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The use of steel in the United Kingdom's transport sector

A stock–flow–service nexus case study

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Abstract

Energy and material flows and material stocks are key requirements for the supply of goods and services, which in turn support societal development. However, most resource accounting methods restrict the analysis to resource flows, which fails to acknowledge the increasing role of in-use stocks in service provision. Using the UK transport sector as a case study, we undertook a material flow analysis through the lens of the stock–flow–service (SFS) nexus. We used the latter to identify how steel consumption and accumulation in vehicles contributed to passenger mobility between 1960 and 2015. Our results show that the efficiency of the steel stock contained in cars and motorcycles decreased from 37.5 to 28.0 passenger-km (pkm)/kg-year. The steel service for buses decreased from 63.6 to 32.1 pkm/kg-year, while that of the national railway increased from 23.8 to 70.3 pkm/kg-year steel. London Underground steel stock–service efficiency improved from 31.5 to 57.0 pkm/kg-year steel. The annual fraction of flows that maintained the steel stock varied according to vehicle category and was between 3.4% and 8.2%. In terms of the stock expansion rate, the greatest change (on average, an annual increase of 3%) was that of "cars and motorcycles." This reflects the demographic transitions and the growing consumer demand for car-based mobility. We discussed how the SFS nexus contributes to a more comprehensive form of resource accounting and reflect upon some of its limitations and how they might be addressed.

KEYWORDS
industrial ecology, mobility as a service, resource efficiency, resource nexus, sustainable materials, UK transport

1 | INTRODUCTION

Sustainable development depends on the societal provision of energy and material flows and material stocks within planetary boundaries (O'Neill, Fanning, Lamb, & Steinberger, 2018; Steffen et al., 2015). Material flow analysis (MFA) is a methodological framework that accounts for resource use from extraction to disposal (Haberl et al., 2019). It has reached a level of maturity and is accepted by policymakers involved in sustainable resource use (Fischer-Kowalski et al., 2011; Krausmann, Schandl, Eisenmenger, Giljum, & Jackson, 2017a; Schandl et al., 2017). The European Union, for example, requires that its Member States provide official MFA data, as mandated by the EU Regulation No 691/2011 (European Parliament, 2011). Various standardized economy-wide material flow accounting principles and methodological guidelines are used at the national, regional, and global level (including Eurostat, 2018, OECD, 2008a, UNEP, 2018a, 2018b).

MFA considers all material flows (except air and water) that support societal activity, measured in physical units (e.g., kg/yr) (Mayer, Haas, & Wiedenhofer, 2017; Schaffartzik et al., 2014). However, most practitioners neglect stock or only include it as "net additions to stocks" so as to balance system inputs and outputs. This means that long-term material accumulation is not captured and that the significance of material assets in socioeconomic development is often overlooked. This is problematic as more than 50% of annual global resource consumption is constituted by stock-building materials such as aggregates, metals, and plastics (Krausmann et al., 2017b; Wiedmann et al., 2015). In this regard, sustainability policies are incomplete if they do not consider societal dependency on stocks as well as flows (Weisz, Suh, & Graedel, 2015). Correspondingly, the quantification of material stocks has become an increasingly integral part of MFA research (Pauliuk & Müller, 2014; Wiedenhofer, Fishman, Lauk, Haas, & Krausmann, 2019). One particular MFA approach, which captures the relationship between stocks, flows, and the services they provide, is the stock–flow–service (SFS) nexus proposed by Haberl, Wiedenhofer, Erb, Görg, and Krausmann (2017). In the latter paper, it was argued that a nexus-based analysis would result in a more complete picture of social metabolism and resource efficiency. Here, we expand upon Haberl et al.'s (2017) proof of concept and operationalize it using the UK transport sector as a case study. Specifically, we model the steel stocks and flows required to support UK passenger mobility between 1960 and 2015. Based upon our results, steel appears to be a good proxy for total vehicle stock efficiency (see Section 4.3). Steel is selected because it is the world's most consumed metal and 200 kg of liquid steel per capita are produced annually (Allwood, 2016). In addition, it accounts for 7–9% of energy-related carbon emissions and is a key component of the many structures involved in almost all services, including transport (Allwood, 2016; Allwood, Cullen, & Milford, 2010; Pauliuk, Milford, Müller, & Allwood, 2013a). It is thus a key material to consider when it comes to framing sustainability and supporting the circular economy. The United Kingdom is used as an example because of its good quality and easily accessible data, including that sourced from the literature review (e.g., Serrenho & Allwood, 2016; Krausmann, Schandl, & Sieferle, 2008; Streeck, Wiedenhofer, Krausmann, & Haberl, 2020).

This paper's nexus interactions are quantified using five indicators, which we refer to as "stock efficiency," "stock degradation efficiency," "stock maintenance rate," "stock expansion rate," and "specific embodied impact." These metrics are derived from pre-existing analysis that has been undertaken within the field of Industrial Ecology. For example, our "stock maintenance rate" captures and formalizes Wiedenhofer, Steinberger, Eisenmenger, and Haas' (2015) and Nguyen, Fishman, Miatto, and Tanikawa's (2019) respective measurement of the amount of material used for stock maintenance purposes relative to the total amount of in-use stock. Strictly speaking, none of the five indicators are new per se but, to our knowledge, they have not been used in an integrated manner to assess resource consumption and accumulation from a service perspective, nor have they been applied to a nexus framework.

Therefore, the aims of this present paper are: (a) to measure the connection between stocks and flows and the services they provide via the nexus proposed by Haberl et al. (2017); and (b) to identify the benefits and potential shortcomings of the SFS nexus when integrated into sustainability initiatives. The authors do not pretend that this paper is a complete analysis of the UK transport sector. For instance, marine and non-motorized forms of transportation are not included nor are the materials required to construct and maintain transport infrastructure (e.g., roads, rails, and airports). Likewise, non-material inputs such as finance and human resources, which are evidently required for transport systems to function, are beyond the scope of this paper.

2 | STOCK–FLOW–SERVICE NEXUS: KEY CONCEPTS

2.1 | Material flow and stock accounting

MFA is a quantitative tool used to investigate the throughput of materials from extraction to manufacture, use, recycling, and disposal. The method involves the quantification of all material and energy inputs, stocks, and outputs required for the functioning of a socioeconomic system (Baccini & Brunner, 2012; Bringezu & Moriguchi, 2018; Fischer-Kowalski et al., 2011). A practitioner can use it to model, understand, and optimize resource management with the exact choice of method dependent on the study's scope and aim (Müller, Hilty, Widmer, Schluep, & Faulstich, 2014; Schwab & Rechberger, 2018). For example, a dynamic MFA approach explicitly considers the evolution of material stocks and flows through time (e.g., Chen & Graedel, 2012). It can be used to assess cross-sectoral interactions, historical consumption patterns, trade, and the build-up of material stocks. It can also facilitate future resource demand projections and identify which materials are critical for the achievement of international, national, and regional policy targets (Cao, Liu, Zhong, Dai, & Pauliuk, 2018; Turner & Poldy, 2001).

Two methods can be applied to model stocks in a dynamic MFA (Gerst & Graedel, 2008). The first is the inflow-driven approach, whereby material stocks are calculated by summing the annual difference between inflows (consumption) and outflows (e.g., waste) (Wiedenhofer et al., 2019). The latter can be calculated via a lifetime distribution function (probability density function) from an economic (e.g., Böhringer & Rutherford, 2008; Lennox, Turner, Hoffman, & McInnis, 2004) or a biophysical (e.g., Elshkaki, Graedel, Ciacci, & Reck, 2016) perspective. The second method is the stock-driven approach, which obtains stock values by adding together the quantities of materials in a given stock, at a given time, based on the data describing the stock. For example, the mass of a particular building stock can be estimated using appropriate factors linked to floor area (as is the case in Pauliuk & Müller, 2014).

