Modelling material flows and stocks of the road network in the United States 1905-2015

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Abstract

Recent years have seen a growing interest in the potential for a more circular economy and the application of material flow accounting to increase the knowledge base on materials accumulating in in-use stocks. This study assesses the dynamics of stocks and flows related to road networks, which are an important destination for recycled construction and demolition waste.

To assess the requirements of construction minerals of the road network in the United States we develop a bottom-up stock driven model to assess long-term inflows, outflows, and materials accumulated in roads. We estimate material requirements using the expansion of the transport network as a driver, and scheduled maintenance and technological coefficients from engineering literature to assess input and output flows. We apply the model to historical data for the United States road network from 1905-2015. We show that the current material stock of construction minerals in the road network of the United States is 15.1 billion tonnes, growing 21-fold since 1905.

During the 20th century, the material requirements of road construction have declined from 35% to 15% of economy-wide material consumption of non-metallic minerals in the United States. The share of roads in economy-wide in-use stocks has also declined from 17% to 13%. This shows that roads, once established, remain in place and the majority of material flows are due to extending and refurbishing them, while the construction of completely new roads make up a much smaller part of the material flows due to the road network.

Keywords: dynamic MFA; circular economy; recycling; material flow accounting; roads; in-use stocks;

1. Introduction

Construction minerals, including cement, bitumen, as well as sand and gravel, represent by far the largest fraction of all materials that are annually extracted and accumulate in buildings and various infrastructures as in-use stock (Krausmann et al., 2017). For many nations, they make up 50% of their domestic material consumption and up to 90% of material stock (Schandl et al., IN PRESS). Their extraction and processing, especially of cement for concrete, is an energy-intensive activity and as a result the embodied greenhouse gas emissions of this material flow category are also significant (Müller et al., 2013).

Despite the fact that non-metallic minerals, such as cement, bitumen, sand and gravel, are relatively benign environmentally, their sheer magnitude poses severe problems with local availability, transportation, land use change and landfilling of construction and demolition waste (Clark et al., 2006; Yoshida et al., 2016). To manage these materials and to improve recycling, it is essential to understand the magnitude of materials accumulated in buildings and transport infrastructure and to assess the dynamics of end-of-life flows to quantify the potential for recycling and for closing of loops (Haas et al., 2015; Wiedenhofer et al., 2015). Existing research has often focused on quantifying construction and demolition waste directly from on-site visits or via waste generation rates, while dynamic material flow approaches utilizing lifetimes have been much rarer (Wu et al., 2014). Recently methods were proposed to directly quantify in-use stocks accumulated within societies to allow to investigate the dynamics of material inputs and waste flows (see Augiseau and Barles, 2016 for a review). Assessing the recyclability of construction minerals waste (Pappu et al., 2007; Schiller et al., 2017), directly linked to in-use stock dynamics and input flows is hence an important step towards investigating the circular economy potential (Haas et al., 2015; Schiller et al., 2016).

Many studies on buildings stocks and flows are available (Augiseau and Barles, 2016), yet road networks tend to be understudied despite their quantitative relevance (Hashimoto et al., 2007, 2009, Kapur et al., 2008, 2009; Schiller et al., 2016; Wiedenhofer et al., 2015), and researchers advocate the importance of focussing on civil and infrastructure networks (Wu et al., 2014). Some studies explicitly discern the stock of buildings and infrastructure, but do not provide information about related material flows; others calculate both stocks and flows, but limit their analysis to specific materials (Shi et al., 2012), while others estimate total material stocks and waste flows, but do not differentiate between buildings and roads (Fishman et al., 2014). So far, material stocks and flows for roads and residential buildings combined have been investigated for the European Union (Wiedenhofer et al., 2015), and for the United States for several types of stocks, but only for cement (Kapur et al., 2008). The main reason why available models that calculate stocks and flows cannot be directly applied to road infrastructure is the different nature of transport infrastructure compared to buildings. While buildings get renovated for many different reasons, and are eventually demolished, cases of actual road removal are extremely rare, and in most cases roads are ‘removed’ simply by impeding vehicle access through gates or barriers (Switalski et al., 2004).

Buildings and roads are also very different with regard to where investment and operational spending comes from and in terms of ownership. Roads are usually common property, require public investment for building and maintenance and fall under different legislative control, depending on the type of road. They only generate an income if they are toll roads and operating models that include private ownership are the exception.

Roads also pose a difficulty for material flow accounting research because establishing the amount of materials required for the construction of roads and their maintenance is far from simple. Most studies so far adopt rule-of-thumb accounting strategies based on a limited number of factors and often without specifically referring to changing technical construction standards

over time; additionally differences in road types and the specifics of road construction and renewal need to be taken into account. This study aims to improve the knowledge base about the material requirements of roads, the magnitude of material accumulated in roads and waste flows from road refurbishment, specifically parametrized for the United States.

In this study, we design a stock-driven model that considers the specificities of different road types and the historical changes of technical construction standards. We establish a bottom-up methodology to estimate physical stocks of roads, and derive the related material requirements for road construction and maintenance using best practice engineering knowledge and physical data about the extent of road networks. This methodology permits us to estimate the material composition of the road network over time, the quantity of materials needed for expansion and maintenance and evolution in the ratio of the two. From this, we can estimate the potential of road construction to absorb road maintenance waste as well as building construction and demolition waste.

