Environmental Development xxx (xxxx) 100676

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

VSI: Sustainable Resource Use

Resource efficiency for UK cars from 1960 to 2015: From stocks and flows to service provision

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ARTICLE INFO

Keywords:
Carbon emissions
Energy efficiency
Material efficiency
Resource accounting
Sustainable transport

ABSTRACT

The transport sector is supported by the continuous provision of energy and material flows and material stocks. However, most resource accounting methods do not assess the role of material accumulation in the delivery of mobility, as a service. Using a UK-based case study, we evaluate the service contribution of both resource stocks and flows in the provision of the passenger-kilometres (pkm) travelled nationally by UK-registered cars between 1960 and 2015. For flows we considered diesel and petrol. For stocks we considered steel, aluminium, and plastics, among others. We used six indicators to analyse the interactions between stocks, flows and service. Our results show that the fuel efficiency of cars increased from 0.46 to 0.69 pkm/MJ over the period. However, there was a decrease in stock efficiency from 24.9 to 17.1 pkm/kg-year. Resource productivity increased from 0.42 to 0.61 pkm/MJ. Stock expansion rate decreased from 0.16 to 0.03 $year^{-1}$ while the specific CO_2 embodied impact reduced from 2.4 to 2.0 tCO2/tonne of resource flow. Consumer preferences for heavier larger vehicles and sociodemographic changes linked to workplace expectations, commuting and urbanisation patterns are key factors influencing UK car stock efficiency. While fuel efficiency has improved and will continue to do so via the mass adoption of electric vehicles, due to policy and legislative developments, there are still sustainability concerns linked to their heavier weight and the environmental impact of their increased material complexity.

1. Introduction

Energy and material resources are continuously mobilised by humans to expand, operate and maintain their material stocks (buildings, infrastructure, vehicles and other machinery) as well as to nourish themselves and their livestock (Fischer-Kowalski and Weisz, 1999; Giampietro et al., 2011). Various studies indicate that resource extraction has been exponential since 1900 (Carmona et al., 2021b; Dittrich et al., 2012; Krausmann et al., 2018; Schandl et al., 2016). For example, metal ore extraction increased 43-fold and fossil fuel consumption increased 15-fold between 1900 and 2010 (Krausmann et al., 2018; OECD, 2015). At the same time, the amount of bulk construction materials, metals and plastics that accumulated as stock, increased 23-fold, going from 35 Gt in 1900 to

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https://doi.org/10.1016/j.envdev.2021.100676
Received 27 April 2021; Received in revised form 6 August 2021; Accepted 19 August 2021

792 Gt in 2010 (Krausmann et al., 2017). These resource patterns have occurred, in part, due to the increased material complexity and compositional variation of market goods (Carmona et al., 2017; National Research Council, 2012).

The transport sector is a significant consumer of both energy and material flows. In 1960 it consumed 23 EJ of energy, by 2014 it required 99 EJ (De Stercke, 2014). The transport sector is also responsible for a considerable amount of material stock accumulation, given the simultaneous exponential increase of transport infrastructure and vehicles. According to the Global Road Inventory Project, by 2015, between 21 and 32 million km of roads existed worldwide, of which, 35 percent were paved. It is expected that between 3 and 5 million km of additional road will be built by 2050 (Meijer et al., 2018). The global car fleet expanded from about 51 million in 1950 to over 800 million in 2007 (Moriarty and Honnery, 2010). In 2014, the global vehicle registration was 161 vehicles per 1000 habitants (OWID, 2021). Individual vehicles have got heavier, as manufacturers have responded to sector and consumer preferences for improved aesthetics, advanced features, and higher levels of safety and comfort (Zoepf, 2011). Cabrera Serrenho and Allwood (2016), for example, calculated that UK car kerb weight increased from 995 kg in 1975 to 1321 kg in 2012. This value would have been even higher if not for the practice of light weighting. The latter involves an absolute reduction in weight of a component or the entire vehicle, in the name of energy efficiency and carbon emission savings (the transport sector contributes to 23 percent of the world's energy-related carbon emissions, see Sims et al., 2014). For example, Restrepo et al. (2020) estimated that the unit mass of an ABS (anti-brake system) actuator declined from 6.2 kg to 1.1 kg between 1989 and 2013. The unit mass of a modern ESC (electronic stability control) system declined from 4.3 kg to 1.6 kg between 1995 and 2010. Craglia and Cullen (2019) found that technological improvements, some of which were achieved via light weighting, increased fuel efficiency in UK cars from 7.6 L/km in 2001 to 6 L/km in 2018. However, if it had not been for the simultaneous rise in UK car kerb weight and engine power, this value would have been 5.6 L/km.

Lightweighting is often achieved through transmaterialisation, which is the substitution of one material for another (see Zhang et al., 2018 for a discussion of the definition). MacKenzie et al. (2014) calculated that a 33 percent reduction in conventional steel and iron consumption in US cars was made possible upon increasing the quantities of high-strength steel (fivefold), magnesium (tenfold), aluminium (fourfold), plastics and composites (twofold), rubber and glass (modest growth). As this example shows, transmaterialisation does not necessarily result in *fewer types of material* being used. In fact, it can actually *reduce* material efficiency by demanding more materials per unit output (see Carmona et al., 2017). Transmaterialisation can also be problematic when it comes to environmental sustainability because it results in the opening of additional mines and a higher number of processing and transportation routes. The practice of transmaterialisation can also make recuperation at the end-of-life stage increasingly difficult and energy intensive, thus impacting upon full life cycle product sustainability (Valero and Valero, 2014).

One way to approach sustainable resource assessments, in order to evaluate both energy and material efficiency, is through a service perspective. Rooted in the two disciplines of Industrial Ecology and Ecological Economics, a service perspective can be used to evaluate how efficiently a unit of material stock or energy/material flow is used to undertake a given activity (Haberl et al., 2017; Kalt et al., 2019; Whiting et al., 2020). This perspective has been used to trace energy flows from primary energy (such as oil or coal) through to services (such as mobility, shelter, thermal comfort) (Cullen and Allwood, 2010; Haefele, 1977; Nakićenović et al., 1996). Although much more limited in scope, and predominantly focused on shelter (e.g. Pauliuk and Müller, 2014; Tanikawa et al., 2021) and transport, some resource service literature goes beyond energy and explores the interaction between material stock and service provision. With regard to material stock employed in transport, most researchers have evaluated passenger mobility as to opposed to freight. For example, Pauliuk et al. (2012) modelled Chinese passenger car stock from 2000 to 2050. Cabrera Serrenho and Allwood (2016) modelled UK car vehicles between 2000 and 2012.