Stock modeling has predominantly focused on metals (Chen & Graedel, 2012), although there are an increasing number of studies that cover other materials including asphalt, concrete, sand, and gravel (e.g., Miatto, Schandl, Wiedenhofer, Krausmann, & Tanikawa, 2017; Nguyen et al., 2019; Wiedenhofer et al., 2015). Hatayama, Daigo, Matsuno, and Adachi (2010) modelled the steel accumulated in buildings, infrastructure, and vehicles on a global scale, while Müller, Wang, and Duval (2010) accounted for the national steel stock in eight developed countries for construction, transport, appliances, and machinery. Pauliuk, Wang, and Müller (2013c) expanded the aforementioned paper by analyzing 200 countries. Serrenho and Allwood (2016) measured the stock demographics of the UK car industry from 2002 to 2012. All such models have been helpful in identifying how stocks evolve over time and within different system boundaries, including at the global, national, and sector level.

2.2 | Material services

The material services concept developed by Carmona, Whiting, Carrasco, Sousa, and Domingos (2019) and Whiting, Carmona, Brand-Correa, and Simpson (2020) is one way of getting closer to the actual purpose behind material flows and stocks. It builds on the concept of energy services, which recognizes that consumers do not demand energy for its own sake, but rather use it as means to achieve certain end states or benefits that have the potential to contribute to their well-being (Cullen & Allwood, 2010; Fell, 2017; Haefele, 1977; Kalt, Wiedenhofer, Görg, & Haberl, 2019; Lovins, 1976; Nakićenović et al., 1993). Whiting et al. (2020) define material services as:

> *"Those functions that materials contribute to personal or societal activity with the purpose of obtaining or facilitating desired end goals or states, regardless of whether or not a material flow or stock is supplied by the market."*

In other words, material services are delivered by specific stock–flow combinations, but not all stocks or flows are transformed into material services, such as "shelter," "illumination," and "thermal comfort." A specific combination of stocks and flows results in a service when it fulfils a defined purpose desired by an end-user. Not all material services contribute to gross domestic product (GDP) because the creation of income is not indicative of service provision. This means that it is possible to distinguish economic activity from the material services offered to individuals or society at large. This opens up the concept's application to traditional or alternative forms of community and trade, including those which existed in historic or prehistoric settlements (Whiting, Konstantakos, Carrasco, & Carmona, 2018). Evidently, ancient people did require material services but did not have what we would recognize today as a market mechanism for their provision (see Whiting et al., 2020).

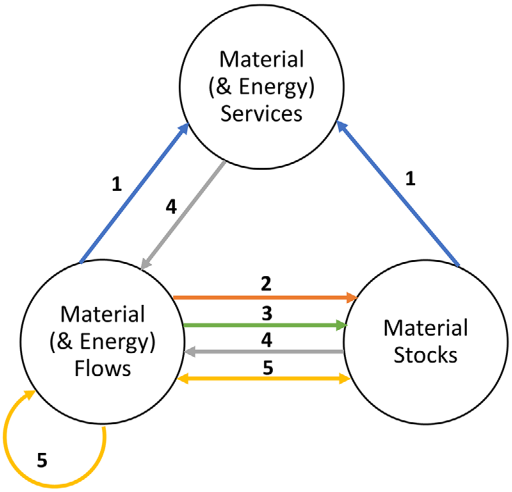
To the extent that material services can be expressed in physical units, the efficiency of specific processes can be calculated as the ratio between the service metric and the corresponding stocks and flows. This ratio then gives an indication of how the average user experiences the SFS interaction. For example, fuels (flows), vehicles, and road infrastructure (stocks) are required to move a person or a commodity from Point A to Point B (mobility as a service).

There are various units that could be employed to measure a material service. However, it is particularly appropriate to select ones which are already commonly used, and well understood, by those working in the sectors that a given service covers. For example, if one aims to measure "illumination," as a material service, it makes sense to use lux, lumen-hour, or candela per square meter, as they are frequently used to gauge light intensity or quantity. The added value of the material service approach is that it takes those lighting outputs and frames them in a way that highlights the efficiency of resource consumption (flows) and accumulation (stock) relative to service output. For "mobility" it makes sense to use passenger-kilometers (pkm) to measure the carrying capacity of, and distance travelled by, a vehicle, as this already is standard practice for transport authorities who wish to compare public transport efficiency before and after a policy change.

In many cases, material service units are proxies, which do not capture all relevant aspects of service provision. For example, a high number of pkm is not necessarily indicative of good service quality. On the one hand, it could mean that the transport network is large, which allows a person to travel further to pursue their aims. On the other hand, it might also signify that the transport system is so overcrowded that a person cannot enter a carriage when a train stops at their station. In this respect, bigger is not always better. In fact, one could argue that a transport service of the highest quality enables a person to travel fewer kilometers and still achieve their end goal. In other words, service units are value neutral and it is for policymakers and end-users to decide together whether a high pkm is desirable or not. It may be that a transport authority proposes policy measures that would decrease carrying capacity because the public demands increased safety. Therefore, practitioners need to be careful when interpreting service units and recommending a course of action. One way to avoid erroneous conclusions would be to conduct a comprehensive literature review and contextual analysis prior to reporting on material service results (see Sections 4.3.1–4.3.3).

2.3 | The stock–flow–service nexus

The term "nexus" is commonly applied by academics and policymakers to identify the complex interconnections that exist between different types of resources (Font Vivanco, Wang, Deetman, & Hertwich, 2019; Williams, Bouzarovski, & Swyngedouw, 2014). It is typically used to explore the effect of the socioeconomic system on natural processes and vice versa, in order to improve resource management (Bleischwitz & Miedzinski, 2018). The nexus concept enables researchers to pinpoint synergies or trade-offs and anticipate potential threats and critical thresholds (Bizikova, Roy, Swanson, Venema, & McCandless, 2013; Cohen, Wolff, & Nelson, 2004; Howells et al., 2013). These advantages have resulted in the promotion and application of the nexus idea by several governments and international organizations interested in sustainable development (Nexus, 2016;



N	Interaction	Description
1	Service delivery	Mobilisation of the stock and flows that maintain and enhance societal function
2	Stock maintenance	Transformation of flow(s) to keep stock at a certain level
3	Stock expansion	Transformation of flow(s) that enlarge stock
4	Stock or flow degradation	Transformation of stock and/or flows into waste due to service delivery or deterioration over time
5	Stock or flow embodied impact	Resource consumption (or pollution generated) due to the production of new flows or the maintenance and expansion of stocks

FIGURE 1 A development of the SFS nexus based on Haberl et al. (2017)

UN-Water, 2016). Common nexus examples include "water-energy," "water-energy-food," and "water-energy-land-food" (e.g., Biggs et al., 2015; Ringler, Bhaduri, & Lawford, 2013; Siddiqi & Anadon, 2011). There are also nexus approaches that incorporate materials. These include the "urban nexus," which considers the interplays between energy, water, food, and waste flows (Lehmann, 2018), and a pentagonal nexus, referred to as the "resource nexus," which takes into consideration energy, food, land, water, and materials (Bleischwitz & Miedzinski, 2018; Font Vivanco, Wang, & Hertwich, 2018). None of the aforementioned concepts consider material stocks or the services that resource flows and stocks provide. The problem with limiting the scope to flows is that this does not allow policymakers to ascertain the role of stock accumulation nor inform them as to what the resources are actually used for.

The SFS nexus captures the interconnections between flows, in-use stocks, and material services (Haberl et al., 2017). As Figure 1 shows, these interactions are not necessarily linear or commeasurable. For example, car-based mobility requires fuel, a vehicle, and road infrastructure (arrows labeled 1 in Figure 1). These relationships can be expressed as efficiencies, such as, for example, the number of pkm provided by a given car.