We apply this methodology to the United States of America, the country with the greatest extent of road network in the world (Central Intelligence Agency, 2013), for the years 1905–2015, to understand the material requirements to maintain in service what is by far the most common mean of transport in the United States (U.S. Department of Transportation, 2015a). For this purpose, we distinguish fourteen different road types and changes of technical construction standards over time. We intend to address the following questions: what is the size and composition of material stock of the US road network? What is the yearly requirement for virgin materials? What amounts of materials are recycled within the system? What is the yearly amount of waste flowing from road renewal? We relate the findings on material accumulation in roads to population, gross domestic product (GDP), and numbers of vehicles in circulation to gain a better understanding of the relationship between provisioning transport and mobility and the material underpinnings.

2. Methodology

2.1. Conceptual approach

While standard material flow accounts provide data on annual extraction and overall consumption of materials, they commonly do not include information about the specific uses of materials in different economic activities (Fischer-Kowalski et al., 2011; UNEP, 2015). In order to determine which fraction of the national yearly consumption of non-metallic minerals in the United States has been required to establish and maintain the road network we needed to develop an analytical approach which combines information about the evolution of the extent of the road network, of different road surfacing technologies, and of the material characteristics of these road types, to establish the overall inflows, accumulated material stocks, and outflows. This approach is operationalised in a model which is a bottom-up technology-based stock and flow representation of the material requirements of roads. The conceptual framework is schematised in Figure 1.

Figure 1 – Conceptual figure of the road material stocks and flows model.

2.2. Model

The model aims to calculate the material inflows, stock, and outflows of road networks, tracking the quantity of recycled asphalt and aggregate that is reused to make a new layer of tarmac, and the amount of scrape materials that can be recovered from the wearing layer and used in sublayers of new roads. The main parameter that feeds the model is the annual extension of the road network by road surface type. Four further variables allow calculation of total material inflows, stocks, and outflows of the road network: the maximum percentage of material removed during roadwork that can potentially be retrieved (maximum yearly recovery rate); the maximum percentage of recycled materials that are legally allowed to be used for repaving the wearing layer of a road (maximum yearly allowed recyclable content); scheduled maintenance intervals which vary according to road classification (the maintenance interval); and material intensity per unit length of road (material intensity). The model outputs are: yearly virgin material inflow, yearly recycled and down-cycled¹ material flow, total stock, and end-of-life waste.

A conceptual flowchart of the model is depicted in Figure 2. Different shapes have different meanings: parallelograms indicate data inputs and outputs; ovals indicate model variables; rectangles indicate internal operations; and hexagons indicate internal datasets. To keep this manuscript lean, we will limit the description of the model to its visual conceptualisation. Interested readers can find a detailed explanation in the Supporting Information §1.

Note that the model will calculate outflows coming only from the wearing layer and not count any outflows coming from sublayers. This is because, in most cases, when a road is ‘removed’ and disappears from statistics, it often means that it has been closed to traffic rather than being physically removed. Thereby these no longer used roads are obsolete or hibernating

¹ By recycled flows we mean those materials which are removed during scheduled maintenance from road wearing layers and are reused in the same layer. With down-cycled flows, we refer to those materials which are collected from wearing layer rubble, and are used in sublayers in the construction/improvement of roads.

stocks (Hashimoto et al., 2007). Only in very rare cases, mostly in protected areas, have a few kilometres of roads actually been removed (Switalski et al., 2004).

Figure 2 – Flowchart of the model. Note that different shapes indicate different functions: parallelograms for inputs/ outputs, ovals for variables, rectangles for operations, and hexagons for internal data.

2.2.1. Road material intensity

Our model simulates the road network in the United States from 1905 to 2015, and uses seven different road types: non-surfaced pavement, surfaced non-paved pavement, low-type pavement, intermediate-type pavement, flexible high-type pavement, rigid high-type pavement, and composite high-type pavement. These types make up the whole road network in the history of the United States road transport system.

Figure 3 – Cross section of pavement typologies. The measurements represent the height of each layer, and are expressed in millimetres.

A visual representation of the cross section of these seven pavement types is displayed in Figure 3. Thickness of layers have been derived from the detailed descriptions available in the Highway Statistic Summaries (U.S. Department of Transportation, Various years). Note that the bold lines present in each pavement in Figure 3 denote the limit between the wearing layer and, where present, a sublayer. A more detailed description of the different pavement types can be found in the SI §2.

2.3. Dataset

The dataset used for this study is sourced from the US Department of Transportation and covers the period from 1905 to 2015. The first report on the extent and type of roads was compiled by the US Office of Public Roads in 1904, separating roads into surfaced and non-surfaced. The report was updated in 1909 and 1914, and is available on a yearly basis from 1921 to 1979. A more detailed classification of road surface types has been available since 1941, and the classification system remained mostly unchanged until 2008. Roads were initially divided into: unpaved, low and intermediate types, high flexible and composite types, and a high rigid type. They were further categorised into rural and urban roads. Since 1996 the previous categories have been further disaggregated into: unpaved, low type, intermediate type, high flexible type, high composite type, and a high rigid type. The years 2009 and 2010 are not reported in the statistics, while from 2011 to 2015 the reports categorised urban and rural roads into the following four surface types: unpaved, bituminous surfaced, composite surfaced, and concrete surfaced (U.S. Department of Transportation, Various years). A detailed description of the material intensities of different surface types can be found in section §2.1 of the Supporting Information.

The data compilation method employed by the Department of Transportation changed over time: in the early years, roads were estimated at the national level through a survey.

