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Mapping and modelling global mobility infrastructure stocks, material flows and their embodied greenhouse gas emissions

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ABSTRACT

Roads and rail-based mobility infrastructures are the basis for mobility services and underpin several Sustainable Development Goals, but also induce material use and greenhouse gas emissions. To date, no stock-flow consistent study has assessed globally accumulated stocks of mobility infrastructures, associated material flows and emissions, and their spatial patterns.

We present global findings on material stocks for all roads, rail-based infrastructures, incl. tunnels and bridges, and model associated material flows and their embodied emissions for the year 2021. The stock-flow consistent model combines crowd-sourced Open Street Maps data with archetypical infrastructure designs, material compositions, assumptions on lifetimes and network growth rates, incl. uncertainty ranges. We derive spatially explicit, national-level stock estimates for 180 countries, map them at a resolution of 5 arcminutes, and derive material flows and their embodied emissions at the country-level.

We find that 314 [218–403] Gt of materials (41 [28–53] tons/cap) have accumulated in global mobility infrastructure, the majority in roads as aggregates and asphalt. Stocks are unequally distributed between countries, from averages of 23 [16–30] tons/cap in low income countries, to 130 [89–164] tons/cap in high income countries. Spatial inequality of per capita stocks per area differs by orders of magnitude, from 10^1-10^4 between rural, suburban, and dense urban areas. We find that 8 [4–16] Gt/year of material flows are due to expansion and maintenance, amounting to 6 [3–10] % of global resource extraction. These translate into 0.36 [0.19–0.69] Gt CO_2eq/year, or 1 [0.5–1.9] % of global GHG emissions in 2021.

Approximately two-thirds of these flows result from maintenance and replacement of stocks, indicating an important lock-in of resource use due to already existing infrastructure stocks. These findings support the crucial role of improving spatial planning, limiting stock expansion and (sub-)urbanization, to achieve more sustainable resource use and mitigate climate change.

1. Introduction

Mobility infrastructure stocks underpin a number of Sustainable Development Goals directly (SDG 3.6, 9.1 and 11.2) and indirectly (Thacker et al., 2019). Networks of mobility infrastructure stocks provide the physical basis for mobility and transport, connect settlements and cities, and shape patterns of land-use and urbanization around the world. However, many world-regions lack access to reliable and sustainable mobility infrastructure, as defined in SDG 9.1 (Virág et al., 2022; Wenz et al., 2020), and the worldwide demand for infrastructure and mobility is expected to rise substantially (European Commission. Joint Research Centre, 2019). At the same time, the current scale and

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future trajectories of stock expansion and maintenance and resulting GHG emissions, as well as service provision have been identified as key challenges for more sustainable resource use and climate change mitigation (Fisch-Romito, 2021; Krausmann et al., 2020; Müller et al., 2013; Rousseau et al., 2022).

National-level assessments identify mobility infrastructure stocks as a major compartment of societies' total material stocks (30–50% in terms of mass), and suggest that mobility infrastructure is a major driver of resource use and associated emissions (Haberl et al., 2021; Miatto et al., 2016; Schiller et al., 2016; Tanikawa et al., 2015; Wiedenhofer et al., 2015). The resource-efficient provision of sufficient mobility infrastructure stocks around the world is thus a crucial sustainability challenge. This paper aims to contribute useful knowledge to tackle this challenge, by providing key quantitative and spatial information on size and patterns of all roads and rail-based mobility infrastructures globally, as well as by providing the first stock-flow consistent estimation of associated material flows and emissions, also in relation to overall societal resource use and greenhouse gas emissions.

We go beyond previous findings on mobility infrastructure stocks and related flows in three aspects. Firstly, while hundreds of life cycle assessment studies on specific types of road or railway infrastructures have been conducted, three recent systematic reviews of that literature showed that much of this work lacks crucial documentation of infrastructure design parameters and inventory data, uses inconsistent modelling approaches, and often lacks clear system boundaries; all of which renders most of these results non-reproducible and limits their value for cumulative global research (Hoxha et al., 2021; Jiang and Wu, 2019; Olugbenga et al., 2019). Overcoming these limitations requires model-based assessments at the level of entire mobility infrastructure networks across spatio-temporal scales, as well as more systematic and transparent methods and data (AzariJafari et al., 2016; Hoxha et al., 2021; Jiang and Wu, 2019; Olugbenga et al., 2019), which we address herein.

Secondly, various studies investigated mobility infrastructure networks at the local to national scale, although with varying scope, detail and coverage of associated flows (Lanau et al., 2019). Most studies used infrastructure archetypes to model material stocks and flows, for example for all mobility infrastructure, material flows and emissions, as well as mobility services in Japan (Tanikawa et al., 2021) or Vienna ((Virág et al., 2021)), for archetypical roads, material flows and emissions in Vietnam, China or the USA (AzariJafari et al., 2021; Miatto et al., 2017, 2021; Nguyen et al., 2018), for the subway material stock in China and globally (Mao et al., 2021), as well as for archetypical roads and rail-based infrastructure and selected flows in cities or islands (Gassner et al., 2020; Guo et al., 2014; Lanau and Liu, 2020; Noll et al., 2019). Recently, studies have started to address local variability of road construction material requirements, as they are depending on ground conditions, compliance with regulations and other factors, reporting substantial data challenges and large variabilities (Ebrahimi et al., 2022; Grossegger, 2022; Kloostra et al., 2022). Across these studies, openly available and comprehensive network-level data, as well as representative and varying material intensities and service lifetimes of infrastructure stocks are key challenges, which result in recommendations for including novel data sources and uncertainty assessments into material stock-flow analysis. Clearly, while local context and specifics matter, modelling the entire road- and rail-based mobility infrastructure stock and associated material flows and emissions at larger spatial scales seems currently only feasible via simplifying from highly data and time intensive approaches.

Thirdly, a growing body of studies at the continental to global network-level addressed specific infrastructure types, but does not provide stock-flow consistent model-based assessments nor maps. For example, Wenz et al. (2020) calculated the life cycle emissions required to provide quasi-universal access to all-season paved roads in proximity to all settlements globally, using archetypical roads and regionalized life cycle factors, finding that tackling under-provision with infrastructures would cause only small GHG emissions. Virág et al. (2022) presented country-level, archetypical total bulk material stocks in road and rail-based infrastructures around the world and analyzed the relation of stocks to travelled distances, the SDGs, wellbeing, as well as affluence (GDP); they found that levels of mobility infrastructure stocks and travelled distances are significantly correlated, however above an intermediate level of 92–207 tons/cap, contributions to wellbeing diminish. Rousseau et al. (2022) presented a global modelling of archetypical paved road material stocks in several world-regions and the hypothetical life-cycle emissions required to completely replacing the entire road stock at once; interestingly they found that across all cities globally, urban area, population density, and GDP per capita all positively correlate with larger paved road material stocks. Wiedenhofer et al. (2015) modelled archetypical European road and railway stocks and found that the material flows for their expansion and maintenance amounted to ~38% of total non-metallic material use in the EU28 in the year 2009. While these studies clearly show the importance of mobility infrastructure in terms of material stocks, material flows, and associated emissions, a globally comprehensive and stock-flow consistent analysis, which considers all road and rail-based mobility infrastructures, their spatial patterns, as well as the ranges of material flows and associated embodied emissions of materials, is missing so far.

Herein, we address the following four research questions.

1) What is the magnitude of material stocks and associated flows related to global road- and rail-based mobility infrastructures, and how are they distributed around the world?
2) What is the role of spatial patterns of population density for infrastructure stock intensity?
3) What are the ranges of annual flows of materials and embodied GHG emissions associated with expansion, maintenance and replacement of accumulated mobility infrastructure stocks?
4) What are the material implications of a hypothetical global catch-up and convergence of global infrastructure stocks to average per capita levels in high income countries?

In section 2 we present our system definition and scope, methods, data and assumptions. Section 3 presents global results on stocks, spatial patterns, and a first approximation of the ranges of associated material flows and their embodied emissions. Section 4 discusses the implications of these results vis a vis global resource use and climate change mitigation, their limitations, as well as promising next steps, before section 5 concludes. The supplementary information provides additional documentation and validation of results, and the supplementary data contains all model data inputs and results.

