Material stock development of the transport sector in the city of Vienna

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Abstract
Societies aim to reduce primary raw material consumption, enhance waste recycling, and reduce waste disposal. In this regard, the circular-economy concept has gained attention and is applied in policy papers, also on the urban level. However, to assess set targets and their achievement, a sound knowledge of anthropogenic material flows and stocks is required. The material turnover of transport systems has not been sufficiently investigated yet, although they have a significant impact on overall material turnover and have a high potential for making use of recycled construction materials. To close this gap, the present study investigates the anthropogenic stocks and flows related to an urban transport system, whereby both infrastructure and vehicles are included.

A bottom-up, multiyear material-flow analysis was employed to calculate the material stock and the related input and output flows of Vienna's transport system for the period 1990–2015. The results indicate the increasing importance of more environmentally friendly modes of transport. The stock of motorized individual transport has increased in absolute terms since 1990, but the stock per capita remains unchanged at 34 t/cap, whereas the per capita stock of public transport (20 t/cap; +8%) and of non-motorized individual transport (4 t/cap; +10%) has increased. However, the primary source of material consumption (>65%) is maintenance of infrastructure. This provides a potential for more circularity because outputs and inputs are equal in terms of mass and material. The study provides a systematic analysis for developing policy and management options for sustainable resource-saving urban transport systems.

KEYWORDS
built environment, construction and demolition waste, industrial ecology, material flow analysis (MFA), transportation, urban metabolism

1 INTRODUCTION

Material demand and waste generation have been constantly growing over the last century (Krausmann, Lauk, Haas, & Wiedenhofer, 2018) and cities are the main drivers of this development because of urbanization (Kennedy, Cuddihy, & Engel-Yan, 2007). This material turnover is dominated by the expansion of the building and transport sectors (Johansson, Krook, Eklund, & Berglund, 2013), leading to an increase in the material stocks (MS) in these sectors, even in highly industrialized societies (Lederer et al., 2020; Miatto, Schandl, Wiedenhofer, Krausmann, & Tanikawa, 2017; Miatto et al., 2019). To build up these MS, large amounts of raw materials are needed, and after their lifetime considerable quantities of construction and demolition waste (CDW) are produced. In order to reduce the material turnover and, in particular, the need for primary raw materials, the European Union aims to realize an increasingly circular economy (European Commission, 2015). Contrary to other materials, the recycling of...
construction materials is to be tackled at the local level because they have an economically and environmentally limited transport distance due to their comparatively low value and high mass (Hiete et al., 2011). In this regard, a number of cities define sustainable development targets in accordance with the circular economy concept (Prendeville, Cherim, & Bocken, 2018).

The city of Vienna incorporated the circular economy idea within its Smart City Wien Framework Strategy (2050). Therein, the target calls for 80% of all components and materials from demolishing buildings to be reused or recycled by 2050 (City of Vienna, 2019). Even though transport infrastructure is not explicitly mentioned in this context, it plays an important role in implementing a more circular material cycle of construction materials since transport infrastructure is of major significance with respect to the potential for making use of recycled construction materials (e.g., road construction) (Hiete et al., 2011). Furthermore, construction activities related to transport infrastructure are the second largest source of demolition waste after buildings (Lederer et al., 2020).

As the transport sector also represents an important source of greenhouse gas emissions and is thus targeted by current CO$_2$-eq emission reduction goals (e.g., the city of Vienna aims to reduce its per capita CO$_2$-eq emissions in the transport sector to 50% by 2030), the transport infrastructure is currently experiencing a transformation phase. This transformation to a more sustainable passenger transport system should be achieved by a shift in modal choice towards public transport, fewer private vehicles, and a zero emissions vehicle fleet (City of Vienna, 2019). To achieve such a significant transformation, the transport infrastructure must be designed and constructed accordingly (e.g., with extensions to the public transport, pedestrian, and bicycle network) (Environment Agency Austria [UBA], 2019). Such systematic changes require corresponding time for planning and implementation as well as time and efforts to persuade the population (e.g., when a reduction in public parking infrastructure meets social resistance) and must be carried out stepwise. So, to reach the 2030 targets, the required structural changes to the transport infrastructure should have already been initiated in recent decades and even be partially implemented today. If the required structural changes are taking place, this reflects an increase and variation in the dynamic of the MS of various transport modes. The dynamics of MS determine the speed at which technological changes can be implemented (Pauliuk & Müller, 2014). This dynamic is particularly relevant for the vehicle fleet, which has high stock renewal rates, but infrastructure should not be neglected either. In this context, a comprehensive understanding of recent developments of the MS in urban transport systems is crucial for the improvement of the future transport system of a city: first, to assess set targets and their achievement, and second, to identify potential fields to reduce primary raw material consumption in order to enhance waste recycling and to reduce waste disposal.

In terms of MS development in general, there are significantly more studies on buildings than on transport infrastructure (e.g., roadways, railway tracks, or subway networks). However, the latter significantly contributes to the total MS of construction materials. The share between MS in buildings and MS in infrastructure depends heavily on the prevailing transport system and its respective density, that is, depending on the area investigated, the share of infrastructure is between 20% and 60% (Augiseau & Barles, 2017). At a country level, the material composition and development of the MS in road networks has been investigated for the European Union (Wiedenhofer, Steinberger, Eisenmenger, & Haas, 2015), the United States (Miatto et al., 2017) and Japan (Hashimoto, Tanikawa, & Moriguchi, 2009). The mass and material composition of the MS in Beijing's road system was analyzed by Guo, Hu, Zhang, Huang, and Xiao (2014), as were the life cycle greenhouse gas emissions (Guo, Hu, Zhang, Zhang, & Zhang, 2017). Tanikawa and Hashimoto (2009) investigated the MS of urban road and railway networks in the city centers of Manchester (GB) and Wakayama (JP).