Following the 1916 Federal Aid Road Act, each State was required to have a highway department to take charge of monitoring, administering, and maintaining its road network. From 1921 onwards, it has been possible to receive more precise data on the extent and condition of roads for all US States. From 1980, the Federal Highway Administration (FHWA) started accounting only for ‘public roads’ as defined by the 23 USC 402, resulting in a slight ‘artificial’ decrease in the total length of the road network (about 1.5% of roads were excluded). Continuous changes in accounting methodology over time have allowed for a progressive increase in the accuracy of the data and, despite being somewhat difficult to harmonise, our overall assessment is that the whole time-series is very well suited for the purpose of this study.

Given the composition of the available data, we decided to disaggregate the total road infrastructure into fourteen categories: seven types of road surfaces (non-surfaced pavement, surfaced non-paved pavement, low-type pavement, intermediate-type pavement, flexible high-type pavement, rigid high-type pavement, and composite high-type pavement), and two functional types (urban and rural roads). For the missing years, such as between 1904 and 1909, we linearly interpolated the missing values, while for those years where categories were grouped (e.g. low- and intermediate-type pavement) we applied shares of types from neighbouring years.

2.4. Sensitivity analysis

While the available data and literature provides a large amount of information and confidence in the parameters that have been used in our model, we decided to verify the accuracy of our results by conducting a sensitivity analysis. We tested which model parameters would have the strongest effect on the overall results, and to which extent. By altering each parameter individually, we determine the overall effects of those changes on the model.

Out of all the parameters in the model, the only one that affects the account of the stock is the material intensity of roads. Using a bottom-up model, all it requires to calculate the stock is an object inventory (in our case the length of roads), and a parameter that acts as the density of these objects (in our case the material intensity of roads per unit of length).

The remaining three parameters of the model (maintenance interval, max yearly allowed recyclable content, and max yearly recovery rate) will affect only the inflows and outflows of materials, but are expected to have no effect on overall stock.

2.5. Limitations of the approach

The model relies on official statistical information for the total extent of the road network, and on engineering knowledge on best practices in construction and maintenance to infer the overall material requirements of this fundamental infrastructure. In simulating the evolution of the material consumption over the past 110 years, we had to use the following assumptions:

The model categorises 14 types of roads (7 types of pavements divided into urban and rural), and for each type of road assumes cyclical renovation at a certain interval. While we apply different periodic maintenance, it must be assumed that in reality shorter or longer lifespans occur, or that these intervals change over time. Furthermore, economic conditions, weather patterns, calamities, or unpredicted alterations in local traffic can shorten or increase the maintenance intervals. This means that the chosen maintenance schedules bear a level of error for which we can’t control.

The total height and width of the road types have been calculated according to technology assumptions and road types, and are based on information provided in official statistics (see SI §2 for a detailed description of this). It is impossible, however, to determine the exact thickness of each road since this greatly depends on traffic and soil composition, which can

only be estimated through on-site surveys. Other parameters that affect design requirements of roads are specific weather patterns (e.g. seasonal heavy rains) and the gradient of the terrain. This creates additional uncertainty for the overall results.

It is also difficult to judge the accuracy of the historical road length data found in the statistics. While we can assume that in recent years, with the progress of technologies for surveying and mapping, the dataset should be very precise, the same cannot be assumed for older statistics.

Roads are recorded in official statistics once they are open for transit, and not during their progressive construction. Relying on reported statistics for the model means a road that took 5 years to be completed will be recorded in the year of completion and not progressively during its construction. That may create certain shifts in material requirements between years but will not affect the overall amount.

The model reports the inflows of ‘virgin’ materials required for the construction and maintenance of new roads. We need to point out that often roads are used to accommodate large amounts of building demolition waste. While this practice is formally a way of down-cycling, in this research we calculate down-cycled materials that stem from the wearing layer of roads and are moved to sublayers. It is hard to judge how much material recycling of building construction waste has occurred historically in the United States. Supporting structures for roads such as bridges and tunnels, for instance, also require large amounts of construction materials which are excluded from this analysis.

Despite these limitations, we trust that this account is the most detailed and robust analysis of material flows in the road sector available to date.

3. Results

3.1. Material stock

This study quantifies material stocks and flows for constructing and maintaining the road network of the United States of America from 1905 to 2015. The model discerns the five materials that are the main constituents of roads: rammed earth, gravel, sand, cement, and bitumen.

The material stock of the United States road network is plotted in Figure 4. The two decades from 1905 to 1925 saw a rapid extension of the road network from 3.8 million to 5.2 million kilometres, which was followed by a long period of incremental growth, including the upgrading of existing roads. The material stock in roads in 1905 was 0.7 billion tonnes and the quantity of materials stocked in each kilometre of road was 180 tonnes. The last century saw material stocks in roads growing rapidly at a compound annual growth rate of 2.8%, reaching 15.1 billion tonnes in 2015. At that time, the total extent of roads was about 6.6 million km, with in an average material content of 2,268 tonnes per km, i.e. more than ten times the level in 1905.

Gravel used in road base dominates material accumulation in roads and the share of materials has shifted somewhat over time. In 1905, the most used material was gravel (65%), followed by rammed earth (16%), and sand (14%). Over time roads increased their average depth to carry more traffic and heavier vehicles. The share of gravel rose to 92%, followed by sand (6%), and cement (2%). Bitumen, which is used as a top layer, never accounted for more than 1% of total stock since asphalt concrete is composed of 95% gravel and only a small share of bitumen (excluding air and other minor components). With bitumen density much lower than gravel, this explains the very low share of this material in the overall stock.

