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The urbanisation-environment conflict: insights from material stock and productivity of transport infrastructure in Hanoi, Vietnam

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Keywords

material stock indicator; resource management; material flow analysis; material efficiency; developing countries; urban planning

Abstract

Developing regions experience rapid population growth and urbanisation, which require large quantities of materials for civil infrastructure. The production of construction materials, especially for urban transport systems, however, contributes to local and global environmental change. Political agendas may overlook the environmental implications of urban expansion, as economic growth tends to be prioritised. While elevating the standard of living is imperative, decision-making without careful environmental assessments can undermine the overall welfare of society. In this study, we evaluate the material demand and in-use stock productivity for the large-scale development plan for transport infrastructure in the city of Hanoi, Vietnam, from 2010 to 2030, combining geospatial and socioeconomic data with statistics on roads and railways. The results show that the total material stock could rise threefold from 66 Tg in 2010 to 269 Tg in 2030, which roughly translates to an addition of 30 Empire State Buildings per year by mass. The materials we account are required for construction exceed the availability of local sand and will need to be gathered farther away. Furthermore, the material stock productivity of the transport infrastructure appears to have been declining overall since 2010, and this trend may continue to 2030. These findings demonstrate the importance of informing urban planning with a comprehensive assessment of construction materials demand, supply capacity, and environmental impacts. Policy priorities for improving the in-use stock productivity are also recommended towards achieving a more efficient utilisation of natural resources.

1. Introduction

Economies require continuous flows of materials to sustain themselves and to develop (Haberl et al., 2017; O'Neill et al., 2018). At the basic level, these materials can be categorised as minerals, fossil fuels, and biomass (Brunner and Rechberger, 2003; Eurostat, 2018). It can thus be said that natural resources are the foundation of economic development (Swilling, 2011; Chen and Graedel, 2015; Fishman et al., 2015). The extraction and transformation of natural resources, however, pose numerous environmental issues such as ecosystem degradation and global climate change (Steffen et al., 2015; Torres et al., 2017). These problems are amplified by the accumulation of materials as physical stocks in the technosphere and their eventual ejection from the technosphere back to the biosphere as wastes and emissions (Brunner, 2004; Hashimoto et al., 2007; Pauliuk and Müller, 2014; Haas et al., 2020). Recognising such challenges, recent global policies have placed the sustainable consumption and production of goods and services at a high priority (Hertwich et al., 2019; Oberle et al., 2019; Hickel and Kallis, 2020).

In the 2030 Agenda for Sustainable Development (Colglazier, 2015), the objectives of sustainable resource consumption, resource efficiency, and waste minimisation (e.g., the 3Rs—reduce, reuse, recycle), together with other interconnected objectives, compose the Sustainable Development Goals (SDGs). The more efficient use of materials promoted by the SDGs can be achieved, for example, by designing products that use fewer materials, extending the functional lifetime of materials, and increasing material recovery (Creutzig et al., 2018; Krausmann et al., 2020)—approaches that are in line with the principles of the circular economy (Stahel, 2016). Material efficiency can be a challenge for developing countries because extensive economic development often requires large quantities of raw materials for the enhancement of infrastructure and the built environment (Martinico-Perez et al., 2018). While the goals of resource efficiency and economic growth may appear at odds with one another, the policies for promoting resource efficiency and circular economy by the European Union maintain that increasing ‘material productivity’ can simultaneously improve national competitiveness and alleviate environmental pressures (Intergovernmental Panel on Climate Change, 2014; European Commission, 2015; Flachenecker, 2018).

One tool that can help decision-makers meet such goals is materials accounting, which could elucidate the interactions between material use, economic activity, social changes, and the environment (Haberl et al., 2019; Haberl et al., 2020). Material accounting has shown that the growth in global material use has accelerated over the past four decades (Krausmann et al., 2017), and projections to 2030 suggest that this trend will likely continue (Fishman et al., 2016). However, this growth has not been globally uniform (Schaffartzik et al., 2019; Oswald et al., 2020), and the total quantity of materials consumed in the Asia-Pacific region exceeds that in any other region (Schandl et al., 2018). From 1970 to 2010, Asia and the Pacific increased its share of global material use from around 25% in 1970 to above 50% in 2010 (Schandl and West, 2010; Schandl et al., 2018).

While balancing economic growth and environmental quality is a critical challenge, especially for emerging markets, there has been a limited number of material consumption studies for developing countries. The majority of such studies have been carried out for developed nations, such as EU members (Eurostat, 2019), the United States (Gierlinger and Krausmann, 2012), and Japan (Krausmann et al., 2011), and other large resource consumers such as China (Schandl and West, 2012; Wang et al., 2012). Apart from China, material consumption research has been conducted for only a few developing nations, namely Bangladesh (Maung et al., 2015), Laos (Vilaysouk et al., 2019), Myanmar (Maung et al., 2015), the Philippines

(Chiu et al., 2017; Martinico-Perez et al., 2017), and Uzbekistan (Raupova et al., 2014). This gap in knowledge stems mostly from limitations in data availability, data reliability, and capacity of national statistical offices (Buenrostro et al., 2001; Moreno-Camacho et al., 2019). More studies on developing countries are necessary to effectively address climate change and other issues, as developing regions have recently been experiencing large growths in material consumption and population (Schandl et al., 2018), and material stocks create lock-in scenarios (Reyna and Chester, 2015; Seto et al., 2016).

Material accounting studies in recent years have increasingly been investigating the material stocks of the built environment. Some studies collectively examined all infrastructure that forms cities (Huang et al., 2017; Gontia et al., 2019), while others focused on specific types, such as residential buildings (Heeren and Hellweg, 2019; Romero Perez de Tudela et al., 2020), non-residential buildings (Ortlepp et al., 2016), and others (Guo et al., 2014; Miatto et al., 2017) (a recent review of research on material stocks in the context of the built environment was provided by Lanau et al. (2019)). Two components of the built environment, road and rail infrastructures, are crucial to urban functionality and economic activity (Démurger, 2001; Palei, 2015). Infrastructure is highly linked to the attainment of the SDGs (Thacker et al., 2019), and is projected to grow at least until 2050 (Meijer et al., 2018). Yet, road and railway systems have been understudied relative to buildings from a material stock perspective, apart from a few studies (Tanikawa and Hashimoto, 2009; Quinn and Fernández, 2010; Guo et al., 2014; Wang et al., 2016; Meijer et al., 2018).

To improve the understanding of material efficiency and requirements of developing countries, in particular the Asia and the Pacific region, this study examines the past, current, and future material stock and productivity for the road and railway systems of Hanoi, the capital of Vietnam, for a planned urban infrastructure expansion. We established a city-scale geographic information system (GIS) database of roads and railways to characterise their total length and spatial distribution at each time-point by type of road or railway. By combining this data with information on the designs and traffic volumes of roads and railways and data on economic output, we analyse the infrastructure's total material stock, stock by material composition, and material productivity. Finally, we provide policy recommendations for rapidly developing countries and cities for establishing an environmentally sustainable and productive transport infrastructure from the viewpoint of material extraction and use.

