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**Young Scientists Summer Program**

# How much mobility infrastructure is required for decent mobility standards? A comparative assessment and explorative modelling

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## Approved by

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# Contents

# Abstract

Global transport substantially contributes to climate change and is one of the sectors with the highest emission growth throughout the last decade. Decarbonizing and mitigating escalating mobility demand is thus key to reaching ambitious climate targets. At the same time, the transport sector is delivering a key societal service and basic need of universal necessity: personal mobility, which is currently not available with sufficient quality and quantity for decent living across the world. Infrastructure stocks are a basic requirement for providing mobility services in terms of accessibility of desired destinations and the mobility modes enabled by them. However, infrastructure stocks require substantial resources for build-up and maintenance and can create lock-ins into unsustainable mobility practices, e.g. by locking-in car-based mobility. This leads to the so far unresolved question of how much mobility would be sufficient and which kinds and how much infrastructure stocks are required to deliver sufficient and climate-friendly mobility globally.

Herein, we firstly assess different strands of literature and compare definitions of decent or sufficient mobility, to shed light on varying conceptualizations of measurements and sufficiency thresholds for mobility. Secondly, we derive several possible relations between (sufficient) mobility thresholds and the required infrastructure stocks, which we then quantitatively investigate across multiple empirical cases. We use data available at global or multi-national scale to empirically explore the connection of mobility and accessibility levels and mobility infrastructure stocks in a descriptive analysis. We find that total distances travelled and the mass of infrastructure stocks are highly correlated, though there seem to be more relevant influencing factors, and that mobility stock levels do not relate strongly to accessibility indicators. For a more differentiated understanding of mobility services, data availability on a multi-national or global level has to be improved.

With this conceptual and empirical investigation, we provide a novel exploration of the connection of material stocks and available measures of societal output of mobility, with the aim to further advance the discussion about decent mobility standards and corresponding infrastructure stocks for a future of sustainable global mobility.

# Introduction: Why define ‘Decent Mobility Standards’?

## The tension of social and environmental sustainability in mobility

Safe, affordable, accessible and sustainable transport is an important societal target for which sufficient high-quality and low-carbon infrastructure is required. However, the current transport system is not delivering on this target. The global transport sector is the third-largest source of $CO_2$ emissions globally (SLoCaT, 2018), due to its fossil fuel-dependency and because improvements in energy intensity of transport have been offset by a trend towards larger and heavier vehicles (Lamb et al., 2021). Temporary reductions of transport emissions due to the COVID-19 pandemic and the lockdown measures in 2020 have not led to structural changes of the transport system, in contrast, fiscal recovery stimuli could even increase emissions again (Le Quéré et al., 2020; Shan et al., 2021). At the same time, 25-35% of global GHG-emissions are caused by industry processing materials, a significant share of which are used for the build-up of infrastructure stocks (Hertwich, 2021; Lamb et al., 2021). While the current level of GHG emissions is critical in the light of approaching planetary boundaries (Rockström et al., 2009; Steffen et al., 2015), a significant share of the global population is living below or at the edge of poverty levels (UNDP, 2020a). Transport activity in terms of distances travelled has expanded globally throughout the last decades and is expected to grow further (International Transport Forum, 2021). Still, a large group of the global population is affected by ‘transport poverty’, the lack of sufficient mobility options (Lucas et al., 2016). The majority of countries worldwide has not achieved decent mobility standards for all. (Kikstra et al., 2021) estimate that the largest part of energy needed to reach DLS globally will be needed in the mobility sector.

Progress towards safe, affordable, accessible, sustainable transport is needed, as reflected in the Sustainable Development Goals (SDGs). However, none of the main 17 targets is explicitly concerned with transport, only some sub-targets touch upon decent personal mobility. SDG sub-target 11.2 plans safe, affordable, accessible, sustainable transport for all and measures satisfaction with public transport in cities. Sub-target 9.1 rates the quality of trade and transport-related infrastructure. Sub-target 3.6 is concerned with reducing deaths and injuries from road accidents (Sustainable Mobility for All, 2021). Even though passenger transport infrastructure stocks are central for enabling sustainable mobility for all, the relation between mobility and infrastructure is not articulated nor measured through specific indicators.

## Defining sustainable and decent levels of personal mobility

The question arises which level of personal mobility is actually needed to serve everyone well but without overstretching resource use and environmental pressures. A number of concepts have been proposed to investigate the relation between sufficient service provision, social wellbeing and environmental limits. Raworth (2012) described the safe operating space with a framework shaped as a “doughnut”, i.e. below planetary boundaries but above social foundations. Other concepts have framed this vision as “sustainable target space (van Vuuren et al., 2021), “consumption corridors” (Di Giulio and Fuchs, 2014; Sahakian et al., 2021) “buen vivir” or a “good life” (Brand et al., 2021) or “provisioning systems” (Fanning et al., 2020; Gough, 2019; Lamb and Steinberger, 2017; Plank et al., 2021; Schaffartzik et al., 2021), material and energy services as well as the stock-flow-service nexus (Carmona et al., 2017; Haberl et al., 2017; Pauliuk et al., 2021; Tanikawa et al., 2020; Whiting et al., 2020). While all of those concepts revolve around minimum and maximum levels of consumption and service provision, none of them directly tackle the question of decent mobility.

Some strands of literature explicitly focus on lower boundaries of sufficiency, also for mobility. One discussion revolves around the concept of ‘transport poverty’, which is described via different dimensions of mobility that have to be fulfilled to prevent mobility deprivation (Lucas et al., 2016). Another prominent concept covering all dimensions relevant for a good life for everyone is the ‘Decent Living Standards’ (DLS) framework (Rao et al., 2018; Rao and Min, 2018a; Rao and Pachauri, 2017), which defines universal minimum conditions for wellbeing based on human needs (Doyal and

Gough, 1984) and capability approaches (Nussbaum, 2003). Within those strands of literature, definitions and operationalizations of minimum levels or basic needs vary. In general, they 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 a need in in contrast to a want (Doyal and Gough, 1984).