Figure 4 – Material stock of the US road network, years 1905–2015. The left ordinate axis plots the material content in gigatonnes ($1 \text{ Gt} = 10^{15} \text{ g} = 1 \text{ Pg}$), while the right ordinate axis plots the total length of roads in km.

3.2. Material flows

3.2.1. Material inflows

We account for the yearly quantities of materials that are required for building and maintaining the road network, i.e. all materials coming from any source other than scraping from existing roads, with no distinction between materials coming from quarrying (properly labelled as virgin materials) and demolition rubble (formally down-cycled materials). We are labelling them as virgin materials, in the sense that they come from outside of our system boundaries (cf. Figure 1).

Figure 5 – Virgin material inflows for constructing and maintaining the US road network. The units are megatonnes ($1 \text{ Mt} = 10^{12} \text{ g} = 1 \text{ Tg} = 1 \text{ million of tonnes}$).

Figure 5 shows that in 1905 the yearly material requirements for roads were 38.6 million tonnes of mainly gravel (83%), sand (12%), and cement (3%). The yearly inflows progressively grew to 535.4 million tonnes in 2015, composed mainly of gravel (93%), sand (3%) and bitumen (3%). While the absolute peak of material requirements for roads was recorded in 1984 with 898.8 million tonnes, it appears that the inflows grew in a roughly linear fashion, at a compound annual growth rate of 2.4%. The peaks of 1980 and 1984 were caused by two large reported increases in flexible paved roads over a steep decrease of unsurfaced and unpaved roads (cf. Figure SI 10), hinting that during those years the US Department of Transportation was investing heavily in improving rather than expanding the existing road network. As reported in the Summary for 1985 ‘Although changes in total mileage are small, there have been many changes in the quality of highways, such as surfacing roads, widening existing pavements, reducing grades, minimising curves, eliminating railroad grade crossings, and other improvements to provide safer, more efficient use’ (U.S. Department of Transportation, 1985). An additional reason is that the model is coded to notice new construction once this has been reported in the official statistics, and accounts for all inflows required for construction in that same year. In reality, the actual construction process might have lasted for a number of years, which creates distortion in yearly inflows, especially for very large projects. To moderate the potential error, Figure 5 displays a 3-year moving average that levels peaks and troughs. Using the 3-year moving average, the highest peak appears in 1980, when around 610 million tonnes of materials were required.

3.2.2. Recycled and down-cycled material flows

The large material requirements for road construction and maintenance come from two sources, as explained above, and they are hard to distinguish in the absence of reliable data. Materials collected during the maintenance of the wearing (upper) layer of roads are often reused in the newly renovated layer but the share of reused material is determined by technical constraints. Less restricted is the use of recovered materials from the wearing layers for beddings

(sublayers) of newly constructed roads. The model accommodates these different types of reuse by dynamically changing the shares of usage of these materials.

Figure 6 – Recycled and down-cycled flows differentiating construction materials into eight different categories, from year 1905 to 2015. The units are megatonnes ($1 \text{ Mt} = 10^{12} \text{ g} = 1 \text{ Tg} = 1 \text{ million of tonnes}$).

Flows of recycled and down-cycled materials are displayed in Figure 6. These flows were practically irrelevant in the early 20th century (0.007 Mt in 1905), and start being noticeable around 1955, when flows reached 11.9 million tonnes of which 6.5 million tonnes were recycled into new top layers of roads and 5.3 million tonnes were down-cycled. In 2015, the total flows were 111.2 million tonnes but, as is clear from the chart, the down-cycled component has been very erratic since 1980. This reflects the fact that in more recent years there has been hardly any construction of new roads but merely a focus on road upgrading, extension and refurbishment, hence the model does not allocate any down-cycled materials for some years. For this reason, we believe that the moving average, showing a flow of 259.8 million tonnes for 2015, is a more realistic value than the actual modelled data. A figure showing the share of recycled and down-cycled materials from roads, as well as the share of material inflows for other sources (virgin and construction demolition), is available in the SI §4.

3.2.3. End-of-life outflows

Those materials which are demolished from the wearing layer, and are not reallocated in renovated pavement (recycled flows) or new road beddings (down-cycled flows), are considered as waste heading for waste disposal (cf. Figure 1).

End-of-life outflows

Figure 7 – End-of-life outflows for five building materials, from 1905 to 2015. The units are megatonnes ($1 \text{ Mt} = 10^{12} \text{ g} = 1 \text{ Tg} = 1 \text{ million of tonnes}$).

The waste flows are shown in Figure 7. In 1905, the end-of-life (EoL) flows were 13.3 million tonnes, which then grew steadily until 1967 reaching 227.2 million tonnes. Since then the yearly EoL flows have fluctuated, peaking at 504.4 million tonnes in 2015, but also showing values as low as 48.3 Mt in 2008 caused by the nature of the statistical reporting and the model's behaviour. The moving average, on the other hand, shows an overall increasing trend in waste flows, peaking at 497.4 million tonnes in 2011.

3.3. Socio-economic indicators

In this section, we present how the road network has evolved over time in comparison to the growth of its material stock, population, and number of vehicles using the road network.

The number of registered vehicles was 78,800 in 1905, and grew massively to 263,610,219 for the year 2015, at a compound annual growth rate of 7.7%, much faster than the road network itself or the material accumulated in roads.

Growth of the US road network and other relevant parameters

Figure 8 – Indicators of population, road mileage, material stock, and number of registered motor vehicle. Indexed as 1905 = 1. Note that the number of registered motor vehicles is indexed on the right vertical axis, while all the other parameters are plotted on the left axis.

