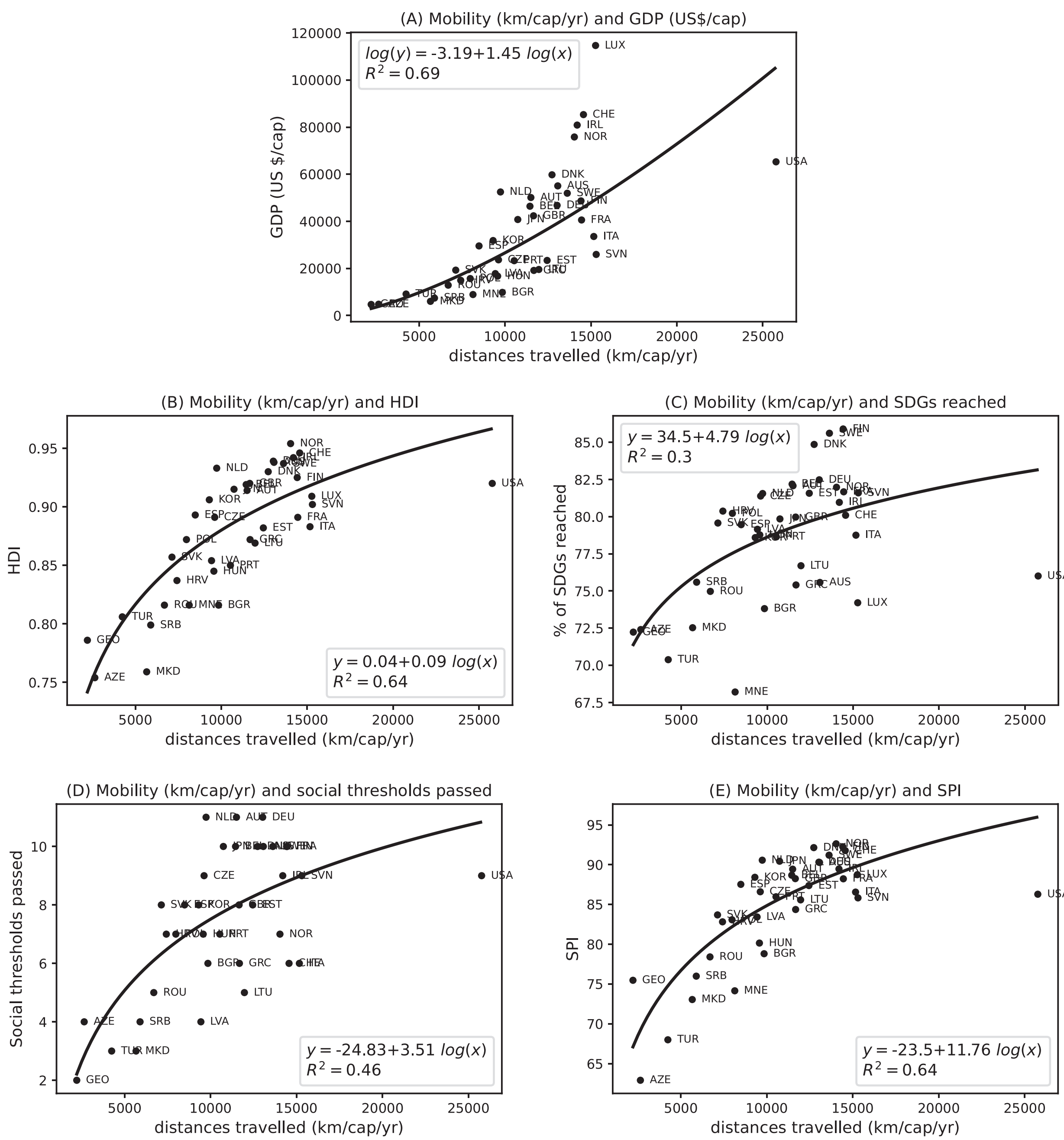

Fig. 2. Regressions of mobility functions (travelled distances) economic activity and well-being. A) GDP (log-log), B) Human Development Index (HDI) 2020 (UNDP, 2020b), C) achievement of Sustainable Development Goals (SDGs) in 2021 (Sachs et al., 2021), D) social thresholds reached (O'Neill et al., 2018), E) Social Progress Indicator (SPI) 2021 (The Social Progress Imperative, 2021). Detailed results: see Table S 3.

log-log regression model to analyse the relative sensitivity of mobility to GDP. For the other indicators, which are range-limited, we use a saturation function (Steinberger et al., 2012; Steinberger and Roberts, 2010). Results of the regression analyses are shown in Fig. 2 (detailed results, also for alternative regression models can be found in Table S 3). The USA is a special case due to its very high mobility levels per capita. However, its omission only marginally changes the correlations discussed below (Table S 5), but not the overall picture.

Notably, GDP rises faster than travel demand, in contrast to the other indicators, where well-being rises faster at lower levels of travelled distances. A 1.45% increase of GDP is associated with a 1% increased average travel distance per year. The correlation of travelled distances against GDP ($R^2 = 0.69$) is comparable to those against HDI and SPI ($R^2 = 0.64$), but weaker against the SDG ($R^2 = 0.3$) and social thresholds achievement indicators ($R^2 = 0.46$). Using only the module 'foundations of well-being' of the SPI would slightly reduce explanatory power ($R^2 = 0.60$, $p = 0.000$, results for the SPI modules can be found in Table S 4). Notably no country (for which we have data) has HDI >0.8, achieved >75% of SDGs, achieved >8 social thresholds and has an SPI >80 with average travel distances of <9600 km/cap/yr. While this by no means suggests that societies *cannot* achieve these well-being thresholds with less travel (indeed, one might find that subpopulations within many countries *have* passed these thresholds with less travel), it lends support for the idea that with current patterns of development, at a country-level, there may be certain minimum levels of travel associated with different thresholds of social progress along different dimensions.