## Infrastructure stocks for mobility

Passenger transport infrastructure stocks are central to providing personal mobility services, but have hardly been investigated so far in relation to mobility outputs. While the role of energy in providing minimum standards below upper thresholds has been explored more often recently (Brand-Correa et al., 2018; Kikstra et al., 2021; Mayer et al., 2017; Millward-Hopkins, 2020; Steinberger and Roberts, 2010), the role of materials in providing decent living remains rather unexplored.

Material use has been growing rapidly throughout the last decades and a large part of materials extracted globally are used to build up and maintain material stocks, which are expected to grow further (Krausmann et al., 2020). A large part of total material stocks consists of transport infrastructure (Haberl et al., 2021b), which is estimated to amount to ~300 Gt of materials, mostly aggregate, asphalt and concrete globally. The road system makes up the largest part of the total mobility system and stock levels in high-income and low-density countries are on average higher than in others (Schug et al., in prep.; Wiedenhofer et al., in prep.). Material stocks in infrastructure are key for a more sustainable social metabolism, not only because of the resources needed to build them up and maintain them, but also because they manifest path dependencies for future use (Baiocchi et al., 2015). Material stocks, such as mobility infrastructure, and their shape (density, distribution), type (road/rail) and quality (road surface and drainage, accessibility of different locations by public transport) influence future mobility behavior and thus 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), mobility stocks are a core element of providing mobility services or practices of using different modes of mobility (Haberl et al., 2021a), which calls for the exploration of both the elements of the nexus and their connection to understand pathways towards more sustainable resource use or, eventually, a socio-ecological transformation. The aim would be to keep the mobility infrastructure as lean as possible, with the lowest environmental impact possible but still providing sufficient mobility to everyone – that is, to minimize stock intensity of mobility – to face this double challenge.

Identifying threshold levels of sufficient infrastructure stocks for decent mobility is not straightforward. First, because of different perspectives on what the desired mobility service actually is and how it can be measured – i.e. in distances travelled, accessibility and affordability. Second, because the assessment of connections between material stocks and services for need satisfaction delivered by them is still in its infancy (Carmona et al., 2017; Haberl et al., 2017; Tanikawa et al., 2020; Whiting et al., 2020). It is, however, crucial to understand also material stock requirements of mobility to find a balance between providing an adequate level of mobility and limiting its environmental impacts to a minimum. In order to do that, the connection of material stocks and the societal output or services of mobility has to be understood. Therefore, we ask the following research questions:

(1) Which definitions of decent mobility are available in the literature? How do they conceptualize the relations between infrastructure stock requirements and mobility functions and services?
(2) How can a stock-flow-consistent conceptualization of decent mobility standards (DMS) be developed?
(3) Which indicators are available and what are the empirical relationships between mobility infrastructure stocks and mobility functions?
(4) What are the empirical relations between mobility infrastructure stocks and widely used indicators on social progress and human development (HDI, SDGs)?

Herein, we conceptually and empirically explore the relations and thresholds of mobility infrastructure stocks and mobility functions (distances travelled) and services (purpose of mobility) at a macro-scale. First, we provide a conceptual review of different strands of literature on safe, affordable, accessible, sustainable personal mobility. Second, we synthesize a stock-flow-consistent conceptualization of decent mobility standards. Third, we empirically explore selective relationships between material stocks of mobility infrastructure and available measures of mobility functions at a macro-scale. Forth, we analyse if there are thresholds of mobility stock levels at different levels of social progress and human development. Fifth, we summarize insights on stock-flow relations for decent mobility standards from the conceptual review and the empirical analysis to structure the conceptual debate of understanding how infrastructure stock levels scale and relate with the provision of decent mobility standards.

## Literature review

### State of the art of mobility measures and sufficiency thresholds

To understand the different views on mobility requirements, first, the definition basic mobility needs and (decent) mobility services has to be clarified. Mattioli (2016) describes mobility needs as universal, objective, satiable and universally valid, but usually vaguely defined and quite general. While needs are conceptualized as invariant, their satisfiers are context-dependent and socio-ecologically variable (Lamb and Steinberger, 2017). Mattioli (2016) differentiates several hierarchical orders of need satisfiers for transport needs: (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 that 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 distances between private settlements and destinations that need to be reached in combination with cuts on public transport funding by the British government. He characterizes the lower order need satisfier of travel as 'derived demand', which does not describe the transport need per se but rather a satisfier, which is variable across space and time (Mattioli, 2016). These satisfiers are what is usually measured and compared in transport research, for example distances travelled, but they need not be very closely related to a decent life or wellbeing: Provided that social participation (in family life, work life, etc.) and access to vital goods/services such as education, health care etc. is possible while travelling very little, because all of this is available in a person's vicinity, a decent life or high wellbeing is also possible travelling very small distances.

In the 'Decent Living Standards' framework, a certain amount of person-kilometres per year and person is assumed to be the minimum standard of decent mobility services, depending on population density and rural/urban settlement type (Rao and Min, 2018a). Following the conceptualization of Kalt et al. (2019), mobility services need to be defined 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.), not as distances travelled (person-kilometers). Structural conditions may dictate the distances necessary to reach this purpose. Therefore, mobility services can for example be expressed by reaching places to fulfil other needs, such as social participation (Virág et al., 2021).

A thorough review of different conceptualizations of how much transport is necessary or enough has been given by Lucas et al. (2016). The authors introduce 'transport poverty' as an overarching concept to describe the problem of personal mobility levels below decent thresholds at the individual, rather than at the household level also to acknowledge gender differences. They define 'transport poverty' as a combination of the subset of 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 causalities or chronic diseases (Barter, 1999). Lucas et al. speak of transport poverty, whenever no transport option is available at all, the options are not suited to the individual's condition or capabilities, do not reach destinations where activity needs can be fulfilled, are not affordable without the individuals or households' remaining income dropping below the poverty line, are very time intensive or only usable under dangerous or unhealthy conditions (Lucas et al., 2016, p. 354).