Figure 8 shows growth in population, road mileage, road stock, and registered vehicles in the United States (indexed to 1905 = 1). The overall road network grew slowest at 0.5% per year on average pointing to a much higher utilisation of roads today than in the past. Population in the United States was 84 million in 1905 and grew to 321 million in 2015, a factor of 3.8 with a compound yearly growth rate of 1.2%. The material stock of roads, as already mentioned in 3.1, was 0.7 Gt in 1905, and 15.1 Gt in 2015, increasing over 21-fold, at a rate of 2.8% per year. The parameter which grew the most was the number of registered vehicles. It was 78,800 in 1905 (about 1 vehicle per 1000 persons), and soared to 263,610,219 for the year 2015 (about 820 vehicles per 1000 persons), growing 3345.3 times in 110 years, with a compound annual growth rate of 7.7% (note that in Figure 8 this is plotted on the right axis, while material stock is plotted on the left axis). The rapid growth of circulating motor vehicles required existing roads to be overhauled and improved to sustain increasing loads and travel speed, but this also posed new issues such as traffic management and increased congestion (Owen, 1958).

3.4. Sensitivity analysis results

The model's sensitivity has been tested as described in 2.4. The account of the stock is linearly affected by alterations in the material intensity parameters. This is because, continuing the analogy described in 2.4, if we interpret road length as a volume, and material intensity as a density, the total weight is calculated as volume per unit of density. The results of this test are shown in Table 1. The overall stock in 2015 accounted for 15.1 Gt. An alteration of ± 1 m to the width of roads generated a difference of ± 1.7 Gt (from 13.4 Gt to 16.8 Gt), while a change in the layer thickness of $\pm 30\%$ showed a change of ± 4.5 Gt (from 10.5 Gt to 19.6 Gt). While these differences might seem relevant at a first glance, the Highway Statistics give ranges of thickness that strengthen confidence in the values we adopted.

Table 1 – Sensitivity analysis of stock, virgin inflows, and waste outflows for the parameter ‘material intensity’.

	Default parameters		Road width $\pm 1m$		Material intensity $\pm 30\%$		Combined (extreme cases)	
Stock	1905	0.7 Gt	1905	0.6 Gt 0.8 Gt	1905	0.5 Gt 0.9 Gt	1905	0.4 Gt 1.1 Gt
	2015	15.1 Gt	2015	13.4 Gt 16.8 Gt	2015	10.5 Gt 19.6 Gt	2015	9.4 Gt 21.8 Gt
Virgin inflows	1905	38.6 Mt	1905	34.1 Mt 43.2 Mt	1905	27 Mt 50.2 Mt	1905	23.9 Mt 56.1 Mt
	2015	535.4 Mt	2015	485.7 Mt 585.2 Mt	2015	374.8 Mt 696.1 Mt	2015	340 Mt 760.7 Mt
Waste outflows	1905	13.3 Mt	1905	11.9 Mt 14.7 Mt	1905	9.3 Mt 17.3 Mt	1905	8.3 Mt 19.1 Mt
	2015	504.4 Mt	2015	457.7 Mt 551 Mt	2015	353.1 Mt 655.7 Mt	2015	320.4 Mt 716.3 Mt

Changes in the remaining three model parameters (maintenance interval, max yearly recovery rate, and max yearly allowed recyclable content) have no effect on the calculation of the total stock, but change the results for inflows and outflows. The results are displayed in Table 2. The maintenance interval is the only parameter which has immediate effect from the beginning, being due to the other parameters being modelled not to kick in until after World War II, and is the parameter that has the overall highest effect on flows. In the extreme case of all the parameters contributing to reduce/increase overall inflows and outflows, the results show a difference of -29.5% $+55.8\%$ of inflows, and -31.2% $+59.2\%$ of outflows.

Table 2 – Sensitivity analysis for virgin inflows and waste outflows the parameters maintenance interval, max yearly recovery rate, and max yearly allowed recyclable content.

	Default parameters		Maintenance interval $\pm 30\%$		Recovery rate median ± 20 y		Recyclable content $\pm 10\%$		Combined (extreme cases)	
Virgin inflows	1905	38.6 Mt	1905	35.6 Mt 44.3 Mt	1905	38.6 Mt 38.6 Mt	1905	38.6 Mt 38.6 Mt	1905	35.6 Mt 44.3 Mt
	2015	535.4 Mt	2015	414.5 Mt 760 Mt	2015	535.4 Mt 535.4 Mt	2015	488.4 Mt 582.5 Mt	2015	377.2 Mt 834.2 Mt
Waste outflows	1905	13.3 Mt	1905	10.2 Mt 19 Mt	1905	13.3 Mt 13.3 Mt	1905	13.3 Mt 13.3 Mt	1905	10.2 Mt 19 Mt
	2015	504.4 Mt	2015	383.5 Mt 728.9 Mt	2015	504.4 Mt 504.4 Mt	2015	457.3 Mt 551.5 Mt	2015	346.1 Mt 803.1 Mt

A more detailed report on the results of the sensitivity analysis, including charts, can be found in the SI §1.6.

4. Discussion

4.1. Of all the materials yearly consumed and stocked in the US, what proportion goes into road construction and maintenance?

