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The stock-service productivity of the European road transport infrastructure

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A R T I C L E I N F O

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A B S T R A C T

An efficient transport infrastructure not only connects markets and people but also positively affects economic activity, development, and growth. However, little research acknowledges the interaction between the material resources of in-use stocks of transport infrastructure and their service provision. Using the European transport sector as a case study, we quantify the mass of materials composing the transport infrastructure and analyze the interactions between in-use stocks and service provision through the stock-service productivity indicator. We also assess the primary factors driving stock-service productivity changes and explore feasible ways to improve productivity. To do so, we decompose changes in stock-service productivity to the effects of transport intensity, affluence, population density, road density, and material stock efficiency at regional and national levels based on the Log-Mean Divisia Index (LMDI) method. The results indicate that (1) the productivity of the materials stocked in the European road infrastructure increased from 51 to 57 freight-kilometers/ton-year during the 2010–2019 period; (2) freight transport intensity and affluence were the dominant driving factors in both regional and national scales, while population density, road density and material efficiency played smaller roles. This study contributes to understanding the deeper relation between resource use and its provided services.

1. Introduction

Infrastructure is crucial for many activities that support well-being and development. The core functionality of infrastructure is to provide services to society including housing, transportation, and social communication (Pauliuk and Müller, 2014; Haberl et al., 2021). Adequate infrastructure could bring ample economic benefits and improved quality of life but can significantly impact the natural environment (Baldwin and Dixon, 2008; Laurance et al., 2009; Rietveld and Bruinsma, 2012). One such impact is the deterioration of ecosystems, which can result from the construction of roads and result in the loss of biodiversity and an alteration of the living habitat of indigenous species. Additionally, soil erosion can occur during road construction, affecting water quality and ecosystems. Further, direct vehicle emissions contribute to air pollution, while vehicle runoffs can pollute the environment with oils, metals, rubber, and other substances. The United Nations Development Programme (UNDP) included infrastructure to be part of sustainable development goals (SDG #9, industry, innovation, and infrastructure) (UN, 2015). Thacker et al. (2019) demonstrated that infrastructure is at the heart of the SDGs and directly or indirectly influences all 17 SDGs.

The need for infrastructure is rising rapidly as the world's population expands, urbanization accelerates, and changing lifestyles demand more services (UNOPS, 2019). A considerable part of all global material extraction accumulates in human-made material stocks such as buildings, transportation infrastructure, and other infrastructures such as water and sewerage systems (Chen and Graedel, 2015; Krausmann et al., 2017; Wiedenhofer et al., 2021; Lwin et al., 2016; Wiedenhofer et al., 2015). In the Stock-Flow-Service (SFS) nexus, in-use material stocks are intermediary objects linking societal services provisioning and material flows (Haberl et al., 2017; Haberl et al., 2021). The longer lifetime stocks are supported by the expansion and maintenance of those flows essential for the stock continuation or expansion. This stock-flow interaction was investigated, for example, material inflows required for stock

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expansion/maintenance, recycling rate, and waste fraction (Miatto et al., 2017; Stephan and Athanassiadis, 2018; Streeck et al., 2020; Södersten et al., 2020; Wiedenhofer et al., 2015). However, compared with the number of studies on the interaction between material stock and material flow for sustainable infrastructure management, the studies on the relationship between material stock and service provision are still modest. The few studies that did so mainly used single indicators of stock-service productivity to concern the service delivered by stock in the use phase (Pauliuk et al., 2013; Pauliuk, 2018), such as the ratio of passenger mobility performed by one unit of in-use materials of transportation infrastructure (Nguyen et al., 2019; Miatto et al., 2021; Virág et al., 2022b; Carmona et al., 2021; Virág et al., 2022a; Gassner et al., 2020). Virág et al. (2022b) employed multiple indicators such as personal travelled distance, mobility infrastructure, and sufficiency thresholds to explore the needed infrastructure level to support decent mobility.