In this paper, the energy/material service (resource service) definition is derived from Fell (2017) and Whiting et al. (2020) as *"Those functions that resources contribute to personal or societal activity with the purpose of obtaining or facilitating desired end goals or states, regardless of whether or not a resource flow or stock is supplied by the market."*

With reference to the above definition, a flow (or stock) provides an energy and/or material service upon interacting with an end-user for the fulfilment of a defined purpose, measurable in physical units. For example, when considering passenger mobility, one could assess how fuels (flows), vehicles and road infrastructure (stocks) combine to move a person or a commodity from Point A to Point B (the service). Potential service units could include passenger-kilometres (pkm), number of trips or duration. No individual unit captures all relevant aspects of service provision (Carmona et al., 2021a). One also has to be careful when interpreting results from any one or all service units. With pkm, for example, it is important to bear in mind that a high number does not necessarily translate into a high quality service. This is because while it may indicate that a person can travel further along the transport network, it may equally mean that the system is overcrowded. In addition, one could argue that a transport service of the highest quality enables a user to travel fewer kilometres, generating fewer emissions and still accomplish their end goals. It is also true that vehicles do more than merely offer passengers mobility, as Sorrell and Dimitropoulos (2008) identify: *"… all cars deliver passenger-kilometres, but they may vary widely in terms of features such as speed, comfort, entertainment, acceleration and prestige"*. In this respect, only measuring one type of service (i.e. mobility), instead of multiple ones (e.g. space comfort, health protection and restoration), may lead to inaccurate conclusions about vehicle performance (Prioni and Hensher, 2000). In other words, one needs to interpret service units carefully prior to proposing an appropriate course of action. In this respect, a comprehensive literature review and contextual analysis can help.

Resource efficiency from a service perspective can be calculated as the ratio between the service metric and the corresponding stocks and flows. However, historically, it has been restricted to energy flows and, therefore, energy efficiency. The latter was defined by Lovins (2004) as any ratio of function, service, or value provided to energy upon being converted. Interest in energy efficiency within the transport sector, and the subsequent development of energy intensity indicators, was triggered by the OPEC oil crisis in 1973 (Lackner, 2017; Moriarty and Honnery, 2012). Since then, there have been various service-based studies that analyse the fuel efficiency (or energy intensity) of the transport sector, particularly at the national level. Lipscy and Schipper (2013), for example, studied the performance of American and Japanese registered cars for 1973, 2000 and 2008. Their results show that the energy intensity of Japanese cars increased slightly, due to traffic congestion. It went from 2.3 MJ/pkm in 1973 to 2.4 MJ/pkm in 2008. On the other hand, American car performance increased (energy intensity decreased) significantly from 3 MJ/pkm in 1973 to 2.3 MJ/pkm in 2008, although a clear reason for this trend was not provided. This contrasts with Banister and Stead (2002), who found that no EU-15 country experienced substantial improvements in energy efficiency (measured in MJ/pkm) between 1970 and 1995. Likewise, Moriarty (2021), concluded that based on International Energy Agency studies, there was no significant change in energy efficiency (MJ/pkm) between 2000 and 2017 for light-duty vehicles registered in 20 OECD countries. The reasons he gave for this trend included a shift to larger vehicles, higher performance demand (speed), and additional energy consumption for the operation of auxiliary features such as power steering. Tiwari and Gulati (2013) compared the energy intensity of cars across seven countries for 2001 and 2007. Vehicle energy intensity was lowest in India at 0.31 MJ/pkm and 0.28 MJ/pkm, respectively. These values were considerably lower than those registered in Canada (2.18 and 2.06 MJ/pkm), China (1.87 and 2.00 MJ/pkm), France (1.72 and 1.53 MJ/pkm), Japan (2.30 and 2.24 MJ/pkm), the UK (1.53 and 1.51 MJ/pkm) and the US (2.29 and 2.46 MJ/pkm). Such findings suggest that improvements in energy efficiency have been minimal. None of the aforementioned studies consider material flows or stocks.

Compared to energy efficiency, stock efficiency studies from a service perspective are scarce. In fact, stock modelling and, particularly the link between material accumulation and service provision, have only come to the forefront since 2010 (See Lanau et al., 2019 for an in-depth literature review). For the most part, material stock efficiency studies have predominantly focused on the impact of material accumulation on Gross Domestic Product (see for example, Dombi, 2019; Fishman et al., 2015; 2014; Huang et al., 2017) or carbon emissions (see Fishman et al., 2021; Pauliuk et al., 2020; Wolfram et al., 2020). Key exceptions to this are Virág et al. (2021) and Carmona et al. (2021a), who evaluated the role of material consumption and accumulation in the provision of a resource service, but did not link it to GDP.

Virág et al. (2021) analysed the stock, flow, and services for both transport infrastructures and vehicle stock in Vienna for a representative year between 2010 and 2018. They demonstrated how car-based mobility requires 70 percent of the energy flows and 70 percent of material stocks but delivers just 48 percent of the passenger-kilometres travelled. Most of the energy flows are used in vehicle operation. Most of the material stock (97 percent) is employed in transport infrastructure, which is predominantly constituted by crushed stone, gravel, and sand (41 Mt), asphalt (14 Mt) and concrete (35 Mt). Vehicles accounted for 1.2 Mt of the material stock, so only 3 percent of the total. Vehicle stock was fundamentally composed of steel (56%), other metals and alloys (15%), and petrochemicals (12%). Therefore, while constituting a much lower value in terms of weight, vehicle composition plays a significant role in sustainable resource use, particularly when it comes to material diversity and criticality (Cimprich et al., 2017; Ortego et al., 2018).

Carmona et al. (2021a) calculated the passenger-kilometres travelled per unit of steel stock contained in UK-registered cars between 1960 and 2015. They estimated that steel stock efficiency for this form of transport decreased from 37.5 to 28.0 pkm/kg-year. This reduction was a product of demographic transitions, the resulting consumer demand for car-based mobility, and consumer preferences for larger cars. All these factors contributed to an increase in car steel stock, which went from 4 to 28 Mt.

This present paper evaluates the resource efficiency of the most frequent form of UK travel (passenger mobility in cars). It builds on Carmona et al. (2021a), by expanding the resource efficiency analysis of UK registered cars to include not only steel but also fuels (diesel and petrol), aluminium, plastics, rubber, and glass. The analysis of multiple materials, including fossil fuels, provides further insights into the transport sector's material dependency and resource efficiency. It also reduces the knowledge gap regarding the interplay, and possible trade-offs, that occur when different material flows and stocks within vehicles combine to offer one unit of service. This is something that Carmona et al. (2021a) were unable to quantitatively evaluate because they restricted their analysis to steel.

The other knowledge gap that this paper addresses is linked to historical long-term stock efficiency trends from a service perspective. As aforementioned, while long term studies regarding resource use efficiency in the transport sector do exist, they are either focused on economic productivity or environmental impacts. In addition, those studies that explore resource efficiency from a service perspective have, thus far, been limited in temporal scope or restricted to a single resource (e.g steel, fuel or aluminium). The innovation of this paper is, therefore, a resource efficiency assessment of the multiple flows and stocks that have contributed to UK car-based mobility over a 55-year period.

The aims of this present paper are thus: (1) to assess the historical fuel and material stock efficiency for UK cars upon incorporating various resources, in addition to steel; (2) analyse the interactions between resource flows and stocks in terms of their respective efficiency, as a product of technological, legislative and sociodemographic developments (3) discuss the challenges associated with a sustainable transport transition and how a service perspective may provide additional insights with regard to passenger mobility in light of the results obtained in this study.