All in all, existing material studies on transport infrastructure either focused on only one transport mode (e.g., roads), or were solely dedicated to material stocks and stock dynamics of the infrastructure, thereby neglecting the generation of CDW, which is crucial from a circular economy perspective (Augiseau & Barles, 2017; Lanau et al., 2019). Although numerous studies describing the anthropogenic metabolism of Vienna are available, making it one of the most well-investigated urban areas in this respective field, they either focus on buildings (Kleemann, Lederer, Rechberger, & Fellner, 2017; Lederer et al., 2020), following a top-down approach (Obernosterer et al., 1998), or investigate a subsystem of the transport modes, such as the subway infrastructure (Lederer, Kleemann, Ossberger, Rechberger, & Fellner, 2016). There is not a single study known to the authors which provides a detailed analysis of Vienna's (or any other city's) transport system distinguishing between all prevailing transport modes, their infrastructures, and vehicles.

The present study aims to provide the lacking quantitative analysis regarding the MS development of the total transport infrastructure and the vehicle fleet on a city level, as well as the related material flows (MF). As for the transport infrastructure, the focus is set on the underlying processes (e.g., network extensions, maintenance) causing the material turnover of construction materials. However, regarding the vehicle stock, of special interest is the stock renewal rate because it provides information about the speed at which technological changes can be implemented. In order to compare different transport modes, both vehicles and infrastructure have to be considered for the environmental assessment (Anderson, Wulfhorst, & Lang, 2015; Chester & Horvath, 2009). The present study thus provides data which is necessary for the development of measures towards a more circular construction material cycle as well as input data for the environmental assessment of various transport modes. Furthermore, by examining the transformation process of the transport sector, new information about the dynamics of this process is provided. Aside from authorities and policy makers, the results are of great interest to experts in such disciplines such as traffic and urban planning since the study provides detailed information about the development of transport infrastructure and the vehicle fleets of different transport modes over time, the material intensity of different transport infrastructures and, finally, their renewal rates. Specifically, the study aims to answer the following questions:
1. What is the mass of the in-use material stock of the transport system (infrastructure and vehicles) in a well-established, highly developed European city and what is the contribution of different transport modes to this stock?

2. Which changes, in terms of the mass and material composition of the material stock, can be observed for the different transport modes within the recent past?

3. What is the annual material demand and waste generation rate of the transport sector broken down by transport mode?

4. Which processes (e.g., new construction, maintenance) primarily cause the material turnover?

To address these questions, Vienna’s transport system development between 1990 and 2015 were investigated.

2 | STUDY AREA

The City of Vienna was chosen as the study area because, as regards the historic development of the prevailing urban transport system, it is comparable to numerous cities in industrialized countries. Furthermore, the case study city is particularly interesting because of the diversity of its well-developed transport system (e.g., various transport modes, broad age distribution of the transport infrastructure) and it is characterized by good data availability. In Vienna, the largest share of traffic area is attributable to motorized individual transport (e.g., roads and parking areas) like almost all large cities worldwide. However, Vienna also has a well-developed public transport system, which has been gradually expanded. It comprises public buses, trams, regional trains and metro lines. The size and the development of the infrastructures investigated from 1990–2015 is presented in chapter 4.1 of the results section. Like in other cities, active mobility (walking, cycling) has regained importance in recent years, which is also reflected in the modal split wherein walking increased from 22% to 27% and biking from 4% to 7%, as presented in Figure 1. Vienna is the largest city in Austria, covering an area of 415 km². Over the period studied, the population of Vienna has increased by over 20%, from 1.5 million to 1.8 million (Statistik Austria, 2019).

3 | METHODS

The “Overview, Design, Details” protocol is used to describe the modeling approach and data used. The protocol was adapted for material flow analysis models by Müller, Hilty, Widmer, Schluep, and Faulstich (2014) and was applied by Noll, Wiedenhofer, Miatto, and Singh (2019). The protocol has the advantage that it provides a structure to systematically describe the model and data, from a generalized overview to an increasing degree of detail, thereby making the complexity of the model manageable for the reader (Müller et al., 2014). Keywords of the protocol are set in italics within the sections 3.1 to 3.3. The calculation was performed in Microsoft Excel and is published in the Supporting Information S2. Additional information regarding input data can be found in the Supporting Information S1.

3.1 | Overview

The purpose of the study is to investigate the development of the in-use material stocks (MS), the material input flows (MF<sup>IN</sup>) and material output flows (MF<sup>OUT</sup>) of the transport system of the city of Vienna. Transport modes considered are motorized individual transport, non-motorized individual transport and public transport.

The materials are expressed in metric tons (t) and their multiple (e.g., Million tons (Mt)). Overall, 13 material categories are considered: asphalt & bitumen; aluminum; batteries; brickwork; concrete; copper; glass; gravel, sand and natural stone; iron & steel; other metals; others (e.g., rubber); plastics; and wood.

The processes defined are transport infrastructure (e.g., roads, metro network) and vehicles (e.g., cars, trains) for each transport mode. The infrastructure is further distinguished in terms of infrastructure for moving transport (e.g., roads, rail tracks) and infrastructure for stationary traffic (e.g.,
parking lanes, train depots). All material input flows, and waste flows generated due to maintenance and demolition are considered regarding infrastructure. For the vehicles, the MF related to new vehicles and decommissioned vehicles are included, but maintenance is neglected.