2. Methods and data

We develop a stock-driven, bottom-up model to assess the material flows and their embodied emissions of the infrastructural basis of mobility, e.g., all roads, all rail-based infrastructure, incl tunnels and bridges, for 180 countries for the year 2021 (Fig. 1). Mobility services, vehicles, trains, and the like, as well as associated buildings are outside the scope of this analysis. Spatially-explicit network data for 18 infrastructure types are derived from crowd-sourced Open Street Maps (OSM) (Geofabrik, 2022; OurAirports, 2021), utilizing algorithms, classifications and procedures developed previously (Haberl et al., 2021; Virág et al., 2022). We compile a dataset on archetypical infrastructure widths and material intensities to estimate material stocks. Using ranges of infrastructure lifetimes and embodied emissions factors, we model ranges of material flows and embodied emissions due to materials production for the year ~2021 (Fig. 1b). Compared to previous work by some of the authors presenting country-level estimates of the mass of mobility infrastructure stocks (Virág et al., 2022), we here improve coverage of countries and expand on the archetypical material intensities, incl. uncertainty modelling; we map and analyze stock

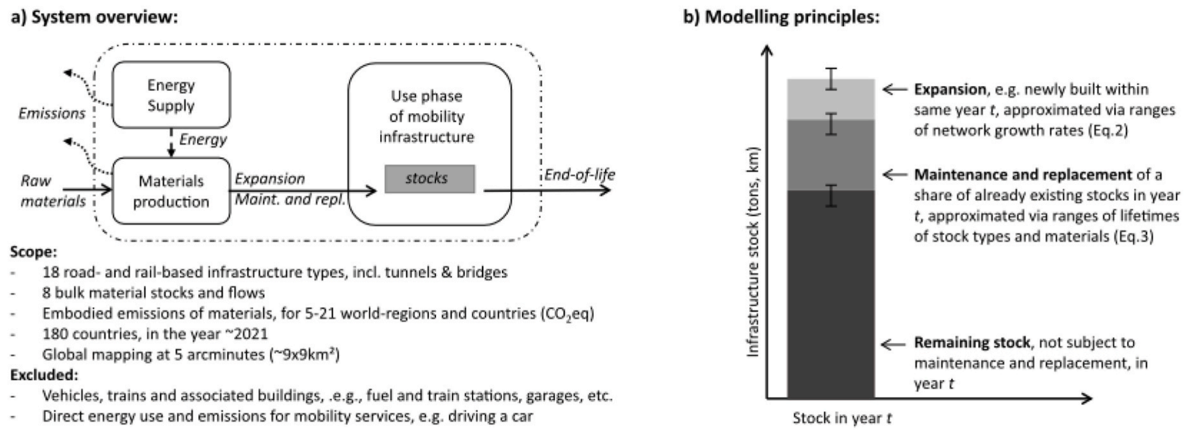

Fig. 1. System overview and scope of the analysis. Please note that the use of infrastructure stocks for mobility, e.g., for driving a car, as well as buildings associated with mobility infrastructure, such as fuel stations, train stations, etc. are excluded.

patterns; approximate ranges of material flows and embodied GHG emissions from material production and energy supply; and explore hypothetical global catch-up and convergence scenarios to per capita stock levels in high income countries for each grid cell, specifically considering population density as mediating factor. The supplementary data includes all model data inputs and results for all countries.

Material stocks *MS* are estimated by multiplying infrastructure network lengths *L,* with their respective widths *w* and material intensities *MI* (mass of materials per m^2), for each infrastructure type *st,* material *m,* country *c* and year *t* (Equation (1)).

$$MS_{st,m,c,t} = L_{st,c,t} * w_{st,c} * MI_{st,m,c} \qquad \text{Eq.1}$$

Material flows for expansion of infrastructure networks are approximated by applying suitable growth rates *g* to the existing infrastructure network *L * w* (see below for how *g* was estimated) (Equation (2)).

$$Expansion_{st,m,c,t} = \left(L_{st,c,t} * W_{st,c}\right) * g_{st,c,t} * MI_{st,m,c} \qquad \text{Eq.2}$$

Ranges of material flows for maintenance and replacements of stocks can be approximated by assuming a "leaching" lifetime model (van der Voet et al., 2002). In the face of insufficient data for more sophisticated approaches, such a leaching model simplifies real-world stock-flow dynamics which are shaped by age-type-cohort ageing dynamics, traffic flows, available budgets for repairs and maintenance, various socio-ecological shocks for stock-building or demolition, or damages to infrastructures due to natural events, as well as local ground and/or weather conditions, etc. Due to data limitations at national to global scales, the leaching lifetime model is the only feasible one to derive a first approximation of the ranges of material flows and embodied emissions globally. We model maintenance and replacements by estimating how much of the infrastructure length *L* remains from the year before, by deducting the newly added length (*L * g*, Eq. (1), Fig. 1b), and estimate from the remaining length, the maintenance and replacement flows based on ranges of lifetimes *LT* by material and infrastructure type to the material intensities *MI* of those respective infrastructures *st* (Equation (3), Fig. 1b). It should be noted that actual service lifetimes and consequently the duration until maintenance or replacement is required or performed, may vary significantly depending on a variety of factors including traffic volume and regional income levels. The approach herein of assumed lifetimes per material and infrastructure type therefore only serves as a first order approximation as more precise data on a global level is not yet available.

$$Maintenance_{st,m,c,t} = \left(\left(L_{st,c,t} - \left(L_{st,c,t} * g_{st,c,t}\right)\right) * w_{st,c}\right) * {}^{1}/{LT_{st,m}} * MI_{st,m,c} \qquad \text{Eq.3}$$

Finally, for these material flows, the associated embodied energy LCA_{EI} and embodied GHG emissions LCA_{GHG} are estimated (Equations (4) and (5)).

$$Energy_{c,t} = \sum \left(Maintenance_{st,m,c,t} + Expansion_{st,m,c,t}\right) * LCA_{EI_{m,c,t}} \qquad \text{Eq.4}$$

$$CO_2eq_{c,t} = \sum \left(Maintenance_{st,m,c,t} + Expansion_{st,m,c,t}\right) * LCA_{GHG_{m,c,t}} \qquad \text{Eq.5}$$

2.1. Data on mobility infrastructure lengths, types, and material compositions

We include 33 detailed OSM data keys covering all roads and rail-based infrastructures, as well as information on airport runway pavement types and lengths from OurAirports, to derive a comprehensive and spatially explicit dataset on infrastructure network lengths for 180 countries, drawing on algorithms developed previously (Haberl et al., 2021). We aggregate the 33 detailed OSM categories into the following 18 infrastructure types.

- six road types (motorways; primary, secondary, tertiary, local, and rural/gravel roads),
- five rail-based types (railways; underground, elevated and ground-level subway; trams and others like monorails or mountain railways),
- all bridges and tunnels for roads and rail-based infrastructure tagged in OSM,
- as well as airport runways.

The OSM dataset was downloaded between August 2022–October 2022 from (Geofabrik, 2022) as PBF files per country, or in some cases per country group when individual countries were not available, e.g., for the Gulf Cooperation Council (GCC). We used Python 3.8.10. and the Pyrosm library (https://pyrosm.readthedocs.io/en/latest/). To derive a global map of material stocks at 5 arcmin resolution, the length of each infrastructure category within a grid cell was calculated and multiplied with the corresponding widths and material intensities. National boundaries were clipped with shapefiles from EUROSTAT to avoid overlap in border regions. Land area and gridded population density were sourced from HYDE 3.2.1. (Klein Goldewijk et al., 2017).

We compiled archetypical data on infrastructure widths and material intensities for eight materials and 18 infrastructure types for six countries, which we used for a global average material intensity, drawing on a large variety of peer-reviewed sources as well as national construction guidelines and infrastructure design manuals (Table 1). We include asphalt, concrete, aggregates (sand & gravel), timber, iron/steel, aluminum, copper, and other metals along consistent system boundaries (see supplementary information for documentation and drawings). For roads we include the asphalt and concrete top layers, as well as the base layers primarily consisting of aggregates; we exclude the subgrade layers usually consisting of compressed local earth. For rail-based

Table 1
Overview of archetypical material intensities per infrastructure types utilized in this study, incl. uncertainty ranges. Please note that for Germany, Austria, the UK, the USA, Japan, China, Nepal, Turkey, South Africa and the GCC countries, country-specific material intensities were used. Iron/steel, aluminum, copper, and timber are summarized as "other materials*" in the table, although they are separately modelled and reported in the supplementary material. Material intensities for bridges and tunnels represent the load bearing structure, while the road surface or railway tracks themselves are estimated separately. We refer to the supplementary information and data for all details.