In the case of transport, fuels have two primary uses: (a) provision of the energy required for the mechanical drive that supports vehicle mobility and, (b) the energy input for vehicle manufacture and road construction. Fuels do not have any further interaction within the nexus, unless society deems them pollution and chooses to clean them up (arrows labeled 5 in Figure 1). Stocks have a greater influence on the SFS nexus because of their longer lifecycle, which is supported by the maintenance/upgrade and expansion of those flows necessary for the continuation or enlargement of vehicle stock or road infrastructure (arrows labeled 2 and 3). The material aspects of maintenance and expansion include lubricants, spare parts, new road surface, and new vehicles. The bigger the stock, or degree of its depreciation, the more flows are required to maintain or increase it. This, in turn, has an impact on how the average user experiences (or perceives) mobility as a service. That said, looking at stocks and flows in isolation can be misleading, especially during policy or technological transitions (e.g., changing from buses to trams), which may effectively reduce stock levels and increase waste flows whilst improving overall service provision. This is why a nexus perspective is helpful when designing and enacting wholescale changes.

Table 1 identifies various indicators that have been proposed by researchers to assess resource use in other contexts (e.g., environmental footprint measurements) and which could be used to evaluate the SFS nexus interactions. It is important, when considering resources from a nexus perspective, that all interactions are measured by at least one indicator and that its selection is explained and supported. The table does not offer an exhaustive list of potential indicators, but rather highlights examples that we judge to be worthy of consideration.

3 | METHODS

3.1 | Quantifying flows and stocks

We created an inflow-driven dynamic material stock model, similar to that proposed by Müller et al. (2014), to calculate the steel employed in vehicles used in the UK transport sector from 1900 to 2015 (Equation 1).

$$M_{\text{Stock}[N]} = \underbrace{M_{\text{Stock}[0]}}_{\text{Initial stock}} + \underbrace{\sum_{n=1}^{N} M_{\text{Inflow}[n]}}_{\text{Inflow}} - \underbrace{\sum_{n=1}^{N} M_{\text{Inflow}[n]} \cdot f_{[n]}}_{\text{Outflow (End of } \mathit{life}, \quad M_{\text{Outflow}[n]})} \quad . \tag{1}$$

TABLE 1 Potential indicators for assessing the SFS nexus interactions

Interaction	Components	Potential indicators	Key references
Service delivery	Service–flow	Material input per service (MIPS): service delivered by material consumption	Mancini, Lettenmeier, Rohn, & Liedtke, 2012; Ritthoff, Rohn, & Liedtke, 2002
		Material intensity: material required per unit of service (or other type of benefit, e.g., GDP). The inverse calculation is known as resource productivity	Miatto et al., 2017; Schandl et al., 2017; Wang, Kuo, Song, Hu, & Zhang, 2017
		Environmental footprints: estimates the environmental impact of product, service, or consumer demand (includes the different impact categories of conventional life cycle assessment and may be combined with input–output techniques). It can also be expressed in terms of the life cycle inventory and resource footprints	Dewulf et al., 2007; Klinglmair, Sala, & Brandão, 2014; Mancini, Benini, & Sala, 2015
		Flow efficiency: the amount of material flow that is consumed to provide a unit of service	Whiting et al., 2020
		Impact efficiency or eco-efficiency: measures benefits (e.g., services) relative to life cycle inventoried inflows or impacts	Huysman et al., 2015
	Service–stock	Stock efficiency or material stock per service (MSPS): service delivered by stock in the use phase. Also referred to as stock–service productivity	Nguyen et al., 2019; Pauliuk, 2018; Pauliuk, Sjöstrand, & Müller, 2013b; Whiting et al., 2020
		Material stock intensity: material required per unit of service (or other type of benefit, e.g., GDP). The inverse calculation is known as stock productivity	Dombi, 2019
Stock maintenance and/or Stock expansion	Stock–flow	Old scrap collection rate (CR): measures the end-of-life (EoL) metal contained in various discarded products	Graedel et al., 2011
		Recycling rate (EOL-RR): fraction of material contained in a recycled product that is returned to raw material production processes	Graedel et al., 2011
		Capital-augmented material footprint (CAMF): amount of materials embodied in the capital goods represented as the fraction of material footprint dedicated to stock maintenance and/or expansion (CAMF/MF)	Södersten, Wood, & Wiedmann, 2020
		Percentage of flow relative to stock: *Stock maintenance*: refers to the material input used to maintain stock relative to total in-use stock. *Stock expansion*: concerns the inflows required for the expansion of stocks relative to total in-use stock	Nguyen et al., 2019; Wiedenhofer et al., 2015
		Non-structural material replacement flows as a fraction of the total material stock: represents the material flow required to maintain stock via the replacing of non-structural materials	Stephan & Athanassiadis, 2018
		Waste fraction: measures the quantity of EoL material diverted into waste or recycling relative to in-use stock	Haas, Krausmann, Wiedenhofer, & Heinz, 2015; Wiedenhofer et al., 2015
		Stock construction and maintenance fraction: proportion of material that goes into stocks relative to total material consumption	Miatto et al., 2017

(Continues)

TABLE 1 (Continued)

Interaction	Components	Potential indicators	Key references
Stock or flow degradation (downgrading)	Service–flow	Material waste per service unit: measures the quantities of waste generated per service unit	de Magalhães, Danilevicz, & Saurin, 2017; Papargyropoulou et al., 2016
		Material output intensity: system performance (e.g., economic performance) relative to the material losses to the environment	Matthews et al., 2000; OECD, 2008b
		Emission efficiency: benefits in relation to the material losses to the environment. The scope could be gate-to-gate, the entire lifecycle, or at the sector or national level	European Commission, 2019; Huysman et al., 2015
Stock or flow embodied impact	Stock–flow	Life cycle environmental requirement of stocks: accounts for the total impact throughout the stock lifecycle including construction, maintenance, and disposal	Stephan & Athanassiadis, 2017
		Embodied impact of stock: summation of all the resources required or emissions generated to create and accumulate stocks (extraction, processing and manufacturing) from year 0 to year *N*	Cheah et al., 2009
	Flow–flow	Resource intensity: resources required to create a unit of flow. Indicators include the energy intensity of a given material	Gutowski, Sahni, Allwood, Ashby, & Worrell, 2013
		Resource efficiency: ratio of useful outputs (including by-products) to all resources consumed directly by a system (or process)	Carmona et al., 2019; Hernandez, Paoli, & Cullen, 2018

In this formula, $M_{\text{Stock}[N]}$ is the in-use stock at time N, $M_{\text{Stock}[0]}$ is the in-use stock at time 0, and $M_{\text{Inflow}[n]}$ represents the measured or calculated steel inflows into UK newly registered vehicles in year n. The outflows ($M_{\text{Outflow}[n]}$) are calculated via a residence time model using a convolution integral (see Müller et al., 2014) and are derived from $M_{\text{Inflow}[n]}$ and the probability density of a lifetime distribution function assigned to each vehicle category ($f_{[n]}$). The latter follows a Weibull distribution.

The model contains seven transport sub-categories: "cars and motorcycles," "trucks," "buses," "national trains," "London Underground," "aircraft," and "ships." Although beyond of the scope of the paper, which is focused on domestic passenger mobility, trucks and ships were included in this model to ensure a complete tracing of steel inflows. Category inflows constitute the quantity of annual steel production diverted into vehicles destined for UK ownership. It does not include the steel contained in infrastructure (e.g., reinforced concrete). The UK steel consumption data were gathered from Dahlström, Ekins, He, Davis, and Clift (2004), Pauliuk and Hasan (2017), and the World Steel Association (2014, 2018).

In the case of the steel used to operate "national trains," 20% was allocated to rolling stock (vehicles) for passenger mobility, 20% to freight and 60% to rail track. For "London Underground" allocation was split equally between tracks and carriages. These percentages were based on the information available for 2015 (DfT, 2018a). Steel stock allocation was also required for aviation. This was done based on the proportion of pkm relative to tonne-kilometers, after the latter was converted into its pkm equivalent. The *Civil Aviation Authority* standard of 80 kg equals one passenger was used as the conversion factor.