In the form of in-use stock, besides passenger movement, the transport system also provides an essential service in terms of freight transportation to the economy. Freight transport service provision plays an important role in supplying, producing, and distributing supplies, materials, goods, and finished products. Among transport modes, roads account for the largest share of freight transport traffic in the European Union (EU) (Nowakowska-Grunt and Strzelczyk, 2019), which is associated with negative externalities for the environment such as air pollution, greenhouse gasses emissions, water pollution (Demir et al., 2015). The European road freight transport accounted for 9% of the global energy consumption in 2018 (IEA, 2020; EU, 2020). Thus, the efficiency of the freight road transportation plays an essential role in the European sustainable transition towards "resource-efficient transport system" (EU, 2001, 2003, 2011). In the field of Industrial Ecology, Tanikawa et al. (2021) argues that to transition toward sustainable patterns of stock use requires a complete understanding of the relations between stocks and services. Although there has been an expansion in the literature studies of road infrastructure stock (Virág et al., 2022a; Tanikawa et al., 2021; Nguyen et al., 2019; Miatto et al., 2021; Gassner et al., 2021), the investigation that considering freight transportation as a service provided by road stock is less common than passenger movement (or mobility).

In addition, the analysis of socioeconomic factors to suggest improved stock-service relations in road infrastructure has been largely underexplored to date. Rarely study has comprehensively investigated the key factors that affect the stock-service relations of road infrastructure, but rather analyzed road stock accumulation and freight transport demand separately. The changes in road stock and road freight transport demand are functions of exogenous and endogenous drivers. For the material stock of roads, past studies have used the IPAT (**I**mpact = **P**opulation × **A**ffluence × **T**echnology) decomposition analysis, which examines population and gross domestic product (GDP) as the primary drivers of stock accumulation (Huang et al., 2016; Fishman et al., 2015). In terms of road freight transport, economic activity and road freight transport intensity are recognized as the main factors affecting the freight transport demand (Alises and Vassallo 2015; Zhu et al., 2020). According to the European Environment Agency, freight transport intensity is defined as the ratio between the volume of freight transport and GDP (EEA, 2004). As European countries have argued the need to improve the efficiency of the freight transport system and reduce the freight transport-related externalities without curbing economic growth, the creation of opportune indicators has attracted wide consideration among European policymakers (EU 2001, 2003, 2011; Saidi and Hammami, 2017; Carrara and Longden, 2017).

This study aims to estimate the service productivity of European road stocks. In addition, this study adopts the Log-Mean Divisia Index (LMDI) method to identify the underlying factors driving the changes in stock-service productivity of 24 European countries from 2010 to 2019. The LMDI is an effective method to quantify the changing values of influencing factors (Ang 2015). It is widely used in energy and environmental fields (Tian et al., 2013; Wang and Feng, 2017; Liu et al., 2021). We disaggregate our analysis into two regions (Central-Eastern Europe and Western Europe) and 24 countries. The division was performed according to Schroten et al. (2019), as reported in Table 1.

Our specific research questions are:

- What are the size and composition of the material stock of the road infrastructure of 24 European countries, Central-Eastern Europe, and Western Europe from 2010 to 2019?
- What are the yearly stock-service productivities of the road in different regions?
- Which socioeconomic factors have acted as drivers of road stock-service productivity in Central-Eastern Europe and Western Europe?

2. Methodology and data sources

2.1. Methodology

Fig. 1 shows a visual summary of the methodology, which comprises the following steps.

(1) *Calculation of the material stocks of the road in Europe:* This study applied a bottom-up accounting method for estimating the materials stocked in existing roads in Europe from 2010 to 2019. Section 1 of the supporting information details the material stock estimates.
(2) Calculation of the stock-service productivity: For the road transport system, the volume of freight transport is compared with the quantity of stocked materials to determine the stock-service productivity of the road.
(3) Decomposition analysis of stock-service productivity and application of the LMDI method to analyze the effects of drivers on changing stock-service productivity: we decompose changes in stock-service productivity in the European countries to quantitatively determine the effects of the changes in stock-service productivity in road infrastructure at the regional and national levels.