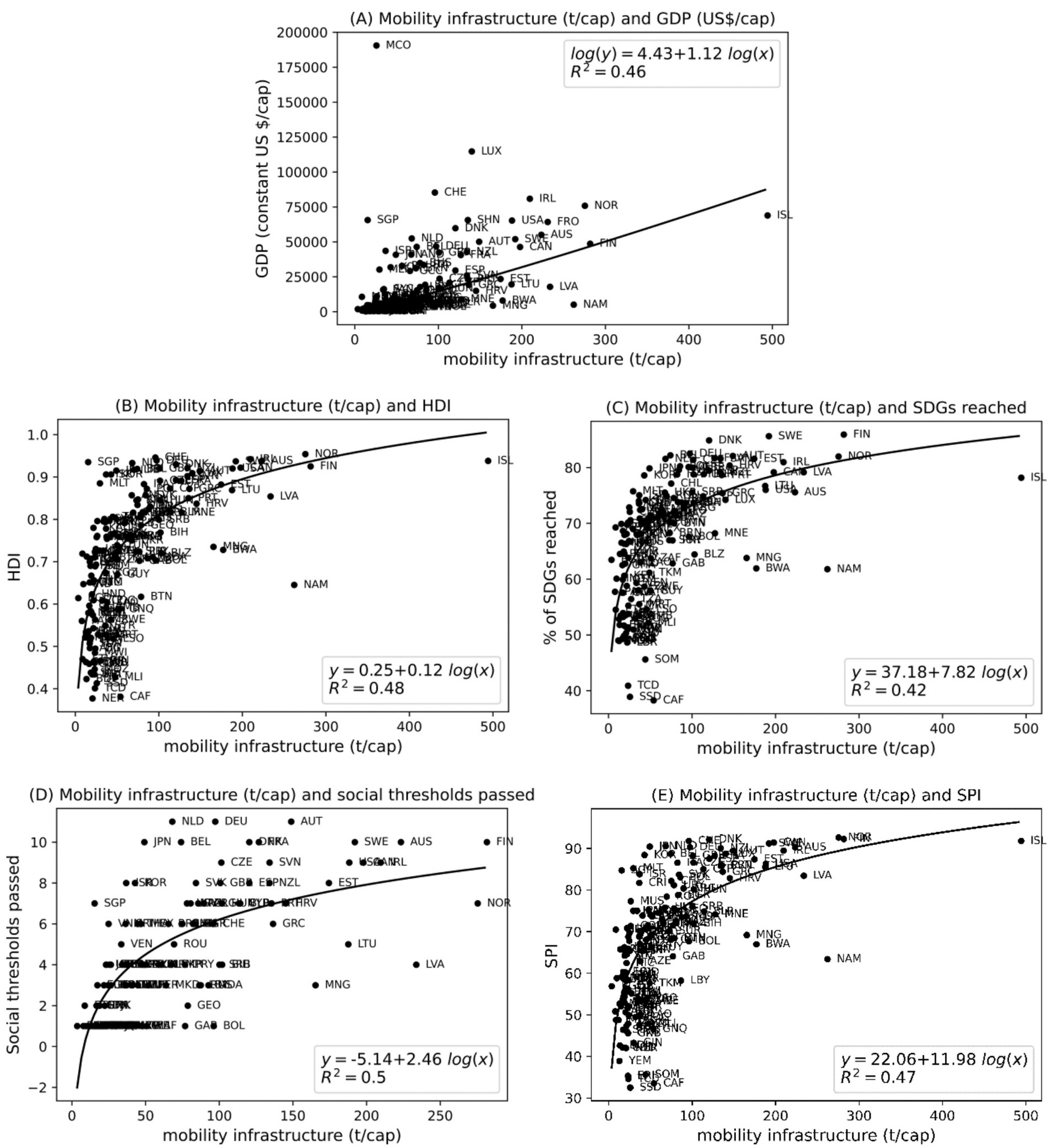

Fig. 3. Regression of mobility infrastructure stocks/capita, economic activity and well-being. A) GDP (log-log), B) Human Development Index (HDI) 2020 (UNDP, 2020b), C) achievement of Sustainable Development Goals (SDGs) in 2021 (Sachs et al., 2021), D) social thresholds reached (O'Neill et al., 2018), E) Social Progress Indicator (SPI) 2021 (The Social Progress Imperative, 2021). Detailed results: see Table S 3, indices 5–9.

4.3. The relationship of mobility infrastructure stocks, economic activity and well-being

We conducted a cross-sectional analysis of the relations between mobility infrastructures, economic activity (GDP) and well-being. The Stock-Flow-Service Nexus framework describes the importance of material stocks for providing societal services (Haberl et al., 2017). As infrastructure stocks for mobility are a precondiction for the connectivity between different locations, and thus the accessibility of services, their availability is a key factor for decent mobility. As above, we used a log-log regression model for GDP and a saturation function to analyse relationships with other well-being indicators. As the global dataset of mobility infrastructures is far more extensive than the available data for travelled distances, a larger number of countries could be included in the analysis (see Fig. 3). Iceland is a specific case due to its far higher mobility infrastructure level per capita than all other countries. However, regression results omitting Iceland from the dataset hardly differ from results using the full dataset (see Table S 6).

Overall, the correlations between mobility infrastructure stocks and well-being indicators are weaker than those with travelled distances, with R^2 in the range of 0.4–0.5 for all indicators. Growth in stocks and GDP are proportional at all income levels: a 1% change in stock comes with a 1.12% change in GDP. Regressions of mobility stock levels per capita against all other indicators of well-being show relatively higher increases in well-being at lower levels of stock, similar to travelled distances. For detailed results see Table S 3, indices 5–9. Again, the results for SPI ($R^2 = 0.47$, $p = 0.000$) and the well-being module of SPI ($R^2 = 0.47$, $p = 0.000$) are very similar (see Table S 4).

For comparability with results of our first analysis of the relationships between travelled distances with GDP and well-being, we drew the same sample of countries, that is only those for which p-km data was available, and repeated the analysis of mobility infrastructure levels and GDP and well-being. The reduced sample (Fig. S 5, detailed results in Table S 3, indices 10–14) achieves a significantly lower goodness of fit for all indicators than the analysis for the full sample, which may just reflect data limitations. The comparison also shows that correlations between infrastructure stocks and well-being indicators are weaker than correlations between travel distances and well-being indicators. This may be because mobility infrastructure stocks likely influence well-being more through travel than other means (such as employment, whose impacts would be temporary). One notable insight is that for the non-economic well-being indicators (as reflected in the almost vertical shape of the envelope at low levels of mobility infrastructure stock) there seem to be several countries that have achieved relatively high levels of well-being with very low levels of infrastructure. This stands in contrast to their relation to travelled distances, which gives more cause for hypothesizing minimum thresholds.

In order to derive first infrastructure level thresholds, we calculate mobility infrastructure levels associated with reaching high wellbeing thresholds for the different indicators by solving the regression equations displayed in Fig. 3 at different wellbeing levels (see Section 4.4 in the SI for details). We find that 92 t/cap of mobility infrastructure are associated with an HDI score of 0.8, i.e. very high development according to the UNDP (2020a). Reaching 75% of SDGs is associated with 126 t/cap. Surpassing 8 of the 11 proposed social thresholds is possible with 207 t/cap, and belonging to the two country groups with highest social progress (Tier 1 or 2, The Social Progress Imperative (2021), SPI > 80.15) requires 127 t/cap of mobility infrastructure. While these results are very sensitive to the choice of the well-being threshold, they point towards possible minimum levels of mobility infrastructure for high well-being.

4.4. The relationship of accessibility, economic activity and well-being

The basis for decent mobility is access to adequate mobility options, which have to be available within a certain distance from each person's home (Rao and Min, 2018b). Accessibility contributes to fulfilling human needs by enabling personal autonomy, employment and leisure participation, thus, efforts to improve people's access to transport systems is also a sub-target in the SDGs (Fisch-Romito, 2021; UN, 2021).

We test these relationships of accessibility of road transport infrastructure (measured using the Rural Access Index, RAI) and economic activity or well-being using all available datapoints that is, all countries for which RAI and the indicator investigated are known. We included the total amount of road infrastructure (including tunnels and bridges) in this analysis. It is not clear which share of low-class roads (LCR) is in adequate condition throughout all seasons, therefore overestimations of mobility infrastructure levels are possible. We use a level-log model for GDP relations and linear regression models for the 'beyond GDP' indicators, as we plot indicators (0–1 or 0–100) against each other and as these models achieve the highest fit and acceptable heteroscedasticity compared to other regression model specifications (detailed results can be found in Table S 3, indices 15–19).

We find that RAI levels are hardly coupled with GDP (regression slope 0.04), and observe a moderate explanatory power ($R^2 = 0.40$, see Fig. 4A). Also for well-being indicators, a moderate explanatory power of RAI is observed, with R^2 ranging from 0.40 (social thresholds) to 0.55 (SPI) (Fig. 4B-E). RAI is not strongly coupled with any of the well-being indicators with all regression slopes being rather low (HDI 0.0, SDGs 0.36, social thresholds 0.09 and SPI 0.52). Again, this is very similar for total SPI and the individual SPI modules (see Table S 4).