2. Study Site

This study focuses on the transport infrastructure of Hanoi, Vietnam. Vietnam is a rapidly developing economy in the Asia-Pacific region that has been increasing its domestic material consumption at a rate almost three times the average of countries at similar levels of development (UNEP, 2016). To ease the pressure of development, in 2012, the Vietnamese government approved the National Green Growth Strategy, which promotes economically productive infrastructure, clean energy technologies, and climate change mitigation, among other goals (Meessen et al., 2015). For the success of this strategy, improving the understanding of trends in material use at the national and city levels is important.

As the capital of Vietnam, Hanoi serves an important transport hub for the country and its economy. The transport system of the city is characterised by railways and a dense road network which has been continuously invested in and expanded, connecting Hanoi with neighbouring provinces, for intra- and inter-provincial freight and passenger transport. Main radial roads include eight national highways as well as Thang Long-Noi Bai and Lang-Hoa Lac expressways, which also connect Hanoi with satellite urban areas of the Greater Hanoi area. The rail system currently consists of two mass rapid transit (MRT) lines and five main radial national lines. The total lengths of existing roads and railways (including urban MRT lines and stations) are estimated at 6,542 km and 215 km, respectively.

Like many cities in developing countries in the Asia-Pacific region, Hanoi is increasingly faced with challenges as a result of rapid urbanisation. For example, the number of registered cars in Hanoi has increased nearly fivefold (486%) over the last 10 years (Vietnam Register and Hanoi City Public Security, 2017), leading to severe traffic congestion and air pollution. To cope with the issue, in 2016, Vietnam's Prime Minister ratified Decision No.: 519/QD-TTg, "Transportation Planning of Hanoi Capital by 2030, with a Vision to 2050", hereafter referred to as the "Master Plan" (Socialist Republic of Vietnam, 2016). Infrastructure upgrades outlined by the Master Plan include a series of urban expressways and national highways that will connect the city centre with new peripheral urban areas planned to be built by 2030. The Master Plan includes a section outlining the necessary environmental assessments, including material consumption and waste disposal required by the plan. However, there has been no detailed quantification of the material requirements of the proposed infrastructure.

Several studies have examined Vietnam's transport system (Tuan and Mateo-Babiano, 2013; Tuan and Son, 2015; Nguyen, T.C. et al., 2019; Schiller et al., 2020), but the study of its material consumption has been limited to the national level (Nguyen, T.C. et al., 2019) or regional (Schiller et al., 2020). Most studies on the transport system focused on the formulation of the National Transport Development Strategy for Vietnam (ALMEC Corporation et al., 2000), which includes the development of a rapid bus transit system (World Bank, 2007), high-level strategies for a transport system considering multimodal transport (ALMEC Corporation et al., 2010), and a focus on transit-oriented development (Japan International Cooperation Agency and Hanoi People's Committee, 2015). To the best of our knowledge, our study is the first city-scale investigation of the material consumption for the planned transport infrastructure in Vietnam. National-scale analyses allow for a high-level understanding of material stocks and flows and can enable international comparisons. Urban-scale assessments, however, can provide the granular data necessary to formulate effective solutions for meeting objectives such as the SDGs (Graedel, 1999; Neuman and Smith, 2010; Kennedy et al., 2015).

3. Datasets & Methodology

The material stock and productivity of Hanoi's transportation infrastructure were quantified using socioeconomic data and design specifications, traffic volumes, and GIS data of roads and railways. Given data limitations, the analysis focuses on 2010 to 2016 and 2030, the year for which the Master Plan is laid out. The Master Plan does not provide cross-sectional construction plans for individual years before 2030. Current spatial data of roads and railways in Vietnam for calculating their lengths were obtained from OpenStreetMap (Geofabrik, 2018), an editable map of the world providing (primarily) open access to underlying map data to promote innovation. Additional information on road and railway characteristics were acquired from the Department of Transport of the Hanoi People's Committee (2016). This data contained information on the roads' location, ownership (municipality or national government), length, width, first year in service, and last maintenance, along with similar statistical data on railways: name, starting point, end point, type, gauge, sleeper type, rail type, fastening devices, and the management company (Hanoi People's Committee, 2016). Furthermore, annual socioeconomic data for the city were obtained from the Hanoi Statistical Office (2016), including data on population, gross regional domestic product (GRDP), administrative area, and volumes of passengers and freight transport. The forecast data used for making the projections of material stock were obtained from the Master Plan (Socialist Republic of Vietnam, 2016) and the Hanoi Capital Construction Master Plan (not to be confused with the transport "Master Plan") (City of Hanoi, 2010) as well as other reports (ALMEC Corporation et al., 2000; World Bank, 2007; ALMEC Corporation et al., 2010; Japan International Cooperation Agency and Hanoi People's Committee, 2015). The socioeconomic data used in our study can be retrieved in the Supplementary Information.

3.1 Material stocks in roads and railways

Based on the outlined data, this study applied a bottom-up accounting method to estimate the total in-use stock of materials in the existing road and railway networks of the study area, as shown in Figure 1. For years 2010 to 2016, the lengths of roads and railways were quantified in ArcGIS by importing the free-of-charge shapefiles for roads and railways from OpenStreetMap (Geofabrik, 2018), and those values were validated against information from the Department of Transport of the Hanoi People's Committee (2016). The widths of roads and railways were obtained from the Department of Transport of the Hanoi People's Committee (2016). Details of the roads and railways planned for 2030 (e.g., location, length, and width) were primarily gathered from the Master Plan (Socialist Republic of Vietnam, 2016) and the Hanoi Capital Construction Master Plan (City of Hanoi, 2010). The planned infrastructure was manually drawn in ArcGIS to spatially reference it.

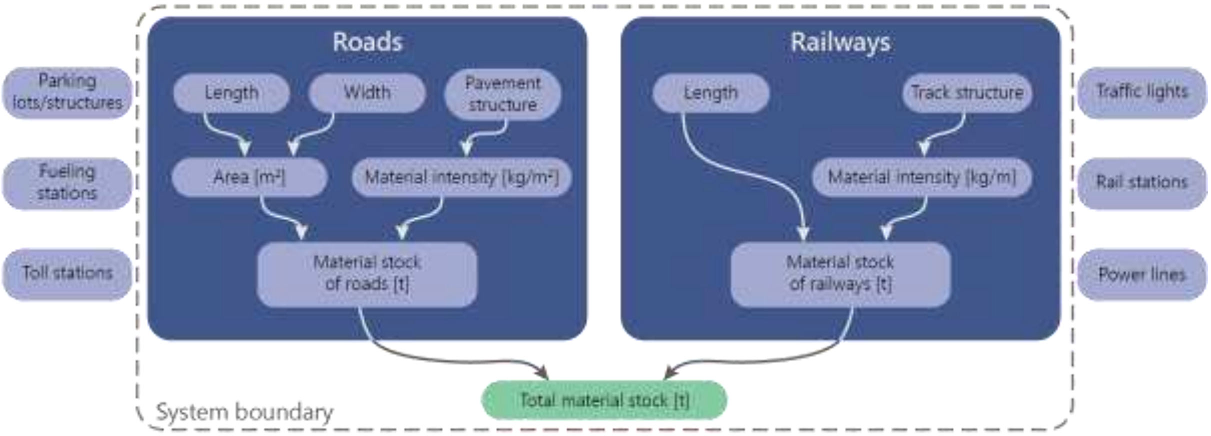

Figure 1 – Methodology to estimate the total material stock in the transportation infrastructure of Hanoi.