The spatial boundary refers to the city of Vienna, and the temporal scale covers the time interval 1990 to 2015. A system overview is presented in the Supporting Information S1 in Table S1-1. It includes an enumeration of all infrastructure and vehicle types considered as well as their allocation to moving or stationary infrastructure.

3.2 Design concept

The basic principles of the model can be described as bottom-up, retrospective, multiyear material flow analysis as defined, among others, by Brunner and Rechberger (2016) and Tanikawa, Fishman, Okuoka, and Sugimoto (2015). In the multiannual static modeling approach chosen, the calculation is based on specific service units (SU) (e.g., m² road, m metro network, number (n) of vehicles) which are combined with specific material intensities (e.g., t/m², t/m, t/n). The model based on SU is set up using the methodology of Müller (2006), which has been previously applied, among others, by Bergsdal, Bohne, and Brattebø (2007); Noll et al. (2019); Wiedenhofer et al. (2015); and Tanikawa et al. (2015).

The input data is expressed in SU and is taken either from official statistics, provider information, internal statistics from the municipality of Vienna, or is calculated by combining various data. Material intensities are taken from the literature combined with own calculations. On the one hand, MF\textsuperscript{IN} are generated due to extensions (e.g., increase in m² road area in the year n) and MF\textsuperscript{OUT} due to decline (e.g., decrease in m tram track length in the year n) of infrastructures and vehicle fleets. On the other hand, MF\textsuperscript{IN} and MF\textsuperscript{OUT} depend on the maintenance of the transport infrastructure as well as the maintenance of underground networks (e.g., pipes and cables), which usually require work on road infrastructure. To calculate these MF, different approaches are applied. If available, reported data on the number of SU maintained per year are used for MF calculation. Otherwise, either an annual renewal rate or mean useful life is used. MF\textsuperscript{IN} and MF\textsuperscript{OUT} related to maintenance are assumed to be equal in composition and intensity since the construction type of the infrastructure remained constant over the period investigated. Furthermore, no distinction is made between primary and secondary material. In other words, internal recycling flows appear as separate MF\textsuperscript{OUT} and MF\textsuperscript{IN}.

Within the analysis no dissipative flows are modeled since these are negligible for the quantitative examination of construction materials. The results are not presented with their spatial distribution within the city. No uncertainty assessment is integrated into the model since data in this regard was not available. The plausibility of the results is examined for each infrastructure component investigated by comparison with the results from other cities found in the literature.

3.3 Model calculations

In the following, a detailed model description, including the calculation procedure, is presented. The initial state and the annual in-use MS are dependent on the total number of service units. In particular, the total MS is calculated by applying Eq. 1, adopted from (Noll et al., 2019; Tanikawa et al., 2015).

\[
MS_{m,i,t} = \sum_{i}^{n} SU_{i,t} \times MI_{m,i} \tag{1}
\]

\(MS_{m,i,t}\) is the total stock in materials \(m\) in all SU \(i\) in the year \(t\) [t]; \(SU_{i,t}\) is the inventory (total service units) of each type \(i\) in the year \(t\) [m² or number], and \(MI_{m,i}\) is the material intensity of a certain material \(m\) in one unit of SU \(i\) [t/m²].

To calculate the annual MF\textsuperscript{IN} for the new installation of new SU, Equation (2) adapted from Noll et al. (2019) is implemented within the model.

\[
MF_{m,i,t}^{IN,NEW} = \sum_{i}^{n} SU_{i,t}^{NEW} \times MI_{m,i} \tag{2}
\]

\(MF_{m,i,t}^{IN,NEW}\) is the annual material input flow for newly installed SU\textsuperscript{NEW} of materials \(m\) of various SU types \(i\) in the year \(t\); \(\sum_{i}^{n} SU_{i,t}^{NEW}\) encompasses all newly built (infrastructure) or newly registered (vehicles) service units of type \(i\) in the year \(t\). The material intensity \(MI_{m,i}\) is expressed in mass per material \(m\) and SU type \(i\).

The annual MF\textsuperscript{OUT} for demolished infrastructures and end-of-life vehicles is calculated according to the same principle, see Equation (3).

\[
MF_{m,i,t}^{OUT,DEM} = \sum_{i}^{n} SU_{i,t}^{DEM} \times MI_{m,i} \tag{3}
\]

\(MF_{m,i,t}^{OUT,DEM}\) is the annual material output flow for removed SU\textsuperscript{DEM} of materials \(m\) of various SU types \(i\) in the year \(t\); \(\sum_{i}^{n} SU_{i,t}^{DEM}\) encompasses all demolished (infrastructure) or deregistered (vehicles) service units of type \(i\) in the year \(t\). The material intensity \(MI_{m,i}\) is expressed per material \(m\) and SU type \(i\).
If real data on the number of SU maintained per year are available, Equations (2) and (3) are used to calculate the MF\textsubscript{IN} and MF\textsubscript{OUT}. However, for all other infrastructure types, the MF\textsubscript{IN} and MF\textsubscript{OUT} is calculated by applying Equation (4) (renewal rate (RR)) or Equation (5) (lifetime based (LT)). The corresponding equation is assigned to each infrastructure type in Table S1-1 in the Supporting Information S1.

\[ MF_{m,i,t}^{RR} = MS_{m,i,t} \times RR_{m,i} \]  

\[ MF_{m,i,t}^{LT} = MS_{m,i,t} / LT_i \]  

MF\textsubscript{IN} and MF\textsubscript{OUT} are annual material needs for a specific infrastructure type in the year \( t \) for the materials \( m \) and infrastructure type \( i \).