5. Towards defining 'decent mobility standards' and their infrastructure requirements

Our comparison of different strands of literature on (decent) mobility has shown that definitions and sufficiency thresholds for mobility are neither straightforward nor agreed-upon (Section 2). Following Lucas et al. (2016), (1) relevant basic services such as healthcare, educational or grocery shopping facilities, have to be accessible with reasonable time and effort, (2) mobility options to reach them have to be available and affordable, and (3) the conditions of travelling have to be safe and healthy. Following Kalt et al. (2019), reaching a decent level of mobility services means reaching 'what is really wanted' from mobility, for example access to social participation.

We therefore concur with previous statements that a generalized definition of decent mobility or decent mobility infrastructure levels, including operational indicators, is currently out of reach. This is also due to its necessarily high context-dependency in terms of socially, temporally and geographically highly variable influences (Lucas et al., 2016). For example, it has already been shown that settlement types and urban form(s) (Holden and Norland, 2005; Newman and Kenworthy, 1996; Wiedenhofer et al., 2018; Wiedenhofer et al., 2013), as well as other socio-economic factors play an important role in determining individual's demands for mobility, consumption and subsequently emissions. As the spatial distribution of services varies between and within countries and regions, it depends on the historically contingent spatial patterns of desired destinations, such as shops, work places, healthcare and other facilities, how much mobility is required for a decent level of access and participation. Important intervening variables are travel-time budgets (Ahmed and Stopher, 2014) and speed of travel, for which no comprehensive data for cross-country analyses like those presented here exist. Thus, there is necessarily a substantial difference between decent mobility within current spatial patterns of societal organization and theoretical patterns optimized for less mobility requirements.

Our results on global mobility infrastructures provide a first quantification of the mass of road and rail infrastructure in 172 countries. This is a valuable basis for analysing connections between infrastructure requirements and mobility services. The relationship between total mobility infrastructure stocks and total travelled distances within a country shows a very strong coupling, and is still considerable when analysing per-capita relations (see Table S 3, indices 22–23). This

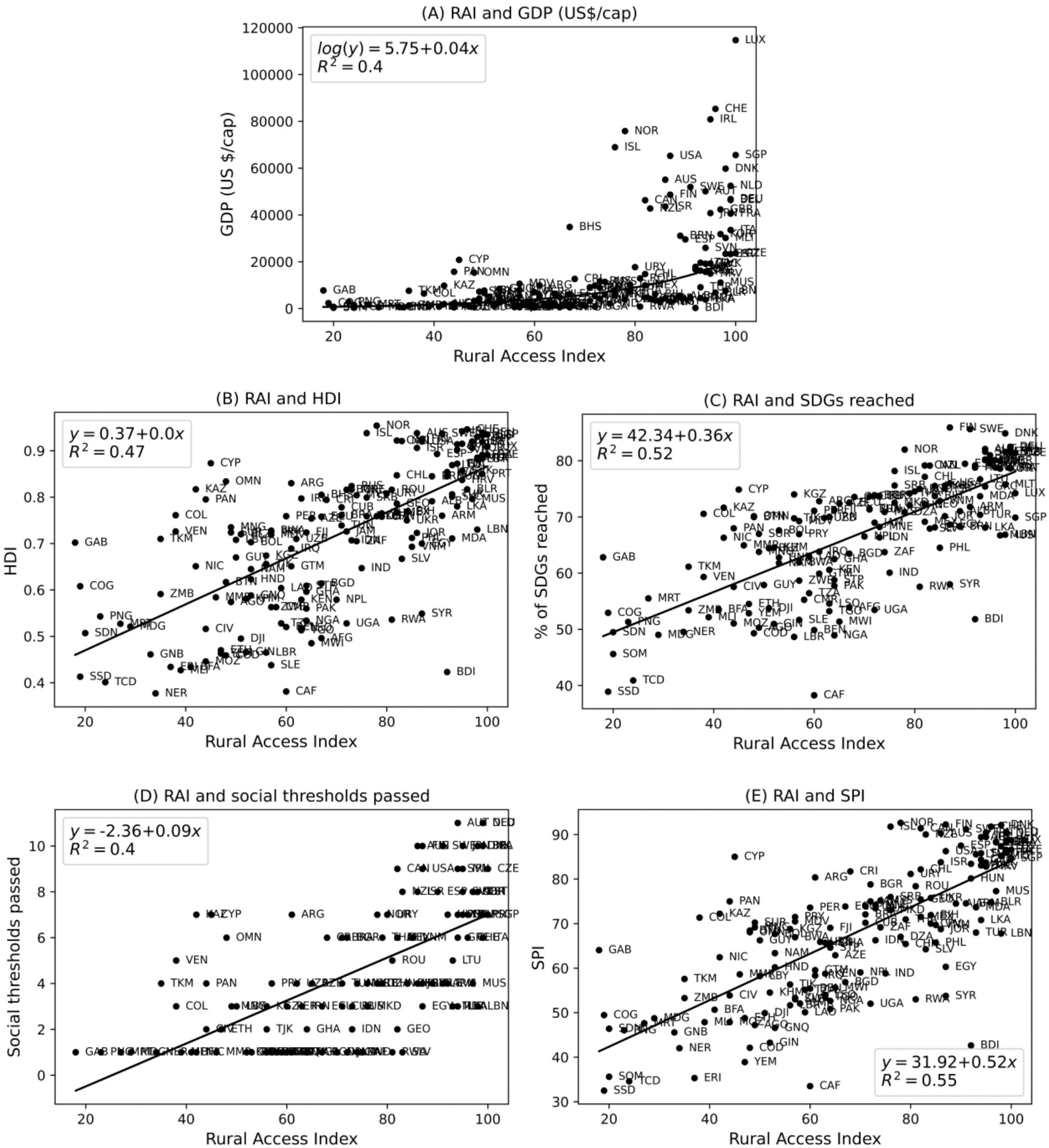

Fig. 4. Regression of Rural Access Index, economic activity and well-being indicators. A) GDP (log-log), B) Human Development Index (HDI) 2020 (UNDP, 2020b), C) achievement of Sustainable Development Goals (SDGs) in 2021 (Sachs et al., 2021), D) social thresholds reached (O'Neill et al., 2018), E) Social Progress Indicator (SPI) 2021 (The Social Progress Imperative, 2021). Detailed results: see Table S 3, indices 15–19.

corroborates expectations of the development of mobility infrastructure and mobility activity being strongly intertwined due to widespread 'predict and provide' approaches in transport planning or unintentional structuration (Mattioli, 2016). The mass of mobility infrastructure is also strongly related to environmental impacts from their build-up, maintenance and use, which require substantial material and energy use and cause GHG emissions (Krausmann et al., 2020a).

The analyses of the relationships between travelled distances, mobility infrastructure stocks and accessibility yielded interesting insights, despite limited data availability for mobility. We found a strong linear relationship between travelled distances and GDP but diminishing gains of well-being, such as high human development levels (HDI), high achievement in SDGs, a high assessment in social thresholds according to the Raworth's doughnut framework or high social progress (SPI) with higher levels of travelled distances. The same relationships are observed between mobility infrastructure levels and GDP (strong, linear coupling) or well-being indicators (diminishing gains at high levels), whereby more available datapoints in the mobility infrastructure dataset strengthened the goodness of fit. Travelled distances seem to be the more informative indicator for well-being but data availability and quality currently is lacking. Well-being is coupled to mobility infrastructure stocks and flows, but decouples at high levels of well-being, while GDP continues to grow with stocks and flows. Similar relationships have been observed for energy use, emissions, economy-wide material stocks of concrete and steel, and need satisfaction for different provisioning factors (Fisch-Romito, 2021; Haberl et al., 2019;

Steinberger and Roberts, 2010; Vogel et al., 2021). Pursuing a strategy of building up more mobility infrastructure is therefore only useful for achieving high average well-being up to a certain extent, but would definitely increase environmental impacts, through material use itself and from the use of fossil fuels for materials processing, construction, and provision of mobility services. Designing future infrastructures in a resource-efficient and service-oriented manner could greatly help to foster well-being while reducing resource requirements and environmental pressures (Roelich et al., 2015).