For validation purposes, we calculated the in-use stock of steel for each year ($M_{\text{Stock}[n]}$) via a dynamic stock-driven model for all categories except "national trains" and "London Underground." The values were derived from the total number of vehicles registered and the average steel composition for each category which, with the exception of "aircraft," was between 60% and 80%. Where the annual difference between the respective results obtained via the two models was more than +/−20% for the same category, we adjusted the outflow of the previous year so that the inflow-driven model's values matched those of the validation.

Following Equation (2), we accounted for the energy embodied in stocks, where $e_{\text{Inflow}[n]}$ represents the energy intensity required to produce the primary or secondary steel that is diverted into newly registered UK vehicles ($M_{\text{Inflow}[n]}$). The value of $e_{\text{Inflow}[n]}$ is calculated using the relative proportion of primary and secondary steel production for a specified year. All other variables are identical to those expressed in Equation (1).

$$E_{\text{Stock}[N]} = \underbrace{E_{\text{Stock}[0]}}_{\text{Initial embodied impact}} + \underbrace{\sum_{n=1}^{N} M_{\text{Inflow}[n]} \cdot e_{\text{Inflow}[n]}}_{\text{Embodied impact of inflow}} - \underbrace{\sum_{n=1}^{N} M_{\text{Inflow}[n]} \cdot f_{[n]} \cdot e_{\text{Inflow}[n]}}_{\text{Embodied impact of outflow(End of Life)}} . \tag{2}$$

We assumed that the energy required to manufacture the steel used by the UK transport sector was identical to the energy demands required for British steel production, even though we are aware that not all steel contained in UK registered vehicles was domestically produced. However, this assumption enabled practical calculations to demonstrate the approach. More information about model data sources, parameters, validation, and adjustments are presented in Sections S1–S4 in Supporting Information S1.

3.2 | Quantifying the transport service

We used the pkm data reported by the *Department for Transport* (DfT) to account for road travel by UK registered vehicles within national borders (DfT, 2018b). In the case of aviation, we used data from the *Civil Aviation Authority* to account for the passenger mobility provided by UK registered aircraft (CAA, 2018). The pkm associated with sea journeys (including ferry crossings) were not calculated.

To better understand the nature and significance of the results, we undertake a contextual analysis. This involves a desk study into the major political, social, and technological transitions that directly or indirectly affected the UK's transport service during the period studied. Key examples include privatization of public transport, changes to national transport legislation, and the increased integration of women into the workforce.

3.3 | Stock–flow–service efficiency indicators

Of the 22 potential indicators identified in Table 1, we selected 5 to measure the SFS nexus interactions (Table 2). The *stock efficiency indicator* (taken from Whiting et al., 2020) shows the relationship between passenger mobility and the amount of steel contained in vehicle stock. The *stock degradation efficiency* depicts the coupling between the physical depreciation of that steel (waste) and service delivery. It is adapted from the emission efficiency indicator proposed by Huysman et al. (2015). The only difference between their metric and ours is that we restrict waste outflows to those linked to stocks. The *stock maintenance rate* (taken from Wiedenhofer et al., 2015 and Nguyen et al., 2019) identifies the minimum fraction of steel inflow required by a service provider to maintain vehicle stock. Steel stock fluctuation over the duration of the case study is captured by the *stock expansion/contraction rate*, which is likewise taken from Wiedenhofer et al. (2015) and Nguyen et al. (2019). The *specific embodied impact* (taken from Cheah, Heywood, & Kirchain, 2009) calculates the amount of energy inputs associated with the steel inflows or steel stocks that

TABLE 2 Selected SFS nexus indicators

Interaction	Indicator	Description	General equations	Case study application
Service delivery(stock–service)	Stock efficiency	The amount of stock required to provide a unit of service	$\frac{\text{Serv.}}{M_{\text{Stock}}}$ (3)	$\frac{\text{Service (passenger} \cdot \text{km/year)}}{\text{Steel stock (kt)}}$ (4)
Stock degradation(flow–service)	Stock degradation efficiency	The amount of stock that degrades (worn out/made obsolete) to provide a unit of service	$\frac{\text{Serv.}}{M_{\text{Outflow}}}$ (5)	$\frac{\text{Service (passenger} \cdot \text{km/year)}}{\text{Steel outflow (kt/year)}}$ (6)
Stock maintenance (stock–flow)	Stock maintenance rate	Fraction of material required to maintain stock at a specified level	$\frac{M_{\text{Outflow}}}{M_{\text{Stock}}}$ (7)	$\frac{\text{Steel ouflow (kt/year)}}{\text{Steel stock (kt)}}$ (8)
Stock expansion (stock–flow)	Stock expansion (or contraction) rate	Fraction of material stock growth (>0) or degrowth in a given period	$\frac{M_{\text{Inflow}[n]} - M_{\text{Outflow}[n]}}{M_{\text{Stock}}}$ (9)	$\frac{\text{Steel Inflow (kt/year)– Steel ouflow (kt/year)}}{\text{Steel stock (kt)}}$ (10)
Stock embodied impact (stock–flow or flow–flow)	Flow or stock specific embodied impact	The amount of resources consumed, or pollution embodied, in a stock (or flow)	$\frac{E_{\text{Stock}}}{M_{\text{Stock}}}$ (11) $\frac{E_{\text{Inflow}}}{M_{\text{Inflow}}}$ (12)	$\frac{\text{Embodied energy in steel stock (GJ)}}{\text{Steel stock (kt)}}$ (13) *Note*: Energy intensity (GJ/t) is a traditional indicator used to measure the flow specific embodied impact. See, for example, Carmona et al. (2019) or UK Steel (2018).

Serv., material service; M_{Stock}, material stock; M_{Inflow}, annual material inflow; M_{Outflow}, annual material outflow; E_{Stock}, embodied impact in stock; E_{Inflow}, embodied impact in a flow. Intensity proxies are used to calculate the following metrics: "Stock efficiency," "Stock degradation efficiency," and "Flow efficiency." This is because material services are measured relative to societal activities whilst flows and stocks are measured in mass.

provide a service. It is key to identifying the most efficient production route for goods manufacture. We calculated the *stock specific embodied impact* and compared it to the *flow specific embodied impact* evaluated by Carmona, Whiting, Carrasco, and Sousa (2019).

In all cases, the indicators in Table 2 were selected because: (a) they measure service units (e.g., pkm) rather than economic performance (e.g., GDP) or well-being (e.g., human development index) and (b) they measure total stock (e.g., tonnes) rather than their equivalent in flow terms (e.g., tonnes/year). These criteria rule out the division of stocks by expected lifetimes, which is a common practice in life cycle assessment (LCA) and an integral component of the MIPS indicator; see, for example, Spielmann, Bauer, Dones, and Tuchschmid (2007) and Saari, Lettenmeier, Pusenius, and Hakkarainen (2007).

3.4 | Sankey representation and sensitivity analysis

Sankey diagrams are a useful tool for the visualization of the amount and proportion of material and energy flows within a system. They allow practitioners to identify resource efficiencies, transformations, and allocations (Lupton & Allwood, 2017). We depict the steel stocks and flows required by the UK transport sector in 2008. This year was selected because we had more data regarding the material efficiency of steel production, manufacturing, and recycling, which resulted in a more comprehensive diagram. We used a Sankey diagram to show how inflows are directed into stock for its maintenance, upgrade, or expansion. For completeness, we also include energy and the associated carbon dioxide flows required to produce steel inflows. The scope for the embodied impact flows corresponds to the following processes: coke production, sintering, furnace operation (blast, basic oxygen, and electric arc), refining, and electricity generation (all values taken from Carmona et al., 2019).

A comparison of our results relative to other studies is presented in Section S6 in Supporting Information S1. We also perform a sensitivity analysis by arbitrarily increasing or decreasing the year on year steel inflow, material efficiency of product manufacture, and vehicle lifetime expectancy within a range of +/−10% (Section S7 in Supporting Information).