First, the total inventory of infrastructure was calculated in units of area for roads and length for railways (as the widths of railways are roughly uniform). Then, the total stock of materials (in mass units) for each mode of transport was appraised by multiplying the inventory of roads or railways with their material intensity factors, which are based on the specific classification of the road or railway. This process can be expressed by equation 1 for roads and equation 2 for railways:

$$MS\_road_{m,i,t} = \sum_{i,t} L_{i,t} * W_{i,t} * MI\_road_{m,i,t} \tag{1}$$

where:

MS_road is the total mass of the stock of material *m* in all items of type *i* in year *t*;
L is the total length (m) of road type *i* existing in year *t*;
W is the width (m) of road type *i* existing in year *t*;
MI_road is the material intensity (kg m^{-2}) of material *m* in a road of type *i* in accord with construction codes in year *t*.

And:

$$MS\_railway_{m,i,t} = \sum_{i,t} L_{i,t} * MI\_railway_{m,i,t} \tag{2}$$

where:

*MS*_railway is the total mass of the stock of material *m* in all items of type *i* in year *t*;
L is the total length (m) of railway type *i* existing in year *t*;
MI_railway is the material intensity (kg m^{-1}) of material *m* in a railway of type *i* in accord with construction codes in year *t*.

Roads were grouped into six categories: (1) national highways, (2) expressways, (3) urban arterials, (4) primary roads, (5) provincial roads, and (6) local roads (e.g., secondary streets, zonal streets, residential streets, branch roads, alleyways, and small rural roads). Railways were categorised broadly as urban or national, with further sub-classifications. The full classification of roads and railways, along with their material intensities are presented in Table 1. These categories and their material intensities were derived from the Vietnamese Ministry of Transport and Ministry of Construction's design specifications: TCVN 4054-2005 - Design Specifications of Highways (Vietnamese Standard, 2005), TCXDVN 104:2007 - Design Specifications of Urban Roads (Vietnamese Standard, 2007), QCVN 07-4: 2016/BXD - National Technical Regulations for Transport Infrastructure Works (Vietnamese Standard, 2016), and Construction Materials Norms 1776/BXD-VP and 1784/BXD-VP (Vietnamese Ministry of Construction, 2007a, b).

These regulations represent the minimum standards for material requirements. Actual construction may vary upon local soil characteristics, climate, and traffic conditions, and may employ materials that exceed minimum specifications, such as reinforced concrete in place of regular concrete in some urban roads. These variations in practices, however, are not systematically reported so are not accounted for in this study. Therefore, our results for material stocks are conservative estimates based on Vietnam's minimum construction standards. Uncertainty analysis is not included, owing to the lack of reliable information on the extent of deviations from construction standards in practice. The standard designs and material contents of roads and railways by classification in Hanoi are presented in the

Supplementary Information §3 and §4, along with a description of how to calculate material intensities for transport infrastructure (Supplementary Information §7).

Table 1 – Material intensity of roads and railways in Hanoi.

Material Intensity	Unit	Aggregate	Bitumen	Cement	Steel	Wood
Roads						
National highways / Expressways	kg m^{-2}	2,303	38			
Urban arterial	kg m^{-2}	2,085	17			
Primary / Provincial roads	kg m^{-2}	1,334	10			
Local roads	kg m^{-2}	648	7			
Concrete roads	kg m^{-2}	715	1	127		
Urban Railways						
Elevated structure	kg m^{-1}	9,280		2,421	241	
Underground structure	kg m^{-1}	21,282		2,776	241	
National Railways						
Single track 1000 mm, prestressed concrete sleeper	kg m^{-1}	2,243		45	92	
Single track 1000 mm, wooden sleeper	kg m^{-1}				92	113
Single mixed 1435 & 1000 mm, prestressed concrete sleeper	kg m^{-1}	2,901		87	135	
Single mixed 1435 & 1000 mm, wooden sleeper	kg m^{-1}				137	179
Double track 1435 mm, prestressed concrete sleeper	kg m^{-1}	5,803		173	212	

The material stocks in roads and railways were analysed by their total mass, material composition, classification type, and spatial distribution. We also examined a measure of the density of stocks in a given area (in this case, the jurisdictional boundary of Hanoi), referred to as spatial stock density. Ancillary facilities of roads and railways, such as fuelling stations and train stations, were not included in material stock calculations of this study (as shown in Figure 1). This omission stems from the lack of information on the distribution and average material content of such infrastructure. Also, the material intensities were assumed to be constant for future construction. While technological innovation or shifts in transportation modes may alter the material intensities over time, substantial changes in intensities appear unlikely over the next decade.

3.2 Material stock productivity

Resource productivity is a metric for the efficiency of material-use in relation to economic output and is generally defined as the ratio between Gross Domestic Product (GDP) and the domestic material consumption of a country, a region, or a smaller area in monetary units per tonne of material (Eurostat, 2018, 2019). The concept of resource productivity is illustrated in Figure 2. The main chart shows three scenarios for future material productivity: (1) if GDP per capita increases relative to material use per capita, material productivity increases (denoted by the green line); (2) if GDP per capita decreases relative to material use per capita, material productivity decreases (red line); and finally, (3) if GDP per capita does not change significantly relative to material use per capita, material productivity will remain at a similar level (yellow line). It is important to emphasize that material productivity is a *relative* measure between GDP and material use. It, therefore, does not indicate the increase or decrease in affluence or material use in absolute terms. Material productivity can increase even if material use per capita increases as long as affluence increases at a greater rate, which could lead to increased environmental degradation.

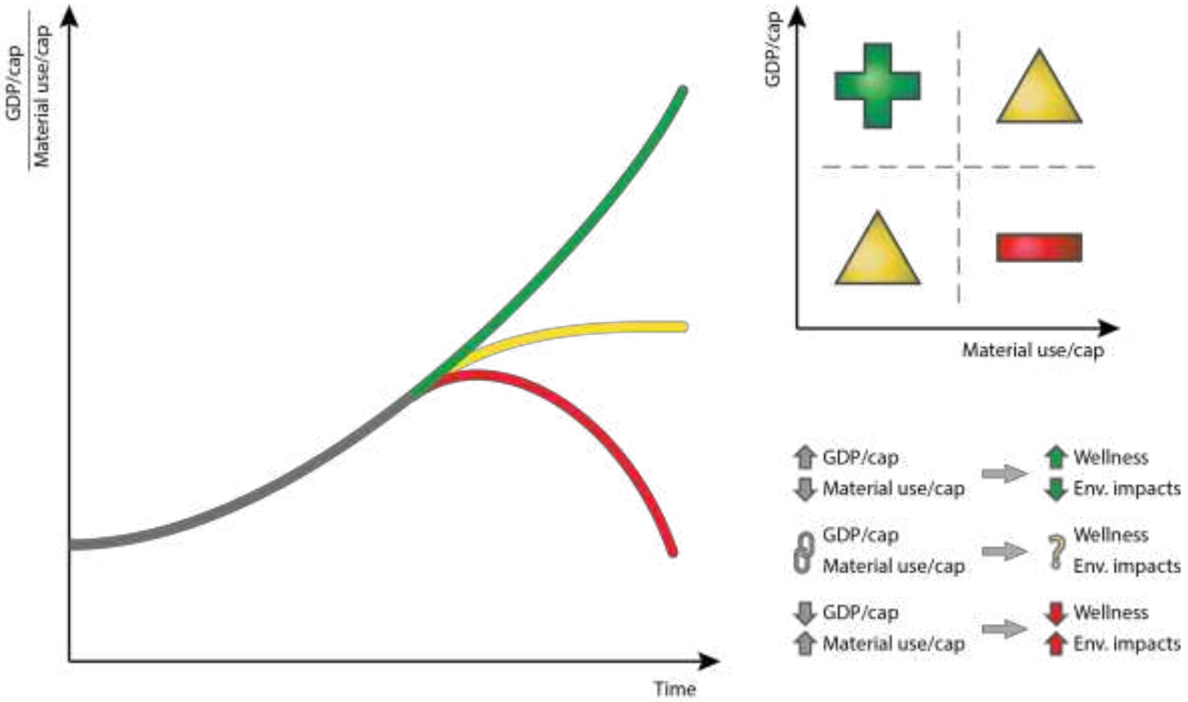

Figure 2 – Conceptual representation of material productivity. The green line denotes an increase in material productivity. The yellow line represents a constant material productivity. The red line represents a decrease in material productivity.