2. Methodology

An inflow-driven stock model was used to estimate the material stocks and material flows quantities, ensuring the fulfilment of the mass-balance principle (Section 2.1). An energy flow analysis was performed to assess the amount of fuel used by UK registered cars (Section 2.2). Finally, a set of indicators was selected to analyse the stock, flow, and service relationships (Section 2.4).

2.1. Stock-flow model

Stock and flow data was estimated via the inflow-driven stock model (Equation (1)) developed by Carmona et al. (2021a).

$$M_{Stock[N,i]} = \underbrace{M_{Stock[0,i]}}_{Initial\ Stock} + \underbrace{\sum_{n=1}^{N} M_{Inflow[n,i]}}_{Inflow} - \underbrace{\sum_{n=1}^{N} M_{Inflow[n,\ i]} \cdot f_{[n,i]}}_{Outflow\ \left(M_{Outflow[n,i]}\right)} \tag{1}$$

where, $M_{Inflow[N,i]}$ represents the annual amount of each type of material i that constitutes newly UK registered vehicles in year n. Outflows represent the annual amount of each type of end-of-life material that no longer serves as stock. $M_{Outflow[n,i]}$ is determined via a residence time model using a convolution integral derived from $M_{Inflow[n,i]}$ and the probability density of a lifespan distribution function $f_{[n,i]}$. In line with several authors (Dahlström et al., 2004; Hamilton and Macauley, 1998; Michaelis and Jackson, 2000; Skelton and Allwood, 2013; SMMT, 2017), the average car's lifetime was assumed to be 11 years for those circulating between 1960 and 1980, and 13 years from 1981 to 2015.

The initial stock value of each type of material (Equation (2)) was derived from the total number of cars registered in 1960 ($N_{[0]}$), their average weight ($W_{[0]}$) and the fractions of material i that constitute them ($x_{[0,i]}$).

$$\mathrm{M}_{\mathrm{Stock}[0,\mathrm{i}]} = \mathrm{N}_{[0]} * \mathrm{W}_{[0]} * \mathrm{x}_{[0,i]} \tag{2}$$

Carmona et al.'s (2021a) model incorporates a sensitivity analysis in order to take into account data uncertainty. The sensitivity analysis considered several variables such as “fraction of material consumption allocated to the transport sector”, “material efficiency of product manufacture” and “vehicle lifetime expectancy”.

2.2. Energy and emission flow analysis

The energy inflows ($E_{Fuel[i]}$) considered in our case study were the quantities of diesel and gasoline utilised during the operation of the vehicle, and not in its manufacture or disposal. In other words, they represent the amount of energy required to propel the vehicle and operate its auxiliary devices, taking into consideration all the losses along the powertrain. Energy mass values ($W_{Fuel[i]}$) were converted from kt to TJ, and vice versa, using the fuel's calorific value for the corresponding year ($Cp_{Fuel[i]}$), as provided by IEA (2017). See Equation (3).

$$E_{Fuel[i]} = W_{Fuel[i]} * Cp_{Fuel[i]} \tag{3}$$

Regarding the emissions outflows, and in line with Krausmann et al. (2018), the fractions of pollutant x - carbon, nitrogen and sulphur - contained in the energy flows ($E_{Fuel[i]}$) following their combustion were converted into their respective emissions and other losses (e.g. ashes, water vapour) ($I_{Fuel[i,x]}$).

$$I_{Fuel[i,x]} = E_{Fuel[i,x]} * f_{[i,x]} \tag{4}$$

2.3. Data sources

The UK Department of Transport keeps good quality and easily accessible data regarding the number of vehicle registrations and distance travelled. There is also considered data for car composition that can be sourced from various academic papers (e.g. Cabrera Serrenho and Allwood, 2016; Craglia and Cullen, 2019).

Fuel (petrol and diesel) consumption values were obtained from the International Energy Agency (IEA, 2017) and the UK's Department for Transport's statistics (DfT, 2018a). Alternative fuels such as biofuels and electricity were not considered. In 2015, biofuels were only responsible for 3 percent of the total energy used in road transport and electricity only accounted for 0.02 percent. Both figures drop lower still (to zero) as one approaches 1960.

Data corresponding to vehicle composition and weight were obtained from various sources. The steel quantities were taken from Carmona et al. (2021a). The aluminium curb weight and percentages were extracted from Cabrera Serrenho and Allwood (2016) and Ducker Worldwide (2017). The average weight and percentage of glass, lubricants and fluids, textile, rubber and other metals, were taken from MacKenzie et al. (2014), Dai et al. (2016) and the American Chemistry Council (ACC, 2017). As far as we are aware, there are no historical data corresponding to the plastic contained in UK vehicles so US values were used; from 1975 to 2010, average weight and percentage was taken from MacKenzie et al. (2014). For 1960 to 1975 and from 2010 to 2015, we relied on the American Chemistry Council (ACC, 2017) report. Where data was unobtainable, linear extrapolations were undertaken.

Petrol's and diesel's specific exergy conversion factors were taken from Dincer and Rosen (2013). Steel, aluminium, and other materials' specific exergy values were obtained from Carmona et al. (2021b). To calculate an exergy value for plastics, we used the values provided by Eboh et al. (2016) for Polyethylene (PE); polypropylene (PP); polyvinyl chloride (PVC) and polyurethane (PU). The percentage for each type of polymer contained within a car was taken from the American Chemistry Council (2017). For the exergy calculations, we assumed that there were no percentage changes among the different types of plastics that constitute the overall “plastic” category.

Fuel-based CO_2 emission values, in tonnes, were taken from the UK's Department for Transport (DfT, 2018a). For the material-based CO_2 emission factors, Remus et al. (2013), Hill et al. (2013), and Whiting and Thistlethwaite (2011) provided those for steel while Odeh et al. (2013) provided the values for aluminium and plastics.

UK car registration data was taken from the Department for Transport (DfT, 2018b, 2012). In 2015, fully electric and hybrid vehicles represented only 0.2 percent of the UK car stock (which is incidentally why electricity consumption is also low), and, consequently, were not analysed in this paper. Passenger-km (pkm) and trips are two metrics typically used in the transport sector to measure and assess the provision of mobility as a service (Litman, 2003, 2007). Passenger-km data for road travel by UK registered cars within national borders from 1960 to 2015 was taken from the Department for Transport (DfT, 2018b). Reliable data for post-2001 trips is available from DfT (2020a). For validation purposes, we calculated the resource efficiency relative to the number of trips taken between 2002 and 2015. Other potential service metrics such as door-to-door traffic times were not analysed due to a lack of data.

2.4. Resource efficiency metrics

We apply six indicators to assess resource efficiency. These are “stock efficiency”, “stock degradation efficiency”, “specific embodied impact”, “stock expansion rate”, “fuel efficiency” and overall “resource productivity”. Each one captures an aspect of the interactions between stocks and flows in the provision of mobility (Fig. 1). The first four indicators were used in Carmona et al. (2021a). The fifth one is derived from pre-existing analysis that has been undertaken within the field of Energy Efficiency (e.g. Lipscy and Schipper, 2013; Tiwari and Gulati, 2013). The sixth indicator converts energy (kJ) and material (kg) flow quantities into their exergy equivalent (kJ) so that the units are commeasurable.