3.4 | Model input

The model input data (service units, material intensities, renewal rates, and useful life per infrastructure type) are derived from various sources, for instance statistics, company information or the literature (for details, see the Supporting Information S1 Section 1–2 and all numbers per year can be found in Supporting Information S2). In the following, an overview of the input data is presented, which is subdivided into, first, road-based infrastructure, second, rail-based infrastructure and, third, vehicles.

In order to calculate the MS of the surface of traffic areas (e.g., roads, bicycles, and pedestrian areas), the total area (\( = \text{SU} \)) is calculated using various sources, such as statistics, company information, or literature (for details, see the Supporting Information S1 Section 1–2 and all numbers per year can be found in Supporting Information S2). The following overview of the input data is subdivided into, first, road-based infrastructure, second, rail-based infrastructure, and third, vehicles.

For road-based infrastructure, three different networks, namely metro, tram, and regional train, are distinguished. The metro network was investigated by Lederer et al. (2016). The data published therein is used as input data in the model. The tram network length (\( = \text{SU} \)) is taken from Wiener Linien (2019), and the material intensities are calculated based on standard cross-sections used for the network in Vienna and the literature data (Schmied, Mottschall, & Löchter, 2013; Wiener Linien, 2012). The track length of the regional train network is provided by the City of Vienna (2016). The mean trenches width and useful life is provided by Wiener Netze (2018).

Input data for bridges (\( \text{SU}: \text{bridge area per bridge type} \)) is calculated using data from AustriaWiki (2018); the respective material intensities are based on Lünser (1999) and Helminger (1978a, 1978b, 1978c), and maintenance MF are calculated using Equation (5).

Road equipment (\( \text{SU}: \text{number of, e.g., light signal systems} \)) is taken from statistics—partially for light signal systems (City of Vienna, 2016; MA 33, 2019a, 2019b)—or it is calculated based on road length and the literature data (Mottschall & Bergmann, 2013, p. 32). The assessment of new road equipment is based on the change in the total number from consecutive years. Material intensities are taken from Mottschall and Bergmann (2013), and the maintenance MF are calculated by applying Equation (4).

The parking area on public property is regarded as constant due to lack of data, and is taken from the City of Vienna Municipal Department 41 (MA 41) (2019a). The respective maintenance MF are calculated by applying Equation (4). For parking spaces on private properties and within private buildings (\( \text{SU}: \text{number of parking spaces} \)), no statistical data is available. Hence, to calculate the number of parking spaces within existing buildings, a sample of \( n = 255 \) of randomly selected buildings (from all buildings in Vienna) was analyzed. Thus, key figures about the number of parking spaces for each building category are generated. These were applied to the total stock of buildings (City of Vienna Municipal Department 41 [MA 41], 2019b) under consideration of legally specified parking space obligation, which requires for newly built buildings: 1 parking space per 100 m\(^2\) usable area (WGvG, 2008). The material intensities per parking space within buildings are taken from the Leibniz Institute of Ecological Urban and Regional Development (IOER) (2017a, 2017b) and related maintenance MF are calculated with Equation (5). The parking spaces (outdoor) on private property are estimated based on total available parking spaces and the total number of registered vehicles (for details see Table S1-2). Material intensities and maintenance related to MF are calculated in the same manner as parking areas on public property.

For rail-based infrastructure, three different networks, namely metro, tram, and regional train, are distinguished. The metro network was investigated by Lederer et al. (2016). The data published therein is used as input data in the model. The tram network length (\( = \text{SU} \)) is taken from Wiener Linien (2019), and the material intensities are calculated based on standard cross sections used for the network in Vienna and the literature data (Schmied, Mottschall, & Löchter, 2013; Wiener Linien, 2012). The track length of the regional train network is provided by the City of Vienna (2016) and Austrian State Railways (OEBB) (2016). Missing years are interpolated. Different construction types of the network are based on investigations of the Orthophoto of 2015 (City of Vienna Municipal Department [MA 41], 2015). The material intensities for track components are derived from calculations based on the values of several sources (Lederer et al., 2016; Mottschall & Bergmann, 2013; Ostermann, Rollinger, & Kehrer, 2016; Schmied et al., 2013). The MF related to the maintenance of the rail-based networks are based on mean useful life per construction element (superstructure, substructure, and buildings), applying Equation (5).
The unit for buildings (e.g., train stations, train depots) is cubic meter gross volume ($m^3$ GV), and input data is derived from the 3D building model for Vienna (City of Vienna Municipal Department [MA 41], 2019b). The material intensities are taken from Kleemann et al. (2017). However, for Vienna’s main train station, actual data (built-in material) are implemented in the model taken from Austrian State Railways (OEBB) (2015).

Finally, the number and type (= SU) of vehicles are taken, for private vehicles, from Statistik Austria (2019), for metro and tram vehicles, from Wiener Linien (2019) and Beyer and Svetelsky (2018), for public bus vehicles, from Stadtverkehr Austria (2019) and Wiener Linien (2019), and for regional train vehicles, from Anon (2019), Austrian State Railways (OEBB) (2019) and Obermayr (2019). Bicycles and pedelecs are calculated based on trade statistics (Chamber of Commerce, 2013; Association of Sport Goods Manufacturer and Supplier of Austria [VSSOE], 2013, 2014, 2015, 2016) and the number of households. The material intensities and mean vehicle weights per vehicle category are derived from several sources (Beyer & Svetelsky, 2018; Federal Ministry Transport, Innovation and Technology [BMVIT], 2013; Cherry, Weinert, & Xinmiao, 2009; Kraftfahrt-Bundesamt [KBA], 2019; Öko-Institut e.V., 2009; Struckl, 2007).