In the absence of other studies that explicitly calculate material stock for the road construction sector of the United States we can refer to other research estimating the share of materials used for roads compared to the overall use of construction materials. In a recent study, Fishman et al. (2014) calculated the stock of construction materials in the United States as 11.8 billion tonnes in 1930 and 107.5 billion tonnes in 2005. Compared to our own calculation, which estimated 2 billion tonnes and 14 billion tonnes of accumulated material in roads for the

same period, it appears that the share of materials stocked in roads decreased over time, from 17% to 13% of overall building material accumulated in stocks. While not accounting specifically for the road stock, Kapur et al. (2008) analysed the stocks and flows of cement in the United States from 1900 to 2000. Their research accounted for 3.9 billion tonnes of cement stocked in the country for the year 2000 across all economic sectors. We estimated an in-use cement stock of 0.3 billion tonnes of cement in roads for the same year, accounting for 8% of total stock.

No further studies have calculated the material stock of construction minerals in the US, but numerous studies have calculated national economy-wide material flows. Gierlinger and Krausmann (2012), covering a period from 1870 to 2005, estimated an apparent consumption of 104 million tonnes of non-metallic minerals in 1905, and 3,578 million tonnes in 2005. Our research accounted for an inflow of 38.6 million tonnes in 1905 and 502.5 million tonnes in 2005, showing a decreasing importance of construction materials for roads, from 37% to 14%. A global study on the apparent consumption of non-metallic minerals from 1970 to 2010 (Miatto et al., 2016) recorded a domestic material consumption for the United States of 1,760 million tonnes for 1970 and 2,654 million tonnes for 2005. Compared to this study, this reflects inflows of 441 million tonnes and 503 million tonnes for the respective years, showing shares of 25% and 19%. A third available dataset reported the apparent consumption of non-metallic minerals in the USA as 1,493 Mt and 3,683 Mt for the years 1970 and 2005 respectively (Schandl et al., IN PRESS). Compared to our findings, the share that is used for streets and highways is 30% and of 14% respectively. Similar shares of road related material use in economy-wide material consumption have been reported for the EU25 (Wiedenhofer et al., 2015)

It appears that, despite having some variability, all studies accord in pointing out that while total material inflows into the road network are increasing, these flows constitute a decreasing share of the economy-wide domestic material consumption in the United States. This is likely due to a priority on improving and upgrading the quality and safety of existing roads, over an increase in the overall network coverage over the past 40 years (cf. Figure 4) (U.S. Department of Transportation, Various years). This trend might be also explained by the stark decrease of road length per capita (46 m/person in 1905 to 21 m/person), paired with the increased urban population (United Nations, Department of Economic and Social Affairs, Population Division, 2015) and decrease of average household size (U.S. Census Bureau, 2016). While this can be interpreted as a positive thing for the environment, in the sense that roads require a decreasing share of materials, our findings also show that absolute demand does not show signs of decrease.

4.2. For how much longer can roads be used to down-cycle demolition rubble?

In many countries, roads have been used as a convenient place to down-cycle construction demolition waste. The slow pace at which new roads were constructed in the United States during the second half of the twentieth century still proved to be sufficient to absorb a good part of the construction and demolition rubble that was produced during those years (U.S. Environmental Protection Agency, 1998). Yet, recent research points out that the twenty-first century will be characterised by unprecedented flows of demolition waste from ageing building stock built in the post-war era (Müller, 2006).

A recent report by the US Environmental Protection Agency calculated that in the years 2012 to 2014 an average of 160.4 million tonnes of C&D were produced from demolished buildings, of which 81.4 million tonnes (51%) were concrete (U.S. Environmental Protection Agency, 2016). For the same years, our model shows an average requirement of 145.4 million tonnes of materials to construct the sublayers of new and upgraded roads. Considering that construction demolition waste in the United States is forecast to double every 16 years (Miatto et al., 2017) the absorptive capacity of road construction and maintenance for this waste flow will

reach its limits. Our model shows a slowly decreasing overall trend in the requirement for new road bedding since the 1950s. At an average requirement of around 150 billion tonnes per year we estimate that by 2033 the waste absorption potential of roads for construction and demolition waste will lie below waste disposal. This number is purely theoretical, and does not take into account the locations at which the construction demolition waste occurs and where it could be used. It is important to note that shipping rubble can quickly become uneconomical, making local quarrying a more viable choice (Robinson Jr and Brown, 2002).

4.3. Changing technological construction standards for roads in the United States

Contrary to what might be commonly assumed, the total length of the road network in the United States did not even double over the last 110 years (cf. Figure 4), and was not linked to the spread and surge of the popularity of motor vehicles (cf. Figure 8). Yet, despite not changing significantly in terms of extent, paving technology has seen a dramatic technological leap: in face of a 1.75-fold extension in the network, the amount of non-metallic minerals that has become part of the road network has increased 21-fold (cf. Figure 8). The average material intensity of roads shifted from 180 t/km in 1905 to 2,268 t/km in 2015.

This huge change of material intensity has been triggered by the incredibly rapid diffusion of motor vehicles at the start of the twentieth century, increasing haulage and travel speed to a point that was not contemplated by contemporaries (Lay and Vance, 1992). At the start of 1900 the majority of roads were simple ways cleared of obstacles to allow the passage of horses and caravans, and they soon proved unsuitable for sustaining the mechanical stress induced by the much faster and heavier new motor vehicles. Engineers had to face the challenge of renovating existing road infrastructure to make it suitable for the new requirements. The answer was an increase in depth of road beds to better distribute and absorb heavy loads, a rapid diffusion of bitumen concrete to stabilise sublayers to allow high speed travel, and the improvement of roads to reduce steep grades and increase curve radiuses (Steinberg, 1926). This is evident when looking at the change in the share of pavement types (cf. Figure SI 9 and Figure SI 10) over time. In 1905, unsurfaced roads made up 91% of the total road network. By the end of WWII unsurfaced roads were less than 50%, and by 2015 only 6% of the whole mileage.