Several approaches to measuring mobility availability or poverty have used different indicators for measuring specific dimensions of mobility (see Table 1), but hardly any of them can be rolled out for a cross-national or global analysis for various reasons: They are often dependent on specific datasets which are not available or comparable in many regions, have not been tested in their impact on satisfactory mobility outcomes and most of them assess only one aspect of mobility and would need to be combined with complementary measures to assess overall mobility.

**Table 1: Indicators of mobility based on Lowans et al. 2021, adapted and extended**

| | **Dimension** | **Metric/Method (Threshold proposed)** | **Studied for** | **Source** |
|---|---|---|---|---|
| **Affordability** | Household expenditure on transport | % of household expenditure on transport (10%) | UK | RAC Foundation 2012 |
| | Commuter fuel poverty | Income spent on work travel (10%) | Yorkshire, Humber, UK | (Lovelace and Philips, 2014) |
| | Car-related economic stress | 1) income after housing and running motor vehicle, (60% of median)<br>2) income spent on running motor vehicle (twice of sample's median = 9.5%) | Great Britain | (Mattioli et al., 2016) |
| | Forced car ownership | Owning at least one car and difficulty to afford one of five items: rent, mortgage, household maintenance, energy, food; (one of five) | UK | (Mattioli, 2017) |
| | Motoring expenditure | Costs for a vehicle compared to median income | England, Wales (UK) | (Chatterton et al., 2018) |
| **Mobility** | Travel (incl. mode) choices | Choice of destination (e.g. which school) and travel mode | Slum residents in Nairobi, Kenya (2004) | (Salon and Gulyani, 2010) |
| | Activity space | Standard distance circle, total distance travelled and number of geographic locations visited, number of unique activity places | Hong Kong | (Tao et al., 2020) |
| | Trip generation | Number of trips | London (2001) | (Schmöcker et al., 2005) |
| | Trip distance | Distances travelled (person-kilometers) | Canadian urban centers (2001/2003) | (Morency et al., 2011) |
| | Duration of regular trips/commuting time | Time use of mobility, commuting time | UK (2008) | (McQuaid and Chen, 2012) |
| **Accessibility** | Accessibility index of employment opportunities | | Boston inner city (1990) | (Shen, 1998) |
| | Synthetic index of adequate service | Access to public transport (incl. expenditure, walking distance to the nerest stop, average travelling time and headway, reliability of service, security and safety) | Brazilian cities | (Gomide et al., 2005) |
| | Transport disadvantage | Availability/lack of public transport options | Melbourne | (Currie et al., 2010) |

| | | | | |
|---|---|---|---|---|
| | Rural activity spaces | Transport activity spaces | Northern Ireland | (Kamruzzaman and Hine, 2012) |
| | Accessibility of services | Modelled travel times to key services (e.g. hospital, education) | England | (Department for Transport, 2014) |
| | Transit access to employment | Locations access by transit and car | Canada | (Allen and Farber, 2019) |
| | Spatial Accessibility Poverty | | North-east Brazil | (Benevenuto and Caulfield, 2020) |
| | Rural Access Index (from surveys / geospatial) | Accessibility of adequate roads from households | 183 countries, different years 1993-2019 | (Worldbank et al., 2016) |
| | Travel time to urban centers | Time to reach the closest urban center by any mode of transport | Globally, 2015 | (Nelson et al., 2019) |
| **Composite measures** | Composite risk of transport poverty | Income, distance to nearest bus/railway station, time to access essential goods and services by walking, cycling or public transport | UK | (Sustrans, 2012) |
| | Composite measure of financial resources, practices and conditions of mobility | Income level, fuel spending, extra travel time in public transport, car use restriction, total average distance travelled, availability of alternative mobility modes, vehicle performance and availability | France | (Berry et al., 2016) |

What is clear from the literature, is that the majority of countries worldwide has not achieved sufficient mobility levels for all population groups. Kikstra et al. (2021) identify the largest part of energy needed to reach 'Decent Living Standards' (DLS) that cover all basic needs globally to be needed in the mobility sector, when measuring person-kilometers travelled. Lucas et al. (2016) estimate that between 10 and 90% of households worldwide across many countries are affected by 'transport poverty', by applying the multi-dimensional conceptualization of sufficient mobility. Mobility conditions and behaviour of lower and higher income populations are differentiated in almost every country, as the poorest groups tend to have fewer transport options and quality of services (Barter, 1999), which makes the question of DMS globally relevant.

## Towards a stock-flow consistent conceptualization of decent mobility standards

We believe that the definition of decent mobility standards should encompass all relevant factors to fulfil the basic need of mobility, which means all need satisfiers, including infrastructure, that are needed in each specific context to guarantee sufficient mobility to reach essential services and participation at all times necessary. Following Lucas et al. (2016), this means that (1) relevant basic services such as healthcare, educational or grocery shopping facilities, have to be accessible with reasonable time and effort (2) the mobility options to reach them have to be available and affordable and (3) the conditions of travelling have to be rather 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. While need satisfiers or functions of mobility can be measured, the measurability deteriorates with closeness to the actual contribution to wellbeing (Kalt et al., 2019). The influence of individual and context-specific factors inhibits defining a measurable level of decent mobility that is equal for everyone globally. As it has been shown for other emission drivers (Baiocchi et al., 2015), we expect settlement types and the specific context, such as urban form (Newman and Kenworthy, 1996; Wiedenhofer et al., 2018, 2013) and socio-economic factors to play an important role in defining how much mobility is needed by the individual. As the distribution of key services vary between and within different countries and regions and mobility services are related to access to products or services (including health care etc.) and participation in social life (family, friends, education, work life, etc.), it depends also on the 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.

We identify the following entry points for a stock-flow-consistent conceptualization along the distinction of functions and services as well as short- medium- and long-term stock-flow-relations. Firstly, the differentiation between mobility functions (distances travelled) and services (what is actually wanted from mobility) are expected to have different relations to mobility stocks (infrastructure) and flows (fuel and electricity). Secondly, we expect a change of use intensity at different developmental stages.