Infrastructure types		Global average material intensities and uncertainty ranges [t/m²]. For 10 countries nationally specific intensities are used, those are shown in the supplementary information and data.					Data sources
		Asphalt	Aggregate	Concrete [a]	Other materials*	Total	
Roads	Motorway	**0.47** [0.14–1.17]	**1.26** [0.76–1.77]	**–** [0.00–0.22]	–	**1.73** [1.12–2.94]	(Alzaim et al., 2020; Alzard et al., 2019; Bai et al., 2019; Chen et al., 2017; CSIR, 2000; DMR, 2014; DMT, 2016; Fishman et al., in preparation; Frantz et al., in print; Haberl et al., 2021; Henderson and van Zyl, 2017; Özgenel, 2016; Tanikawa et al., 2015; Wiedenhofer et al., in preparation)
	Primary	**0.38** [0.11–0.76]	**1.06** [0.65–1.52]	**–** [0.00–0.12]	–	**1.43** [0.79–2.28]	
	Secondary	**0.33** [0.08–0.68]	**0.96** [0.54–1.15]	**–** [0.00–0.08]	–	**1.30** [0.76–1.84]	
	Tertiary	**0.26** [0.04–0.60]	**0.86** [0.41–1.02]	**–** [0.00–0.39]	–	**1.12** [0.58–1.62]	
	Local [b]	**0.09** [0.04–0.30]	**0.41** [0.09–0.97]	**–** [0.00–0.25]	–	**0.50** [0.35–1.25]	
	Rural [c]	**0.04** [0.00–0.21]	**0.26** [0.15–0.54]	**–** [0.00–0.03]	–	**0.30** [0.26–0.75]	
	Motorway bridge	–	–	**1.18** [0.11–1.53]	**0.14** [0.12–0.21]	**1.32** [0.22–1.75]	(Fishman et al., in preparation; Haberl et al., 2021; Tanikawa et al., 2015; Watt, 2019; Wiedenhofer et al., in preparation)
	Other road bridge			**1.00** [0.11–1.30]	**0.16** [0.14–0.21]	**1.15** [0.24–1.51]	
	Road tunnel	–	–	**2.80** [0.56–4.56]	**0.12** [0.10–0.17]	**2.92** [0.66–4.73]	
	Runway (flexible)	0.28	0.69	–	–	0.97	(Federal Aviation Administration, 2016; Haberl et al., 2021)
	Runway (rigid)	–	0.69	0.37	–	1.06	
Rail-based	Railway	–	**0.35** [0.24–0.81]	**0.03** [0.00–0.04]	**0.03** [0.02–0.04]	**0.41** [0.27–0.85]	(Fishman et al., in preparation; Frantz et al., 2023; Haberl et al., 2021; Tanikawa et al., 2015; Wiedenhofer et al., in preparation)
	Railway bridge	–	–	**0.51** [0.12–1.67]	**1.12** [0.10–1.46]	**1.62** [0.22–3.12]	
	Railway tunnel	–	–	**4.14** [3.37–5.04]	**0.12** [0.05–0.15]	**4.26** [3.43–5.19]	
	Subway underground	–	**0.65** [0.00–2.61]	**10.00** [0.42–13.19]	**0.55** [0.25–0.66]	**11.20** [0.67–16.45]	
	Subway elevated	–	**0.49** [0.43–0.67]	**3.49** [0.11–4.61]	**0.28** [0.02–0.36]	**4.25** [0.55–5.65]	
	Subway ground-level	–	**0.49** [0.43–0.67]	**1.78** [0.11–2.34]	**0.20** [0.02–0.26]	**2.46** [0.55–3.26]	
	Tram/other	–	**0.03** [0.00–0.04]	**0.42** [0.00–0.56]	**0.02** [0.02–0.03]	**0.47** [0.03–0.62]	

[a] Concrete in roads is assumed to be used only in the USA and China due to lack of information for other countries.
[b] For the local road MI we assume that 50% are paved and 50% are unpaved; where only 25% of these unpaved roads are considered as gravel roads, whereas 75% are assumed to be compacted local earth, which have a material intensity of zero.
[c] The rural road MI is weighted at the national level based on shares of each OSM track key length in total track length, where the first track key is assumed to be asphalted while the remaining track keys are assumed to be 50% gravel and 50% compacted local earth roads.

infrastructure we include the metal rails and sleeper plates, the wooden or concrete sleepers, as well as the ballast layers made of aggregate. Material intensity factors for tunnels and bridges cover the load-bearing structures themselves, except the road or rail structure itself, which are estimated via roads and railways specific material intensities (e.g., the asphalt layer on top of a bridge).

The compilation of archetypical material intensities for ten countries shows relatively good agreement of *MI* factors per infrastructure type (supplementary information and data). However, not enough datapoints were available to assign specific intensities locally/regionally or for most countries; the main differentiation we apply are that roads in the USA are significantly wider than anywhere else. While many LCA studies for roads and other mobility infrastructure are available, they often focus on material mixes in different road constructions technologies, e.g., asphalt (flexible) vs concrete (rigid), and usually do not report crucial design parameters such as widths or road type, inhibiting reproducibility and re-usability (Hoxha et al., 2021; Olugbenga et al., 2019). As most road statistics, legal construction guidelines, as well as the crowd-sourced OSM information used herein is structured along road types themselves – e.g., kilometers of motorways or local roads, only a limited number of studies could be used to derive material intensities per infrastructure types. To not cause variation in results across countries which are solely driven by small differences in the limited number of underlying studies, we therefore opted for using nationally specific material intensities where they could be consistently sourced, e.g., Germany, Austria, the UK, the USA, Japan, and China, and globally averaged archetypical material intensities for all other countries (Table 1). Similar to Rousseau et al. (2022), we use the 25th and 75th quantile range across the ten nationally specific material intensities to derive uncertainty ranges for each material intensity.

2.2. Modelling ranges of material flows and embodied emissions

Ranges of stock growth rates are utilized to derive a first approximation of the material flows due to infrastructure expansion within one year (see Eq. (2), Fig. 1b). This simplification is used because international time series data on infrastructure networks is incomplete and unreliable, as evidenced by the fact that four major international data sources yield conflicting levels and trends – see supplementary information section 4, summarizing data from (European Commission, 2020; Eurostat, 2021a, 2021b; OECD, 2021; UNECE, 2021a, 2021b). Even after substantial efforts at harmonization and data cleaning, as documented in the supplementary information, no robust country-level data nor trends could be derived. What is clear is that growth rates fluctuate between 0 and 2%/year, with much higher rates for high income countries. To derive a first approximation of the ranges of material flows due to the expansion of infrastructure stocks, we calculate three variants, by summarizing all countries into World Bank income groups and assuming that the upper-middle and high income countries have either low/average/high infrastructure growth rates of +0.5/+1/+2 %/year. For the low income and lower-middle income countries we halved those growth rates to arrive at low/average/high ranges, i.e., +0.25/+0.5/+1 %/year.

Ranges of average service lifetimes per infrastructure types and materials are used to estimate maintenance and replacement flows (see Eq. (3) and Table 2). These are derived from the literature, a recent systematic review of road LCA studies (Hoxha et al., 2021), direct communication with experts, and own assumptions. To derive ranges of yearly material flows, we assume a ±30% deviation from the average service lifetimes reported in the literature.

To model embodied energy and GHG emissions of materials production, we summarize literature values and information from LCA databases to derive at ranges of energy & GHG lifecycle information for 5–21 countries/world-regions (Table 2 and supplementary information section 4 for a full documentation of all sources utilized). The main processes and influencing factors on current and future energy and GHG intensities as well as data sources and publications that appear as particularly useful/reliable were identified for this purpose. Existing reviews about LCAs of infrastructure construction were consulted (Hoxha et al., 2021; Jiang and Wu, 2019; Olugbenga et al., 2019). Data referring to historical years in the timeframe 2010–2020 are adopted for the respective reference year(s) and country/region from the literature

Table 2
Overview of the ranges of service lifetimes and embodied emissions per material. Service lifetimes are applied by infrastructure type and material, with mean lifetimes and ±15% min/max ranges. Embodied emissions factors are shown as mean value and in brackets min/max by world-regions (see supplementary information).

Material	Lifetimes [years ±15% as ranges]			Global average embodied emissions of each material, their uncertainty ranges, and the world-regionalization used [tCO_2e/t material flow]	
	Roads and runways	Railways and trams	Bridges, tunnels, subways [c]	Global average embodied emissions of materials production and energy supply, their minimum and maximum uncertainty ranges, as well as world-regionalization used herein	
Asphalt	12 and 29 [a]	–	–	**0.047** [0.032–0.071]	Five SSP regions (IIASA, 2018): R5OECD90 + EU, R5REF, R5ASIA, R5LAM, R5MAF
Aggregates	120	120	120	**0.003** [0.001–0.008]	
Iron/steel	–	30	120	**2.147** [1.874–2.531]	
Copper	–	50	120	**4.271** [2.405–6.354]	
Timber	–	50	–	**0.295** [0.249–0.400]	
Other	–	50	120	–	
Cement [b]	33	50	120	**0.709** [0.543–0.891]	Country data for Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, South Korea, Russia, Saudi Arabia, South Africa, Turkey, United Kingdom and the USA, and a global Rest of the World factor.
Aluminum	–	50	120	**9.789** [6.197–14.237]	Africa, Asia (excl. China), China, GCC, North America, South America, Europe, Oceania
Data sources	Hoxha et al. (2021)	UIC (2016)	Watt (2019)	Various sources, see supplementary information section 4.	