The United States, similar to other countries, has experienced a co-evolution of vehicle technology and road engineering requirements. This has especially been the case for heavy vehicles for freight transport, which have increasingly replaced other means of transport such as shipping and rail (U.S. Department of Transportation, 2015b). Further increases in transport volume and vehicle tonnage may require further technical upgrades of roads in a context where the cost, both financial and material, for roads has been dominated by maintenance rather than for new roads (cf. Figure SI 12 and U.S. Department of Transportation, Various years). Using this model and the data collected, these issues could be explored further.

5. Conclusions

Roads provide an invaluable service to modern societies: they allow people and goods to move quickly and efficiently, while at the same time offering a useful way to dispose of construction demolition waste originating from the building sector. Until today a detailed longitudinal report of the material requirements, waste production, and absorption potential of this important in-use stock, as well as an estimation of its share of the total yearly consumption of construction minerals, was not available for the United States.

This research has introduced a novel methodology to investigate the material stocks and flows of road networks. The material stock has been calculated through a bottom-up approach,

and the flows have been derived using a series of technical parameters that estimate materials required to extend and maintain the network. These technical parameters were sourced from national specific construction standards. The results show that the United States road stock increased 21-fold over 110 years, growing from 0.7 billion tonnes in 1905 to 15.1 billion tonnes in 2015. This massive growth of in-use materials has not only been driven by the extent of roads, but rather more by technical improvements including greater road base depth and better surfacing. This is reflected in a 13-fold increase in the construction materials intensity of road construction, which was on average across 14 different road types, 180 t/km in 1905 and 2,268 t/km in 2015.

With regard to material flows, we estimate that, by 2015, 615 million tonnes of non-metallic minerals were used every year to maintain existing roads in operation, which amounts to approximately 15 to 20% of the economy-wide domestic consumption of non-metallic minerals in the United States. Of these, about 520 million tonnes were sourced from quarries or construction demolition. An additional 115 million tonnes are consumed every year, on average, to build new roads or upgrade existing ones. At the same time, we estimate that the average yearly amount of materials being treated as road waste had reached 350 million tonnes in 2015.

The sheer values that characterise the twenty-first century are very different from the early twentieth century. 17 million tonnes of materials, practically all coming from virgin natural resources, were necessary to maintain the network. On average, but with a clear growing trend over time, 33 million tonnes of materials were required yearly to grow and improve the road network, while end-of-life flows accounted for 17 million tonnes of waste, reflecting the very low recycling potential at that time. The majority of the material requirements shifted from new construction and upgrades to maintenance.

While we are now, for the first time, able to sense the scale of material flows and stocks of road networks in relation to the consumption of the whole United States economy, a series of unresolved questions arise. Firstly, the dynamics of the building stock are an important factor for the quantities of down-cycled materials that end up in road construction. This information would enable more directly linking economy-wide material consumption to their specific uses and in-use stocks. Secondly, the potential for greater circularity of materials in the economy could be further explored if different in-use stock dynamics would be investigated jointly, to infer potentials towards closing regional material loops also between different stock types (Schiller 2016, 2017, Wiedenhofer et al. 2015, Tanikawa et al. 2015). Furthermore, it would have been interesting to also include the current energy requirements to maintain, extend, and improve the road network, and how would this change in case of a mode shift in transportation away from roads? How would a change in current practices affect CO₂ emissions and related reductions in maintenance turnover? What are the financial requirements for road maintenance and who is going to pay? Despite these obvious further research needs, we now have a methodology that can be applied at a national level to improve accounts for non-metallic minerals for road construction using more detailed information about the extent of the road network and characteristics of different types of roads. In this regard, this study marks an important advancement in the pursuit of measuring the metabolic performance of economies to provide headline indicators and policy guidance for sustainable material management.