### 3.5 Model output and evaluation

As model output, the in-use MS for different transport modes is generated for every single year from 1990 to 2015. Further, the model calculates the annual resource demand caused by network extensions, infrastructure maintenance, and newly registered vehicles. The waste generated due to demolition activities, maintenance work, and end of life vehicles is quantified. The results of the analysis are given separately for each transport mode, infrastructure category and vehicles. 13 different material categories are distinguished. To evaluate the results and compare them to other cities, the results are displayed in stock per capita (t/capita) as well as per transport performance (passenger kilometer traveled (PKT)/t). For this, the MS are divided by the inhabitants (Statistik Austria (2019)). However, passenger kilometers traveled (Austrian Institute for Regional Studies [OEIR], 2019) are divided by the mass of MS in the corresponding year. To describe the development of the transport behavior of the population, the modal split is used provided by Wiener Linien (2019). Modal split and passenger kilometers traveled only consider transport performance for passenger transport; cargo transport is not included. The modal split represents the percentage distribution of traffic routes differentiated according to the means of transport (Ostermann et al., 2016).

### 4 RESULTS

#### 4.1 Development of service units

Rising population and the objective of promoting specific transport modes lead to changes and expansion in the transport system. An overview of these changes from 1990 to 2015 is presented in Table 1. The developments are presented for each transport mode and the therein contained categories for the years 1990 and 2015 (annual values are presented in the Supporting Information S2).

The transport behavior of Vienna’s population changed regarding the choice of transport mode. The share of motorized individual transport on the modal split decreased from 37% to 27% in the year 2015 (Figure 1, left). However, when considering the transport performance in terms of passenger kilometers traveled (PKT), the share of each transport mode is relatively constant over the same period (Figure 1, right). In total, the PKT within Vienna has increased by 36%, from 8,151 million PKT per year (mio PKT/a) in 1990 to 11,075 mio PKT/a in the year 2015.

#### 4.2 Material stock

The in-use MS of the transport system has increased by 26%, from 83 Mt in 1990 to 103 Mt in 2015 (Figure 2). The MS per capita (60 t/capita) increased slightly due to expansion activities in the middle of the period under consideration and has returned to 1990 levels due to stronger population growth in recent years (Figure 3b). In comparison, the overall MS in buildings in Vienna was calculated to be 210 t/capita according to Kleemann et al. (2017).

The infrastructure is distributed into three-quarters infrastructure for moving transport and one-quarter infrastructure for stationary traffic. The latter is only significant for motorized individual transport. Almost half of the motorized individual transport in-use MS is required for parking infrastructure. The proportion has even increased during the period considered (from 37% to 44%). This is mainly because the number of underground garages has increased significantly (by +38%) and parking space in an underground garage needs significantly more materials than a parking space at an outdoor parking lot. All vehicles together (cars and motorcycles 77%, lorry vehicles 14%, regional train 3%, metro, tram, and public bus vehicles together 4%) have a share of the total MS of around 1% (1.2 Mt) compared to the total infrastructure, as represented in Figure 2.

The three transport modes investigated show differences in their MS development, as presented in Figure 3a. The largest MS is attributed to motorized individual transport (62 Mt), followed by public transport (36 Mt), and non-motorized individual transport (6.6 Mt).
| Category | Service Unit (SU) | Unit | 1990 | 2015 | Change +/−  |
|----------|-------------------|------|------|------|------------|
| m.t.i.   | Total road area   | m²   | 21,199,000 | 22,843,000 | +8%        |
|          | Total road bridge area | m² | 789,000 | 941,000 | +19%        |
|          | Traffic light-signal system | n (number) | 890 | 1,310 | +47%        |
|          | Traffic signs and sign gantry | n | 55,000 | 60,000 | +9%         |
|          | Guard railing     | m   | 27,000 | 37,000 | +37%        |
|          | Area parking lanes and parking area on public property | m² | 3,911,000 | 4,261,000 | +9%        |
| s.t.i.   | Number of parking spaces in buildings and car parks | n | 117,000 | 213,000 | +82%        |
|          | Number of parking spaces on private property | n | 371,000 | 455,000 | +22%        |
| v.       | Total cars        | n   | 547,000 | 686,000 | +25%        |
|          | Total motorcycles | n   | 42,000 | 86,000 | +105%       |
|          | Total lorry type N1 (< 3.5 t) | n | 40,000 | 60,000 | +50%        |
|          | Total lorry type N2 (3.5–12 t) | n | 11,000 | 2,000 | −82%        |
|          | Total lorry type N3 (12–40 t) | n | 5,000 | 3,000 | −40%        |
| m.t.i.   | Total bicycle lane area | m² | 106,000 | 385,000 | +263%       |
|          | Total sidewalk area | m² | 8,998,000 | 10,935,000 | +22%       |
|          | Total pedestrian zone area | m² | 106,000 | 350,000 | +230%       |
|          | Total pedestrian and cycling bridge area | m² | 18,000 | 38,000 | +111%       |
| s.t.i.   | Bicycle stands    | n   | 130 | 39,000 |  |
|          | Rental bike stations (public) | n | 0 | 120 |  |
| v.       | Total bicycles    | n   | 917,000 | 1,121,000 | +22%       |
|          | Total pedelecs    | n   | 0 | 49,000 |  |
|          | Total citybikes   | n   | 0 | 2,000 |  |
| m.t.i.   | Regional train network length (both directions) | m | 40,000 | 87,000 | +118%       |
|          | Tram network length (both directions) | m | 182,000 | 190,000 | +4%         |
|          | Regional train stations buildings | m³ | 188,000 | 175,000 | −7%         |
|          | Regional train station platform roof | m² | 812,000 | 513,000 | −  |
|          | Regional train station facilities (platforms, underground crossing, shelter, stairways, and elevators) | n | 280 | 300 | +7%         |
| s.t.i.   | Tram depot buildings | m³ | 1,701,000 | 1,701,000 | ±0%         |
|          | Bus garage buildings | m³ | 176,000 | 451,000 | +156%       |
| v.       | Metro vehicles (all types) | n | 250 | 430 | +72%         |
|          | Regional train vehicles (all types) | n | 150 | 290 | +93%         |
|          | Tram vehicles (all types) | n | 1350 | 880 | −35%         |
|          | Bus vehicles (all types) | n | 650 | 1,130 | +74%         |