Table 1 presents the indicators used to convey the relationships among energy and material stocks, flows, and services. The *fuel efficiency* indicator (Equation (5)) represents the ratio of passenger-kms to energy consumption. *Stock efficiency* (Equation (6)) shows the relationship between passenger mobility and car stock. It can reveal the significance of material accumulation, which may help practitioners to better understand how vehicle size and design impacts upon service delivery. Together, these two indicators can be used to evaluate existing sustainable transport policies and propose new ones. This is because by assessing *stock efficiency* relative to *flow efficiency*, trade-offs become more apparent. The *stock degradation efficiency* indicator (Equation (7)) depicts the coupling between material (non-monetary) depreciation and service delivery. It quantifies the amount of material stock that has degraded (and needs to be replaced) to provide a unit of service. *Resource productivity* (Equation (8)) shows the ratio of passenger mobility to the total amount of energy (fuel) consumption and material outflow (e.g., worn out aluminium). Exergy characterises both these flows under one single unit (Whiting et al., 2017). The *stock expansion rate* measures the speed of stock accumulation (Equation (9)) as the ratio of the net additions to stock (inflows minus outflows) to material stock. *Specific embodied impact* (Equation (10)) calculates the carbon emissions generated during both stock production and its in-use phase per unit of service. It allows a practitioner to identify shifts in material composition, given that steel production, for example, will generate, on average, 1.24 tonne CO_2 while aluminium production is responsible for 7.28 tonne $CO_{2.}$ In equations (5)–(8), a higher value corresponds to more efficient resource use. For Equation (10), a lower value means that the process/technology is more efficient, in the sense that less carbon is produced per pkm.

3. Results and analysis

3.1. Stock, flows and service evolution

Fig. 2a shows how car stock, fuel consumption, and passenger mobility evolved from 1960 to 2015. Mobility increased fivefold from 139 to 659 billion pkm, reaching a maturation point in 2005, after which service provision stabilised. Both the average distance travelled, and average occupancy rate decreased, although not at the same rate (Fig. 2d). In 1960, the average distance travelled by car was 13,878 km/year. The highest average distance travelled was registered in 1992 at 17,011 km/year. By 2015, this value had

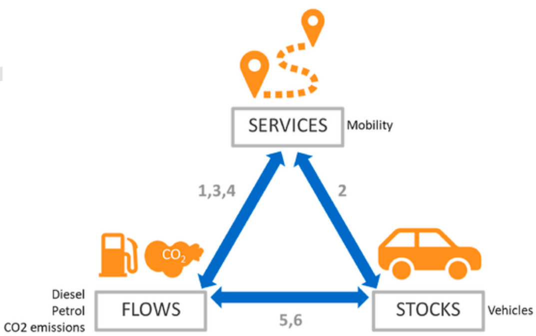

Fig. 1. The interplay between stocks and flows in the provision of mobility. Note: The numbers highlight the indicators used to measure a specific aspect of the stock, flow and service interactions - 1) energy (fuel) efficiency; 2) stock efficiency; 3) stock degradation efficiency; 4) resource productivity; 5) stock expansion rate, and 6) specific embodied impact.

Table 1
Resource efficiency indicators.

N	Indicator Name	Indicator Equation	Description of Corresponding Stock and/or Flow
1	Energy (fuel) efficiency	$\frac{Serv\ [pkm/year]}{E_{Fuel}\ [kJ/year]}$ (5)	Flow: The energy contained in the fuels (diesel and gasoline) used for the operation of the vehicle. It does not include the energy required in vehicle manufacture or disposal.
2	Stock efficiency	$\frac{Serv\ [pkm/year]}{M_{Stock}\ [kt]}$ (6)	Stock: The total mass of all vehicles operating at the end of a given year.
3	Stock degradation efficiency	$\frac{Serv.\ [pkm/year]}{M_{Outflow}\ [kt/year]}$ (7)	Flow: the mass of end-of-life flows - all the components that constitute the vehicle (i.e. steel, aluminium, plastics, spent lubricant, spent tyres).
4	Resource Productivity	$\frac{Serv.\ [pkm/year]}{B_{Fuel}\ [kJ/year] + B_{MOutflow}\ [kJ/year]}$ (8)	Flow: The exergy embedded in fuels and end-of-life flows (see indicators 1 and 3).
5	Stock expansion rate	$\frac{M_{Inflow}\ [kt/year] - M_{Outflow}\ [kt/year]}{M_{Stock}\ [kt]}$ (9)	Flow: The net difference in mass between new vehicle inputs and end-of-life vehicle outputs Stock: The total mass of all vehicles operating at the end of a given year.
6	Specific embodied impact	$\frac{I_{Fuel}\ [ktCO_2/year] + I_{MInflow}\ [ktCO2/year]}{M_{Fuel}\ [kt/year] + M_{MInflow}\ [kt/year]}$ (10)	Flow (numerator): The mass of CO_2 emitted during vehicle manufacture and operation. Flow (denominator): The energy, in mass terms, used to operate a vehicle added together with the mass of new vehicle inputs.

Abbreviations: *Serv.*: Material service, E_{Fuel}: Energy flow, M_{Stock}: Material stock, M_{Inflow}: Annual material inflow, $M_{Outflow}$: Annual material outflow, B_{Fuel}: Exergy contained in energy flow, $B_{MOutflow}$: Exergy contained in material outflow, I_{Fuel}: Impact of fuel consumption. $I_{MInflow}$: Lifecycle impact of inflow.