We also find from our cross-sectional regression analyses that across the sample of countries, average infrastructure levels of ~92–207 t/cap are associated with high levels of well-being. This applies to HDI-levels >0.8 (very high development, reached at 92 t/cap), an achievement of >75% of SDGs (reached at 126 t/cap), >8 of the 11 proposed social thresholds (reached at 207 t/cap) or SPI-levels >80.15 (reached at 127 t/cap). In total, 13–34% of countries in our sample reach these high well-being thresholds, more than half of them with lower levels of mobility infrastructure per capita than suggested by the regression. These infrastructure levels are sensitive to the well-being threshold chosen and, as discussed, there are many context- and region-specific factors to be considered when trying to define levels of decent mobility infrastructure, which is why the stock levels mentioned above can only serve as a first guidance. There are examples of countries with high well-being at rather low or moderate infrastructure levels, which would be worthwile to investigate in detail in future research.

Interestingly, we do not find a clear relationship between road infrastructure stocks and RAI (see Fig. S 6 and Table S 3, indices 20–21). Previous research has shown that the relationship between economy-wide total cement and steel stocks in society, and achieved accessibility (measured by RAI) is non-linear and saturating (Fisch-Romito, 2021). From our research, we conclude that in order to reach high access levels globally (e.g. RAI >0.8), simply increasing average mobility infrastructure stocks per capita is not necessarily helpful, as a large variety of RAI levels are observable with road stocks of less than ~150 t/cap (see Fig. S 6), rather it will depend on the spatial patterns of settlements and infrastructures how large stocks are required to ensure good accessibility. Furthermore, our empirical results on the relationship of RAI and several well-being indicators revealed a linear shape with moderate fit and rather low to moderate coupling. This is somewhat surprising, as the accessibility of adequate mobility infrastructure is assumed to enhance mobility options and thus social participation and well-being.

As a caveat we note that all analyses are based on average per-capita values, thus omitting the question of unequal distribution of mobility infrastructure benefits within countries. This, however, is an important aspect to be considered. Previous analyses have shown that poorer groups of society may be affected by transport poverty even in wealthy countries, mostly because of lacking accessibility or affordability (Lucas et al., 2016). Another caveat is that because this study is focused on personal mobility, we could not address the possibility that some personal mobility may in the future be replaced by freight transport or increased telecommunication (both of which were beyond our scope). Examples include shopping being replaced by home delivery, working in offices by more hours worked at home or personal meetings replaced by tele-conferencing. Experiences during the current COVID Pandemic, which has disrupted prevalent mobility patterns and practices, could help to better understand these potentially important developments (Adey et al., 2021). We also note that walking, cycling and other modes of active personal transport are poorly, if at all, reported in international statistics, which may result in substantial underestimation of travelled distances in particular in poorer countries (Hillman and Whalley, 1979).

Overall, these findings call the strategy of a necessary global convergence of infrastructure stocks at the levels found in wealthy, industrialized countries into question. The build-up of infrastructure stocks drives GHG emissions and environmental pressures, land take and environmental burdens from subsequent higher usage of mobility infrastructure, while seemingly only contributing little to achieving high levels of well-being beyond certain thresholds (Fisch-Romito, 2021; Haberl et al., 2019; Krausmann et al., 2020b).

6. Conclusions

Sustainable, decent and sufficient mobility is an important goal for both well-being and reaching climate targets. While several ideas to defining and operationalizing (decent) mobility and its various relevant aspects have been put forward, systematic, comparable and widely applicable indicators are currently not available or only cover one relevant aspect of mobility and are not compatible methodologically (Lowans et al., 2021; Lucas et al., 2016). We therefore used existing indicators, such as travelled distances (p-km) and rural access (RAI). We furthermore provided a first estimate of material stocks of global mobility infrastructures for 172 countries, representing the material basis of mobility, as well as a proxy for environmental pressures and impacts due to construction, maintenance and operation of these infrastructures. In a cross-sectional analysis we find that travelled distances and mobility infrastructure stocks are linearly coupled with GDP. We also find diminishing gains of well-being from both high mobility activity (p-km) as well as high levels of mobility infrastructure stocks. Connectivity of rural households to decent mobility infrastructure is obviously important for well-being, which is widely measured by the Rural Access Index. Interestingly, no strong relationship to accumulated road stocks could be found, as high RAI levels could be observed at a large variety of road stock levels. We hypothesize that spatial patterns and an emphasis on accessibility might matter more for a high RAI than the overall quantity of road stocks. In summary, these findings suggest that constantly expanding mobility infrastructure stocks, as well as steadily increasing mobility activity in terms of travelled distances translate into improved well-being only up to a certain point, but also drive resource use, environmental impact and economic growth. Policies should therefore aim to design settlement and infrastructure patterns in a manner that helps reducing resource requirements while improving the delivery of key services for improved societal well-being, e.g. by favouring active mobility (walking and cycling) as well as public transport. Clearly, from this exploratory study we also suggest that a better understanding and measurement of relevant aspects of mobility services is necessary to provide decent mobility standards globally.

CRediT authorship contribution statement

Doris Virág: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Dominik Wiedenhofer:** Conceptualization, Methodology, Writing – review & editing. **André Baumgart:** Data curation, Visualization. **Sarah Matej:** Data curation. **Fridolin Krausmann:** Conceptualization, Writing – review & editing. **Jihoon Min:** Conceptualization, Writing – review & editing. **Narasimha D. Rao:** Conceptualization, Writing – review & editing. **Helmut Haberl:** Conceptualization, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements

This research has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Programme (MAT_STOCKS, grant agreement No 741950); from the the transnational project "MyFairShare - Individual Mobility Budgets as a Foundation for Social and Ethical Carbon Reduction" co funded by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation, and Technology (FFG funding no. 884278) within the ERA-NET Cofund Urban Accessibility and Connectivity (ENUAC); as well as from the Energy Demand Changes Induced by Technological and Social Innovations (EDITS) project, which is part of the initiative coordinatedby the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA) (and funded by Ministry of Economy, Trade, and Industry (METI), Japan). Part of the research was developed in the Young Scientists Summer Program at the International Institute for Applied Systems Analysis, Laxenburg (Austria) with financial support from the Austrian Academy of Sciences as National Member Organization. We thank Danielle Densley Tingley, Jing Guo, Zhiwei Liu and Maud Lanau for their contributions to the material intensities of infrastructure.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107511.

References

Adey, P., Hannam, K., Sheller, M., Tyfield, D., 2021. Pandemic (Im)mobilities. Mobilities 16, 1–19. https://doi.org/10.1080/17450101.2021.1872871.

Adey, P., Cresswell, T., Yeonjae Lee, J., Nikolaeva, A., Novoa, A., Temenos, C., 2022. Moving Towards Transition. Commoning Mobility for a Low-Carbon Future. Zed Books, London.

Agnew, M., Schrattenholzer, L., Voss, A., 1979. A Model for Energy Supply Systems Alternatives and their General Environmental Impact (Monograph). WP-79-006. IIASA, Laxenburg, Austria.

Ahmed, A., Stopher, P., 2014. Seventy minutes plus or minus 10 — a review of travel time budget studies. Transp. Rev. 34, 607–625. https://doi.org/10.1080/01441647.2014.946460.