aIf there is no comparable value in 1990 (e.g., zero), the column “change” remains empty.

bMain train station (Hauptbahnhof) excluded in the total volume; actual data on the built-in material is included in the model.
FIGURE 2  Overall material stock development of Vienna’s transport infrastructure classified into infrastructure for moving transport (e.g., roads, train tracks), infrastructure for stationary traffic (e.g., park garages, train depots), vehicles, and annual material input and output flows. Underlying data used to create this figure can be found in the Supporting Information S2.

FIGURE 3  Material stock (MS) development from 1990 to 2015: (a) Material stock in infrastructure and vehicles per transport mode and material category; (b) Specific material stock in infrastructure and vehicles per capita divided into transport mode; (c) Material stock of the motorized individual transport vehicle fleet divided into material category. Underlying data used to create this figure can be found in the Supporting Information S2.
Non-motorized individual transport shows the highest relative growth rate, with an increase of 34% (+1.7 Mt). Growth is mainly due to the expansion of bicycle and pedestrian networks (+1.6 Mt), but also due to new services such as a public rental bike system (+>0.1 Mt). The relative increase in MS of public transport (+32%; +8.7 Mt) was higher in comparison to motorized individual transport (+22%; +11 Mt).

Regarding the relative material composition of the in-use MS, there has been no significant shift in the ranking, but the percentage distribution has changed. The two categories “gravel, sand, and natural stone” (58% → 53%) and “asphalt & bitumen” (16% → 14%) have decreased in relative terms. However, the share has increased for the material categories “concrete” (21% → 27%) and “iron & steel” (3% → 4%). All other material categories have a share of 1% or less of the overall in-use MS. The distribution and development of the various materials differs for the three transport modes, as shown in Figure 3a.

The vehicle number has increased (see Table 1), also in relative terms. For instance, the number of cars per 1,000 inhabitants increased in Vienna from 391 to 410, those of motorcycles from 28 to 47. Furthermore, the mean vehicle weight has increased; consequently, the total MS of vehicles increased by 32%. The motorized individual transport vehicle MS development is presented in Figure 3c. It also shows that the material composition has not changed significantly. Motorized individual transport vehicles have a share of over 90% of the total MS of all vehicles considered. This subcategory is dominated by cars (in 2015 >75%). However, the proportion of lorry vehicles has significantly declined, from 26% in 1990 to 15% in 2015 due to a drastic decrease (−70%) in the number of heavy lorry vehicles registered in Vienna (see Table 1).

Considering how intense infrastructure is used in terms of passenger kilometers traveled per ton of MS, the values for the transport modes investigated are in the same order of magnitude, with a range of 94 to 115 million passenger kilometers traveled per ton of MS.

### 4.3 Material input (MF\text{IN}) and Material output (MF\text{OUT})

The annual amount of materials built-in exceeds the removed materials from the system, as indicated by the growth of the overall MS. Moreover, the annual material demand (input flow) varies much more (from 1.5 to 3.8 Mt/year; mean 2.2 Mt/year) than the waste generation (output flow; 1.4 to 1.8 Mt/year; mean 1.6 Mt/year). This is explained by single construction activities. For instance, due to significant extensions of the metro network in the years 1991 and 1995, the MF\text{IN} into the system in these years are higher (yellow bars in Figure 2). In contrast, the calculated MF\text{OUT} is constant and amounts to about 1.6 Mt per year (blue bars in Figure 2).

Network expansions are also clearly reflected in the built-in material quantities when transport modes are compared. Figure 4 shows a comparison of MF\text{IN} and MF\text{OUT} into and from infrastructures per transport mode and material category. In chart (a) and (b) the MF are summed up to
5-year periods. In these periods in which public transport networks are being expanded, the respective quantities of MF\text{IN} are comparable to those of motorized individual transport. In other periods, the amount of material that is built in the public transport network is significantly less than that built in the motorized individual transport network. Hence, for the maintenance of the network, larger quantities of material are needed for the larger motorized individual transport network than for the public transport network, which is also reflected in the higher MF\text{OUT} of the motorized individual transport network. The dismantled materials are mainly caused by maintenance and are thus relatively constant in quantity and composition. If networks are extended, MF\text{IN} and MF\text{OUT} are different in terms of material composition. For instance, in the 5-year period (1991 – 1995) the MF\text{IN} in public transport is dominated by concrete, while at the same time much smaller amounts of concrete are dismantled. This is due to the extensions of the metro network in these years. However, in the following two periods (1996–2000 and 2001–2005) the material composition of the MF\text{IN} and MF\text{OUT} are comparable.