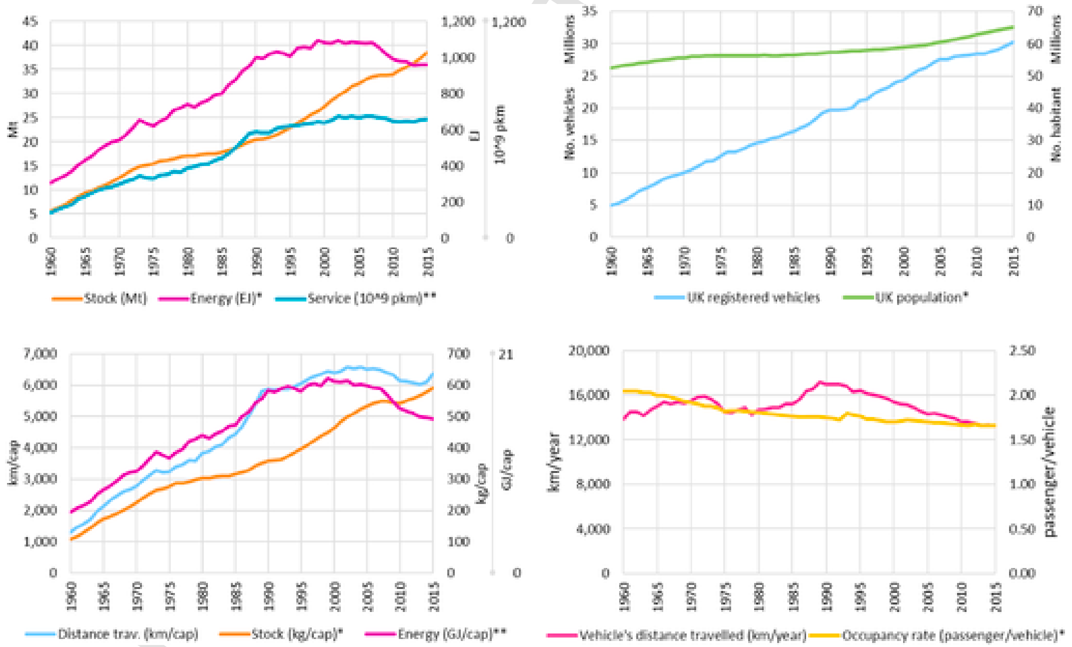

Fig. 2. Car use between 1960 and 2015.2a – Top-left: Total cars stock, energy consumption and service provision. 2b – Top-right: Population and number of vehicles. 2c – Bottom-left: Per capita values (distance, stock, and energy). 2d – Bottom-right: average travelled distance by vehicle (km/year). Note: * - secondary axis, ** - third axis.

decreased to 13,312 km/year. The average occupancy rate decreased steadily from 2.04 in 1960 to 1.66 in 2015. This means that passenger mobility was predominantly supported by an ever-increasing number of UK car registrations (4900 in 1960 and 30,250 in 2015), particularly, since the UK population increased very slowly over the period (Fig. 2b). Fuel consumption, likewise, increased threefold from 304 EJ to 959 EJ over the period, with peak consumption in 2002. In material stock terms, there was a sevenfold growth over the period, which is higher than that recorded for service provision or fuel consumption. Total stock increased from 5 Mt in 1960 to 38 Mt in 2015. Likewise, car stock per capita in 1960 was 106 kg/person and rose to 592 kg/person in 2015 (Fig. 2c). Both these values resulted, not only from a higher number of cars on the road but also, from the tendency to purchase heavier and larger cars. The average kerb weight went from 1.13 tonnes in 1960 to 1.27 tonnes in 2015. This 12 percent increase is explained, in part, due to a growing preference for SUV models – which weigh between 1.6 and 1.9 tonnes – their market share rose from 4.5 to 22.5 percent between 2001 and 2015 (Maxxia, 2016; SMMT, 2014). For more information regarding the stock, flows and service see tables S1 and S2 of the Supplementary Information.

Fig. 3a shows the breakdown of those materials (steel, aluminium, plastics, and others) that constituted car stocks from 1960 to 2015. The steel fraction decreased from 72 percent to 61 percent, which was made possible via the addition of aluminium and plastics. Plastics are favoured by the car industry because of their light weight, low cost, moulding ability (which enhances aesthetics) and their impact absorption properties, which makes driving safer (Lyu and Choi, 2015; Park et al., 2012). The aluminium and plastics fractions grew from 2.2 percent to 7.6 percent and from 0.6 percent to 7.8 percent respectively. The fraction of the other elements remained relatively constant, registering 25 percent in 1960 and 23 percent in 2015. In 2015, the main constituents of the "others" category were lubricants and fluids (26%), rubber (22%), glass (11%) and copper and brass (8%).

Fig. 3b shows an increasing adoption of diesel-powered vehicles. In 1960, petrol represented 99% of all fuel consumed by cars. By 2015, there was an even split between the two. The tendency towards diesel powered vehicles began in earnest in 2001 (when petrol vehicles constituted 79 percent of the total) following a reduction in UK exercise duty for lower carbon emitting vehicles. Diesel fuel burns more efficiently, thus reducing the emissions released per litre consumed relative to petrol. The impact of this policy was immediate and resulted in a 38 percent increase in the number of new diesel registrations in 2002 (BEIS, 2019).

3.2. Efficiency indicators

3.2.1. Energy, stock, and stock degradation efficiency indicators

Energy efficiency increased from 0.46 pkm/MJ in 1960 to 0.69 pkm/MJ in 2015, as shown in Fig. 4. As aforementioned, peak fuel consumption occurred in 2002 (Fig. 2a). A similar trend can be found in the energy efficiency indicator when trips are used to measure mobility instead of pkm. For 2002, energy efficiency was 37 trip/GJ. By 2015, this value was 40 trips/kg-year. This eight percent improvement is similar to the one experienced in energy efficiency when measured in pkm (equivalent to 12 percent). There are several variables that can affect fuel consumption per kilometre travelled. Zacharof et al. (2016) analysed the effect of 28 factors. They found that while an increase in vehicle mass negatively impacts upon fuel consumption from anything between six to 20 percent, other factors such as driving style or traffic conditions can also be significant and may increase fuel consumption by up to 30 percent. Aerodynamics and road conditions also play a role.

Although one cannot be certain as to the reasons for the fuel efficiency increases in the 1960s, there are various possibilities. The first one is the introduction of the national speed limit of 70 mph on all roads (as enacted under *Motorways Traffic (Temporary Speed*

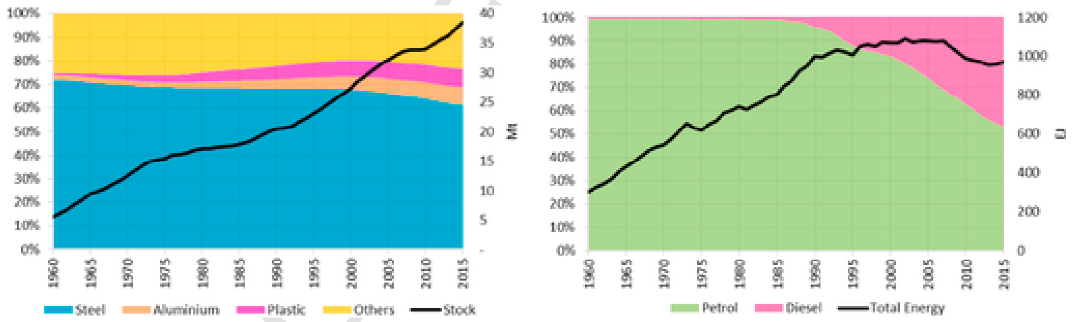

Fig. 3. UK vehicle stock and fuel consumption from 1960 to 2015. Left: Total stock by material type. Right: Total consumption by fuel type.

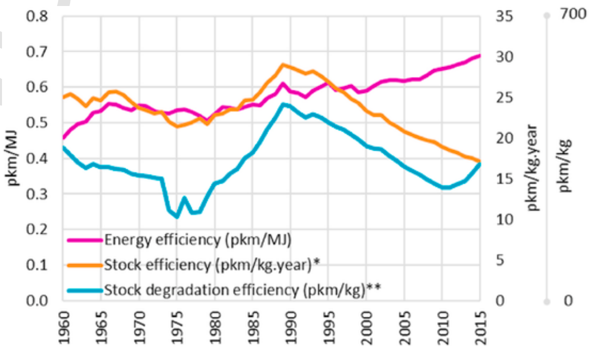

Fig. 4. Energy and Stock Efficiency indicators. Note: * - secondary axis, ** - third axis.