Alzaim, M., Gedik, A., Lav, A.H., 2020. Effect of Modulus of bituminous layers and utilization of capping layer on weak pavement subgrades. Civil Eng. J. 6, 1286–1299. https://doi.org/10.28991/cej-2020-03091548.

Alzard, M.H., Maraqa, M.A., Chowdhury, R., Khan, Q., Albuquerque, F.D.B., Mauga, T.I., Aljunadi, K.N., 2019. Estimation of greenhouse gas emissions produced by road projects in Abu Dhabi, United Arab Emirates. Sustainability 11. https://doi.org/10.3390/su11082367.

Bai, J., Qu, J., Maraseni, T.N., Wu, J., Xu, L., Fan, Y., 2019. Spatial and temporal variations of embodied carbon emissions in China's infrastructure. Sustainability 11. https://doi.org/10.3390/su11030749.

Baiocchi, G., Creutzig, F., Minx, J., Pichler, P.-P., 2015. A spatial typology of human settlements and their CO_2 emissions in England. Glob. Environ. Chang. 34, 13–21. https://doi.org/10.1016/j.gloenvcha.2015.06.001.

Banister, D., 2008. The sustainable mobility paradigm. In: Transport Policy, New Developments in Urban Transportation Planning, 15, pp. 73–80. https://doi.org/10.1016/j.tranpol.2007.10.005.

Barrington-Leigh, C., Millard-Ball, A., 2015. A century of sprawl in the United States. PNAS. https://doi.org/10.1073/pnas.1504033112.

Barrington-Leigh, C., Millard-Ball, A., 2017. The world's user-generated road map is more than 80% complete. PLoS One 12, e0180698. https://doi.org/10.1371/journal.pone.0180698.

Barter, P., 1999. Transport and Urban Poverty in Asia. Regional Development Dialogue 20.

Bengtsson, M., Alfredsson, E., Cohen, M., Lorek, S., Schroeder, P., 2018. Transforming systems of consumption and production for achieving the sustainable development goals: moving beyond efficiency. Sustain. Sci. 13, 1533–1547. https://doi.org/10.1007/s11625-018-0582-1.

Bongardt, D., Schmid, D., Huizenga, C., Litman, T., 2011. Sustainable Transport Evaluation. Developing Practical Tools for Evaluation in the Context of the CSD Process (No. Background Paper no.10). UN Department of Economic and Social Affairs, Comission on Sustainable Development, German Development Cooperation (GIZ), Eschborn, Germany.

Brand, U., Muraca, B., Pineault, É., Sahakian, M., Schaffartzik, A., Novy, A., Streissler, C., Haberl, H., Asara, V., Dietz, K., Lang, M., Kothari, A., Smith, T., Spash, C., Brad, A., Pichler, M., Plank, C., Velegrakis, G., Jahn, T., Carter, A., Huan, Q., Kallis, G., Martínez Alier, J., Riva, G., Satgar, V., Teran Mantovani, E., Williams, M., Wissen, M., Görg, C., 2021. From planetary to societal boundaries: an argument for collectively defined self-limitation. Sustain. Sci. Pract. Pol. 17, 265–292. https://doi.org/10.1080/15487733.2021.1940754.

Brand-Correa, L.I., Martin-Ortega, J., Steinberger, J.K., 2018. Human scale energy services: untangling a 'golden thread'. Energy Res. Soc. Sci. 38, 178–187. https://doi.org/10.1016/j.erss.2018.01.008.

Carmona, L., Whiting, K., Carrasco, A., Sousa, T., Domingos, T., 2017. Material services with both eyes wide open. Sustainability 9, 1508. https://doi.org/10.3390/su9091508.

Cassiers, I., Thiry, G., 2014. A high-stakes shift: turning the tide from GDP to new prosperity indicators. Redefin. Prosp. 21.

Chen, J., Zhao, F., Liu, Z., Ou, X., Hao, H., 2017. Greenhouse gas emissions from road construction in China: a province-level analysis. J. Clean. Prod. 168, 1039–1047. https://doi.org/10.1016/j.jclepro.2017.08.243.

Coote, A., 2021. Universal basic services and sustainable consumption. Sustain. Sci. Pract. Pol. 17, 32–46. https://doi.org/10.1080/15487733.2020.1843854.

Creutzig, F., Baiocchi, G., Bierkandt, R., Pichler, P.-P., Seto, K.C., 2015. Global typology of urban energy use and potentials for an urbanization mitigation wedge. Proc. Natl. Acad. Sci. U. S. A. 112, 6283–6288. https://doi.org/10.1073/pnas.1315545112.

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Chang. 8, 260–263. https://doi.org/10.1038/s41558-018-0121-1.

Creutzig, F., Callaghan, M.W., Ramakrishnan, A., Javaid, A., Niamir, L., Müller-Hansen, F., Minx, J.C., Sovacool, B.K., Afroz, Z., Andor, M., Antal, M., Court, V., Das, N., Díaz-José, J., Doebbe, F.C., Figueroa, M., Gouldson, A., Haberl, H., Hook, A., Ivanova, D., Lamb, W.F., Maizi, N., Mata, É., Nielsen, K.S., Onyige, C.D., Reisch, L.A., Roy, J., Scheelbeek, P.F., Sethi, M., Some, S., Sorrell, S., Tessier, M., Urmee, T.P., Virág, D., Wang, C., Wiedenhofer, D., Wilson, C., 2020. Reviewing the scope and thematic focus of 100,000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abd78b.

CSIR, 2000. Guidelines for Human Settlement Planning and Design: The Red Book, Vols. 1 & 2. Council for Scientific and Industrial Research.

Department of Municipal Affairs and Transport, 2016. Pavement Design Manual (No. TR-513). Government of Abu Dhabi, Abu Dhabi, United Arab Emirates.

Department of Roads, 2014. Pavement Design Guidelines (Flexible Pavement). Ministry of Physical Infrastructure and Transport, Government of Nepal, Kathmandu, Nepal.

Di Giulio, A., Fuchs, D., 2014. Sustainable Consumption Corridors: Concept, Objections, and Responses, 23. Okologische Perspektiven in Natur-, Geistes- und Wirtschaftswissenschaften, Gaia, p. 184. https://doi.org/10.14512/gaia.23.S1.6.

Doyal, L., Gough, I., 1984. A theory of human needs. Crit. Soc. Policy 4, 6–38. https://doi.org/10.1177/026101838400401002.

Eisenmenger, N., Pichler, M., Krenmayr, N., Noll, D., Plank, B., Schalmann, E., Wandl, M.-T., Gingrich, S., 2020. The sustainable development goals prioritize economic growth over sustainable resource use: a critical reflection on the SDGs from a socio-ecological perspective. Sustain. Sci. 15, 1101–1110. https://doi.org/10.1007/s11625-020-00813-x.

European Commission, 2020. EU Transport in Figures 2020, p. 168.

Fanning, A.L., O'Neill, D.W., Büchs, M., 2020. Provisioning systems for a good life within planetary boundaries. Glob. Environ. Chang. 64, 102135 https://doi.org/10.1016/j.gloenvcha.2020.102135.

Fanning, A.L., O'Neill, D.W., Hickel, J., Roux, N., 2021. The social shortfall and ecological overshoot of nations. Nat. Sustain. 1–11 https://doi.org/10.1038/s41893-021-00799-z.

Fisch-Romito, V., 2021. Embodied carbon dioxide emissions to provide high access levels to basic infrastructure around the world. Glob. Environ. Chang. 70, 102362 https://doi.org/10.1016/j.gloenvcha.2021.102362.