Our derived hypothesis puts the relation of mobility output and mobility stocks and flows (use intensity) into focus and is illustrated in Figure 1. Increasing mobility functions (distances travelled) more or less linearly increase energy use, except for efficiency gains and shifts between mobility modes (see Figure 1a). With increasing mobility functions, also infrastructure stocks have to grow. People adapt their lifestyles to existing mobility systems and more favorable arrangements, regulations and infrastructures are created, which stabilize the system (Geels, 2005). With rising concerns about congestion, slowly more mobility stocks is created, which then increases the mobility activity in a dynamic of unintentional structuration (Mattioli, 2016). In the past, infrastructural improvements have provided access to more distant destinations and thus increased mobility functions, while the total time used for mobility had more or less stagnated, more distant, but not necessarily better destinations could be accessed. At some point, the increase in travelled distances is to become relatively smaller than the increase in mobility stocks, when 'peak travel' is approached as it has happened in eight industrialized countries already (Millard-Ball and Schipper, 2011)

If mobility services instead of functions are put into focus (Figure 1b) we expect a different relation to stocks and flows. We project the relation of mobility infrastructure and service provision levels to be non-linear. When mobility stocks are being built up, services can only slowly increase. After reaching a certain threshold of 'sufficient' infrastructure stocks, use intensity can increase further and decouple relatively from infrastructure stock growth and the improved connections offered by the mobility system offer better service provision. At a certain point, when the mobility system is well developed and extensive enough, enough mobility services are provided and the additional services provided by any further increase in mobility stocks diminish, in a dynamic which has been observed also for other examples of resource use and social outcome (O'Neill et al., 2018) or for energy demand or carbon emissions and well-being (Jorgenson, 2014; Lamb et al., 2014; Steinberger and Roberts, 2010).

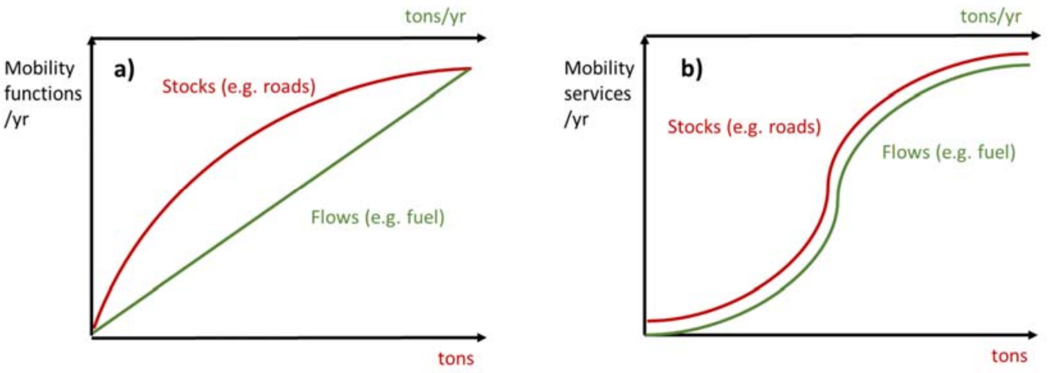

**Figure 1: Hypothesized relations of mobility infrastructure stocks and flows for mobility and mobility functions (a) in contrast to mobility services (b)**

# Empirical exploration

## Stock-function relations

As travelled distances are the most common measure for mobility and the indicator with the best data availability, we focus the first part of empirical explorations on the relationship of travelled distances and mobility stocks by using a cross-sectional international analysis.
Currently, the Open Street Map (OSM) database is considered as the most complete data source of mobility infrastructure. Building up on this data, (Wiedenhofer et al., in prep.) have provided a first global mobility stock assessment using stock-driven material flow analysis. In this dataset, the current mass (2020) of different stock types (railways, subways, other light rails, roads of the types motorway, primary, secondary, tertiary, local and urban road and airport runways) has been quantified. Data about travelled distances are available mostly for industrialized countries, in different periods from (European Commission, 2020; ICCT, 2017; ITF, 2021; Worldbank/UIC, 2021). Data cleaning had to be done, some unrealistically high or low values had to be replaced by national sources (Ministry of Transport, 2020) or excluded entirely, if no other reliable source was available. The most recent datapoint after 2015 has been used and some data cleaning was necessary to prepare a usable dataset of current mobility levels measured in distances.

The correlation of road stocks (r=0.98) and rail stocks (r=0.74) and p-km is rather strong. Also, regression analyses achieve a high fit (total $R^2 = 0.92$, road $R^2 = 0.90$, rail $R^2 = 0.69$) (see Figure 2). This supports the assumption that the development of mobility stocks and mobility activity are strongly intertwined, due to widespread 'predict and provide' approaches in transport planning or unintentional structuration. Total mobility levels are of course also influenced by the size of the country, both in terms of area and population, and even stronger is the influence of GDP (roads r=0.98, rails r=0.58).

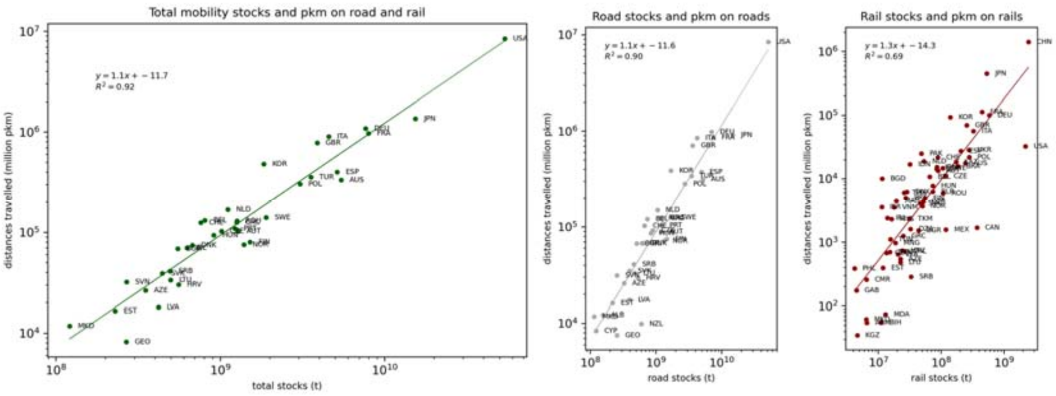

**Figure 2: Regression for total stocks, road stocks and rail stocks with person-kilometers travelled. Note: log-log-scale.**