In chart (c) and (d) in Figure 4 the MF\text{IN} and MF\text{OUT} related to infrastructure are summed up for the period investigated. The motorized individual transport network has the highest resource demand and waste generation compared to all transport modes. It shows that the material category “asphalt & bitumen” was mainly built into the individual transport network. However, the largest share of concrete was built into the public transport network. The mass of built-in material in the motorized and non-motorized individual transport network within the 26 years amounts to roughly 50% of the initial in-use stock (1990). For the public transport network, the figure amounts to 85%.

The total MF\text{OUT} is also dominated by the motorized individual transport network (see Figure 4d). The MF\text{IN} and MF\text{OUT} for motorized individual transport infrastructure are dominated by maintenance processes, or more specifically, by mineral road construction material (50%). The summed-up MF\text{IN} (5-year periods) per process category shows that the maintenance of roads causes most MF\text{IN}, followed by maintenance of subsurface infrastructure (pipes and cables) and new road construction (see Figure 5).

5 | DISCUSSION

5.1 | The relevance of maintenance

The total in-use MS of the transport infrastructure in Vienna, including vehicles, is on average ∼46 times the annual MF\text{IN}. In other words, every 50 years the same amount of built-in material is built into the system as the amount of initial MS provided that the maintenance intensity remains unchanged. However, for expanding networks such as public transport, this rate is higher due to new construction (∼30 years).

Well-developed systems with low growth rates are characterized by lower fluctuations of the MF\text{IN}. Further, the MF\text{IN} is then dominated by maintenance, which is clearly reflected in the results for motorized individual transport. In the last 5 years, 10% of the use of road construction material was caused by new road construction and 55% by road maintenance. The findings on the importance of maintenance for MF\text{IN} and MF\text{OUT} in well-established, highly developed cities and regions is in line with other studies. For instance, Wiedenhofer et al. (2015) showed that for the time period 2004–2009 the inputs for maintenance of the European road and rail network exceeds the inputs for expansion between 1 and 6 times.

For the island of Samothraki in Greece, Noll et al. (2019) present a steadily growing resource requirement for the maintenance of buildings and infrastructure, which goes up to >80% of the overall input of construction material. Miatto et al. (2017) showed that most material inputs into the United States road network have shifted from new construction towards maintenance in the period investigated, from 1905 to 2015. Regarding road maintenance, the present paper illustrates that maintenance of subsurface networks contributes significantly to the MF\text{IN} and MF\text{OUT}. In Vienna, on average 28% (0.2 Mt/year) of annual MF\text{IN} for road construction is caused by maintenance of subsurface networks.
5.2 | Modified vehicle fleet

In its Smart City Wien Framework Strategy, the city of Vienna has defined a target according to which by 2050 all cars within the city limits must use alternative propulsion technologies (City of Vienna, 2019). In 2015, the proportion of vehicles with alternative propulsion technologies was less than 0.2% of all registered vehicles. Accordingly, the material composition of the MS (see Figure 3c) remains relatively constant. If the achievement of the targets is taken seriously, there will be significant changes in the composition of \( \text{MF}^{\text{IN}} \) and \( \text{MF}^{\text{OUT}} \) in the future. For instance, a higher share of batteries within vehicles can be expected. However, it will take many years before the entire fleet is converted to new propulsion technologies.

Although the stock renewal rate is 10% per year, so far most new vehicles have a fossil fuel driven propulsion technology (>98% in 2015). The propulsion technologies have not changed regarding lorry vehicles either. However, the number of registered heavy-duty vehicles have declined significantly. This is not due to a reduction in goods transport. In Austria, goods transport capacity (ton-kilometers) has increased by 170% since 1980 (Federal Ministry Transport, Innovation and Technology [BMVIT], 2012, 24). There is no data available for Vienna specifically, but it can be assumed that Vienna, with its strong economic performance, has the same or an even higher increase relative to Austria as a whole. In the year 2015, 75% of the goods transport volume (t) on roads in Austria was provided by lorry vehicles registered in Austria, but only 46% of the transport capacity (ton-kilometers) was provided by national carriers (Statistik Austria, 2017, 28). Heavy goods such as building materials are thus more likely to be supplied by national carriers, whereas international carriers supply consumer goods. The registered vehicles within a region, therefore, do not necessarily reflect the vehicle fleet traveling in this area.

5.3 | Model output in comparison to waste statistics

The available data concerning CDW arising in Vienna has been collected in an article by Lederer (2020) and is based on several sources (Lechner et al., 1995; City of Vienna Municipal Department 48 [MA 48], 2007, 2012; Environment Agency Austria [UBA], 1998). A comparison of waste statistics and the calculated model \( \text{MF}^{\text{OUT}} \) is only reasonable for selected waste fractions since only certain fractions within the available data sources can be clearly assigned to waste generated by civil engineering surfaces (e.g., CDW from buildings) and to waste generated by civil engineering underground (e.g., CDW from road and railway construction). Based on waste code numbers, two waste fractions are clearly attributable to the transport network, namely road construction waste (from surface layer) and track ballast waste. The calculated mean \( \text{MF}^{\text{OUT}} \) for “asphalt and bitumen” is around 0.27 Mt/year. This value is almost identical to the mean amount of road construction waste of 0.28 Mt reported in the statistics (values for 12 years). However, the calculated mean \( \text{MF}^{\text{OUT}} \) for “track ballast” of 0.12 Mt/year is five times higher than the mean reported track ballast waste (0.02 Mt/year). Only values for 6 years are reported in the statistics, thus the mean value gives rise to great uncertainties. Furthermore, some CDW fractions (e.g., track ballast, concrete waste) is processed at construction sites and reinstalled in the system, as described for the rehabilitation of rail infrastructure in Vienna by Gassner, Lederer, and Fellner (2018). In the model presented, however, such flows are accounted for as \( \text{MF}^{\text{IN}} \) and \( \text{MF}^{\text{OUT}} \). Hence, it also enables material and waste flows currently not regarded in waste statistics to be captured. For the circularity of materials in the construction sector, this means that official data tend to underestimate the real recycling rates, as on-site recycling activities are often not accounted for.