[a] The top-layered asphalt wearing course in roads is modelled to be replaced every 12 years, while the lower-layered asphalt layers are modelled to be replaced every 29 years, both with an ±30% uncertainty range (Hoxha et al., 2021); see supplementary information for a drawing of typical road and railway construction layers.
[b] The embodied emissions factors are derived for cement, for the modelling we added the emissions from aggregate to arrive at a factor for concrete.
[c] These lifetimes relate to the load bearing structural parts of tunnels and bridges. The road surface and railway tracks are modelled using material intensities excl sub-base layers and lifetimes for roads and railways respectively.

(see supplementary information section 4). GHG intensities for countries or regions not available from literature are derived from region-specific CO_2 intensities of final energy and/or electricity supply, depending on whether the respective industrial processes are primarily based on fuels or electricity.[2]

The scope of the summarized embodied energy and emissions data largely follows "cradle-to-gate" system boundaries. Not considered processes are transport to the site, construction, use phase, i.e., excluding traffic emissions or carbonation of concrete, demolition, as well as collection and transport for reuse and recycling, which are considered as minor contributors to total life cycle emissions (Hoxha et al., 2021; Jiang and Wu, 2019; Olugbenga et al., 2019). A notable exception is asphalt, where the data refers to laid material, including transport and construction because on-site heating of asphalt before layering constitutes a substantial energy use and sufficient data was available. CO_2 as well as any other GHG reported in the summarized literature are considered; the unit of GHG intensities is thus tons of CO_2-equivalents (t CO_2e). The intensities summarized in Table 2 and shown in subsequent figures therefore all refer to final energy and GHG emissions per material flow. We refer to the supplementary information for a detailed documentation of all the studies used to derive embodied energy/emissions factors utilized herein, as well as the discussion section on limitations and potential next steps.

2.3. Modelling a catch-up and convergence to per capita stock levels in high income countries

The aim of this scenario modelling exercise is to explore how much material is required for a hypothetical global catch-up to per capita stock levels found in high income nations, and to investigate how spatial patterns of population and infrastructure intensity mediate these stock-flow relations. The scenarios are calculated based on all raster cells, mapped at 5 arcmins or $\sim 9 \times 9 \text{km}^2$ cells (Fig. 4), within defined population density bins, per infrastructure type and material stock, using gridded population density for the year 2017 from HYDE 3.2.1. (Klein Goldewijk et al., 2017). We used detailed population density bins to capture average stock intensities for each bin, starting with steps of 1 cap/km^2 from 0 to 50, in steps of 5 from 50 to 95, in steps of 10 from 100 to 1,000, in steps of 100 cap/km^2 from 1000 to 4,000, in steps of 500 from 4000 to 10,000 and in steps of 2000 cap/km^2 from 10,000 to 20, 000, with one last bin containing all cells with population densities above 20,000 cap/km^2. For each population density bin, we calculated the average material stock per infrastructure type across all raster cells in high income countries and used the averages for the catch-up estimation for each raster cell within the same population density bin in all other non high income countries. The average stock intensity was chosen over the median, because at lower population densities most of the cells, especially for some infrastructure types like motorways, contain zero stocks/cap, which does not represent the overall stock intensity in this population density bin.

To quantify uncertainty, we estimated lower and upper stock ranges for this catch-up and convergence scenario, utilizing the 25th and 75th percentiles around the medians found for high income countries as density-dependent catch-up values, again only for those cells of the bin which have stocks greater than zero. Percentiles were preferred as a more robust measure over standard deviations, due to wide and not normally distributed stock intensities across all cells of each bin, which are partially also due to local data errors or overlaps with water bodies and mountainous regions. Finally, we ensured that national stock levels estimated for the year 2021 are not reduced by the scenario, nor its lower and upper ranges, by retaining the baseline stock estimate in those grid cells also in the scenarios. This was most prominently the case for China, Russia and Malaysia, especially in the lower range scenario.

3. Results

We present results on mobility infrastructure stocks globally and internationally for four income groups for the year 2021 and explore global patterns of infrastructure stocks and their relation to population density. We then show the material flows for expansion, maintenance and replacement of infrastructure stocks, as well as the associated embodied GHG emissions.

3.1. Global and world-regional mobility infrastructure stocks

We find that the mass of global mobility infrastructures in ~2021 amounted to 314 [218–403] Gt (Fig. 2a). Most of these material stocks, namely 295 [203–377] Gt, are accumulated in roads of various types (motorways, primary, secondary, tertiary, local and rural roads) and their associated bridges and tunnels. Another 18 [15–26] Gt are stocked in rail-based infrastructure (railways, railway bridges and tunnels, subways, trams, and other rails) (Fig. 2a). Due to differing compositions of mobility infrastructure networks and their specific material construction around the world, shares in material stocks differ. In roads, this is mainly due to varying pavement thickness and material composition. Consequently, motorways, for example, make up only 1.4% of the global road network length, but account for 12% of material stocks in roads, with 37 [27–43] Gt. Despite their low material intensity, the mass of local roads amounts to almost 124 [82–174] Gt, i.e., 42% of road stocks, because of their vastly greater network length which amounts to 66% of all road kilometers. Railways and railway bridges and tunnels account for the largest share in the global rail-based infrastructure stock, accounting for almost 15 [12–22] Gt (83%). We generally find very good agreement between these stock estimates and the literature (see supplementary information).

From a material perspective (Fig. 2b), mobility infrastructure stocks are dominated by sand and gravel, primarily used as base and sub-base layers. In roads, sand and gravel account for 69% (203 [140–259] Gt) of total stocks, followed by asphalt (25%, 74 [51–95] Gt). In rail-based infrastructure, sand, gravel, and concrete are both dominant with 11 [8–17] Gt (60%) and 5.8 [4.8–7.6] Gt (31%) respectively, followed by iron/steel with less than 1.3 [1.0–1.8] Gt (7%). The substantial amounts of concrete in rail-based infrastructure can be attributed to concrete railway sleepers and subway tunnels.

Considering the global distribution of mobility infrastructure stocks across world regions, we find a clear positive relation between income levels (GDP), infrastructure lengths and material stocks (Fig. 3c&d). Lower income countries overall have a significantly lower share in global stocks and lower per capita stocks in general, both with regards to mass and network length. More than 82% of all stocks are in upper-middle and high income countries (Fig. 3c), which make up a combined 59% of all countries. The other 41% of countries (low and lower-middle income countries) host the remaining infrastructures.

On a per capita level, we find global stocks of 45 t/cap (median) or 42 t/cap (average) with most countries lying within the interquartile (IQ) range between 23 t/cap (25th percentile) and 87 t/cap (75th percentile) (Fig. 3d). The population-weighted average of low income countries is 19 t/cap with an IQ ranging from 17 to 24 t/cap. Lower-middle income countries exhibit even lower per capita mobility infrastructures with a weighted average of 15 t/cap and an IQ ranging from 18 to 38 t/cap. The weighted average of upper-middle income countries is 38 t/cap with an IQ ranging from 37 to 79 t/cap. Significantly larger per capita stocks can be observed for high income countries, with a weighted average of 122 t/cap and an IQ ranging from 69 to 149 t/cap. Niue ranks first in per capita stocks with 773 t/cap, followed by Iceland with 496 t/cap, while Bangladesh comes in last with only 3.6 t/cap, highlighting the considerable range in per capita stocks around the world.

[2] Non-CO_2 greenhouse gases are disregarded in this context, due to their small relevance in the context of energy generation.