The subplot of Figure 2 further explains the relationship between material productivity, environmental impacts, and human well-being. Until a certain level of affluence is reached, an increase in GDP per capita (disregarding material use) is usually associated with an increase in well-being (Easterlin, 2015). In contrast, higher material consumption per capita results in lower societal well-being as a result of the associated increase in environmental degradation (O'Neill et al., 2018). It is important to note that material consumption in this context refers to *domestic* material consumption (i.e., the net material input to an economy). An economy with high levels of personal expenditure along with high rates of material recovery could support high levels of well-being.

Several studies have explored the topic of material productivity at various spatial scales and locations (Steinberger and Krausmann, 2011; Schandl and West, 2012). In our study, the stock productivity term is adapted and applied to an urban infrastructure context. GRDP is used instead of GDP for the urban-scale analysis and combined with the material stock in road and railway networks to examine the economic productivity of material-use by the transport sector (in U.S. dollars per tonne of material stock in 2010 constant dollars). As a metric, only using GRDP/tonne neglects the social dimension of improved mobility. Hence, the material stock is also compared with the passenger traffic (in passenger-kilometre) and freight traffic (in tonne-kilometre). Low stock productivity suggests that more transport service can be obtained from the in-use stock or that the material stock is excessive. On the other hand, high stock productivity means the material stock is used more efficiently or is overused. The study does not attempt to define an optimal stock productivity level, but instead provides an initial account of the efficiency of the in-use material stock at the subnational scale. In doing so, we also offer a point of reference for comparative studies in the future.

4. Results

4.1 Total material stock in roads and railways

The estimated material stock in Hanoi's roads and railways from 2010 to 2016 and those in 2030 following the Master Plan are presented in Figure 3A. In 2010, the combined stock in roads and railways was 65.6 Tg, of which 99% (64.8 Tg) was stored in roads and only 1% (0.8 Tg) was in railways. By 2016, the road stock had increased to 75.2 Tg, while the stock in railways had remained constant, reflecting the lack of investment in rail transport infrastructure. By 2030, the material stocks in roads and railways are estimated to increase to 260.0 Tg and 8.7 Tg, respectively, translating to a more than threefold increase in the combined stock (to 268.7 Tg) from 2016.

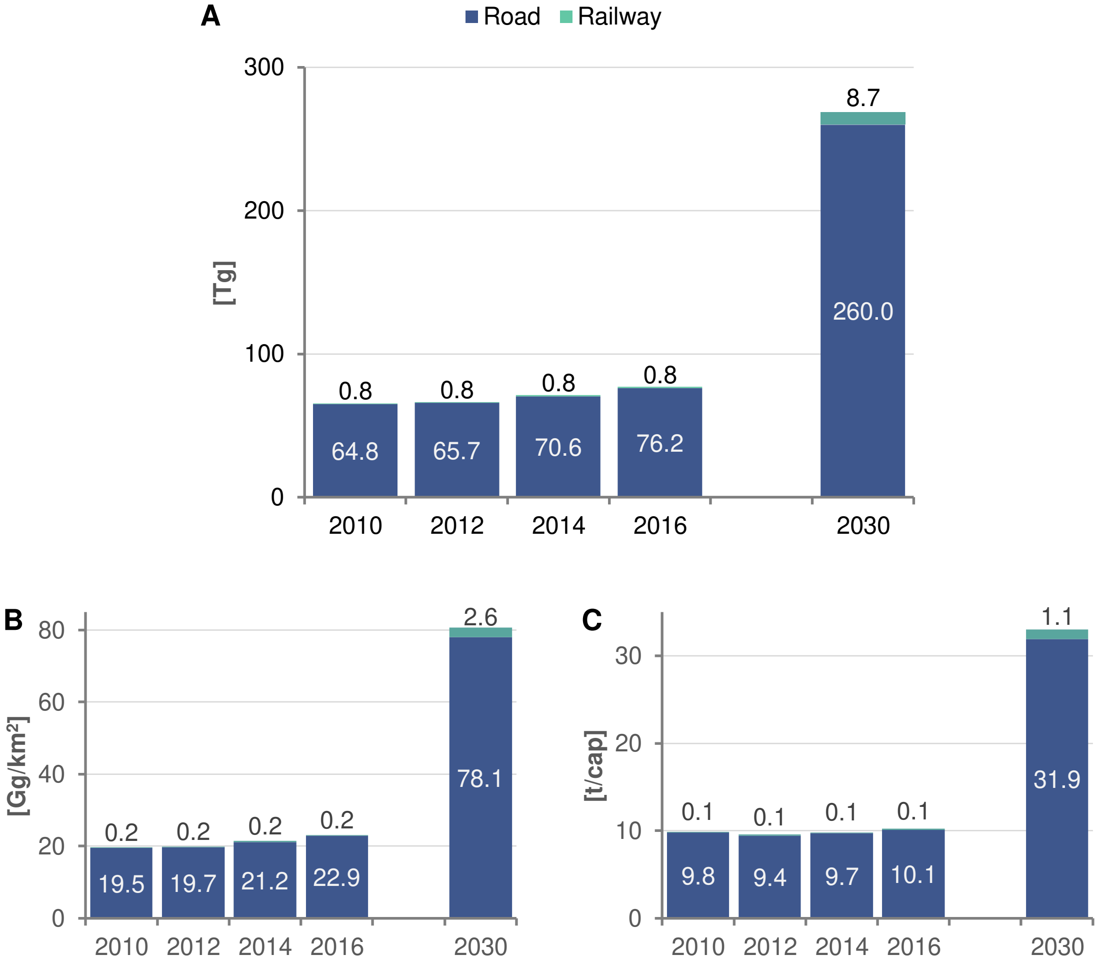

Figure 3 – A: total material stock in transportation infrastructure in Hanoi from 2010 to 2016 and estimated quantity in 2030 [unit: Tg = 10^{12} g = 10^6 t = Mt]]; B: material stock spatial density [unit: Gg km^{-2} = 10^9 g km^{-2} = 10^3 t km^{-2} = kt km^{-2}]; C: material stock per capita [unit: t capita^{-1}].