We define stock-service productivity as the ratio of annual freight (in freight-km) to the material stock of the transport network (in mass). In order to explore the main factors driving the changes in stock-service productivity and to uncover feasible improvements, we decompose changes in stock-service productivity into a freight transport intensity (ratio of annual freight to GDP, FG) effect, an affluence (ratio of GDP and population, i.e., GDP per capita, GP) effect, a population density (ratio of population and land area, PA) effect, an road density (ratio of land area and road length, AL) effect (inverted for calculation purposes), and a material stock efficiency (ratio of road length and material stock, LM) effect (Table 2).

The decomposition analysis of stock-service productivity is described in Eq. (1):

$$\mathrm{S}_{k,t} = \frac{F_{k,t}}{\mathrm{MS}_{k,t}} = \frac{F_{k,t}}{\mathrm{GDP}_{k,t}} \times \frac{\mathrm{GDP}_{k,t}}{\mathrm{P}_{k,t}} \times \frac{\mathrm{P}_{k,t}}{\mathrm{A}_{k,t}} \times \frac{\mathrm{A}_{k,t}}{L_{k,t}} \times \frac{L_{k,t}}{\mathrm{MS}_{k,t}} = FG_{k,t} \times \mathrm{GP}_{k,t} \times \mathrm{PA}_{k,t} \times \mathrm{AL}_{k,t} \times \mathrm{LM}_{k,t} \quad (1)$$

Where indices k and t denote the country k and year t; the variables are described in detail in Table 1.

Table 1
Divides 24 European countries into two regions.

Central-Eastern European Countries (CEEC)	The Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia.
Western European Countries (WEC)	Austria, Denmark, Finland, France, Germany, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain, Sweden, United Kingdom, Norway, and Switzerland.

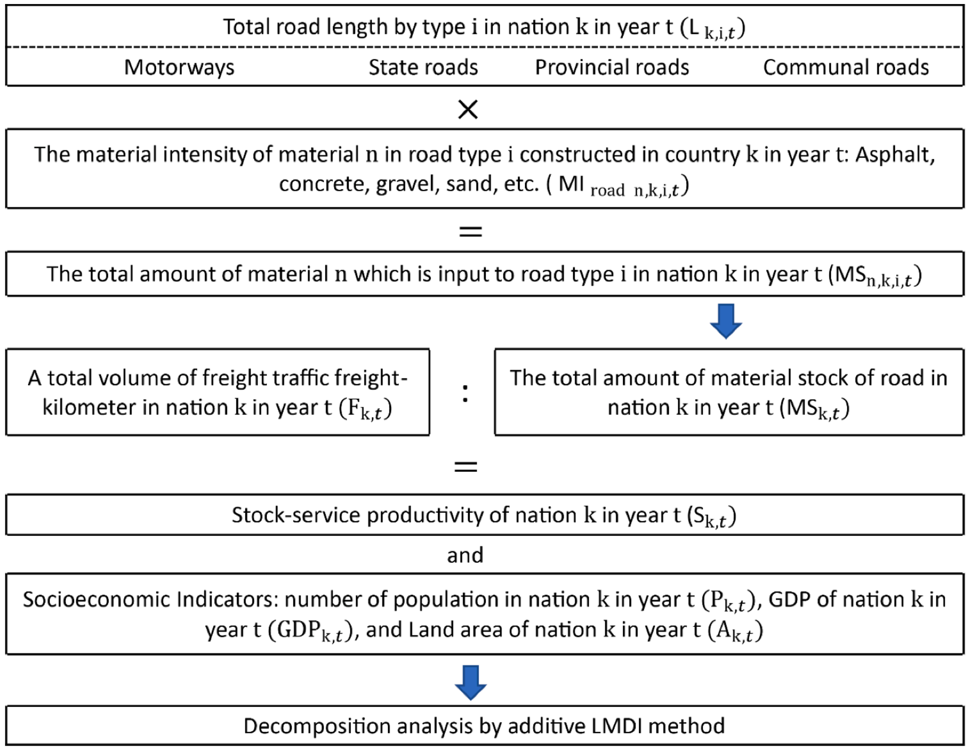


Fig. 1. Research steps.