Fishman, T., Wiedenhofer, D., Frantz, D., Guo, J., Liu, Z., Schug, F., Tanikawa, H., Haberl, H., n.d. Comparing four approaches to mapping buildings and infrastructure material stocks, for the case of Japan. In preparation.

Frantz, D., Schug, F., Wiedenhofer, D., Baumgart, A., Virág, D., Cooper, S., Gomez-Medina, C., Lehmann, F., van der Linden, S., Hostert, P., Haberl, H., n.d. The Weight of a Nation - High Resolution Material Stock Map ofthe Conterminous United States. In preparation.

Fulton, L., Cazzola, P., Cuenot, F., 2009. IEA Mobility Model (MoMo) and its use in the ETP 2008. In: Energy Policy, Carbon in Motion: Fuel Economy, Vehicle Use, and Other Factors affecting CO_2 Emissions From Transport, 37, pp. 3758–3768.

Geofabrik, 2021. OpenStreetMap Data. https://download.geofabrik.de/ downloaded between August 23 and August 31 2021.

Gilbert, R., Irwin, N., Hollingworth, B., Blais, P., 2002. Sustainable Transportation Performance Indicators (STPI), 20.

Gough, I., 2019. Universal basic services: a theoretical and moral framework. Polit. Q. 90, 534–542. https://doi.org/10.1111/1467-923X.12706.

Gough, I., 2020. Defining floors and ceilings: the contribution of human needs theory. Sustain. Sci. Pract. Pol. 16, 208–219. https://doi.org/10.1080/15487733.2020.1814033.

Haberl, H., Wiedenhofer, D., Erb, K.-H., Görg, C., Krausmann, F., 2017. The material stock–flow–service Nexus: a new approach for tackling the decoupling conundrum. Sustainability 9, 1049. https://doi.org/10.3390/su9071049.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173–184. https://doi.org/10.1038/s41893-019-0225-2.

Haberl, H., Wiedenhofer, D., Schug, F., Frantz, D., Virág, D., Plutzar, C., Gruhler, K., Lederer, J., Schiller, G., Fishman, T., Lanau, M., Gattringer, A., Kemper, T., Liu, G., Tanikawa, H., van der Linden, S., Hostert, P., 2021. High-resolution maps of material stocks in buildings and infrastructures in Austria and Germany. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.0c05642.

Henderson, M., Van Zyl, G., 2017. Management of unpaved roads: developing a strategy and refining models. In: Presented at the 36th Annual Southern African Transport Conference, CSIR International Convention Centre, Pretoria, South Africa.

Hertwich, E.G., 2021. Increased carbon footprint of materials production driven by rise in investments. Nat. Geosci. 14, 151–155. https://doi.org/10.1038/s41561-021-00690-8.

Hillman, M., Whalley, A., 1979. Walking is Transport. Policy Studies Institute, London.

Holden, E., Norland, I.T., 2005. Three challenges for the Compact City as a sustainable urban form: household consumption of energy and transport in eight residential areas in the greater Oslo region. Urban Stud. 42, 2145–2166. https://doi.org/10.1080/00420980500332064.

ICCT, I.C. on C.T, 2017. Global Transportation Roadmap Model (August 2017 version).

Iimi, A., Ahmed, F., Anderson, E.C., Diehl, A.S., Maiyo, L., Peralta-Quiros, T., Rao, K.S., 2016. New Rural Access Index: Main Determinants and Correlation to Poverty (Working Paper). World Bank, Washington, DC. https://doi.org/10.1596/25676.

International Transport Forum, 2021. ITF Transport Outlook 2021. OECD, ITF Transport Outlook. https://doi.org/10.1787/16826a30-en.

ITF, 2021. ITF Transport Statistics. OECD. https://doi.org/10.1787/g2g5557f-en (data downloaded June 2nd, 2021).

Janic, M., 2006. Sustainable transport in the European Union: a review of the past research and future ideas. Transp. Rev. 26, 81–104. https://doi.org/10.1080/01441640500178908.

Jaramillo, C., Lizárraga, C., Grindlay, A.L., 2012. Spatial disparity in transport social needs and public transport provision in Santiago de Cali (Colombia). J. Transp. Geogr. Spec. Sect. Theoret. Perspect. Clim. Change Mitigat. Transp. 24, 340–357. https://doi.org/10.1016/j.jtrangeo.2012.04.014.

Kalt, G., Wiedenhofer, D., Görg, C., Haberl, H., 2019. Conceptualizing energy services: a review of energy and well-being along the energy service Cascade. Energy Res. Soc. Sci. 53, 47–58. https://doi.org/10.1016/j.erss.2019.02.026.

Kenworthy, J.R., 2020. Passenger transport energy use in ten Swedish cities: understanding the differences through a comparative review. Energies 13, 3719. https://doi.org/10.3390/en13143719.

Kenworthy, J.R., Laube, F.B., 1999. Patterns of automobile dependence in cities: an international overview of key physical and economic dimensions with some implications for urban policy. Transp. Res. A Policy Pract. 33, 691–723. https://doi.org/10.1016/S0965-8564(99)00006-3.

Khandker, S.R., Bakht, Z., Koolwal, G.B., 2006. The Poverty Impact of Rural Roads: Evidence from Bangladesh. World Bank, Washington, DC. https://doi.org/10.1596/1813-9450-3875.

Kikstra, J.S., Mastrucci, A., Min, J., Riahi, K., Rao, N.D., 2021. Decent living gaps and energy needs around the world. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ac1c27.

Krausmann, F., Wiedenhofer, D., Haberl, H., 2020a. Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. Glob. Environ. Chang. 61, 102034 https://doi.org/10.1016/j.gloenvcha.2020.102034.

Krausmann, F., Wiedenhofer, D., Haberl, H., 2020b. Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. Glob. Environ. Chang. 61, 102034 https://doi.org/10.1016/j.gloenvcha.2020.102034.

Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., Aylmer, C., 2013. Beyond GDP: measuring and achieving global genuine progress. Ecol. Econ. 93, 57–68. https://doi.org/10.1016/j.ecolecon.2013.04.019.

Lamb, W.F., Steinberger, J.K., 2017. Human well-being and climate change mitigation. WIREs Clim. Change 8, e485. https://doi.org/10.1002/wcc.485.

Lamb, W.F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J.G.J., Wiedenhofer, D., Mattioli, G., Khourdajie, A.A., House, J., Pachauri, S., Figueroa, M., Saheb, Y., Slade, R., Hubacek, K., Sun, L., Ribeiro, S.K., Khennas, S., De La Du Can, S. R., Chapungu, L., Davis, S.J., Bashmakov, I., Dai, H., Dhakal, S., Tan, X., Geng, Y., Gu, B., Minx, J., 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environ. Res. Lett. 16, 073005 https://doi.org/10.1088/1748-9326/abee4e.

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., Ehlert, C., 2019. Taking stock of built environment stock studies: Progress and prospects. Environ. Sci. Technol. 53, 8499–8515. https://doi.org/10.1021/acs.est.8b06652.

Litman, T., 2021. Transportation Affordability. Evaluation and Improvement Strategies. Victoria Transport Policy Institute.

Lowans, C., Del Rio, D.F., Sovacool, B.K., Rooney, D., Foley, A.M., 2021. What is the state of the art in energy and transport poverty metrics? A critical and comprehensive review. Energy Econ. 105360 https://doi.org/10.1016/j.eneco.2021.105360.

Lucas, K., Marsden, G., Brooks, M., Kimble, M., 2007. Assessment of capabilities for examining long-term social sustainability of transport and land use strategies. Transp. Res. Rec. 2013, 30–37. https://doi.org/10.3141/2013-05.