Limit) (England) Regulations 1965, which became a permanent change in 1967). This legislation inadvertently increased fuel efficiency per mile when cars travelled on faster roads such as motorways and dual carriageways. Another potential reason for improved fuel efficiency is linked to the introduction and proliferation of higher-octane fuels in the late 1950s and 1960s (as specified in the British Standard *BS 4040-1:1967*, see also Ritson et al., 2018). Such fuels combat the effect of knock, diminishing fuel consumption while also improving engine performance (see Splitter et al., 2016 for an in-depth discussion of octane fuel efficiency being counteracted by the development of American power cars in the US market). The post 2002 improvements in fuel efficiency are very much a product of technological advancements and legislative responses to an increasing appetite for eco-options. Based on Craglia and Cullen's (2019) results, we estimate that technological improvements increased fuel efficiency of new UK manufactured cars from 0.69 pkm/L in 2001 to 0.77 pkm/L in 2018. However, this value would have been 0.81 pkm/L had it not been for the increased mass and engine power of UK registered vehicles. The European Union has also triggered fuel efficiency improvements via legislation and the setting of voluntary emissions targets for car manufacturers. In the late 1990s to early 2000s, the EU implemented a voluntary strategy to reduce carbon emissions from cars by (1) setting a target of 140 g CO_2/km by 2008/2009 in new passenger cars; (2) Fuel-economy labelling to enable consumers to make an informed choice and (3) the promotion of car fuel efficiency by fiscal measures (European Commission, 2000). Mandatory legislation followed in 2009 with the *Regulation (EC) 443/2009*. By 2015, the average EU registered car's CO_2 emissions had dropped to 120g per km travelled, under type approval (test) conditions. This is an equivalent fuel saving of 2.7 L per 100 km travelled, relative to the average consumption registered in the same conditions in 1995. That said, a 35 percent saving under test conditions is substantially higher than the real road savings we estimated in this paper (12 percent). These savings would have been higher still if not for the increases in vehicle curb weight.

Stock efficiency declined sharply following its peak at 29 pkm/kg-year in 1989 (Fig. 4). A similar trend was found in the stock efficiency indicator when trips were used instead of pkm. In 2002, there were 1.4 trips/kg-year. By 2015, this value was 0.9 trip/kg-year. This 27 percent decline is similar to the one experienced in stock efficiency when measured in pkm, which was 25 percent. There are various sociodemographic reasons for this, including changes in work patterns and expectations, particularly for women who have been increasingly able to establish their career (Roantree and Vira, 2018). At the same time, the occupancy rate may have decreased due to legislative changes such as the enforcement of seat belts (via *Motor Vehicles (Wearing of Seat Belts) Regulations 1993*), and a reduction in family size (ONS, 2019), both of which would have triggered a higher number of vehicles circulating with fewer passengers.

Lower levels of car sharing between family members meant that vehicles were parked for longer. This observation is supported by Morris (2016) who states that US cars are parked 95 percent of the time, and by Bates and Leibling (2012) who state that the typical UK-registered car is only on the move for 6 hours per week and that for the remaining 162 hours it is stationary or parked. In addition, the average car user travels further than they did previously, which reflects the UK's urbanisation patterns (houses as opposed to flats) and willingness to commute, as opposed to any particular economic variable (Stapleton et al., 2017). In fact, commuting journeys represent one-fifth of all miles travelled, and most commutes are undertaken by car (DfT, 2017). The average annual distance travelled by a car user increased fivefold from 1297 km/cap in 1960 to 6378 km/cap in 2015 (See Supplementary Information Table S7).

In 1960, car stock outflow was 2.7 kg/pkm and rose to 3.0 kg/pkm in 2015. Stock degradation efficiency declined from 1960 to 1973 before rising sharply between 1977 and 1990. The increase from 1977 coincides with the establishment of the second-hand car market. This observation is supported by the early publications of national/regional magazines such as *Auto Trader*, which served to connect second-hand car sellers and buyers. The second-hand market reduces car prices and encourages car ownership (Thomas, 2003). This is especially the case for those who cannot afford a brand-new car. The possibility of second-hand ownership also increases a car's lifespan, temporarily diverting it away from landfill and encouraging repairs. Since 1991, the price of the UK average car has dropped significantly relative to inflation. A decrease in real prices from 1991 to 2009 was also observed (Cambridge Econometrics, 2015). This, in turn, incentivised consumerism and made increasing the longevity of one's car a less attractive option. The 2008 economic crisis delayed car disposal, which increased stock degradation efficiency relative to the previous decade.

These observations are supported by Fig. 5, which presents the stock expansion rate i.e. a function of society's capacity to maintain and expand stock levels. This rate decreased substantially between 1960 and 1980, upon which it stabilised. It went from 0.23 year^{-1}

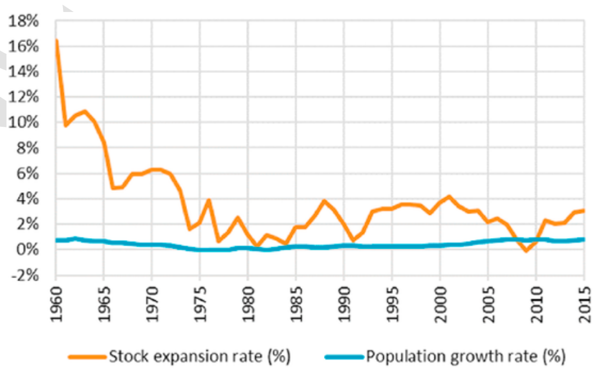

Fig. 5. UK car stock expansion rate vs. UK population growth rate from 1960 to 2015. Note: UK population growth rate from (World Bank, 2021).

in 1960 to 0.06 year^{-1} in 2015. One might expect a relative decrease in the stock expansion rate if the UK population growth rate slows, which was the case between 1960 and 1980. However, since the 2000s, the population growth rate accelerated but the stock expansion rate stabilised. This consumption pattern is, in part, a product of the second-hand market development explained above.

3.2.2. *Resource productivity*

Fig. 6 shows the evolution of resource productivity, defined as the combined amount of energy and material required to provide passenger mobility in both mass and exergy terms. Both patterns are determined by fuel consumption. In the exergy analysis, material outflows represented 1.1 percent of the resources consumed in 1960 and 2.4 percent in 2015. Similarly, when accounting in mass terms, material outflows increased from three percent of the total resource consumption in 1960 to six percent in 2015. This reflects an increase in energy efficiency and, to a lesser extent, a reduction in the number of cars that were disposed of. There were no significant differences in the mass and exergy trends, although it is worth noting that should electric vehicles become more common, these patterns will diverge. This is because electricity has no mass and is pure exergy. In other words, the mass line will indicate a higher level of efficiency to a much greater degree than its exergy counterpart.