For testing the hypothesis, we used per capita values for both stocks and mobility functions to exclude the influence of area and population size of countries. The correlation is a lot weaker per capita (roads: r=0.50, rails: r=0.43) but still exists. Polynomial regressions achieved a higher fit than linear regressions, although overall not very high (total $R^2 = 0.350$, road $R^2 = 0.297$, rail $R^2 = 0.196$) (see Figure 3). Only some outlier countries have very large mobility levels person on average, regardless of the mass of mobility stock, for example the US on roads and Japan on rails. For rails, the stock density on potential settlement area also shows a high correlation (r=0.75) in contrast to roads (r=0.13). A possible explanation could be that rail connections improve with stock density, thus become more attractive as a mobility mode and get used more frequently probably as well, whereas roads have to be used also to get to less well-connected destinations.

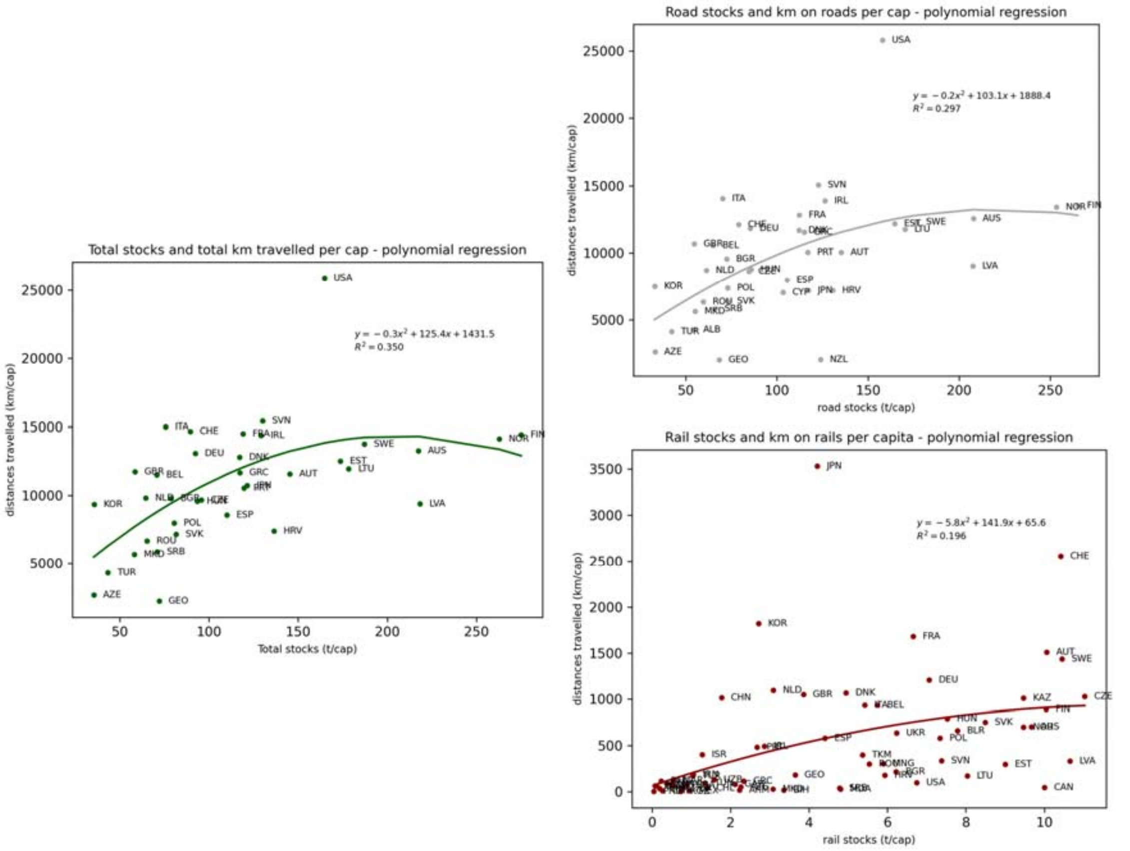

**Figure 3: Polynomial regression for total stocks, road stocks and rail stocks per capita with person-kilometers travelled per capita.**

The hypothesized relationship of mobility stocks and mobility functions could not be tested entirely in the cross-sectional analysis, as data for countries with very low stock and mobility levels is not available and mostly industrialized countries could be analyzed. The relationship at later developmental stages of mobility systems does show the expected concave form, that is the slowing of mobility function increase with growing stocks, but the goodness of fit is not very high.

## Stock-function levels and social wellbeing

To tackle the open question of levels of decent mobility and corresponding mobility stock levels, we used different measures of mobility deprivation, human development, social progress to see the relationship between mobility stock levels and reaching certain development thresholds.

Comparing stock levels for regions with estimates of mobility deprivation (Kikstra et al., 2021), (see Figure 4), suggests that current mobility stock levels even in wealthier regions are below sufficiency levels. These results, however, have to be interpreted vis a vis assumed inequality within the different regions, which is considered in the DMS deprivation estimates. Even though mobility stocks per average capita might be high, the distribution of benefits between social groups can be inequal to a degree, that leaves a high percentage of the population below decent mobility.

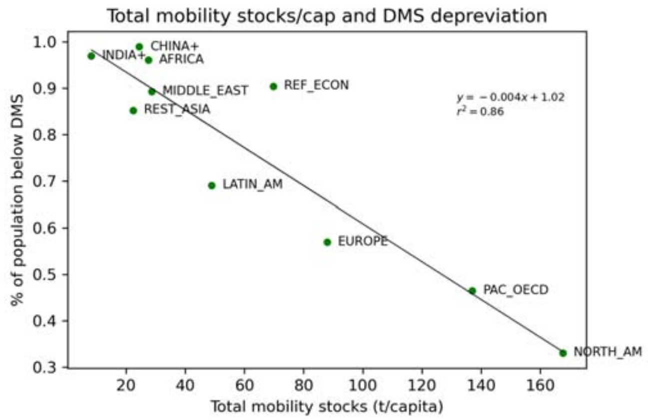

**Figure 4: Mobility stocks (t/cap) and share of population that lives below decent levels of mobility as defined by (Kikstra et al., 2021), grouped by regions.**

Measuring social progress or wellbeing in general is not straightforward. GDP, which is most commonly used to express a development stage, is actually limited in its validity to represent social progress (Stiglitz et al., 2009). In order to make the stock and mobility level per capita visible at different developmental stages, three different indicators of social progress have been used to cluster countries: the Human Development Index (UNDP, 2020b), the social foundation of the Doughnut framework based on the analysis of government submissions to the Rio+20 conference (O'Neill et al., 2018; Raworth, 2012) and the UN Sustainable Development Goals (United Nations, 2020).