Table 2
Description of Variables present in Eqs. (1) and (2).

Variables	*General equations*	*Unit*	*Description*
$S_{k,t}$	$\frac{F_{k,t}}{MS_{k,t}}$	Freight-km/ metric ton	The amount of stocked materials required to provide a unit of freight traffic in the country k in year t
$F_{k,t}$	n/a	Freight-kilometer	The volume of freight traffic in country k in the year t
$GDP_{k,t}$	n/a	US dollar	GDP of country k in year t
$P_{k,t}$	n/a	Person	The total population of the country k in the year t
$A_{k,t}$	n/a	Square kilometer	The total land area of the country k in the year t
$L_{k,t}$	n/a	Kilometer	The total road length of the country k in the year t
$MS_{k,t}$	n/a	Metric ton	The total amount of materials stocked in the road network of the countr the year t
$FG_{k,t}$	$\frac{F_{k,t}}{GDP_{k,t}}$	Freight-kilometer/ US dollar	Freight transport intensity of the country k. in the year t.
$GP_{k,t}$	$\frac{GDP_{k,t}}{P_{k,t}}$	US dollar/ person	The affluence of the country k in the year t
$PA_{k,t}$	$\frac{P_{k,t}}{A_{k,t}}$	Person/square kilometer	Population density ofhcountry k in the year t
$AL_{k,t}$	$\frac{A_{k,t}}{L_{k,t}}$	square kilometer /kilometer	The inverse of road density of the country k. in the year t
$LM_{k,t}$.	$\frac{L_{k,t}}{MS_{k,t}}$	Kilometer/ metric ton	Material stock efficiency of the country k in the year t

The change between two periods can be described as Eq. (2):

$$\Delta S_k = S_{k,t+1} - S_{k,t} = \Delta S_{FG} + \Delta S_{GP} + \Delta S_{PA} + \Delta S_{AL} + \Delta S_{LM} \tag{2}$$

According to the LMDI method (Ang, 2015), each effect can be formulated as follows:

$$\Delta S_{FG,k} = \sum_k \omega(S_{k,t+1}, S_{k,t}) \times \ln\left(\frac{F_{k,t}}{GDP_{k,t}}\right) \tag{3}$$

$$\Delta S_{GP,k} = \sum_k \omega(S_{k,t+1}, S_{k,t}) \times \ln\left(\frac{GDP_{k,t}}{P_{k,t}}\right) \tag{4}$$

$$\Delta S_{PA,k} = \sum_k \omega(S_{k,t+1}, S_{k,t}) \times \ln\left(\frac{P_{k,t}}{A_{k,t}}\right) \tag{5}$$

$$\Delta S_{AL,k} = \sum_k \omega(S_{k,t+1}, S_{k,t}) \times \ln\left(\frac{A_{k,t}}{L_{k,t}}\right) \tag{6}$$

$$\Delta S_{LM,k} = \sum_k \omega(S_{k,t+1}, S_{k,t}) \times \ln\left(\frac{L_{k,t}}{MS_{k,t}}\right) \tag{7}$$

The logarithmic mean of two positive numbers, x and y, is defined as follows: $\begin{cases} \omega(x, y) = \dfrac{x - y}{\ln(x) - \ln(y)}, & x \neq y \\ x \text{ or } y, & x = y \end{cases}$

2.2. Data sources

We collected data on the road types, road length (unit: kilometers, km), and freight transport by road annually (unit: freight-kilometers, freight-km) in 24 European countries from 2010 to 2019 from the Eurostat database (EU, 2020). In this database, roads were divided into motorways, state roads, provincial roads, and communal roads. We employed the data from the European Road Federation (ERF, 2022), and applied either interpolated for missing years in between or extrapolated using averaged rate of change from (Wiedenhofer et al., 2015) for those years that data were unavailable (Supporting Information Section S2). Because of the United Kingdom (UK)'s data incompleteness, we collected the UK road lengths and freight transport data between 2013 and 2019 obtained from the Government of the UK (GOV, 2020).