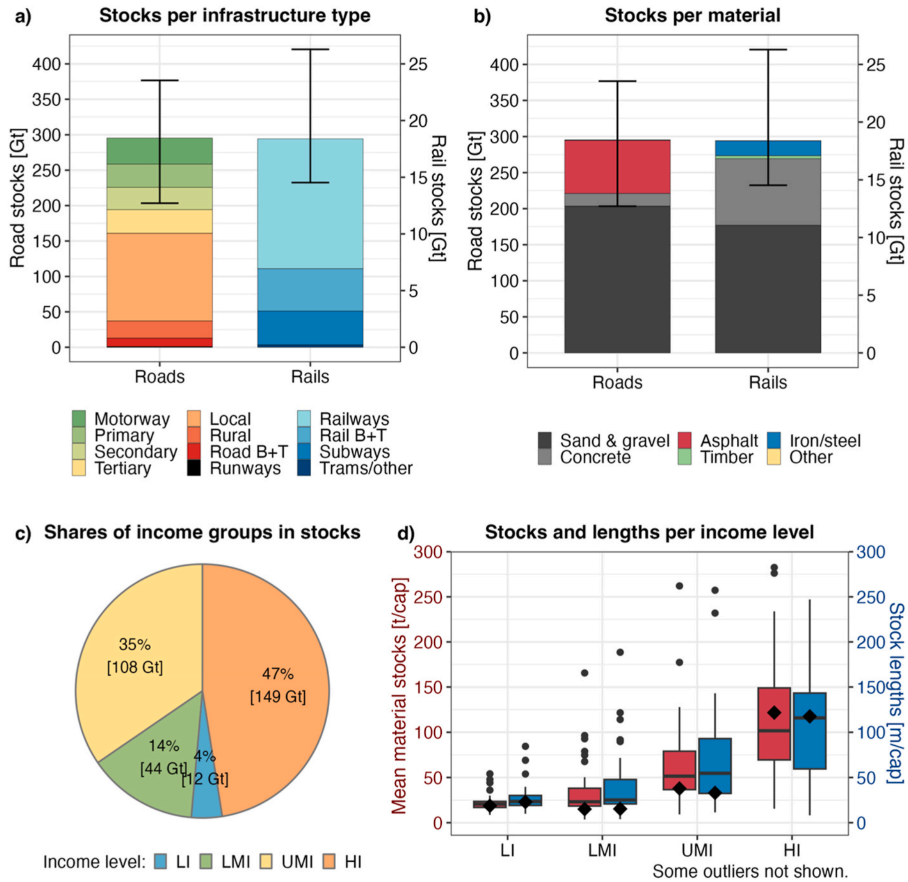

Fig. 2. Global mobility infrastructure networks, by type of infrastructure (a), by material (b), by income groups (c), and per capita material stocks as well as network length per capita (d). "Other materials" include aluminum and copper. "B + T" refers to bridges and tunnels. LI, LMI, UMI and HI refer to countries grouped as low income, lower-middle income, upper-middle income, and high income by (World Bank, 2021).

3.2. Mapping global patterns of mobility infrastructure stocks

We converted spatially explicit infrastructure networks as captured in OSM into a globally gridded map at 5 arcmin resolution, which allows us to analyze patterns of total and per capita stock intensity around the world (Fig. 3a). We find hotspots of mobility infrastructure stock intensity of ~100,000 tons/km^2 in densely settled cities around the world, especially in Europe, the USA, China, Japan, South Korea, and India. We also find intermediate intensities of 1000–20,000 tons/km^2 in many regions of the world, especially in larger regions around cities and main settlement zones.

Interestingly, when mapping per capita stocks, the picture partially reverses, and some hotspots of stock intensity per area turn into areas with only intermediate to relatively low levels of per capita stocks, at ~10–100 tons/cap/km^2 (Fig. 3b). This is most clearly visible in Europe, India, and China, where relatively low per capita stocks are found at high levels of per capita income, because areas with higher population density seem to be serviced well with relatively less material stock intensity per population. On the other hand, in relatively sparsely settled regions in high income countries, we find extremely high levels of per capita stocks intensity of ~5.000–50.000 tons/cap/area, most clearly visible for example in the USA and in Australia. At the same time, we find that in most low to lower-middle income countries, stocks per area and stocks per capita are very low, except in highly dense and comparatively affluent urban areas.

The spatial patterns of mobility infrastructure stocks intensity and human population density can be investigated more systematically from these gridded material stock maps (Fig. 4; please note log and linear axis). We do find a relatively uniform relation between higher population density and larger mobility infrastructure stocks, especially in high income and upper-middle income countries. We also find that higher national income levels are clearly associated with higher stocks, compared to lower income levels at similar population densities (Fig. 4, c. f. Fig. 2d). In low income and lower-middle income countries, we also see that low to intermediate population densities have consistently smaller material stocks. Only at the highest population densities in rather urbanized or urbanized areas, material stocks increase in an approximately exponential manner, but even then, remain considerably lighter than in countries with higher income levels.

That stock levels vary substantially at the same level of population density indicates that differences in stock intensities are dependent on national income levels for regions with similar population density (Fig. 4). Especially in high income regions, we find median stocks of 94–140 kt/km^2 at the highest population densities above 3000 cap/km^2. This effect is less pronounced for the upper-middle income regions and becomes very small in the lower income groups.

Approximately 52% of global infrastructure stocks are found in regions with population densities below 100 cap/km^2, with a large share of stocks (19%) present at population densities above 10 and below 50cap/km^2 (Fig. 4e). Dominated by stocks in high and upper-middle income countries, the East coasts of USA and Brazil, as well as Western Europe and Western Russia contribute prominently to these high stock levels at this rather low population density.

3.3. Flows of materials and embodied emissions

A first approximation of the ranges of material flows and embodied emissions required to expand and maintain infrastructure material

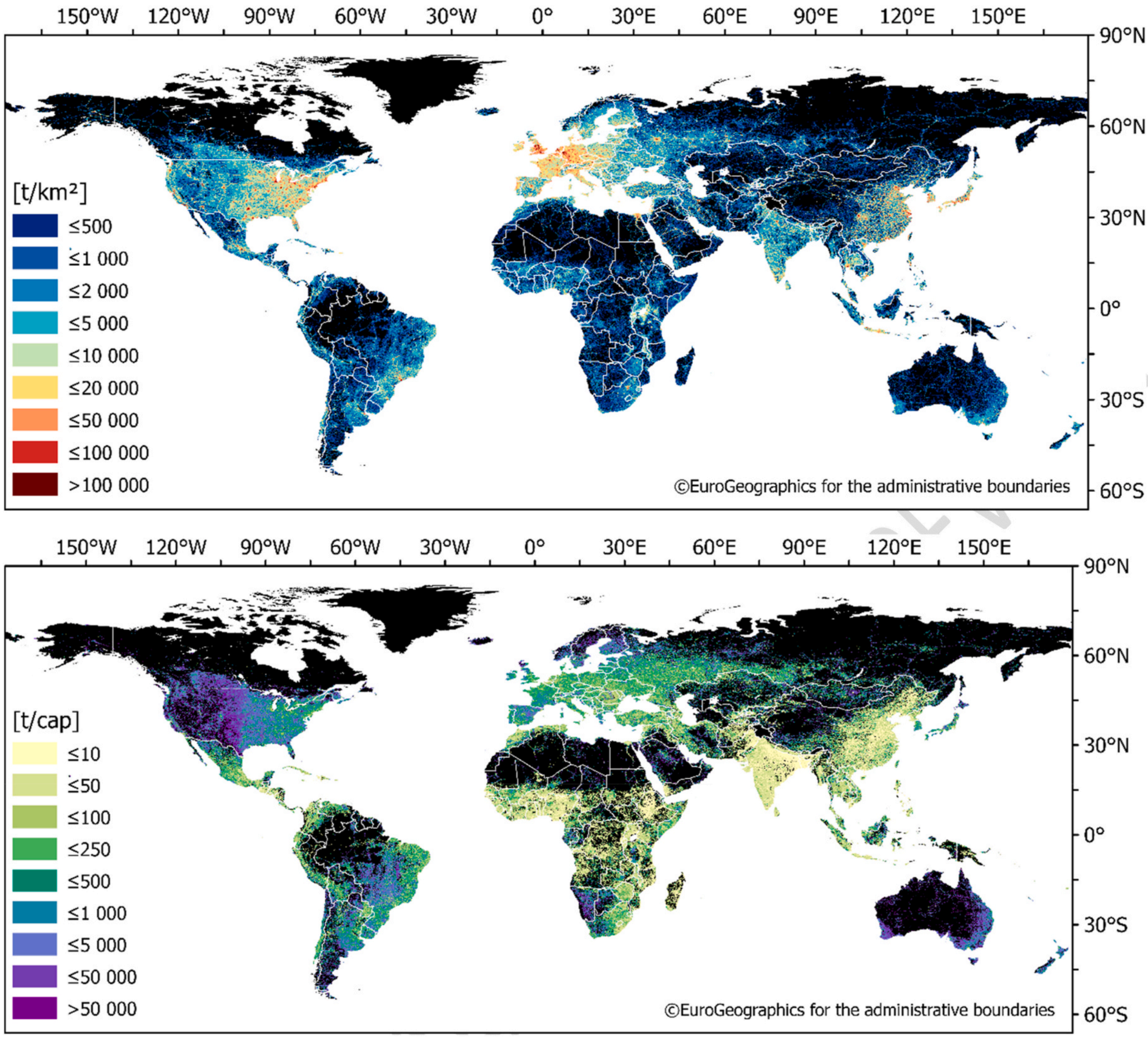

Fig. 3. Global maps of mobility infrastructure stocks for the year 2021 at 5 arcmin resolution, showing a) total materials in mobility infrastructure networks per square kilometer, and b) total stocks per capita per square kilometer. The supplementary information also contains maps per disaggregated infrastructure types. Gridded population data for the year 2017 from HYDE 3.2.1. (Klein Goldewijk et al., 2017).

stocks can be derived from the estimated material stocks, using ranges of low/average/high service lifetimes per material and infrastructure type, as well as ranges of infrastructure growth rates and embodied emission factors (see methods section).