Figure 5 depicts mobility stocks and distances per capita by social objectives. We group the countries by the number of social thresholds used in the Doughnut framework they have reached. In the group of countries, that have surpassed at least 9 out of the 11 social thresholds, the lowest observed road stock level is 61.4 t/cap and the lowest observed rail stock level is 2.9 t/cap. In this group, the lowest mobility levels lie at 7,189 km/cap on roads and 45 km/cap by rail.

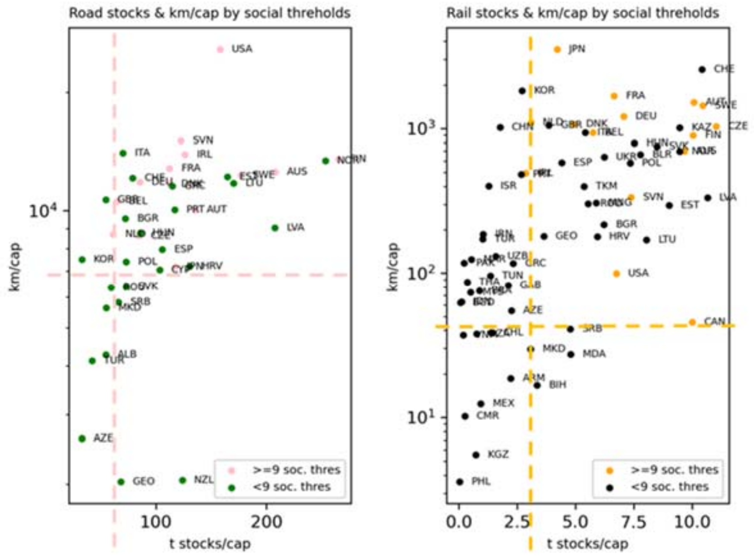

**Figure 5: Road (left) and rail (right) stocks (t/cap) and distances travelled (km/cap) for countries according to their passing of social thresholds (O'Neill et al. 2018). Dashed lines indicate the position of the country with the minimum stock/capita (x-axis), respectively distance travelled/capita (y-axis, note: log-scale) that reach 9 or more social thresholds.**

Figure 6 shows mobility stocks and distances per capita for countries that have reached a certain percentage of the SDGs. We introduce thresholds of 70% and 80% and group the countries accordingly. In the group of countries with >80% of SDGs reached, the lowest observed road stock level is 61.3 t/cap and the lowest observed rail stock level is 2.9 t/cap. The lowest mobility levels within this group are 7,201 km/cap on roads and 180 km/cap by rail.

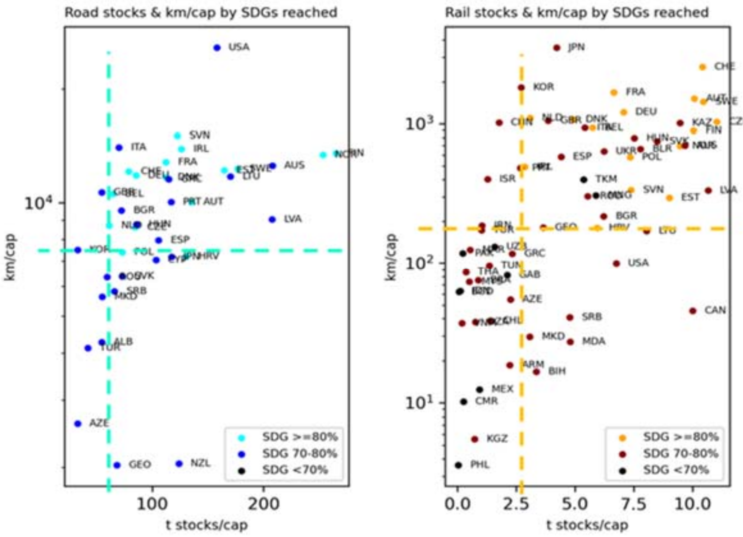

**Figure 6: Road (left) and rail (right) stocks (t/cap) and distances travelled (km/cap) for countries according to their reaching SDGs. Dashed lines indicate the position of the country with the minimum stock/capita (x-axis), respectively distance travelled/capita (y-axis, note: log-scale) that have fulfilled 80% or more of SDGs.**

Figure 7 displays mobility stocks and distances per capita for countries that have reached a certain threshold of human development as expressed in the 'Human Development Index' (HDI). We separate countries with an HDI above 0.7 (high development) and countries with and HDI above 0.8 (very high development). In the group of countries with HDI >= 0.8, the lowest observed road stock level is 32.9 t/cap and the lowest observed rail stock level is 0.5 t/cap. Lowest mobility levels lie at 2,045 km/cap on roads in New Zealand, which is a data outlier and an island, the next lowest mobility levels are observed in Turkey with 4,125 km/cap. The lowest mobility by rail lies at 38 km/cap.