3.2.3. *Specific embodied impact*

Fig. 7 represents the CO_2 embodied impact of the fuels and materials required for car transportation. Diesel cars tend to have a lower volumetric fuel consumption than their petrol counterparts. However, the CO_2 emissions per unit of diesel combustion are approximately 13 percent more than those arising from the combustion of one unit of petrol (ICCT, 2019). Developments in clean tech installed in both petrol and diesel cars did, to some extent, abate these emissions. The CO_2 emissions embodied in the materials reduced significantly from 6 tCO2/t in 1960 to half that by 2015. This was due to the implementation of energy efficiency strategies and technological developments in the industrial sector (Carmona et al., 2019; Dahlström and Ekins, 2005; Fischedick et al., 2014). As noted in Section 2.4, carbon emissions are not uniform across all sectors and the embodied impact of steel (1.24 tCO2/t) is considerably lower than that of aluminium (7.28 tCO2/t) and plastic (4.18 tCO2/t) (Gutowski et al., 2013). This is not particularly problematic, but it is worth noting that there has been a shift away from steel to other materials (See Section 3.1).

3.2.4. *Summary of the results: Sankey representation*

Fig. 8 shows the Sankey representation of the energy and material flows (lines) and car stocks (cylinder) that combined to provide passenger mobility (circles) in 1960, 1980, 2000 and 2015.

The highest increase in service provision happened between 1960 and 1980 at an equivalent of a nine percent average annual growth rate. For the period 1981 to 2000, there was a three percent annual growth rate. The rate then dropped to an annual average increase of 0.2 percent between 2001 and 2015. For stock, the average annual expansion rate was ten percent between 1960 and

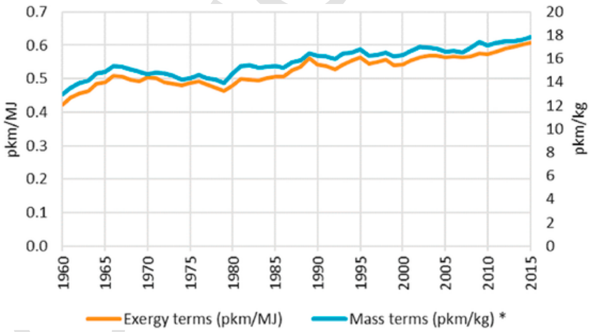

Fig. 6. The UK's car resource productivity from 1960 to 2015. Note: (*) represented on the right axis.

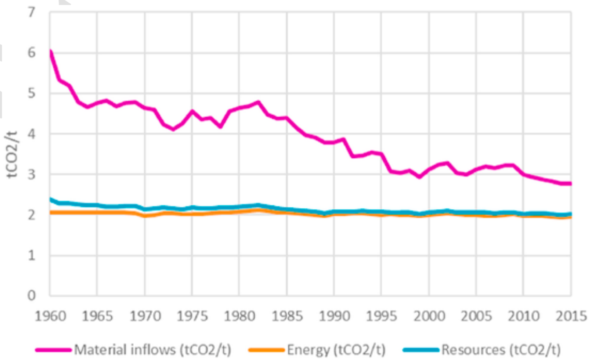

Fig. 7. Specific embodied carbon emissions of the resources used to provide passenger mobility.

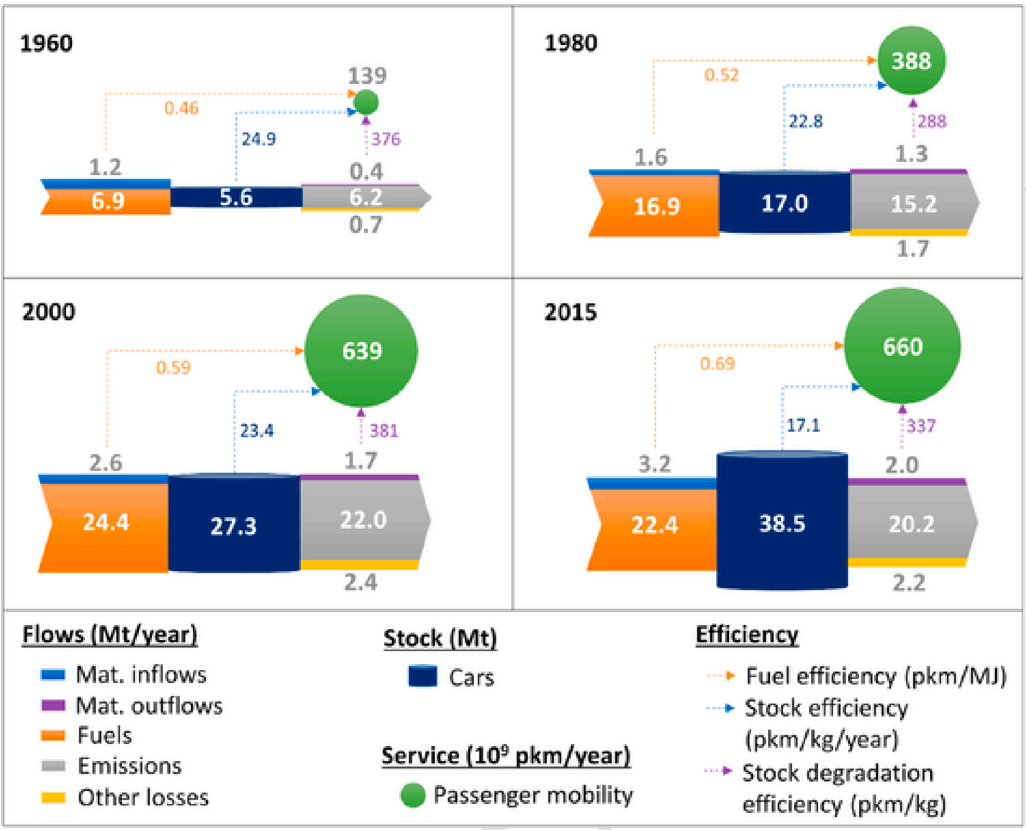

Fig. 8. Stock-flow-service Sankey diagram of UK-based car mobility. Note: "Material inflows" represents all the flows that feed into a new vehicle (metal, lubricant, rubber, glass). The "material outflows" represent all the components that constitute the vehicle (i.e. steel, aluminum, plastics, spent lubricant, spent tyres). "Emissions" refers to the fractions of carbon, nitrogen and sulphur contained in the energy flows following their combustion. "Other losses" is predominantly constituted by ashes and water vapour.

1980. It remained at three percent from 1981 to 2015. For fuel and material inflows, the growth rate was six percent in 1960–1980, two percent in 1981–2000 and -0.4 percent (negative) between 2001 and 2015.

In 1960 the amount of energy and materials inflows (8.2 Mt/year) was 1.5 times higher than the value corresponding to the car stock (5.6 Mt). By 2015, this pattern had reversed and stock quantities (25.5 Mt/year) were 1.5 times higher than the resource inflows used to maintain and operate material stock (38.5 Mt). This is indicative of energy efficiency improvements in the transport sector combined with the preference for car-based mobility and larger cars. The emissions generated per unit of fuel remained stable throughout the period.