We estimate that in the year 2021, 8.4 [4.2–15.6] Gt/year of materials are used globally for mobility infrastructure stocks, ~66% of which are used to maintain and replace existing stocks, while ~34% are modelled for the expansion of the stock (Fig. 5a). Most of these material flows are estimated to be required in upper-middle and high income countries (Fig. 5b). Asphalt amounts to about half of these material flows, while sand and gravel for base and sub-base layers makes up for another third. Concrete, iron, steel, and timber constitute a minor amount of material flows in mass units. Using low and high ranges of lifetimes and infrastructure growth rates, we model 4.2–15.6 Gt/year for expansion and maintenance globally.

Interestingly, we find good agreement between our results and reported bitumen consumption data, despite the simplified global assumptions used to derive ranges of material flows (Fig. 5e). Because the modelled flows presented herein include primary and secondary/recycled materials, we deducted the amounts of secondary bitumen flows, assuming 0-10-25-50% recycling rates of bitumen from low to high income country groups, arriving at modelled ranges of primary bitumen used in the four income regions. Compared to reported data, mean modelled primary bitumen consumption is 23% higher for high income countries and 18% lower for upper-middle income countries.

Using world-regionalized embodied emissions data for materials production, we estimate that the 8.4 [4.2–15.6] Gt/year of materials cause embodied emissions of 358 [185–693] Mt CO_2eq/year during materials production and energy supply (Fig. 5c). Production of asphalt (46%) and iron and steel (28%) are the major causes of emissions, followed by concrete (21%). Sand and gravel, while constituting 44% of the mass flows, only causes a negligible fraction of total emissions (3%). Most emissions are due to materials production in upper-middle and especially high income countries (Fig. 5d). Network expansion causes ~29% of these embodied emissions, while maintenance and replacement make up ~71%. We also find that the embodied emissions primarily occur in high income and upper-middle income countries, while low and lower-middle income countries taken together only account for 12% of total embodied emissions related to mobility infrastructure stock expansion and maintenance (Fig. 5d).

3.4. A hypothetical, population-density scaled scenario of per capita stock catch-up and convergence to infrastructure levels found in high income countries

Finally, we explore the ranges of material flows and embodied

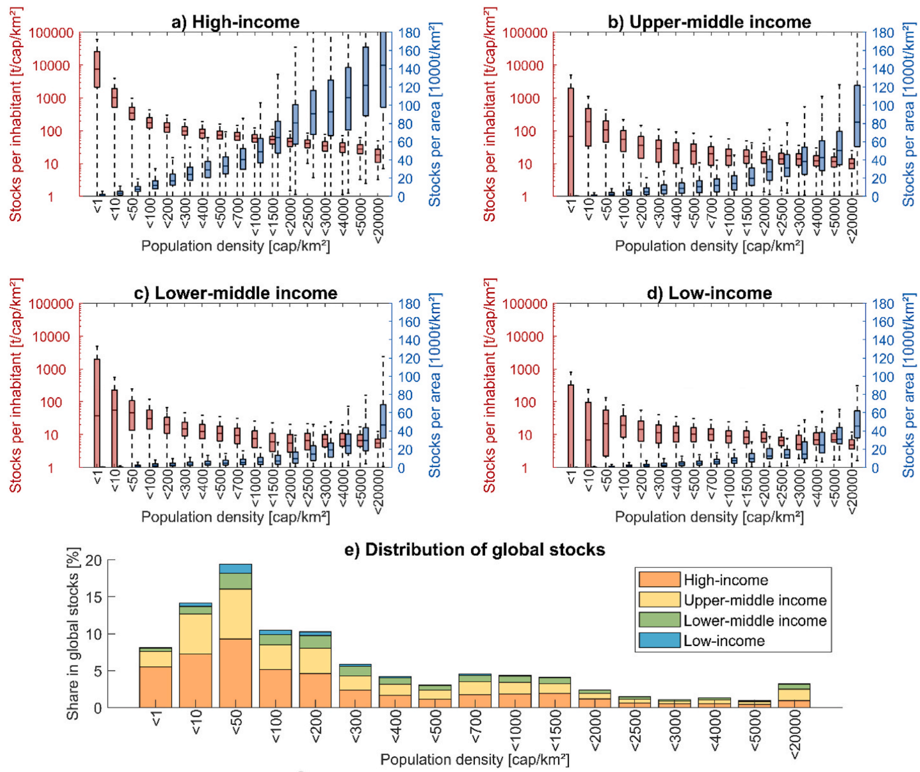

Fig. 4. Mobility infrastructure stocks and population density, for four global income groups. Due to the very wide spread of stock intensities at very low population densities, values for stock intensity per inhabitant are shown as logarithm (left hand axis), while the right-hand axis is not. Gridded population data for the year 2017 from HYDE 3.2.1. (Klein Goldewijk et al., 2017). Please note that partial inclusion of water bodies or uninhabitable land, as well as small errors in OSM, can result in very low population densities having zero stock also.

emissions which would be required for a hypothetical global catch-up of mobility infrastructure stock intensity per area, to the per capita levels per population density bin found in high income countries, assuming that global population size and density remain constant (see methods section). Note that this scenario is not meant as a future trajectory nor realistic forecast, but rather exploratory modelling of the mass of stocks hypothetically needed at current population (density) numbers and the subsequent ranges of material flows and emissions.

We find that this global catch-up and convergence of mobility infrastructure stocks results in a 2.6 [2.5–3.7] fold increase of the mass of mobility infrastructure stocks to 831 [545–1496] Gt, compared to the stock estimates from 2021 at 314 [218–403] Gt. This increase is primarily due to additional roads and specifically asphalt and aggregates (Fig. 6a). Stocks in low income countries increase by a factor of 9 from 12 to 112 Gt (99 Gt increase) and by a factor of 5 in lower-middle income countries, from 44 to 246 Gt (202 Gt increase). Stocks in upper-middle income triple from 108 to 325 Gt (216 Gt increase). While relative increases are highest in low income and lower-middle income countries, the increase in upper-middle income countries is comparable in absolute terms (Fig. 6b). This catch-up scenario requires in total 517 [231–1182] Gt of material flows for expansion over current stocks (Fig. 6c). Furthermore, such a population-density dependent globally equalized stock level would imply future annual material flows of 16 [9–38] Gt/year for maintenance and replacement (Fig. 6d). This would constitute an increase of 293% for materials flows locked in for maintaining mobility infrastructure assumed to exist in the catch-up scenario.

4. Discussion

4.1. Robustness, limitations, and next steps

Our estimates agree well with the infrastructure types-specific literature, ranging from stock estimates globally (Mao et al., 2021; Rousseau et al., 2022; Virág et al., 2022), for world-regions (Wiedenhofer et al., 2015, 2021), and nations (Ebrahimi et al., 2022; Miatto et al., 2017; Nguyen et al., 2018; Tanikawa et al., 2015). We find a surprisingly good match of the modelled material flows with reported data on annual bitumen consumption which is primarily used for paving roads (Fig. 3e); for the other materials, we find that the modelled flows amount to small shares of global extraction and use (all comparisons are shown in the supplementary information section 1). Overall, these comparisons confirm that our stock-flow results are well in line with previous studies and reported data.

Several next steps remain for future research. First, while OSM was evaluated as more than 80% complete, it often lacks attribute information on type and design of infrastructures, e.g., road types, lane widths or pavement surfaces; it is not globally harmonized, nor quality ensured (Barrington-Leigh and Millard-Ball, 2017; Meijer et al., 2018). However, comparisons of official statistics and GRIP4 with OSM show substantial gaps to complete omissions in official data and GRIP, especially for lower order road infrastructure such as residential/local/rural/gravel roads (see supplementary information and (Haberl et al., 2021; Meijer et al., 2018). OSM also includes detailed information on rail-based infrastructure, incl. subways, making it a promising and fully open data source. It is important to note however, that the completeness of OSM is shaped by internet access and open governance structures encouraging crowd-sourcing information; additionally, very densely and very sparsely settled areas seem to be relatively more complete (Barrington-Leigh and Millard-Ball, 2017). Because attribute information on infrastructure types and designs depend on user inputs, grouping and assumptions are necessary to match OSM classes with infrastructure design parameters (see methods). Future work might focus on introducing age-type-cohort information, enabling fully dynamic stock-flow modelling. Quality improving and harmonization procedures