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7. References

- Augiseau, V., Barles, S., 2016. Studying construction materials flows and stock: A review. *Resour. Conserv. Recycl.* doi:<http://dx.doi.org/10.1016/j.resconrec.2016.09.002>
- Central Intelligence Agency, 2013. *The World Factbook 2013-14*. Washington, D.C.
- Clark, C., Jambeck, J., Townsend, T., 2006. A Review of Construction and Demolition Debris Regulations in the United States. *Crit. Rev. Environ. Sci. Technol.* 36, 141–186. doi:10.1080/10643380500531197
- Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting. *J. Ind. Ecol.* 15, 855–876.
- Fishman, T., Schandl, H., Tanikawa, H., Walker, P., Krausmann, F., 2014. Accounting for the material stock of nations. *J. Ind. Ecol.* 18, 407–420.
- Gierlinger, S., Krausmann, F., 2012. The physical economy of the United States of America. *J. Ind. Ecol.* 16, 365–377.
- Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *J. Ind. Ecol.* 19, 765–777. doi:10.1111/jiec.12244
- Hashimoto, S., Tanikawa, H., Moriguchi, Y., 2009. Framework for estimating potential wastes and secondary resources accumulated within an economy – A case study of construction minerals in Japan. *Waste Manag.* 29, 2859–2866. doi:10.1016/j.wasman.2009.06.011
- Hashimoto, S., Tanikawa, H., Moriguchi, Y., 2007. Where will large amounts of materials accumulated within the economy go?—a material flow analysis of construction minerals for Japan. *Waste Manag.* 27, 1725–1738.
- Kapur, A., Keoleian, G., Kendall, A., Kesler, S.E., 2008. Dynamic Modeling of In-Use Cement Stocks in the United States. *J. Ind. Ecol.* 12, 539–556.
- Kapur, A., van Oss, H.G., Keoleian, G., Kesler, S.E., Kendall, A., 2009. The contemporary cement cycle of the United States. *J. Mater. Cycles Waste Manag.* 11, 155–165. doi:10.1007/s10163-008-0229-x
- Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., Haberl, H., 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proc. Natl. Acad. Sci.* doi:10.1073/pnas.1613773114
- Lay, M.G., Vance, J.E., 1992. *Ways of the World: A History of the World's Roads and of the Vehicles that Used Them*. Rutgers university press.
- Miatto, A., Schandl, H., Fishman, T., Tanikawa, H., 2016. Global Patterns and Trends for Non-Metallic Minerals used for Construction. *J. Ind. Ecol.* n/a–n/a. doi:10.1111/jiec.12471
- Miatto, A., Schandl, H., Tanikawa, H., 2017. How important are realistic building lifespan assumptions for material stock and demolition waste accounts? *Resour. Conserv. Recycl.* 122, 143–154. doi:<http://doi.org/10.1016/j.resconrec.2017.01.015>
- Müller, D.B., 2006. Stock dynamics for forecasting material flows—case study for housing in The Netherlands. *Ecol. Econ.* 59, 142–156.
- Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S., Brattebø, H., 2013. Carbon Emissions of Infrastructure Development. *Environ. Sci. Technol.* 47, 11739–11746. doi:10.1021/es402618m
- Owen, W., 1958. Automotive Transport in the United States. *Ann. Am. Acad. Pol. Soc. Sci.* 320, 1–8.
- Pappu, A., Saxena, M., Asolekar, S.R., 2007. Solid wastes generation in India and their recycling potential in building materials. *Build. Environ.* 42, 2311–2320. doi:<https://doi.org/10.1016/j.buildenv.2006.04.015>

- Robinson Jr, G.R., Brown, W.M., 2002. Sociocultural dimensions of supply and demand for natural aggregate—examples from the Mid-Atlantic Region, United States. *US Geol. Surv. Open-File Rep.* 2, 350.
- Schandl, H., Fischer-Kowalski, M., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T., IN PRESS. *Global Material Flows and Resource Productivity: Forty Years of Evidence*. *J. Ind. Ecol.*
- Schiller, G., Gruhler, K., Ortlepp, R., 2017. Continuous Material Flow Analysis Approach for Bulk Nonmetallic Mineral Building Materials Applied to the German Building Sector. *J. Ind. Ecol.* doi:10.1111/jiec.12595
- Schiller, G., Müller, F., Ortlepp, R., 2016. Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resour. Conserv. Recycl.* doi:10.1016/j.resconrec.2016.08.007
- Shi, F., Huang, T., Tanikawa, H., Han, J., Hashimoto, S., Moriguchi, Y., 2012. Toward a Low Carbon–Dematerialization Society. *J. Ind. Ecol.* 16, 493–505. doi:10.1111/j.1530-9290.2012.00523.x
- Steinberg, S.S., 1926. Building American Highways for Safety. *Sci. News-Lett.* 10, 85–86.
- Switalski, T., Bissonette, J., DeLuca, T., Luce, C., Madej, M., 2004. Benefits and impacts of road removal. *Front. Ecol. Environ.* 2, 21–28. doi:10.1890/1540-9295(2004)002[0021:BAIORR]2.0.CO;2
- UNEP, 2015. Global material flow and resource productivity dataset. [WWW Document]. URL (accessed 11.5.15).
- United Nations, Department of Economic and Social Affairs, Population Division, 2015. *World Urbanization Prospects: The 2014 Revision* (No. ST/ESA/SER.A/366).
- U.S. Census Bureau, 2016. Changes in household size 1940-2016.
- U.S. Department of Transportation, 2015a. Weight of Shipments by Transportation Mode [WWW Document]. URL https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/data_and_statistics/by_subject/freight/freight_facts_2015/chapter2/table2_1 (accessed 5.19.17).
- U.S. Department of Transportation, 2015b. Freight Facts and Figures 2015.
- U.S. Department of Transportation, 1985. Highway Statistic Summary to 1985. U.S. Department of Transportation, Washington, D.C.
- U.S. Department of Transportation, Various years. Highway Statistic Summary. U.S. Department of Transportation, Washington, D.C.
- U.S. Environmental Protection Agency, 2016. Construction and demolition debris generation in the United States, 2014.
- U.S. Environmental Protection Agency, 1998. Characterization of building-related construction and demolition debris in the United States (No. EPA530-R-98-010). United States Environmental Protection Agency.
- Wiedenhofer, D., Steinberger, J.K., Eisenmenger, N., Haas, W., 2015. Maintenance and expansion: modeling material stocks and flows for residential buildings and transportation networks in the EU25. *J. Ind. Ecol.* 19, 538–551. doi:DOI: 10.1111/jiec.12216
- Wu, Z., Yu, A.T.W., Shen, L., Liu, G., 2014. Quantifying construction and demolition waste: An analytical review. *Waste Manag.* 34, 1683–1692. doi:10.1016/j.wasman.2014.05.010
- Yoshida, K., Fishman, T., Okuoka, K., Tanikawa, H., 2016. Material stock's overburden: Automatic spatial detection and estimation of domestic extraction and hidden material flows. *Resour. Conserv. Recycl.* doi:http://dx.doi.org/10.1016/j.resconrec.2016.09.010

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