Lucas, K., Mattioli, G., Verlinghieri, E., Guzman, A., 2016. Transport poverty and its adverse social consequences. Proc. Inst. Civ. Eng. Transp. 169, 353–365. https://doi.org/10.1680/jtran.15.00073.

Mattioli, G., 2016. Transport needs in a climate-constrained world. A novel framework to reconcile social and environmental sustainability in transport. Energy Res. Soc. Sci. 18, 118–128. https://doi.org/10.1016/j.erss.2016.03.025.

Mayer, A., Haas, W., Wiedenhofer, D., 2017. How Countries' resource use history matters for human well-being – an investigation of global patterns in cumulative material flows from 1950 to 2010. Ecol. Econ. 134, 1–10. https://doi.org/10.1016/j.ecolecon.2016.11.017.

McCollum, D.L., Wilson, C., Pettifor, H., Ramea, K., Krey, V., Riahi, K., Bertram, C., Lin, Z., Edelenbosch, O.Y., Fujisawa, S., 2017. Improving the behavioral realism of global integrated assessment models: an application to consumers' vehicle choices. Transp. Res. Part D: Transp. Environ. 55, 322–342. https://doi.org/10.1016/j.trd.2016.04.003.

Millward-Hopkins, J., 2020. Providing decent living with minimum energy_ a global scenario. Glob. Environ. Chang. 10.

Mögele, M., Rau, H., 2020. Cultivating the "car state": a culturally sensitive analysis of car-centric discourses and mobility cultures in southern Germany. Sustain. Sci. Pract. Pol. 16, 15–28. https://doi.org/10.1080/15487733.2020.1756188.

Moore, J., Lucas, K., Bates, J., 2013. Social disadvantage and transport in the UK: A trip-based approach (working paper). In: Transport Studies Unit, School of Geography and the Environment.

Newman, P.W., Kenworthy, J.R., 1996. The land use—transport connection. Land Use Policy 13, 1–22. https://doi.org/10.1016/0264-8377(95)00027-5.

Nussbaum, M., 2003. Capabilities as fundamental entitlements: Sen and social justice. Fem. Econ. 9, 33–59. https://doi.org/10.1080/1354570022000077926.

O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1, 88–95. https://doi.org/10.1038/s41893-018-0021-4.

Özgenel, M., 2016. Rural arterial road planning and design steps (Session 12: Roads: Planning, Design and Construction Issues). In: Presented at the International Cofference on Traffic and Transport Engineering, Belgrade, Serbia, pp. 663–669.

Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Glob. Environ. Chang. 24, 132–142. https://doi.org/10.1016/j.gloenvcha.2013.11.006.

Pauliuk, S., Fishman, T., Heeren, N., Berrill, P., Tu, Q., Wolfram, P., Hertwich, E.G., 2021. Linking service provision to material cycles: a new framework for studying the resource efficiency–climate change (RECC) nexus. J. Ind. Ecol. 25, 260–273. https://doi.org/10.1111/jiec.13023.

Peng, Z.-R., Zhu, Y., Song, S., 2008. Mobility of the Chinese urban poor: a case study of Hefei City. Chin. Econ. 41, 36–57. https://doi.org/10.2753/CES1097-1475410102.

Plank, C., Liehr, S., Hummel, D., Wiedenhofer, D., Haberl, H., Görg, C., 2021. Doing more with less: provisioning systems and the transformation of the stock-flow-service nexus. Ecol. Econ. 187, 107093 https://doi.org/10.1016/j.ecolecon.2021.107093.

Rao, N.D., Baer, P., 2012. "Decent living" emissions: a conceptual framework. Sustainability 4, 656–681. https://doi.org/10.3390/su4040656.

Rao, N.D., Min, J., 2018a. Decent living standards: material prerequisites for human wellbeing. Soc. Indic. Res. 138, 225–244. https://doi.org/10.1007/s11205-017-1650-0.

Rao, N.D., Min, J., 2018b. Decent living standards: material prerequisites for human wellbeing. Soc. Indic. Res. 138, 225–244. https://doi.org/10.1007/s11205-017-1650-0.

Rao, N.D., Pachauri, S., 2017. Energy access and living standards: some observations on recent trends. Environ. Res. Lett. 12, 025011 https://doi.org/10.1088/1748-9326/aa5b0d.

Rao, N.D., Mastrucci, A., Min, J., 2018. Applying LCA to estimate development energy needs: The cases of India and Brazil. In: Designing Sustainable Technologies, Products and Policies. From Science to Innovation. Springer, Cham, Switzerland, pp. 397–406.

Rau, H., Sattlegger, L., 2018. Shared journeys, linked lives: a relational-biographical approach to mobility practices. Mobilities 13, 45–63. https://doi.org/10.1080/17450101.2017.1300453.

Raworth, K., 2012. A Safe and Just Space for Humanity. Can we Live within the Doughnut? Oxfam Discussion Paper.

Roberts, P., Kc, S., Rastogi, C., 2006. Rural Access Index: A Key Development Indicator (No. TP-10), Transport Papers. The World Bank, Washington, DC.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.

Roelich, K., Knoeri, C., Steinberger, J.K., Varga, L., Blythe, P.T., Butler, D., Gupta, R., Harrison, G.P., Martin, C., Purnell, P., 2015. Towards resource-efficient and service-oriented integrated infrastructure operation. Technol. Forecast. Soc. Chang. 92, 40–52. https://doi.org/10.1016/j.techfore.2014.11.008.

Røpke, I., 2009. Theories of practice — new inspiration for ecological economic studies on consumption. Ecol. Econ. 68, 2490–2497. https://doi.org/10.1016/j.ecolecon.2009.05.015.

Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., Rockström, J., 2019. Six transformations to achieve the sustainable development goals. Nat. Sustain. 2, 805–814. https://doi.org/10.1038/s41893-019-0352-9.

Sachs, J., Kroll, C., Lafortune, C., Fuller, G., Woelm, F., 2021. The Decade of Action for the Sustainable Development Goals: Sustainable Development Report 2021. Cambridge University Press, Cambridge, United Kingdom.

Sahakian, M., Fuchs, D., Lorek, S., Di Giulio, A., 2021. Advancing the concept of consumption corridors and exploring its implications. Sustain. Sci. Pract. Pol. 17, 305–315. https://doi.org/10.1080/15487733.2021.1919437.

Schaffartzik, A., Pichler, M., Pineault, E., Wiedenhofer, D., Gross, R., Haberl, H., 2021. The transformation of provisioning systems from an integrated perspective of social metabolism and political economy: a conceptual framework. Sustain. Sci. 16, 1405–1421. https://doi.org/10.1007/s11625-021-00952-9.

Scheiner, J., Rau, H., 2020. Mobility and Travel Behaviour across the Life Course. Edward Elgar, Cheltenham, Northhampton.

Schiller, G., Müller, F., Ortlepp, R., 2017. Mapping the anthropogenic stock in Germany: metabolic evidence for a circular economy. Resour. Conserv. Recycl. 123, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007.

Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., Ürge-Vorsatz, D., 2016. Carbon lock-in: types, causes, and policy implications. Annu. Rev. Environ. Resour. 41, 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.