Figure 3B plots the spatial stock density, which has increased by 3.1 Gg km^{-2} from 2010 to 2016—equivalent to a compound annual growth rate (CARG) of 2.4%. The spatial stock density in 2030 is estimated to be 80.7 Gg km^{-2}, corresponding to a much higher CARG of

9.4% from 2016. The material stock per capita is graphed in Figure 3C. The results show an increase from 9.9 tonnes per capita (t capita^{-1}) in 2010 to 10.1 t capita^{-1} in 2016 (a 0.3% CARG). Similar to the trend in Figure 3B, the material stock per capita is projected to increase sharply, reaching 33.0 t capita^{-1} by 2030 (an 8.8% CARG from 2016 to 2030).

4.2 Spatial distribution of material stock

The expansion of the road stock from 2016 to 2030 is mapped in Figure 4. Many of the existing primary and secondary urban roads in inner districts are planned to be expanded with additional lanes (4 to 6) for vehicles and two lanes for motorcycles. The overall length of the road network will nearly double, from 6,542 km in 2016 to 11,776 km in 2030. Most of the roads will be constructed in the peripheral areas surrounding Hanoi's historical centre to better connect it with the most rapidly urbanising areas to the west and north of the city.

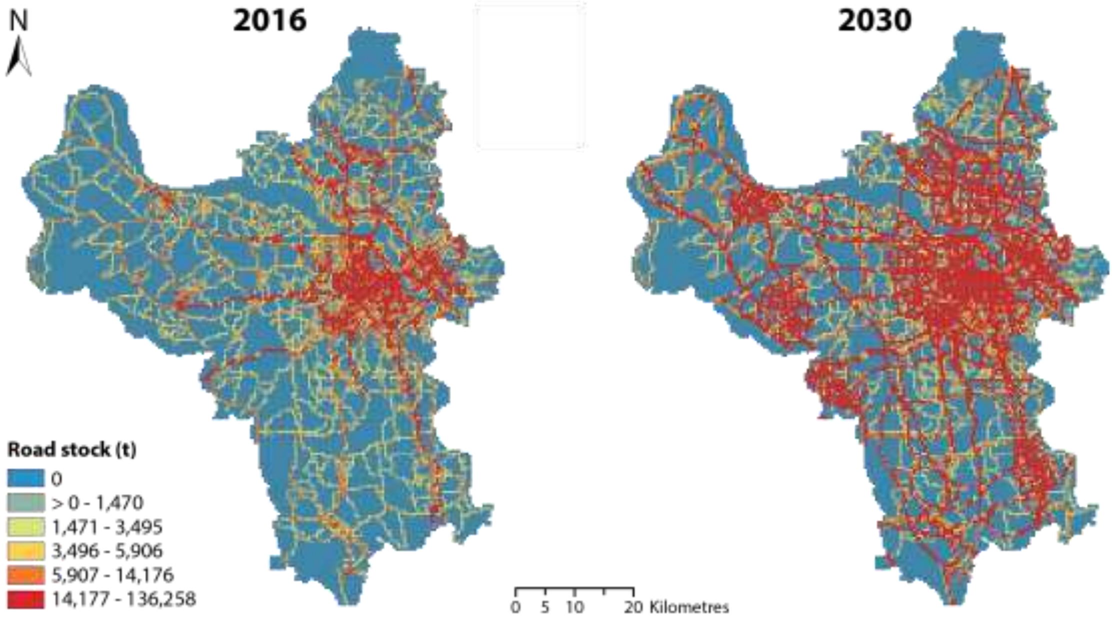

Figure 4 – Spatial distribution of existing and projected road stock, 2016 and 2030. The figure is plotted on a 500 m grid.

4.3 Compositional analysis

In 2016, the total stock in the overall road system reached 75.2 Tg, of which the highest fractions were primary roads (21%) and local roads (20%). The third and fourth largest elements of the road stock were expressways and urban arterials (both at 18%), followed by national highways at 15%. Provincial roads accounted for about 8% of the total road stock (Figure 5A). By 2030, urban arterials will have the highest growth rate in terms of total length (Figure 5B), and their stock will account for 34% of the total road stock. The total length of expressways may be shorter than some road types, but they will still have the second highest stock at 26% of the total road stock because of their wider cross-section and higher material intensity. As upgrades are planned for primary roads inside the current ring road and national highways (outside of the ring), their shares of the total road stock are expected to increase to 15% and 13%, respectively. The relative road stock of provincial roads may fall from 20% of the total in 2016 to 6% in 2030 due to rapid expansions of other road types; however, their absolute quantities may still show a twofold increase, both in total length and stock.

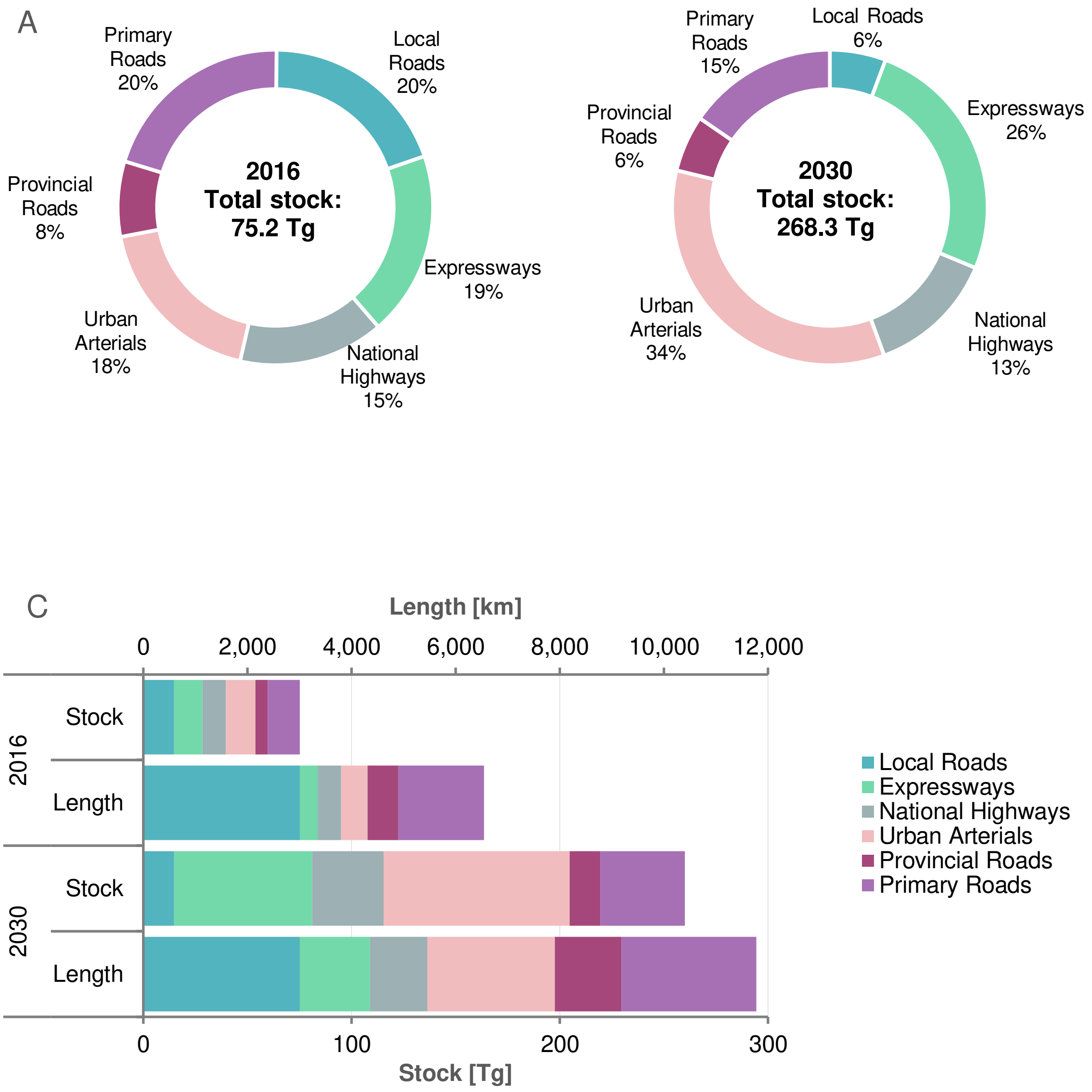

Figure 5 – A: Material stock by type of road in 2016; B: material stock by type of road in 2030; C: length [km] and material stock [Tg] of roads in Hanoi in 2016 and 2030.