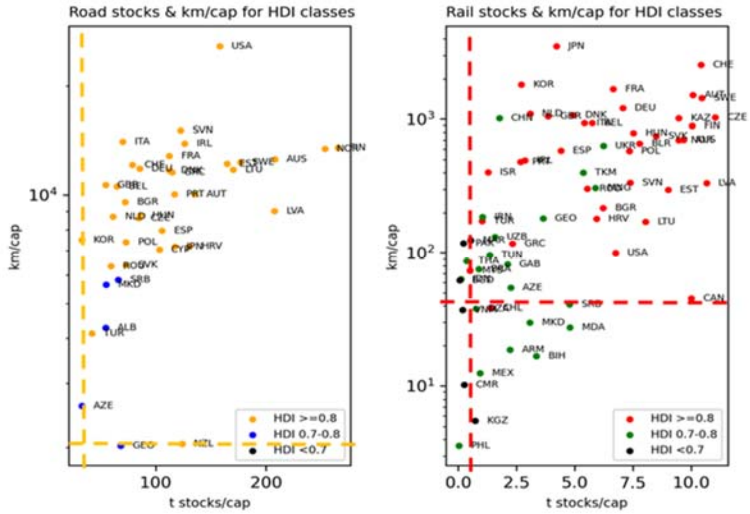

**Figure 7: Road (left) and rail (right) stocks (t/cap) and distances travelled (km/cap) for countries according to their stage of human development (HDI). Dashed lines indicate the position of the country with the minimum stock/capita (x-axis), respectively distance travelled/capita (y-axis, note: log-scale) that achieve an HDI of >= 0.8.**

Table 2 summarizes the minimum stock levels and minimum mobility levels for each group of countries reaching certain development thresholds. We see that minimum stock levels range between 33 and 61 t/cap for roads and between 0.04 and 2.9 t/cap for rails. Lowest mobility levels within the group of countries reaching the development thresholds range between 2,025 km/cap on roads and between 4 and 180 km/cap on rails. The stock intensity varies between 4.4 and 9.8 kg road stock/p-km and 1.2 to 2.8 kg of rail stock/p-km travelled.

**Table 2: Minimum mobility stock (t/cap), minimum travel distances (km/cap) and minimum stock intensity of mobility (t stock/p-km) per group of countries according to HDI (Human Development Index), social thresholds reached and % of SDGs reached for road and rail-based mobility.**

| | **Stock level (t stock/cap)** | **Mobility level (km/cap)** | **Stock intensity of mobility (kg stock/p-km)** |
|---|---|---|---|
| | | **Roads** | |
| HDI >= 0.8 | KOR=32.9 | NZL=2,045 / TUR=4,125 | KOR=4.4 |
| HDI >= 0.7 | AZE=33.1 | GEO=2,025 | MKD=9.8 |
| > 9 social thresholds (Raworth/O'Neill) | NLD=61.4 | JPN=7,189 | USA=6.1 |
| > 80% of SDGs | NLD=61.3 | HRV=7,201 | BEL=6.1 |
| > 70% of SDGs | KOR=32.9 | GEO=2,025 | KOR=4.4 |
| | | **Rails** | |
| HDI >= 0.8 | MYS=0.5 | CHL=38 | JPN=1.2 |
| HDI >= 0.7 | PHL=0.04 | PHL=4 | CHN=1.7 |
| > 9 social thresholds (Raworth/O'Neill) | IRL=2.9 | CAN=45 | JPN=1.2 |
| > 80% of SDGs | IRL=2.9 | HRV=180 | NLD=2.8 |
| > 70% of SDGs | VNM=0.2 | KGZ=6 | JPN=1.2 |

## Stocks and accessibility

Decent mobility requires access to adequate mobility options, this means mobility options have to be available within a certain distance from each person's home (Rao and Min, 2018b). Mobility infrastructure shapes potential transport routes and therefore comprises a basic factor of accessibility. The analysis of stocks and accessibility measures seems promising, as we expect a higher correlation between those parameters than with actual mobility activity. As discussed, several prerequisites have to be fulfilled to reach adequate mobility levels, and some of them are not or only indirectly related to infrastructure stocks, such as affordability or the access to motorized transport, which is not the case for accessibility. We analyze two different accessibility measures. First, the accessibility of road infrastructure from people's homes, using the Rural Access Indicator (RAI), and second, the accessibility of urban centers, where many desired locations are assumed to be located, such as schools, workplaces or healthcare centers. Of course, the existence and density of these key activities, such as employment, educational or health facilities, is a crucial factor of need satisfaction. This general availability of services is not directly related to mobility infrastructure. To our knowledge, no data source containing the location of all relevant key services in different countries globally exists. However, as a proxy the location and accessibility of urban centers can be used, as we expect most services to be located in settlements of at least 5,000 inhabitants.

The Rural Access Index (RAI) measures accessibility of adequate roads from households (Roberts et al., 2006). There are two versions of the Rural Access Index, a measure of households' access to roads in acceptable quality: one derived from surveys and one assessed with geospatial analysis. Both express the percentage of households, that can reach a road of good or fair quality within 2 km. Road conditions are described as good or fair, if at least a maintainable road with camber and drainage is available. As from surveys only very few and rather outdated datapoints are known, the geospatial version of the RAI was used. As displayed in Figure 8, countries with good accessibility levels (RAI>80) show different stock levels, depending on population density. Urbanization does not seem to have an impact on stock levels per capita.

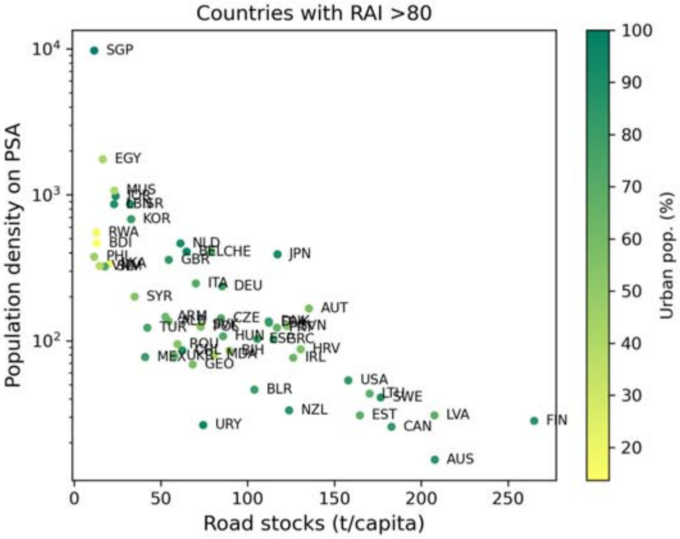

**Figure 8: Road stock (t/cap) and population density on PSA (potential settlement area) in countries with good accessibility levels (RAI>80). The color of the scatter dots indicates the % of urban population.**

A cross-sectional international exploration of accessibility of urban centers measured in travel times versus infrastructure levels (Nelson et al., 2019) using lowest thresholds for defining an urban area (>5,000 inhabitants) showed that average mobility stocks of roads and rails per capita do not influence the velocity of travelling into urban areas per average person. The average travel time is shorter, if population density is higher and also the relationship of stock levels per capita and population density is visible (see Figure 9).