4 | RESULTS AND ANALYSIS

4.1 | Stock–flow–service Sankey diagram

The Sankey diagram, presented in Figure 2, highlights the relationship between the flows (lines), stocks (rectangles), and services (circles) supported by steel for the UK's passenger transport in 2008. The flows and stocks contained within the red dashed area do not follow the criteria of a conventional Sankey diagram; there are two reasons for this. First, flow inputs are not equal to their outputs. This is because for non-fuels, as opposed to fuels (which are not depicted here), inputs are likely to accrue as stocks and may leave the system many years after their expected lifetime. Second, flows and services do not share the same units. For example, the modeling of stock efficiency for the national railway involves an inflow and two outflows (colored green and orange). The inflow constitutes the steel used for the maintenance, upgrade, or expansion of rolling stock. The green outflow is the end of life steel that is either diverted into landfill or recycled. The orange outflow is the amount of pkm of passenger transport.

The means of transport that consumed the most steel, as represented by the thickness of the green lines, were "cars and motorcycles" followed by "buses." Therefore, in 2008, when it comes to transport, the United Kingdom preferred to divert its steel into cars. However, in terms of conversion from stocks into services, "national railway," "London Underground," and "aircraft" (domestic flights) are much more efficient, as represented by the size of the orange circle relative to the thickness of the green block. This efficiency is also represented by the stock efficiency indicator (grey tap symbol).

In 2008, 55% of the iron and steelmaking sector's non-fuel material inputs (the principals being iron ore, limestone, and scrap steel) were converted into crude steel, of which 75% was transformed into vehicle components (e.g., galvanized cold rolled coil). In addition, 75% of refined steel was embodied in vehicles (USGS, 2011; World Auto Steel, 2020). The remaining non-fuel inputs were converted into waste or by-products such as slag, dust, and sludge, which were then diverted into other industries (ochre colored line). Most end of life steel was recycled. The scrap was reused either in the steel sector or elsewhere.

4.2 | Steel stock and service evolution

From 1960 to 2015, passenger mobility increased from 270 to 784 billion pkm. Figure 3a shows the pkm breakdown according to transport category. In 1960, public transport constituted 44% of pkm. By 2015 this had dropped to 15%. The "cars and motorbikes" category appears to reach a maturation point in 2005, where upon service provision stabilizes. The UK's steel stock employed in transport increased between approximately 6.8 and 25.9 Mt (Figure 3b). "Cars and motorbikes" steel stock represented 59% in 1960 and 91% in 2015. Overall, the total steel contained in "car

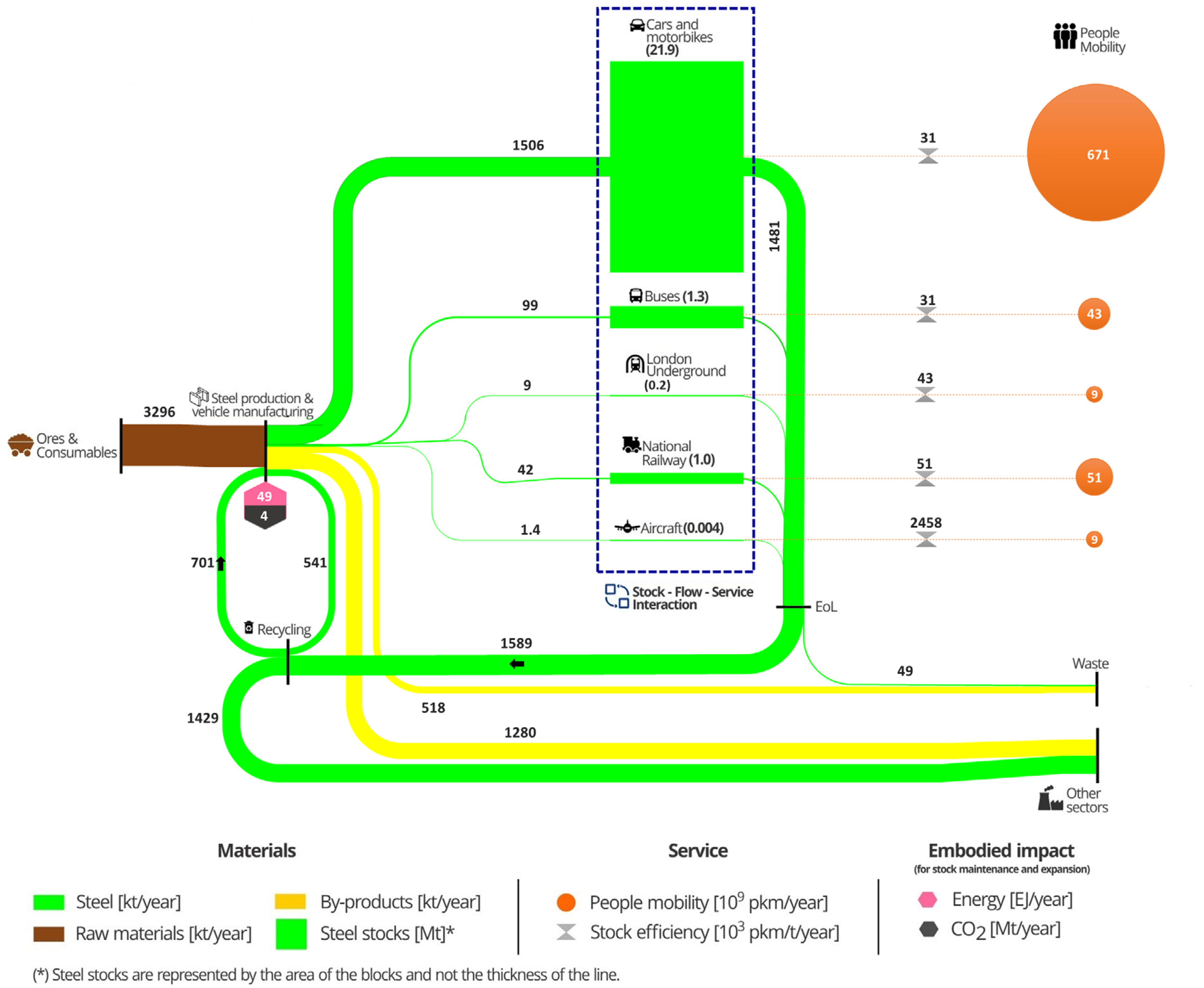


FIGURE 2 Sankey diagram representing the steel flows–stocks–service in the UK's passenger transport sector for 2008. *Note*: Aircraft refers to domestic flights only

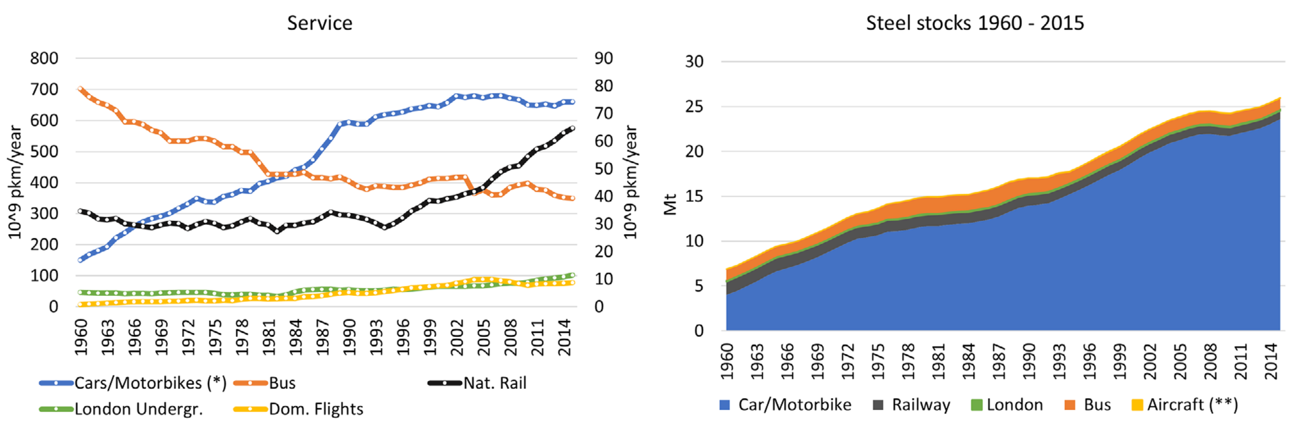


FIGURE 3 Steel stock and service evolution UK's passenger transport (1960–2015). (a) Annual passenger-kilometer as proxy of service delivery. *Source*: (CAA, 2018; DfT, 2018b). *Notes*: (*) The "car/motorbikes" category is plotted on the left axis whilst the others are plotted on the right axis. (b) Steel stocks for the UK's passenger transport; (**) "Aircraft" refers to domestic flights only. The underlying data used to create this figure can be found in Supporting Information S2