The shares of the total material stock in local roads, branch roads, alleyways, and other small road types decrease from about 20% in 2016 to only 6% in 2030. This is because the total length and stock of these road types were assumed to remain constant from 2016, as these road types are not considered in the Master Plan (Figure 5). The rapid increases in the relative and absolute lengths of major roads, such as urban arterials, expressways, and national highways, can be explained as the result of expansion and construction of routes connecting each of the outer districts of the city centre and connecting the city centre with new satellite urban areas.

The stocks of roads by material composition are shown in Figure 6. In 2016, gravel accounted for about 85% of the total stock, as it was widely used as the main ingredient of base and sub-based courses in all types of roads. Sand came in second place at 13% because it was used to make the admixture of asphalt concrete and to backfill after removing the organic layers under the roadbed of expressways. The more expensive materials, bitumen and cement, accounted for smaller shares (both 1%). This was because bitumen is used only in the surface courses of asphalt roads, and cement is used as a supplement for enhancing the strength and cohesiveness of the base course of expressways (other concrete structures such as bridges and tunnels are outside the scope of this study). The material compositions of stocks in 2030 will be similar to that of 2016 because the construction code used in 2016 was assumed to be also applicable in 2030. Gravel will still account for the largest share (84%) of the total stock. The second largest component will be sand at 14%, followed by bitumen and cement with each at 1%.

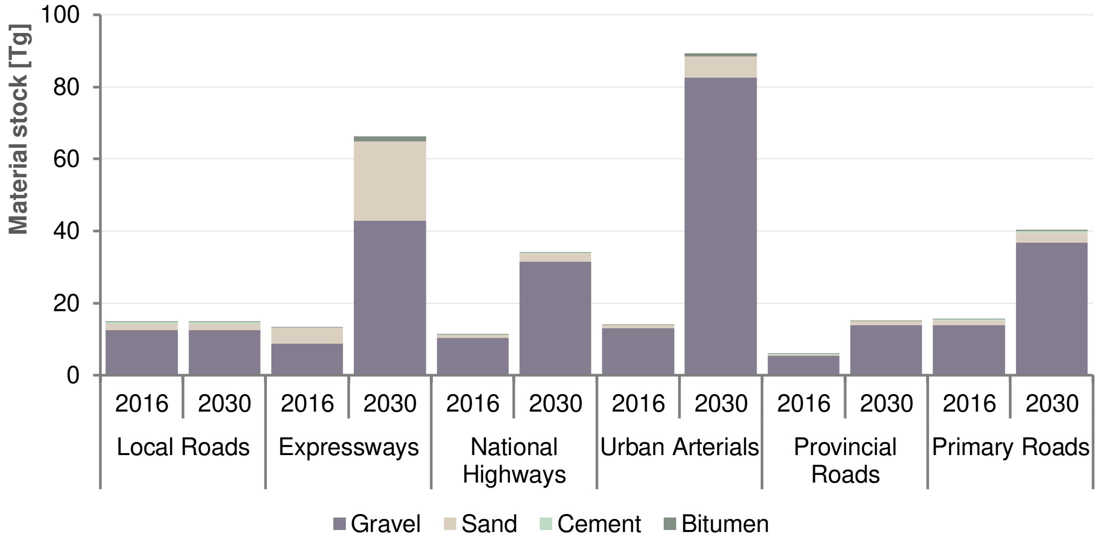

Figure 6 – Material stock composition by road type in 2016 and 2030.

In the case of railways (Figure 7), their total length in 2016 was approximately 215 km, corresponding to a material stock of 780 Gg. The total length is estimated to increase tenfold by 2030 through significant improvements and expansions of national railways and the MRT network. With respect to the material compositions of stocks in railways, there will be a considerable change between 2016 and 2030. In 2016, most of the routes were national railways, which use less material-intensive track structure (i.e., gravel for ballast, concrete for sleepers, and steel for rails) than urban railways. Aggregates accounted for 87% of the total railway stock, followed by cement at 9% and steel at 3%. Wood is also used in railways as sleepers in some locations like stations and bridges, but its stock is negligible. In 2030, concrete structures are expected to be widely used for elevated and underground sections of almost all lines, as outlined in the Master Plan. This is why the combined share of cement and sand is projected to increase to nearly half of the total railway stock. In contrast, the share of gravel may decrease to 50%, as ballast track structures will no longer be constructed. Steel rails will account for approximately 2% of the total railway stock.

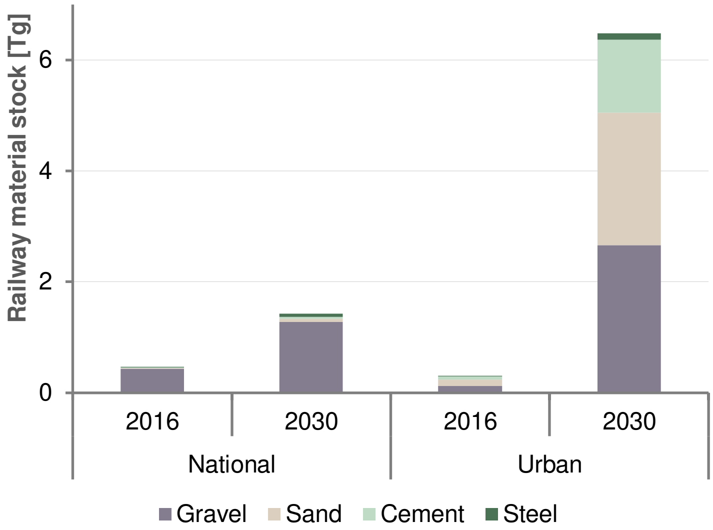

Figure 7 – Material stock composition by railway type in 2016 and 2030.

4.4 Stock-service productivity

The estimated stock productivity of Hanoi's road and rail infrastructure is presented in Figure 8A. The GRDP per unit of material stock decreased from 320 USD t^{-1} in 2010 to 276 USD t^{-1} in 2016. It is also expected that this number will further decrease to around 230 USD t^{-1} by 2030, owing to the GDP growth rate easing as Vietnam's economy matures. Figure 8A also suggests that the passenger transport productivity of the in-use stock appears to have been declining overall. With regard to freight transport, material productivity increased slightly from 258 t km t^{-1} in 2010 to 285 t km t^{-1} in 2016. The future stock productivities of passenger and freight transport were not modelled, as forecasts for 2030 were not available for the volume of passenger and freight transport.