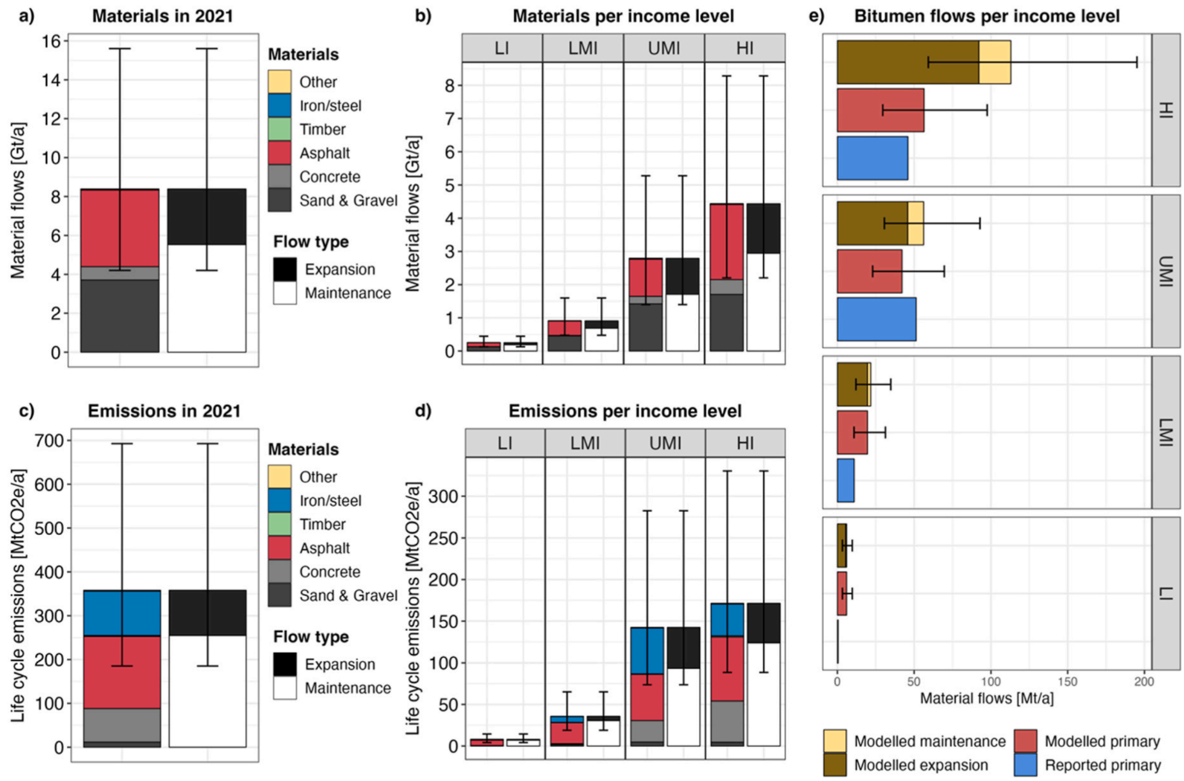

Fig. 5. Material flows and embodied GHG emissions due to mobility infrastructure maintenance and expansion, for global material flows (a) and material flows by income groups (b). Global cradle-to-gate embodied emissions and emissions by income group are shown in (c) and (d) respectively. Total and primary modelled bitumen flows for both maintenance and expansion are compared with reported data on bitumen consumption from UN (e). The uncertainty ranges shown represent the combined effect of low-high assumptions on material intensity, service lifetimes, infrastructure growth rates, as well as embodied emissions (see methods section). Other materials include aluminum, copper and other metals. NGR refers to network growth rates, LT to lifetimes and LCE to embodied emissions.

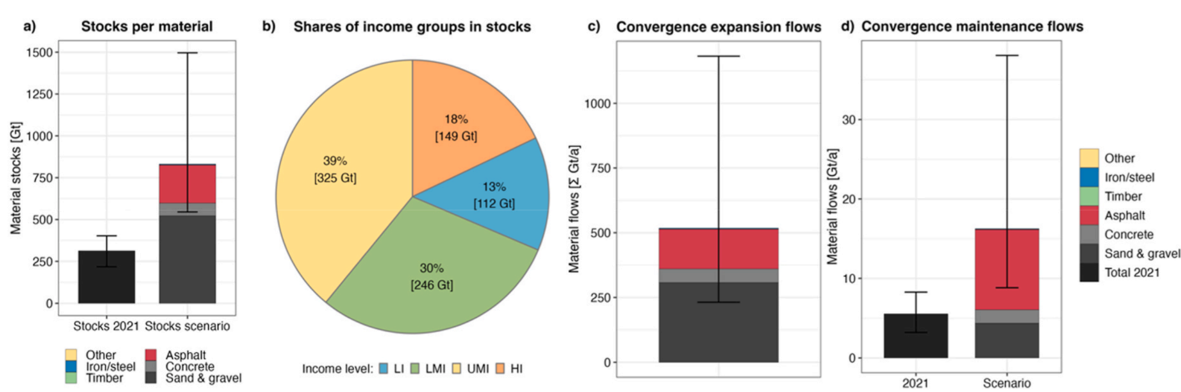

Fig. 6. A hypothetical infrastructure catch-up and convergence scenario, to median per capita stock levels across all raster cells (5 arcmin, ~9 × 9km^2) in high income countries. (a) Global stocks in the year ~2021 and in the scenario, (b) stock levels in the convergence scenario for each income region, (c) material flows and embodied emissions for global convergence, and (d) ranges of annual material flows and embodied emissions for the maintenance and replacement of the scenario stock level. Error bars show the modelled range resulting from low-median-high ranges for the median [25th – 75th percentile] per capita stock levels across the raster cells in high income countries in the year ~2021, as well as ranges of lifetimes and embodied emissions by material and infrastructure type.

developed for GRIP (Meijer et al., 2018), novel sources such as digitized historical maps (Uhl et al., 2022), or combinations with other statistics like CIA factbooks (Rousseau et al., 2022), as well as drawing on municipal and company data (Kloostra et al., 2022), all constitute interesting next steps towards a more harmonized and comprehensive understanding of mobility infrastructure stocks.

Second, improving data on infrastructure design parameters, incl. material compositions, components and design lifetimes are important avenues for further work. Herein, globally archetypical values, country-specific information for six countries, and uncertainty ranges were used (methods section, Table 1 and supplementary data). National guidelines and construction manuals were an important source for these design parameters, suggesting that the stock estimates herein constitute the "minimum" material composition and widths, as legislated. Actual on-site material stocks and flows, as well as their quality and potential for repair and recycling additionally depend on a range of factors, such as local soil conditions, local construction plans, historical circumstances, widening of existing roads esp. in high income countries, government budget priorities, as well as compliance of construction companies with standards and regulations (Ebrahimi et al., 2022; Grossegger, 2022;

Kloostra et al., 2022; Miatto et al., 2017). Recently, two studies at local and national level developed spatially and historically refined and stratified design parameters (Ebrahimi et al., 2022; Kloostra et al., 2022), although it is not clear how well these approaches can be transferred to data scarce world-regions and globally. Expanding and regionalizing archetypical material intensities incl uncertainty ranges, for example considering climatic considerations in road construction (Rousseau et al., 2022), therefore seem like promising future research avenues.

Third, expanding the scope of covered aspects of mobility infrastructure would also be relevant; for example, parking lots can amount to substantial additional material stocks, which however seems to necessitate remote sensing approaches (Frantz et al.,; Haberl et al., 2021). Further aspects to be included range from general parking infrastructure including garages, to various facilities and buildings associated with ports, airports, railway and subway stations, as well as technical systems for lighting, traffic regulation, electric charging infrastructure, to safety systems. While these might not amount to large additional material stocks, their associated life cycle emissions might be relevant.

Fourth, a better understanding of service lifetimes, maintenance intervals and subsequent material flows might be achieved by dynamically modelling for example, age-type-cohorts, the influence of traffic conditions, or socio-economic as well as climatic and weather influences. This requires overcoming lacking data especially at world-regional to global levels. The simplified leaching lifetime model utilized herein enables a first approximation, yielding surprisingly good agreement with for example reported data on global bitumen consumption (Fig. 5e). Therefore, it seems that more refined modelling assumptions seem like a more feasible way forward, in the absence of large-scale bottom-up research developing novel primary data globally from, for example, municipal data (Kloostra et al., 2022).

Finally, a more complete and refined understanding of the life-cycle emissions from materials extraction, production, energy supply, construction activity, recycling as well as waste management would be desirable. We covered the major life cycle stages for emissions, e.g., materials production and energy supply, because detailed studies suggest that local transport of materials, construction activity, as well as energy and emissions during demolition, material recovery and recycling/downcycling activities are usually minor contributors to overall life cycle emissions of mobility infrastructures (Hoxha et al., 2021; Jiang and Wu, 2019; Olugbenga et al., 2019), especially for materials with high recycling and re-use rates (asphalt, steel, aluminum, copper), where specific context such as average transport distances matters mostly (AzariJafari et al., 2021; Hoxha et al., 2021; Olugbenga et al., 2019). For aggregates, we assume that secondary materials are associated with the same energy and GHG intensities as natural aggregates, as literature data indicate similar ranges and is rather inconclusive as to whether recycled or natural aggregates have lower life cycle energy use and emissions (Hossain et al., 2016; Hoxha et al., 2021; Marinković et al., 2010; Olugbenga et al., 2019). We also do not cover the carbonation of concrete during the use phase over many decades, and especially at the end-of-life phase, where substantial carbon uptake can occur over decades (AzariJafari et al., 2021; Xi et al., 2016). Carbonation is characterized by numerous influencing parameters, such as the sizes and geometrical shapes of concrete elements, the surface area exposed to air, demolition, recycling practices, as well as waste storage practices. However, concrete of the highest strength classes is typically used for pavements and infrastructures (Pade and Guimaraes, 2007), which is characterized by particularly low carbonation rates during use. In summary, while the estimates presented herein cover the major emissions' contributors, a more comprehensive and dynamic understanding for all life cycle stages, incl. construction activities especially for tunnels, bridges and subways, recycling and waste management, as well as clearing of previous land-uses, would be desirable (Hoxha et al., 2021; Olugbenga et al., 2019; Saxe and Kasraian, 2020).