5.4 | Material stock to those of other case studies

The MS of the transport system contributes 22% to the total in-use MS in buildings and infrastructures. This corresponds to a share of about 20% for networks in heavily built-up areas referred to in the literature (Augiseau & Barles, 2017). When considering the MS per capita together with those for buildings calculated by Kleemann et al. (2017), the total in-use MS in Vienna (buildings and transport infrastructure) is around 270 t/capita (in 2015), which is below the global average for industrialized countries of 335 t/capita in 2010 (Krausmann et al., 2017) as well as for the countries of Japan (310 t/capita) and the United States (375 t/capita) specifically (Fishman, Schandl, Tanikawa, Walker, & Krausmann, 2014). However, it is comparable to the MS of 247 t/capita calculated with a bottom-up approach by Tanikawa and Hashimoto (2009) for the City of Wakayama. Wakayama has only about one fifth of the population of Vienna and has no metro network. In the same article, the authors also presented values for the City of Manchester; but with a MS of 111 t/capita, the values are much lower. With 248,000 t/km², the MS for buildings and transport infrastructure per area are the lowest for Vienna, compared to 1,121,000 t/km² (Wakayama) and 418,000 t/km² in Manchester. In contrast to the study at hand, only segments of the cities that were fully covered with buildings and streets are considered, which explains the lower material density with respect to area in Vienna.

All in all, the comparison with other studies shows, first, that only limited information about the material stock in the transport infrastructure of other cities is available. The building stock is more often the focus of investigations. This observation is interesting insofar as this transport infrastructure MS is managed by a few stakeholders only, making it thus much easier to implement new management concepts, such as the circular economy. Second, existing key figures for the per capita MS of the transport infrastructure might vary significantly between different regions, which most probably result from the settlement structure, but potentially may also derive from different methodologies, system boundaries and accounting systems applied in the studies. Only a larger number of MS studies, determined with comparable methods, will allow significant
comparison between cities. This circumstance also illustrates the importance of bottom-up studies when it comes to the setting or the assessment of set targets aiming to reduce the material consumption and increase recycling management within a specific region (e.g., Smart City Wien Framework Strategy), since figures from other regions provide only limited information about MS and especially MF for a specific region or rather are associated with large uncertainties.

5.5 | Limitations

The study at hand provides a detailed assessment of the transport system. However, as a transport system is complex, there are limitations and uncertainties to be dealt with in future research. Firstly, although the material inventory presented has a high level of detail, service units and material intensities were clustered in joint categories. As a result of the clustering, uncertainties and simplifications naturally occur. Secondly, no explicit recycling loops or cascading uses are included, but solely the magnitudes of MF (input, output) are discussed. Hence, no recycling rates are discussed in the paper at hand. Thirdly, the city level as system boundary presents some difficulties in terms of assessing transport systems. Cities are open systems and depend on the outside world (e.g., import and export of goods and labor) (Bai, 2007). Hence, cities are traffic hubs, and transport infrastructures are larger than what city dwellers alone might require for their exclusive needs. Fourthly, the data concerning transport performance is insufficient since there is no data source which publishes passenger kilometers traveled for Vienna on an annual or regular basis. In general, the availability of data can be described as inadequate with respect to traffic performance data (Ostermann et al., 2016). Consequently, to present a consistent time series, only values from one source (Austrian Institute for Regional Studies [OEIR], 2014) are considered in the study at hand.

6 | CONCLUSION AND OUTLOOK

To evaluate the in-use MS and related MF of Vienna’s transport infrastructure, a comprehensive model was set up. The retrospective investigation shows that the MS is still growing even though the city of Vienna already has a well-developed transport system. The distinction between different transport modes enables a direct comparison of the prevailing networks and their developments. It turns out that the dynamics of the transport modes investigated are different. Furthermore, they differ significantly in the material composition, thus impacting the recyclability of wastes generated thereof and the potential utilization of recycling materials. Within the period considered, the MS is dominated by motorized individual transport, followed by public transport, and non-motorized individual transport. However, the results highlight that the MS for the transport modes “public transport” and “non-motorized individual transport” have increased significantly over the last 25 years. This requires large quantities of $\text{MF}_{\text{IN}}$ for new construction of infrastructure, whereas the transport mode “motorized individual transport” shows a much lower growth rate. This is due to a change in transport policy, which promotes public transport and active mobility. Further, the results show that within well-developed systems the $\text{MF}_{\text{IN}}$ and $\text{MF}_{\text{OUT}}$ are more strongly related to maintenance and refurbishment processes. Moreover, the maintenance of other infrastructure networks can have a significant influence on the material consumption, as shown for the road infrastructure with the underground networks. Hence, a central management system for road maintenance and the maintenance of underground installations has great potential for saving resources, waste prevention and for promoting local use of secondary raw materials (e.g., for road substructure).

For future research, a common model of transport infrastructure and buildings should be considered to model all construction and demolition waste. In this way, the cascading use of construction material can be investigated. Furthermore, forecasts are of great interest with a focus on the targets set by the city of Vienna.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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