Figure 8B separately plots the passenger and freight productivity for roads and railways. While the passenger transport productivity for the total infrastructure stock appeared to have been decreasing, a separate examination of roads and railways revealed that the two types of infrastructure have contrasting trends in productivity. The passenger transport productivity for railways decreased sharply while that for roads actually increased. The productivities for the two modes of freight transport also followed similar trends to that of passenger transport.

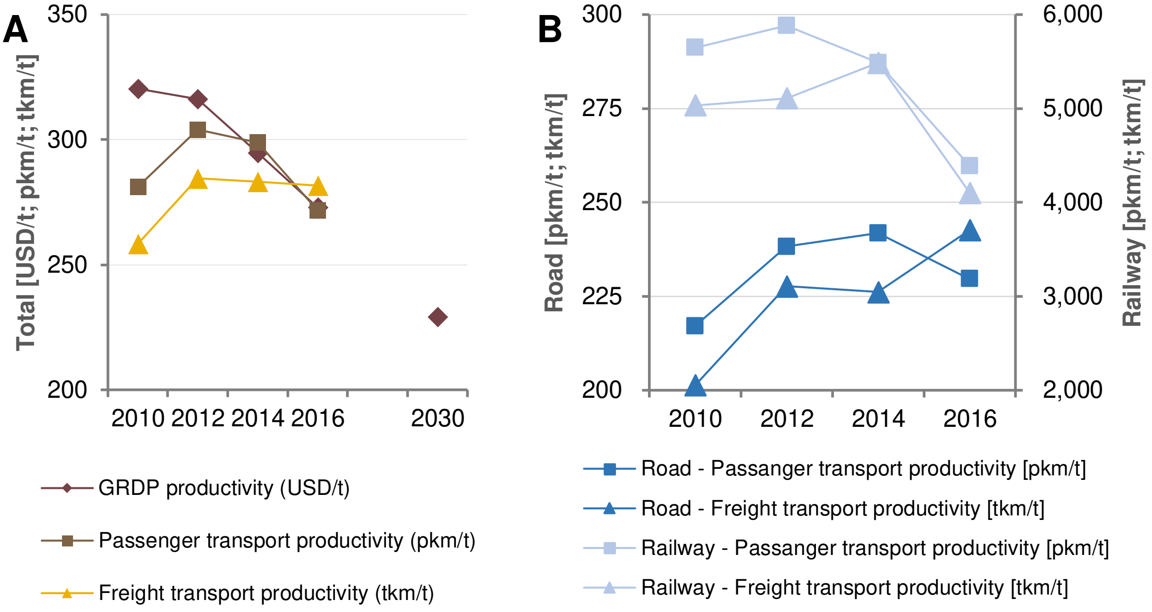

Figure 8 – A: Material stock productivity for gross regional domestic product (GRDP) per metric tonne of total transport infrastructure stock [USD t^{-1}], passenger-kilometre travelled per tonne of total infrastructure stock [pkm t^{-1}], and tonne-kilometre of freight travelled per tonne of total infrastructure stock [tkm t^{-1}]. B: Passenger transport productivity [pkm t^{-1}] and freight transport productivity [tkm t^{-1}] for road infrastructure (left axis) and railway infrastructure (right axis).

5. Discussion

5.1 Comparison of material stock with the literature

Comparing the results for Hanoi by this study with those of others is difficult, as most material stock analyses of transport infrastructures have been conducted at the national level. In addition, few results have been published on developing countries. A comparison of material stock for Hanoi's land transport infrastructure with those for several other locations is provided in Table 2. The material intensities used by these studies can be found in the Supplementary Data. These studies also did not include ancillary facilities in their material stock calculations.

Table 2 – Comparison of material stock for Hanoi's land transport infrastructure with those for other locations.

Author	Location	Period	Material stock per capita [t $capita^{-1}$]
National and multinational studies			
Daxbeck et al. (2009)	Austria	2003	128
Han and Xiang (2013)	China	2008	5.4
Wiedenhofer et al. (2015)	European Union	2004–2020	79–84
Miatto et al. (2017)	United States	1905–2015	8–47
Nguyen, T.C. et al. (2019)	Vietnam	2003–2012	16–29

Author	**Location**	**Period**	**Material stock per capita [t capita^{-1}]**
Subnational studies			
Guo et al. (2014)	Beijing, China	2011*	8
Athanassiadis et al. (2015)	Brussels, Belgium	2011	25
Noll et al. (2019)	Samothraki, Greece	1971–2016	12–52
Gassner et al. (2020)	Vienna, Austria	1990–2015	55–58
Yu et al. (2021)	Nanjing, China	2017	14
This study	Hanoi, Vietnam	2010, 2016, 2030	8.7, 10.1, 32.9

* The study does not explicitly state the year of the analysis. 2011 is the latest publication year of the underlying data.

From the data presented in Table 2, we see how the earlier material stocks per capita for Hanoi are similar to earlier values for Samothraki and Beijing. Hanoi's expected material stock per capita in 2030 is closer to the values for Brussels, suggesting that Hanoi is on the trajectory of urbanising to levels typical of European cities. Hanoi also shows many similarities with the per capita stock of the United States of the early 20th century (Miatto et al., 2017), but we find the comparison of city-level with national-level studies somewhat meaningless. Countries typically consist of mostly rural areas and a few urban areas, where the majority of a nation's material stocks are concentrated, without many areas in the middle of the stock accumulation spectrum. As such, the number for material stock per capita at the national-level usually lacks the context and details for comparison with city-level studies to yield practical insights (except for smaller countries such as Singapore). Comparisons for urban areas should be conducted only with other urban areas.

5.2 *Interpreting material stock productivity*

The decline in material stock productivity (Figure 8A) includes the result of factors that are closely linked to transport and those that are not. The historical declining trend for passenger and freight transport productivity (Figures 8A and 8B) suggests the presence of either increasing congestion or excess roads and railways, which leads to inefficient use of material stocks. Indeed, congestion has been a growing problem in Hanoi as the number of motor vehicles multiply, thereby negatively affecting the economy as well as the environment and human health (Chu and Thi, 2017; Chung, 2017; Nguyen and Kajita, 2018; Nguyen, M.Q. et al., 2019). Hanoi's GRDP has also been shaped by factors other than those directly affected by transport material stock, such as foreign direct investment (although investment decisions may be partially influenced by the conditions of transport infrastructure) (Kim, 2020). While the management of transport material stocks will not directly affect the latter type of factors, addressing the former type of factors (e.g., alleviating congestion) can help improve Hanoi's economic productivity, optimise the return on investment in transport infrastructure, and maintain a high rate of economic growth.

Because congestion is a known issue in Hanoi, the projected decrease of Hanoi's material stock productivity by 2030 may not necessarily indicate a problem. Like many infrastructure development plans, especially in rapidly developing regions, the Master Plan adds beyond the optimal capacity for traffic at the time of completion with future demand increases in mind.

This would lead to a temporary decrease in passenger and transport productivity. In addition, the projected material productivity does not account for the new infrastructure's economic impact to areas surrounding Hanoi and to Vietnam at large that stems from more efficient transport and exchange of goods.