4.2. Mobility infrastructure stocks and flows and the global social metabolism

By drawing on previous inflow-driven "top-down" modelling of economy-wide material stocks and flows (Krausmann et al., 2017; Wiedenhofer et al., 2021), as well as international data sets on resource use and emissions (Friedlingstein et al., 2021; UNEP-IRP, 2022), we can, for the first time, assess the role of mobility infrastructure stocks and modelled ranges of material flows and emissions for the entire global socio-economic metabolism. Country-level studies suggested that mobility infrastructure stocks constitute a major share of economy-wide material stocks and cause large amounts of material flows (Haberl et al., 2021; Schiller et al., 2016; Tanikawa et al., 2015; Wiedenhofer et al., 2015). Herein, we find that mobility infrastructure stocks make up 30 [22–36]% of global economy-wide material stocks, and that our modelled material flows constitute ~6 [3–10]% of global resource extraction, as well as 12 [6–22]% of global non-metallic minerals extraction (Table 3). The production of these materials, from a cradle-to-gate life-cycle assessment and excluding transport, construction and use, causes 1 [0.5–1.9] % of global GHG emissions; 2/3 of which are due to maintenance and replacement of existing infrastructure stocks (Table 3). While this might seem rather small, these emissions are equivalent to that of an entire high income country of the size of Italy.

While these results suggest that infrastructure expansion, maintenance and replacements themselves currently pose a modest challenge for climate change mitigation and more sustainable resource use, several important considerations remain. Firstly, as the hypothetical global catch-up scenario to infrastructure levels in high income countries shows a potential 2.6 [2.5–3.7]-fold increase of infrastructure stocks (Fig. 5), future material use for infrastructure expansion and maintenance might become substantial, depending on the timeline of such a catch-up to materialize. However, a stock stabilization would enable a saturation or even decrease of material flows and emissions, also leveraging the transformative potentials of circular economy strategies (Wiedenhofer et al., 2021). In this regard, Rousseau et al. (2022) showed that urban area, population density and affluence (GDP) are major drivers of urban paved road stock accumulation, arguing that limiting urban area growth is important to slow or even limit stock growth, although insufficient infrastructure provision in many parts of the world should not be forgotten here.

Secondly, we did not cover materials and emissions due to mobility services as supported by the infrastructure networks; indeed, different mobility networks (e.g., railways vs. roads) incentivize or discourage mobility practices with vastly different resource requirements or emissions per person- or ton-kilometer; in the year 2019, direct emissions from all global transport and mobility amount to 15% of global GHG emissions (Lamb et al., 2021). Understanding how settlement patterns and mobility infrastructure need to be designed and transformed to be more resource-efficient, to overcome automobile lock-in, while also providing the physical basis for sustainable mobility for all (Mattioli et al., 2020; Virág et al., 2022; Wenz et al., 2020), are therefore important issues for just climate change mitigation.

Finally, while we quantified stock-flow relations and GHG emissions, other environmental impacts should not be forgotten, because the substantial amount of resource use and infrastructure network expansion also contributes to, for example, the 'tragedy of the sand commons' (Torres et al., 2017), biodiversity losses due to the extraction of non-metallic minerals and metal ores (Luckeneder et al., 2021; Torres et al., 2021; UNEP-IRP, 2019), as well as land use changes driven and enabled by infrastructure expansion, incl. various socio-economic impacts and benefits (Busch and Ferretti-Gallon, 2020; Vilela et al., 2020).

5. Concluding remarks

We present the first comprehensive global mapping and model-based

Table 3
The role of global road and rail-based mobility infrastructures for the global socio-economic metabolism. Please note that, a) all numbers are rounded and therefore might not completely add up, and b) that in this study the cars, trains, airplanes, as well as all tailpipe emissions are excluded, as shown in Fig. 1 in the methods section. Numbers in brackets indicate modelled uncertainty ranges.

	Raw material extraction	Material uses	Material stocks	Energy- and materials related GHG emissions	Sources
Mobility infrastructure	5.4 [2.7–9.7] Gt/year	8.4 [4.2–15.6] Gt/year	314 [218–403] Gt, in 2021	0.36 [0.19–0.69] Gt CO2eq/year	This study
Maintenance and replacement	3.6 [2.0–5.2] Gt/year	5.5 [3.2–8.2] Gt/year		0.26 [0.15–0.41] Gt CO2eq/year	
Expansion flows	1.8 [0.6–4.5] Gt/year	2.8 [1.0–7.3] Gt/year		0.10 [0.04–0.29] Gt CO2e/year	
Global economy-wide resource use and material stocks	96.2 Gt/year of raw materials in 2019, incl. all non-metallic minerals, ores, fossil fuels and biomass		1064 [1013–1116] Gt in 2015, total in-use stocks	36.3 Gt/year	(2021); Krausmann et al., (2017); UNEP-IRP 2022, IEA 2022)
Ores and metals	9.7 Gt/year of ores in 2019		32 [31–33] Gt in 2015, in-use metal stocks		
Non-metallic minerals, incl. limestone, sand and gravel aggregates, stones, clays, industr. Minerals	44.8 Gt/year of raw materials in 2019		1007 [956–1059] Gt in 2015, in-use non-met. minerals stocks		
Share of mobility infrastructure stocks and flows in global metabolism	6 [3–10]% of total extraction 12 [6–22]% of non-metallics extraction		30 [22–36] % of total global stocks	1 [0.5–1.9] % of global GHG emissions	

assessment of mobility infrastructure stocks and associated material flows and their embodied emissions. Our study aims at providing a key piece of information required to assess the biophysical basis of global mobility services. We found an accumulated material stock of 314 [218–403] Gt in 2021, which amounts to approximately one-third of global economy-wide material stocks of all buildings, infrastructure and machinery. We find substantial global and spatial inequality in infrastructure stocks, with clear relations between both population density and national income levels (GDP) jointly shaping infrastructure stock levels, which is in line with findings on urban areas and paved roads by Rousseau et al. (2022), where additionally the extent of urban areas was identified as major driver of accumulated stocks.

The modelled material flows for expansion and maintenance, ~8.4 [4.2–15.6] Gt/year, amount to ~10% of global resource extraction, indicating substantial environmental pressures during resource extraction and materials processing, infrastructure construction, as well as maintenance and replacements. The associated embodied emissions amount to 0.36 [0.19–0.69] Gt CO_2-eq/year, approx. 1 [0.5–1.9] % of global energy-related GHG emissions. We also find that ~2/3 of these material flows and emissions are due to maintenance and replacements of existing infrastructure stocks, constituting an important lock-in. In a hypothetical global catch-up and convergence scenario to the average infrastructure stock intensity found in high income countries, we find a potential 2.6 [2.5–3.7]-fold increase of global infrastructure stocks, resulting in tripling of associated material flows.

While sufficient mobility infrastructure and safe as well as affordable mobility services for everyone are clearly required, transforming them into climate-neutral and resource-efficient modes is of crucial importance, as policymakers and stakeholders aim to reduce GHG emissions fast enough to mitigate rapidly progressing climate heating. Infrastructures are a pivotal leverage point for climate change mitigation and resource efficiency, as they constitute materialized long-term path dependencies. Supply- and demand-side measures seem necessary to achieve such a transformation of mobility infrastructure, which are currently dominated by roads and car-bound mobility. These measures start from industry and energy supply decarbonization, to more resource-efficient and long-lived infrastructure designs, as well as improved spatial planning, including limiting the outward growth of urban and sub-urban areas, as well as changing mobility demand away from individual motorized transport, subsequently requiring less and different infrastructure stocks with potentially lower maintenance and replacement; ideally with an emphasis on sufficient and sustainable mobility for all.

CRediT authorship contribution statement

Dominik Wiedenhofer: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Visualization, Project administration. **André Baumgart:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Sarah Matej:** Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Doris Virág:** Investigation, Resources, Data curation, Writing – review & editing. **Gerald Kalt:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Maud Lanau:** Formal analysis, Investigation, Writing – review & editing. **Danielle Densley Tingley:** Resources, Writing – review & editing. **Zhiwei Liu:** Formal analysis, Investigation. **Jing Guo:** Formal analysis, Investigation. **Hiroki Tanikawa:** Resources. **Helmut Haberl:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

Data are also available via: https://zenodo.org/records/10158807

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139742.

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