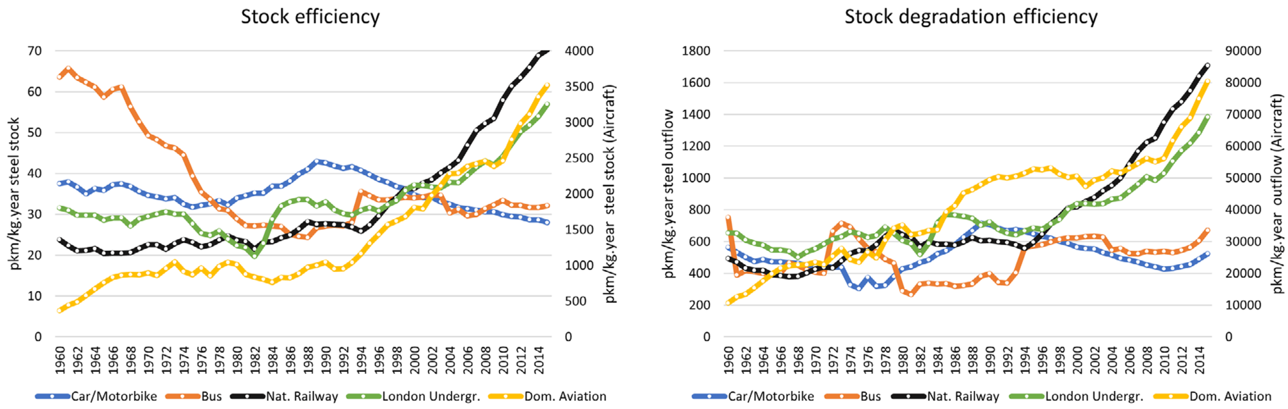


FIGURE 4 SFS nexus efficiency of the UK's passenger transport (1960–2015). (a) Steel stock service efficiency. (b) Steel stock degradation efficiency. Please note efficiencies linked to aircraft (domestic flights) are shown on the secondary axis. The underlying data used to create this figure can be found in Supporting Information S2

and motorcycles" increased from 4 Mt in 1960 to 26 Mt in 2015. As previously noticed by MacKenzie, Zoepf, and Heywood (2014) and Serrenho and Allwood (2016), the observed increase in steel stocks was solely due to an increase in the number of cars on the road and not related to changes in vehicle weight. The proportion of motorcycles relative to cars fell substantially over the period. In 1960, for every three cars on the road there was one motorcycle, whereas the ratio was 23:1 in 2015.

The steel contained within trains was 1.5 Mt in 1960 but had reduced to 1.0 Mt by 2015. In fact, for 48 years of the 56-year period analyzed, the steel contained in stock declined. The sharpest decline can be directly linked to the *Beeching Reports* (Beeching, 1963, 1965), which advocated for the closure of less frequently used routes. The service reductions for national rail continued until 2010, which was another factor that contributed to the better performance captured by the *stock efficiency* indicator (although this does not mean that the quality of the service improved). The amount of steel contained in bus fleets was 1.2 Mt in 1960. In 1980, the steel stock quantity peaked at 1.8 Mt but declined back to 1.2 Mt in 2015. The amount of steel contained in domestic flights-related stocks was 3 kt in 1960. This figure had stabilized by 2015. That said, steel is not a significant material for this sub-category, as it accounts for approximately 12% of a plane's constituents (Mezei & Boros, 2016). The service and stock data for each transport category is included in Supporting Information S2.

4.3 | Stock–service and flow–service interactions

Figures 4a and 4b capture different efficiencies relative to the service delivery. Figure 4a presents the service provided by steel for passenger mobility relative to stock levels. Figure 4b shows the efficiency of service provision relative to annual end of life flows. Figure 4b follows a very similar pattern to that presented in Figure 4a. Any differences are linked to policy implementation or improvements in vehicle life expectancy. The steel *stock efficiency* in "cars and motorcycles" decreased from 37.5 to 28.0 pkm/kg-year. This change was not linear given that the peak of 43 pkm/kg-year was reached in 1989. In addition, between 1960 and 2015 the steel *stock efficiency* of "buses" went down from 63.6 to 32.1 pkm/kg-year. From 1994 onward, bus *stock efficiency* was stable whilst the "national railway" and "London Underground" became more efficient. National rail efficiency increased from 23.8 to 70.3 pkm/kg-year. The efficiency of "London Underground" went from 31.5 to 57.0 pkm/kg-year. Aviation (domestic flights) presented the highest efficiency in terms of service relative to steel stock. This category went from 365 to 3520 pkm/kg-year. A comparison of the resource requirement per one passenger kilometer supported by steel is shown in Table S4 in Supporting Information S1.

Table 3 shows overall vehicle stock efficiency for 2015 once the material analyzed is expanded to include aluminum, plastics, and other components (e.g., rubber and glass), in addition to steel. In all cases, the efficiency indicator value of total stock is (by definition) lower than that of steel alone. However, in terms of category ranking, "cars and motorcycles" remain the least efficient and "aviation" (domestic flights) the most efficient. This suggests that steel is currently a good proxy material for vehicle stock efficiency.

4.3.1 | Cars and motorbikes

In 1960, the steel contained in cars facilitated 56% of the road transport pkm. By 2015 this had increased to 84%, which reflected societal preferences and changes in infrastructure and transport policies. In 1990, there was an inflection point in pkm per kilogram of steel, which we think is linked to lower occupancies in cars. In other words, the increase in car ownership led to a decrease in the average number of people travelling in any

TABLE 3 Overall stock efficiency in 2015 upon the expansion of material scope

Transport mode	Material (kt)					Service	Stock efficiency	
	Steel	Aluminum	Plastic	Others	Total	(10^9 pkm)	Steel(pkm/kg-year)	All materials(pkm/kg-year)
Cars and motorcycles	23,589	2,950	3,020	9,012	38,571	660	28	17
Bus	1,226	204	150	463	2,043	39	32	19
National Railway	920	383	153	77	1534	65	70	42
London Underground	201	84	34	17	335	11	57	34
Aviation (domestic flights)	2	12	4	1	19	9	3,520	450

given car. Arguably, much of this change was due to more progressive attitudes toward women working, especially following childbirth, along with women's increased expectations regarding career trajectory. The *Institute for Fiscal Studies* reports, for example, that female full-time employment, went from 29% in 1985 to 44% in 2017 (Roantree & Vira, 2018). This demographic change is also reflected in the gender split of driving license holders. In 1975, while 69% of males held a driving license, only 29% of females did so. By 2010, 80% of males and 66% of females held a license (Department for Transport, 2011). Family size also affects these numbers. In 1971, 35% of UK households contained dependents, but by 2008 this had reduced to 28% (Office for National Statistics, 2009). This means that it is very likely that fewer children are car passengers. In addition, while seat belt fittings had been legally enforced since 1968 (for the front seat passengers) it was not until 1991, due to *The Motor Vehicles (Wearing of Seat Belts in Rear Seats by Adults) Regulations*, that all car passengers were obliged to wear a seat belt and that the number of passengers was strictly monitored. This led to a reduction in the number of persons transported in any given car, especially with respect to the 1960s.