Several strategies exist for increasing the material stock productivity for Hanoi's roads and railways, some of which are already being pursued by the Hanoi government. One option is to encourage the shift from a road-based to a rail-based transport system. This idea has been the main topic of many transport forums (e.g. (European Commission, 2016; SLoCaT, 2018)), as rail transport is more efficient than transport by roads in terms of energy, emissions, passenger and freight volumes. Another option for improving stock productivity is by increasing the lifespan and quality of the stocks, thereby reducing the material demand for maintenance while providing the same level of service in a given period of time. Stock lifetime extension can be achieved by improving the design and construction standards and building higher quality roads and railways. Expanding the existing transport infrastructure following the Master Plan will also help improve mobility; however, this strategy has several potential issues, as discussed in the following section.

5.3 Policy implications

5.3.1 Legal quarrying and potential risks to local material supply

The analysis of the material requirements of Hanoi's Master Plan could serve as a reference for other developing countries with ambitious, large-scale plans to expand their transportation infrastructure. The near-threefold increase of material stocks for Hanoi's transport infrastructure over the study period results from the expansion of the road and railway networks. Such development comes with several implications. In Vietnam, the regulation of quarrying licences is the duty of the Vietnamese provincial departments. In 2015, the estimated amount of construction minerals that can be retrieved from legal quarries in Hanoi and its hinterland province Hoa Binh is 11 Tg of sand and 715 Tg of gravel (Schiller et al., 2020). In this study, we calculated that, between 2016 and 2030, the implementation of the Master Plan requires a total of 26 Tg of sand and 156 Tg of gravel. While gravel does not seem to be at risk of shortage—the predicted demand is 22% of the available supply—sand will likely be a rare commodity, at least at the local level (demand is 236% of the available local supply). The demand for sand is even more problematic when considering that our estimates account solely for infrastructure and that the construction of buildings will require even additional sand (Schiller et al., 2020). This poses a challenge both to local constructors, as they will have to look farther to receive a stable supply of sand, and policymakers, who will have to face the difficult decision of allotting more quarrying licences. This is another confirmation of the prediction of future sand shortages (Torres et al., 2017; Bendixen et al., 2019) and increased sand prices (Sverdrup et al., 2017).

The extraction of construction minerals poses serious environmental consequences (Langer and Arbogast, 2002; Cheshire et al., 2014). The overexploitation of sand causes accelerated changes in water flow and erosion of river banks (Thornton et al., 2006; Wantzen and Mol, 2013) and water quality (Bayram and Önsoy, 2015). Posing limits to sand quarries while fostering the use of secondary materials seem to be the best actions to preserve the environment. Yet, so far, the construction materials industry has tended to prefer investments in exploration, mining, and processing activities rather than the more expensive (and less profitable) investments in recycling technologies (Nunes et al., 2007; Tangtinthai et al., 2019). It is therefore critical to reinforce the legal framework and to regulate the relevant procedures for quarrying and producing sand and gravel with particular attention to the safeguard of natural ecosystems, people, and development ambitions.

5.3.2 Recycling of construction and demolition waste

It is essential to direct policies to increase recycling rates of construction and demolition (C&D) waste in Hanoi as well as to incentivise recycling technologies and businesses that consider C&D waste as secondary resources, as it is often done in other countries (Jin et al., 2017; Miatto et al., 2017). Significant quantities of construction minerals are required for the expansion as well as maintenance of the transport network. However, the domestic material consumption for transport infrastructure can be limited by reutilizing C&D waste, some of which is generated from the maintenance of the transport infrastructure itself. Future material demand can be also reduced by ensuring high-quality road construction that will last longer and will require fewer materials for maintenance. It is thus recommended to introduce, as early as possible, regulations encouraging the use of recycled materials for maintenance and construction of roads and proper design standards for maximising the lifetime services of infrastructures.

5.3.3 Greenhouse gas emissions

While cement accounts for a small fraction (1%) of the material stock, the quantity of cement required to implement the Master Plan is massive, at 1.6 Tg by 2030 or an average of 114 Gg year^{-1}. Cement production is one of the most significant GHG emitting industrial sub-sectors (World Bank, 2010; Hertwich et al., 2019). The total emission related to the production of cement used to implement the Master Plan was calculated to be 1.1 Tg of CO_2 using the emission factor of 675 kg CO_2 per tonne of cementitious material (average for Asia for the year 2009) (Klee et al., 2011). The main solutions to reduce GHG emissions include improving the efficiency of cement kilns, reducing transportation distances between producers and construction sites, and decreasing the quantity of cement used (Fischedick et al., 2014; Shanks et al., 2019). The use of alternative materials through industrial symbiosis or addition of supplementary cementitious materials also play a relevant role in reducing the emissions associated with cement production (Chertow and Miyata, 2011; Yang et al., 2015; Sun et al., 2017; Miller and Myers, 2020). Policies to promote cleaner production of cement and to limit overall cement requirements (such as recycling and lifetime extension as discussed in the previous section) will greatly benefit climate change mitigation efforts.

Furthermore, it is important to consider the emissions related to the use of the transportation network. A large-scale expansion of roads and the population growth can lead to significant increases in GHG emissions. Appropriate policies to encourage mass transit can limit GHG emissions and improve the efficiency of road transport (Creutzig et al., 2015), generating more economic benefit. It will be necessary for policymakers to limit the rebound effect of large infrastructure projects, such as increases in commuting distances and ownership of personal vehicles, that may increase passenger and freight-related emissions in the long run.

6. Conclusions

In 2015, the Vietnamese government approved the ambitious Master Plan for the urban transport system of Hanoi towards 2030, with a vision to 2050. However, there was no detailed quantification of the material requirements of the proposed infrastructure. A GIS inventory was constructed for Hanoi's existing road and railway network and the future network following the Master Plan. The study examined the in-use stock by its total quantity, material composition, spatial distribution, and productivity. We found that the total material stock will increase more than threefold by 2030 (by almost 200 Tg) in a span of only 14 years, of which 97% will be stored in roads. The per capita stock in 2016 was 10 t capita^{-1}, and it is projected to increase to 33 t capita^{-1} by 2030. The demand sand is of key concern, as the plan requires nearly 2 Tg year^{-1} on average to fully implement the plan and exceeds local availability. The material stock productivity of the existing transport infrastructure appears to have been declining and the trend may continue without adequate consideration of the material-use per service output.

To further improve the robustness of the results, future research will need to: (1) improve data on the material composition of structures (e.g., elevated and underground concrete structures such as bridges, tunnels, flyovers, and interchanges), maintenance activities, and flows of construction materials for the city; (2) improve transport data including the volumes of passenger and freight transport; (3) generate robust data on waste generation for road maintenance through the implementation of a dynamic material stock and flow model, and (4) conduct further analysis on the material stock productivity. These steps are necessary to better assess the material use efficiency of the stock and to develop a further understanding of urban infrastructure expansion and their environmental implications.

The material demand by Hanoi will surely increase further as more investments and large-scale constructions are mobilised to develop Hanoi's satellite urban areas, drastically changing the urban form. In addition, the material requirements for the maintenance of existing and future roads and railways were not covered by our study. To limit the negative consequences of rapid development, Vietnam's policymakers are recommended to employ policy measures such as mandating a minimum recycled content for construction materials and to commission studies for better understanding the potential impacts on the natural environment and, ultimately, the people.

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