4. Discussion and conclusions

In this case study, we undertook a long-term resource efficiency analysis of the fuels (energy flows) and various materials stocks and flows, including steel, aluminium, plastics, rubber, and glass that provided UK car-based passenger mobility over a 55-year period. In terms of this article's aim 1, and in line with Carmona et al.'s. (2021a) finding that UK steel stock efficiency for car and motorcycle mobility declined by 19 percent, between 1960 and 2015, our results showed that stock efficiency decreased by 32 percent. In other words, a greater quantity of stock was required per passenger-kilometre travelled in 2015 compared to 1960. At the same time, 12 percent less material outflow (waste) was generated per unit of passenger-kilometres travelled. Both trends were a product of the UK's preference for (a) increased car ownership and (b) heavier more materially complex vehicles, which (c) happened to be parked for a longer period of time. When one solely focuses on energy consumption, wider resource patterns, and their associated problems, are at best overlooked or worse ignored. Thus sustainability transitions that emphasise energy savings over resource savings more generally may promote fuel reductions that then trigger material overconsumption. Aside from the environmental harm that can result, it can also give society the false impression that things are getting better.

To fulfil aim 2, we explored changes in vehicle composition due to policy, demographic, and technological transitions. The data show that car manufacturers shifted away from steel and increasingly towards plastics and aluminium, along with trace quantities of other materials, including rare earths. The EU legal requirement and the policy drive to cut carbon emissions at the exhaust pipe from 140 g/km in 2008 to 130 g/km in 2015 (ICCT, 2018) was one of the reasons behind a shift towards lighter materials for the sake of energy efficiency improvements. In fact, our results show that light weighting strategies did, in part, permit a 51 percent increase in energy efficiency. While the latter improved because of better engine performance and fuel quality, it is also true that had the average 2015 car remained at the 2001 weight, the fuel efficiency would have been 0.85 pkm/MJ instead of 0.69 pkm/MJ. Likewise, the stock efficiency would have been 19.5 pkm/kg instead of 17.11 pkm/kg.

In line with aim 3, we researched additional sustainability concerns that remain unresolved when it comes to complex interactions among resource stocks and flows. The first is linked to transmaterialisation, whereby conventional materials, such as steel, copper, glass and zinc are increasingly replaced with different elements to perform more or less the same function (Carmona et al., 2017). This process is employed to reduce carbon emissions, enhance some aspects of user comfort or vehicle aesthetics and to some extent, counteract the consumer preference for heavier larger vehicles. However, any such gains must be juxtaposed against the *additional* environmental harms (e.g. the ecotoxicity caused by the mining and processing of rare earth elements, see Mestre et al., 2019) that result from increasing a vehicle's material complexity in order to save fuel or reduce carbon emissions. The second concern relates to the heightened material diversity of vehicles (see Carmona et al., 2017). Almost every additional stock or flow requires the opening of different kinds of mines, the building of additional processing plants and road infrastructure and typically invokes other forms of human encroachment on ecologically sensitive areas (see Aguilar-Fernández, 2009; Hindery, 2013). Material complexity also significantly complicates waste disposal and recovery, due to the need for additional inputs of energy and land (Jones, 2020; Miller et al., 2014; Valero and Valero, 2014). Unfortunately, these environmental challenges will not be solved by the electric car, which is touted as a green option due to its higher fuel efficiency and lower specific CO_2 emissions (MacKay, 2008). While electric cars are more fuel efficient, they may not be more material stock efficient because their average kerb weight, at 1595 kg, is 320 kg heavier than the average UK conventional car (Redelbach et al., 2012). This is unsurprising given the addition of the lithium battery and the incorporation of an increased number of features that improve overall vehicle performance or user experience (e.g. seat warming) but require additional chemical elements and highly complex compounds. For the electric car to be sustainable, it must be more *resource* efficient, not just energy efficient. This is especially the case if the benefits of fuel efficiency gains are predominantly experienced in wealthier nations (or urban areas) while the negative impacts of mining and disposal occur in poorer countries (or communities) that are less equipped to deal with these environmental impacts. The socioenvironmental justice concerns are not negligible when one considers that fully electric and plug-in hybrids accounted for more than one in 10 UK registrations in 2020, which were only one in 30, just a year earlier (SMMT, 2021). That said, some of this problem could be rectified, or at least reduced, with car designs and sectorial practices that promote longevity and increased energy density in future lithium batteries (see Asp et al., 2019; Carlstedt and Asp, 2020).

Service efficiency, as opposed to energy or material efficiency in isolation, invites policymakers, car industry heads, and consumers to consider why one uses a car in the first place and what exactly the benefits of using that car happen to be. While some people own a car for the joy of driving per se, most people have one because it allows them to travel flexibly from one point to another in order to achieve a given aim. In 2019, the top three reasons for car travel in the UK were "visiting friends and family, sporting and culture events, and holiday destinations" (30 percent), "shopping" (20 percent) and "commuting to work" (15 percent) (DfT, 2020b). In this respect, the ideal solution is to re-design (or design) urban spaces so that people may travel fewer kilometres, generating fewer emissions, fewer waste outflows and still accomplish their goal of visiting family or getting to work, for example. Given that our results indicate that car-based passenger mobility is becoming less stock efficient, even though fuel efficiency is increasing, it is difficult to imagine a truly sustainable transport transition without first reducing car dependency. One way to do this could include the adoption of work practices such as the four-day work week or remote working, which require little infrastructural change and yet could play a significant role given that, in 2013, 63 percent of UK commuter journeys were undertaken by car (DfT, 2017). While one can argue that leaving a car in the garage more frequently is not conducive to increased resource efficiency, it does help people to reimagine life without a car. It also demonstrates to them the value of a more local lifestyle rather than a commuter one.

As people increasingly operate more locally (as we have seen with the COVID pandemic) there is a greater demand for local amenities including cycle lanes and pedestrian spaces, which proliferated during various COVID lockdowns (Pandit et al., 2020). Where car dependency cannot be reduced, a service perspective highlights the need for using cars more intensively. This can be done through car sharing initiatives and regulated ride hailing operations (Hertwich et al., 2019). Finally, while a service perspective does not provide all the answers, it offers insights as to the importance of sustainable *mobility*, as opposed to merely a sustainable car. Future research could involve an expanded scope of analysis to incorporate public transport and additional service units beyond passenger-km (e.g. duration, congestion index). A service-based projection of resource efficiency that models the impact of the mass adoption of electric/hybrid passenger vehicles, in line with the UK's transport decarbonisation plan (see DfT, 2021) may also be beneficial to policymakers and other stakeholders.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

MARETEC acknowledges the support of Fundação para a Ciência e a Tecnologia (FCT) through the project UIDB/EEA/50009/2020 (MARETEC 2020–23). LGC acknowledges the financial support of the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 101027892. K.W. acknowledges the support of the Fonds de la Recherche Scientifique – FNRS under Grant No CR-40001149. We thank Hanna Murray-Carlsson for her feedback and advice, which improved the quality of the paper considerably. We thank Gail W. for her insights on UK transport context.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2021.100676.

Author contributions

B.R.: Data curation, Methodology, Writing – review & editing. L.G.C.: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, review & editing. K.W.: Formal analysis, Writing – original draft, review & editing. T.S.: Conceptualization, Formal analysis; Methodology, Writing – review & editing; Supervision.

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