Occupancy rate declines as disposable income increases because consumers prefer convenience over monetary savings. In other words, *stock efficiency* decreases because people who would have previously shared a car no longer choose to do so (Clark, 2012). Occupancy rate went from an average of 2.1 passenger/vehicle to 1.6 passenger/vehicle between 1960 to 2015. This preference is also reflected in the increased number of cars owned by a single family. The reduction in car prices relative to salary, especially once the second-hand market becomes fully established, plays an integral role in encouraging car ownership. This is because it offers access to people who would otherwise not buy a car and does not cause a high percentage of people who prefer to buy new cars to switch to pre-owned vehicles (Thomas, 2003). Since 1991, the price of the UK average car has dropped significantly relative to inflation. In 2001, prices were 20% lower compared to 1991 (at constant prices). A decrease in real prices from 1991 to 2009 was also observed (Cambridge Econometrics, 2015). During the same period, petrol prices rose but this was compensated by increases in bus and rail fares (Dargay & Hanly, 2007). Improved fuel efficiency may have also offset car price rises. The highest stock efficiency was achieved in 1989 because of an increase in distance travelled per vehicle (17,200 km/year/vehicle). By 2015, this distance had reduced to levels lower than those registered in 1960, dropping from 14,000 to 13,300 km/year/vehicle. Road infrastructure can also play a part in changing behavior and reducing steel *stock efficiency*. For example, in 1986 the London ring road, the M25, rapidly decreased travel time and incentivized car rather than public transport trips. Time is a major component of variable costs in car travel, so increasing access to, and the quality of, roads will induce more private vehicle ownership and greater trip frequency (Noland, 2001; Noland & Lem, 2002).

With specific regard to the *stock degradation efficiency* for "cars and motorcycles," the improvement registered from 2010 onward, reflects a reduced vehicle replacement rate, as evidenced by the average in-use car age of 8.0 years in 2015, compared to the 6.6 years obtained in 2003 (NimbleFins, 2020). Similarly, vehicles were, on average, sent for scrap upon reaching 13 years of use in 2003 and 14 years of use in 2015. The extended lifespan of those vehicles registered in this category is derived from multiple factors. Technological innovation has enhanced longevity, as has the reduced average distance travelled per vehicle. However, it also likely that the reduced propensity to spend money on material goods, following the 2008 global recession, played a role. This assumption is supported by Wu et al. (2019) who found that the economic recession that started in 2008 reduced national consumption by 1%. The problem with achieving sustainability targets in this way is that it does not reflect a permanent behavioral or operational change and, thus, as soon as the economy starts to grow again these declines are reversed.

The pattern uncovered in the transitional periods between 1975 and 1989 is due to the fact that only 3–4% of the total number of registered "cars and motorcycles" were annually replaced (or scrapped). Between 1990 and 2010, this value had doubled to 6–7% (Leibling, 2008). The reduction in outflow registered in 2010 onward may have been caused by better quality car design and parts.

4.3.2 | Buses and rail

The main reason for the decrease in the *stock efficiency* of buses was the reduction in the occupancy rate from 20 to 9 passengers/vehicle over the studied period. The prominent growth in both *stock efficiency* and *stock degradation efficiency* for national trains, after 1995, was due to the privatization of the British rail industry. Higher quality rail services have also been achieved with the support of government subsidies (Full Fact, 2018).

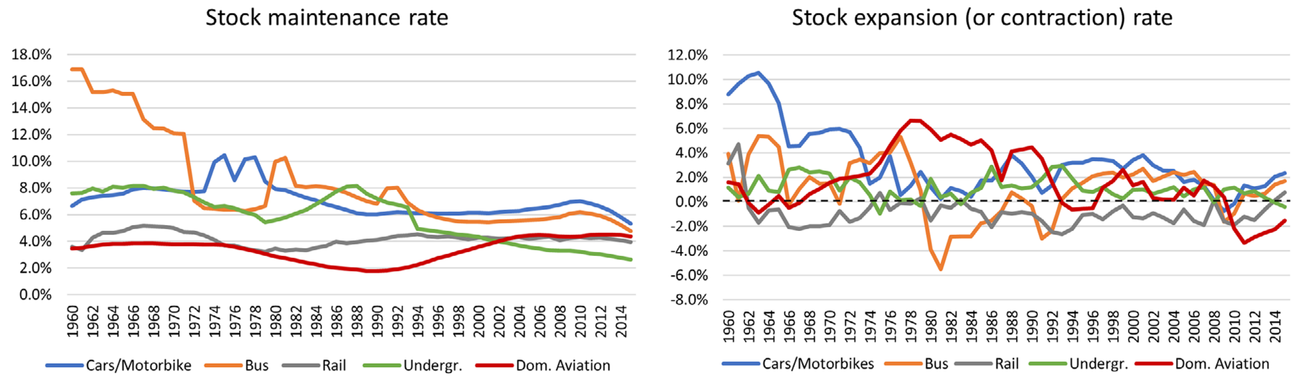


FIGURE 5 Stock–flow interaction. (a) Annual steel stock maintenance rate. (b) Annual steel stock expansion (or contraction) rate. The underlying data used to create this figure can be found in Supporting Information S2

Therefore, higher railway *stock efficiency* may reflect consumer preferences for improved rail services relative to the slower and less comfortable road-based public transport options. The lowest recorded *stock efficiency* (Figure 4a) for bus and London Underground occurred in the 1980s due to various policy changes. For example, following a decline of bus passenger numbers in the 1960s, the UK government restructured bus operations with the *Transport Act 1968*. The service was streamlined again in 1986, following an amended *Transport Act*, which privatized all bus services except those of London and Northern Ireland - pkm subsequently increased, as is reflected in the rise of *stock efficiency*. Similarly, railway privatization in 1994 increased rail *stock efficiency*.

An example of how policy can influence the *stock degradation efficiency* can be seen in the mid-1960s through the increase in bus *stock degradation efficiency*. This occurs because the UK government took the decision to export London's Leyland buses to Hong Kong rather than scrap them.

4.3.3 | Domestic aviation

Aviation passenger transport represents approximately 85% of the total pkms offered by aircraft, with the remainder allocated to freight. Although not a significant factor for steel stocks, aviation does interplay with other forms of transport and how individuals choose to travel, as the following example indicates. In 1992, as a direct result of the European Commission initiative *Open Skies*, there was surge in UK air travel. *Open Skies* created a single European Market for both air passenger and freight transport. All UK aircraft carriers were, from then on, considered EU aircraft carriers, opening the door to increased frequency and routes, including connecting domestic flights (Christidis, 2016). This policy also allowed for the proliferation of low-cost airlines and fares. Given that *stock efficiency* increased, this suggests that these developments led to higher occupancy rates. These air policies may have also taken some pkm away from cars and buses but did not seem to affect trains (Figure 4a).

4.4 | Stock–flow indicators

Figure 5 presents the *stock maintenance rate* (Figure 5a) and the *stock expansion (or contraction) rate* (Figure 5b). The fraction of flows linked to maintenance varies according to category and is between 3.4% and 8.1%. The steel *stock maintenance rate* for "cars and motorbikes" was 7.1% on average, whilst the steel *stock expansion rate* was 3%. However, in 2009 and 2010, the category experienced a steel stock contraction of 0.7% and 0.2%, respectively, due to the global economic crisis. In terms of *stock degradation efficiency* and *stock maintenance rate*, there was a relative stabilisation for both indicators between 1960 and 1974. This was followed by a *stock degradation efficiency* increase and *stock maintenance* decrease from 1975 until 1989. There was then a *stock degradation efficiency* decrease and *stock maintenance rate* increase from 1990 until 2010, followed by a simultaneous increase in *stock degradation efficiency* and decrease in *the stock maintenance rate* in the final years of the analysis. It appears that "average age" and "vehicle replacement rates" are the two input variables that impact the most upon these tendencies.