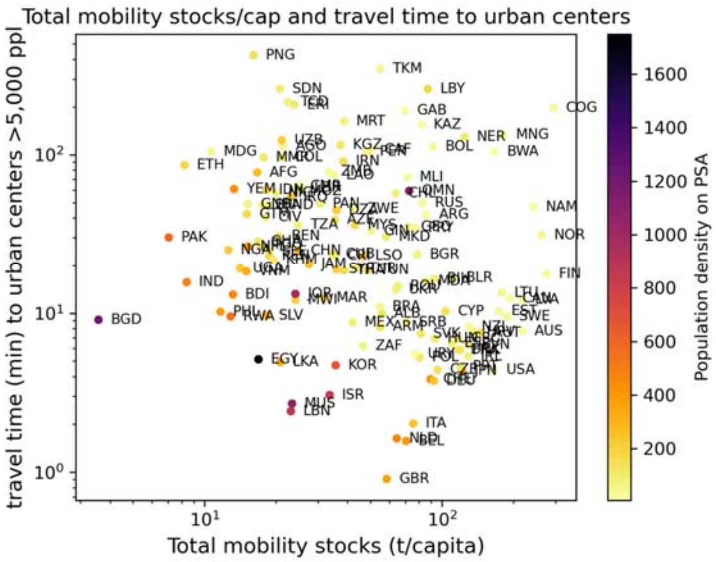

**Figure 9: Total mobility stocks (road & rail, t/capita) and travel time to urban centers with >5,000 inhabitants. The color of the scatter dots indicates population density on PSA (potential settlement area).**

## What are the relevant insights for defining ‘Decent Mobility Levels’?

In the cross-country analysis, a correlation of mobility stock levels of roads and rails and travelled distances has been confirmed. This supports previous findings of mobility stock and traffic volume developing jointly, because of planning of infrastructure after anticipated demand and unintended structuration processes. The hypothesized relation between mobility functions and mobility stocks (Figure 1a) could partly be confirmed in the cross-sectional analysis. There is a strong correlation between mobility infrastructure and mobility functions among the countries investigated, but data for countries with low mobility infrastructure stocks and distances travelled is not available. To investigate different developmental stages of mobility systems, also the analysis of stocks and distances travelled in a time series for different countries would be interesting. This, however, is not yet possible, as historical levels of mobility stock levels have not been explored so far. As the field of material stock analysis has only recently emerged and the global mobility stock has just been quantified for the first time, this is not feasible at this point of time. For investigating the hypothesized relationship to mobility services (Figure 1b) indicators that better displays the services of mobility are necessary, rather than just the function of travelled distances. As has been shown in the literature review, other measures are mostly available for specific aspects of mobility, i.e. affordability, and have been investigated mostly in case studies for small areas, but not on a national to global scale and many of the analyses have been conducted years or decades ago. Surprisingly, mobility stock levels per capita do not seem to influence accessibility of either road infrastructure or of urban centers, where a lot of desired services are anticipated. This finding could also be due to the inequal distribution of mobility infrastructure and its benefits within different nations.

The results of the different analyses suggest that there are more and stronger influencing factors on mobility activity (at least in terms of distances travelled) than mobility stock provision. GDP and population density on potential settlement area have been proven relevant and there might be more factors involved that could not have been analyzed. The investigation of historic development of stocks, their spatial distribution, political factors, affordability of transport options, the spatial spread of relevant services and cultural factors vis a vis mobility stock levels is a promising field for future research. It has been shown that the poorest groups do not equally benefit from transport infrastructures as higher income groups, for issues of accessibility or affordability (Lucas et al., 2016; Starkey and Hine, 2014). A separate focus on stock-service links for different income groups is therefore another important issue.

Analyzing stock levels and mobility function levels in countries that have reached certain development thresholds results in different minimum levels of observed stock and travelled distances. The lowest mobility levels observed in groups of countries with rather high human development, social progress or high achievement in SDGs range far below what is defined as a decent standard in the DLS framework. However, the distribution of benefits among different individuals is important and could not be considered within this analysis due to a lack of comparable mobility data at sub-national level. The lowest mobility stock levels among countries with high development of 32-61 t of road stock/cap and 0.1-2.9 t of rail stock/cap are not even reached by half of the countries globally. The lower 50% of countries investigated reach only 42 t/cap of road stocks and 0.9 t/cap of rail stocks. Reaching decent mobility thresholds according to the DLS framework seems to need an even higher average level of stocks/cap, which is not reached by most countries. Here, the inequal distribution of mobility benefits plays an important role.

The definition of a decent mobility standard and an accordingly decent mobility infrastructure level is not possible on a general level, as many individual factors and spatial arrangements (distribution of services, settlement type) play an important role. Decent mobility standards vary between regions, settlement types and individual situations. Established measures, however, provide a first important orientation to understand minimum requirements. Lucas et al. (2016) concludes in his review, that transport poverty is “extremely under-explored”. Data gaps exist and more measures are needed to make a step further. This is also true for assessing mobility standards and their sufficiency globally. More detailed but globally comparable information about mobility activity, relevant individual characteristics and settlement types would be necessary to assess mobility levels of different regions and groups. The decision of how much is sufficient is in the end a normative one and different approaches of how to define that level have been discussed. However, this analysis could deliver a first orientation for mobility and mobility infrastructure levels at different stages of development, which hopefully serves as a first step for future research in this field.

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