Shi, F., Huang, T., Tanikawa, H., Han, J., Hashimoto, S., Moriguchi, Y., 2012. Toward a low carbon-dematerialization society: measuring the materials demand and CO_2 emissions of building and transport infrastructure construction in China. J. Ind. Ecol. 16, 493–505. https://doi.org/10.1111/j.1530-9290.2012.00523.x.
Shove, E., Walker, G., 2014. What is energy for? Social practice and energy demand. Theory Cult. Soc. 31, 41–58. https://doi.org/10.1177/0263276414536746.
Shue, H., 1993. Subsistence emissions and luxury emissions. Law Pol. 15, 39–60. https://doi.org/10.1111/j.1467-9930.1993.tb00093.x.
SLoCaT, 2018. Transport and Climate Change Global Status Report 2018. http://slocat.net/tcc-gsr (downloaded July 26th, 2021).
Social Exclusion Unit, 2003. Making the Connections: Final Report on Transport and Social Exclusion. Social Exclusion Unit, London.
Spinney, J., 2021. Mobility is dead: Post-pandemic planning as an opportunity to prioritize sustainability and accessibility. In: Andrews, G.J., Crooks, V.A., Pearce, J. R., Messina, J.P. (Eds.), COVID-19 and Similar Futures: Pandemic Geographies, Global Perspectives on Health Geography. Springer International Publishing, Cham, pp. 125–131. https://doi.org/10.1007/978-3-030-70179-6_16.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347. https://doi.org/10.1126/science.1259855.
Steinberger, J.K., Roberts, J.T., 2010. From constraint to sufficiency: the decoupling of energy and carbon from human needs, 1975–2005. Ecol. Econ. 70, 425–433. https://doi.org/10.1016/j.ecolecon.2010.09.014.
Steinberger, J.K., Roberts, J.T., Peters, G.P., Baiocchi, G., 2012. Pathways of human development and carbon emissions embodied in trade. Nat. Clim. Chang. 2, 81–85. https://doi.org/10.1038/nclimate1371.
Stiglitz, J., Sen, A., Fitoussi, J.-P., 2010. Mismeasuring our Lives. The New Press.
Sustainable Mobility for All, 2021. Implementing the SDGs. https://www.sum4all.org/. (Accessed 26 August 2021).
Tanikawa, H., Fishman, T., Okuoka, K., Sugimoto, K., 2015. The weight of society over time and space: a comprehensive account of the construction material stock of Japan, 1945-2010: the construction material stock of Japan. J. Ind. Ecol. 19, 778–791. https://doi.org/10.1111/jiec.12284.
Tanikawa, H., Fishman, T., Hashimoto, S., Daigo, I., Oguchi, M., Miatto, A., Takagi, S., Yamashita, N., Schandl, H., 2020. A framework of indicators for associating material stocks and flows to service provisioning: application for Japan 1990-2015. J. Clean. Prod. 125450 https://doi.org/10.1016/j.jclepro.2020.125450.
Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G., Hall, J.W., 2019. Infrastructure for sustainable development. Nat. Sustain. 2, 324–331. https://doi.org/10.1038/s41893-019-0256-8.
The Social Progress Imperative, 2021. Social Progress Index 2021. https://www.socialprogress.org (last accessed June 10, 2022).
UN, 2015. Transforming our World: The 2030 Agenda for Sustainable Development.
UN, 2021. Sustainable transport, sustainable development (Interagency report). In: Interagency report for second Global Sustainable Transport Conference 2021.
UNDP, 2020a. Human Development Index (HDI) Human Development Reports. URL. http://hdr.undp.org/en/content/human-development-index-hdi (accessed October 2021).
UNDP (Ed.), 2020b. The Next Frontier: Human Development and the Anthropocene, Human Development Report. United Nations Development Programme, New York, NY.
van Vuuren, D.P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D., Nakicenovic, N., Rockstrom, J., Riahi, K., Sperling, F., Bosetti, V., Cornell, S., Gaffney, O., Lucas, P., Popp, A., Ruhe, C., vonSchiller, A., Schmidt, J., Soergel, B., 2021. Defining a Sustainable Development Target Space for 2030 and 2050.
Virág, D., Wiedenhofer, D., Haas, W., Haberl, H., Kalt, G., Krausmann, F., 2021. The Stock-Flow-Service Nexus of Personal Mobility in an Urban Context. Environmental Development, Vienna, Austria. https://doi.org/10.1016/j.envdev.2021.100628.
Vogel, J., Steinberger, J.K., O'Neill, D.W., Lamb, W.F., Krishnakumar, J., 2021. Socio-economic conditions for satisfying human needs at low energy use: an international analysis of social provisioning. Glob. Environ. Chang. 102287 https://doi.org/10.1016/j.gloenvcha.2021.102287.
Wenz, L., Weddige, U., Jakob, M., Steckel, J.C., 2020. Road to glory or highway to hell? Global road access and climate change mitigation. Environ. Res. Lett. 15, 075010 https://doi.org/10.1088/1748-9326/ab858d.
Whiting, K., Carmona, L.G., Brand-Correa, L., Simpson, E., 2020. Illumination as a material service: a comparison between ancient Rome and early 19th century London. Ecol. Econ. 169, 106502 https://doi.org/10.1016/j.ecolecon.2019.106502.
Whiting, K., Carmona, L.G., Carrasco, A., 2021. The resource service cascade: a conceptual framework for the integration of ecosystem, energy and material services. Environ. Dev. 100647 https://doi.org/10.1016/j.envdev.2021.100647.
Wiedenhofer, D., Lenzen, M., Steinberger, J.K., 2013. Energy requirements of consumption: urban form, climatic and socio-economic factors, rebounds and their policy implications. Energy Policy 63, 696–707. https://doi.org/10.1016/j.enpol.2013.07.035.
Wiedenhofer, D., Steinberger, J.K., Eisenmenger, N., Haas, W., 2015. Maintenance and expansion: modeling material stocks and flows for residential buildings and transportation networks in the EU25: stocks and flows in the EU25. J. Ind. Ecol. 19, 538–551. https://doi.org/10.1111/jiec.12216.
Wiedenhofer, D., Smetschka, B., Akenji, L., Jalas, M., Haberl, H., 2018. Household time use, carbon footprints, and urban form: a review of the potential contributions of everyday living to the 1.5°C climate target. In: Current Opinion in Environmental Sustainability, 1.5°C Climate Change and Urban Areas, 30, pp. 7–17. https://doi.org/10.1016/j.cosust.2018.02.007.
Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., Krausmann, F., 2019. Integrating material stock dynamics into economy-wide material flow accounting: concepts, modelling, and global application for 1900–2050. Ecol. Econ. 156, 121–133. https://doi.org/10.1016/j.ecolecon.2018.09.010.
Wiedenhofer, D., Drewniok, M., Frantz, D., Gauch, H., Lanau, M., Schug, F., Serrenho, A., Densley Tingley, D., Virág, D., 2021. High-resolution mapping of material stocks of buildings and infrastructure in the United Kingdom and Ireland.
World Bank, 2019. GDP (Current US$) | Data [WWW Document]. URL. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD (accessed November 15th, 2021).
World Bank, 2021. Transport - The Essential Connector. https://www.worldbank.org/en/topic/transport/overview#1. (Accessed 14 October 2021).
World Bank, DFID, Department for International Development of the United Kingdom, ReCAP, Research for Community Access Partnership, 2016. Rural Access Index. https://rai.azavea.com/ (downloaded May 7th, 2021).
Worldbank/UIC, International Union of Railways, 2021. Mobility at a Glance: Country Dashboards.
Zhao, X., Ke, Y., Zuo, J., Xiong, W., Wu, P., 2020. Evaluation of sustainable transport research in 2000–2019. J. Clean. Prod. 256, 120404 https://doi.org/10.1016/j.jclepro.2020.120404.
Zhou, J., 2012. Sustainable transportation in the US: a review of proposals, policies, and programs since 2000. Front. Architect. Res. 1, 150–165. https://doi.org/10.1016/j.foar.2012.02.012.