The steel *stock maintenance rate* for UK national rolling stock was 4.5%. The average steel stock contraction rate was 0.7%. London Underground had an average steel stock maintenance rate of 6% and a stock expansion of 1.3%. The steel *stock maintenance rate* for buses was 8% whilst the *steel expansion rate* was 1.1%. Steel stock maintenance for aviation was 3.4%, whilst steel stock expansion was 1.7%. In general, stock maintenance rates stabilized after 1995 and although the stock for some modes of transport experienced big contractions, there was a continuous demand for steel throughout this period. Table S3 in Supporting Information S1 summarizes the evolution of *stock efficiency* compared to *stock maintenance* and *stock expansion* rates for all studied transport modes between 1960 and 2015.

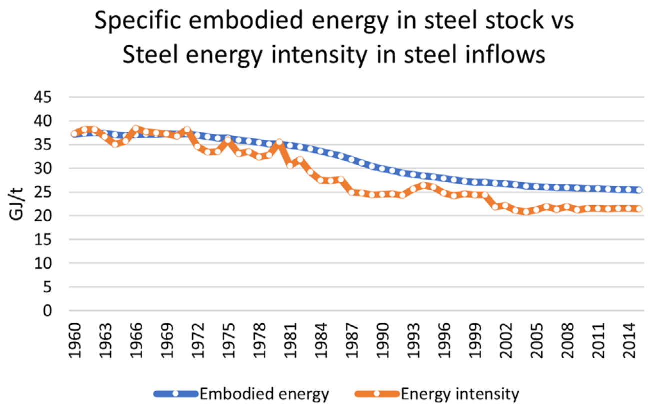


FIGURE 6 Specific embodied energy for passenger transport steel stock. Energy intensity data from Carmona et al. (2019). The underlying data used to create this figure can be found in Supporting Information S2

The annual changes to *stock specific embodied impact* relative to the energy intensity of UK steel production are presented in Figure 6. The improved performance in the steel sector becomes apparent upon comparing the growth in steel stock for passenger transport relative to the increase in the embodied energy for that same steel. The former grew by 3.8 times between 1960 and 2015 (from 6.9 to 26 Mt), whilst the latter increased by 2.8 times (from 256 to 660 PJ).

5 | DISCUSSION

Our empirical operationalization of the SFS nexus concept proposed by Haberl et al. (2017) supports the notion that restricting resource accounting to energy flows overlooks the role of stock accumulation and its contribution to the socioeconomic system. The nexus framing of efficiency adds important dimensions to resource consumption and accumulation analysis, thereby creating a much richer picture compared to conventional eco-efficiency measures such as Joule/GDP or tonnes CO_2/GDP (Haberl et al., 2020). For example, 33.5 kg of steel stock was required in 2010 to deliver 1 pkm of mobility when travelling by car. The same pkm required a maintenance flow of 2.3 kg of steel and 58 MJ of energy (at the production stage) to ensure the car functioned properly. The case study also shows that “car and motorcycle” *stock efficiency* and *stock degradation efficiency* decreased between 1994 and 2015 by 35% and 27%, respectively. This result suggests that Ventura’s (2020) finding that the fuel efficiency of vehicles categorized under “car and motorcycles” increased 12% over the same period (from 0.59 to 0.66 pkm/MJ) must be juxtaposed with stock indicators to give a more comprehensive overview of the transport sector. By only considering energy in isolation, one could obtain the false impression that the car industry is becoming more sustainable. However, when reframed according to a nexus perspective it becomes apparent that efficiency improvements are, at least in part, made possible through a greater dependency on materials (as measured in pkm/kg). This result (along with other preliminary findings in Carmona, Whiting, Carrasco, & Simpson, 2020 and Whiting et al., 2020) makes a strong case as to the need to distinguish flows and stocks in the MFA and LCA methodologies. Researchers still tend to conflate energy and mass flows, as stocks are usually converted into their flow equivalents, which is the only way to add two incommensurable properties. Distinguishing between these two dimensions of resource use would give policymakers and industry leaders the tools they need to take a more nuanced approach to resource management, including efficiency.

When we calculate the service component of the *stock efficiency* of “cars and motorcycles,” we recognise that fuel savings were counteracted by a 5% increase of steel per unit vehicle and a reduction in service provision by 25%. This leads us to believe that business policies and strategies that drive changes in fuel savings, via alterations to a vehicle’s mass, do not result in a commensurate quantitative increase in passenger mobility, when measured in terms of distance travelled. However, such initiatives may improve service quality by satisfying other parameters such as safety, comfort, and fuel costs. In this respect, the operationalization of the nexus, and the use of the material service concept, more generally, highlights and quantifies the trade-off between energy and materials that is overlooked when outputs are solely measured in terms of GDP or the Human Development Index.

By prompting a researcher to consider the nature of multiple aspects of resource use, the nexus perspective prevents the oversimplification of the complex interactions that occur within socioeconomic metabolism. For example, if one only follows the trend of *stock efficiency* without also considering the *stock maintenance* and *stock expansion (contraction)* rates, one might be led to believe that the service is improving due to the shortage of stock, when, in fact, it is not. Likewise, if one does not consider *specific embodied impact intensity*, particularly when measuring energy consumption and carbon emissions, environmental issues may be overlooked. This is especially the case when one is estimating the sustainability of different production routes (e.g., electric arc furnace vs. direct reduction iron).

It is important to point out that a higher service efficiency does not necessarily mean that the service provided to the average end-user is "good" or "suitable." This is because efficiency does not capture all aspects of mobility. For example, people do not tend to own cars because they are efficient but because they provide a greater flexibility of destination, scheduling, security, and privacy. Likewise, a transport authority interested in meeting national sustainability targets will emphasise metrics that go beyond mere efficiency, such as equity/fairness, road safety, space comfort, average duration of trip, urban aesthetics, and air pollution issues.

The inherent complexities emerging from the service perspective imply that any given material service should be assessed using more than one set of units. Selecting units that represent the primary function of a particular service, and which are already commonly used, is useful when attempting to improve specific aspects of a service, as long as one recognizes that a high number of units does not necessarily translate into high level of service. Arguably, the most efficient way to provide mobility is to design and operate routes that enable a person to achieve their end goal whilst travelling the least number of kilometers in the shortest time possible and making use of the lowest possible amount of resources. This is, in short, why a contextual analysis is essential to the interpretation of nexus results.

Another strategy that may achieve a more comprehensive resource use evaluation involves the combination of nexus indicators with methods from the social sciences to ascertain user perception and preferences. Suitable ones include those explored by Litman (2007), Shove (2007), and Mattioli, Anable, and Vrotsou (2016). Questionnaires, in particular, can assess qualitative experiences associated with transport use. In the context of the case study, "London Underground" registered a 120% rise in pkm but only a 22% increase in rolling stock. This led to a higher *stock efficiency*, which would seem to signal, from a sustainability perspective, an improvement in service provision. However, as it was achieved by "train crowding," the quality of the end-user experience deteriorated, a reality confirmed by the lower levels of satisfaction recorded in the *TfL London Underground Customer Satisfaction Survey 2010/11* (TfL, 2011).

6 | CONCLUSIONS

Our findings suggest that the SFS nexus does indeed offer rich insights into the complex interactions that emerge from specific combinations of stocks and flows and the way in which they provide services. The operationalization of the nexus highlights the need to consider stocks in their own right because if one automatically converts stocks into flows, the potential trade-offs between energy flows, material flows, and material stocks can be masked. A service perspective offers an evaluation of societal functions that does not require an economic lens. The latter emphasises wealth creation and public budgets but can lead to services falling short of end-user requirements.

It seems that steel is a good proxy for a transport sector's resource use calculations, upon extending the analysis into aluminum, plastics, glass, and rubber. However, this needs to be explored in more detail. There is also scope for an expansion of the case study to include air, road, and rail infrastructure.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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