Population, population density, and land area data are taken from Eurostat (2010–2019). The data series of GDP (unit: US dollar in constant 2015 prices, US$) are collected from the World Bank (WB, 2022).

We estimated the road material intensities for four types of road: motorways, state roads, provincial roads, and communal roads (EU

2020). Additional information is available in the Supporting Information Section S3.

3. Results and discussions

3.1. Stock-service productivity

The total material stock of the road network for the 24 European countries we investigated showed a marginal increase during our study period: it increased slightly from about 33 billion tons (Bt) to 34 Bt in 2019 (Fig. 2a). This modest growth rate reflects the small extension of total road lengths, which went from 4.355 million km to 4.364 million km. WE's stocks were around 28 Bt for the whole study period, almost quadruple the amount of CEE material stocks at 7 Bt. The quantity of per capita material stock remained stable at around 72 t/cap for the whole period of analysis. This result is relatively lower when compared to the prior work of Wiedenhofer et al. (2015), who estimated this per capita stock to be around 128 t/cap. We attribute such a difference to the variance of road lengths, material intensities, population, and the studied periods between the two studies.

The comparison of the volume of freight transport between the considered regions provided context to the changes in stock-service productivity (Fig. 2b). The demand for freight transport in WE decreased slightly in the first half of the study period and had returned to 2010 levels at 1300 billion freight-km in 2019. In 2011, the European Commission (EC) published the Transport White Paper "Roadmap to a Single European Transport Area – Towards a competitive and resource-efficient transport system" which aim to increase the modal shift from road to more sustainable transport (EU, 2011; Islam et al., 2016). For example, in 2015, the smallest share of road transport in freight volume was recorded in Latvia (44), Austria (53), the Netherland (56) due to the increased participation of other modes of transport, such as rail (Lativia, Austria) or inland waterway (the Netherlands) (Nowakowska-Grunt and Strzelczyk, 2019; EU, 2020). Together with economic slowdown, this White Paper regulation led to the downward trend in freight transport demand in the WE an region from 2011 to 2015, but not in the CEE countries. The volume of freight transport in the CEE regions grew steadily from approximately 400 billion ton kilometers (freight-km) in 2010 to 600 billion freight-km in 2019. In 2010, the demand for freight transport in WE was triple the CEE region, but in 2019 it was only twice as much.

The stock-service productivity for the road of different regions followed different trends from 2010 to 2019 (Fig. 2c). In 2010, the region's stock-service productivities were about 57 and 50 freight-km/ton for CEE and WE countries. Since 2011, the WE stock-service productivity has experienced a decline to the lowest point of 45 freight-km/ton in 2015 before rising slightly back to 2010 levels in 2019. In comparison, the growth of the CEE stock-service productivity far exceeded that of WE, reaching 85 freight-km/ton in 2019. These different patterns reflected the influence of changes in freight transport demand and material stocks on stock-service productivities of regions. On average, the average stock-service productivity of Europe increased from 51 to 57 freight-kilometers/ton-year from 2010 to 2019. The slight increase in material stock productivity suggests that the existing road infrastructure has been experiencing growing traffic. The increment in traffic is often associated with a reduction in maintenance intervals. Or, in other words, an increase in the material requirements for regular road maintenance (Wiedenhofer et al., 2015; Gassner et al., 2020). Calculating maintenance flows is out of the scope of this study and remains a potential future development.

3.2. Regional LMDI decomposition

The year-by-year effects are shown in the waterfall chart (Fig. 3).

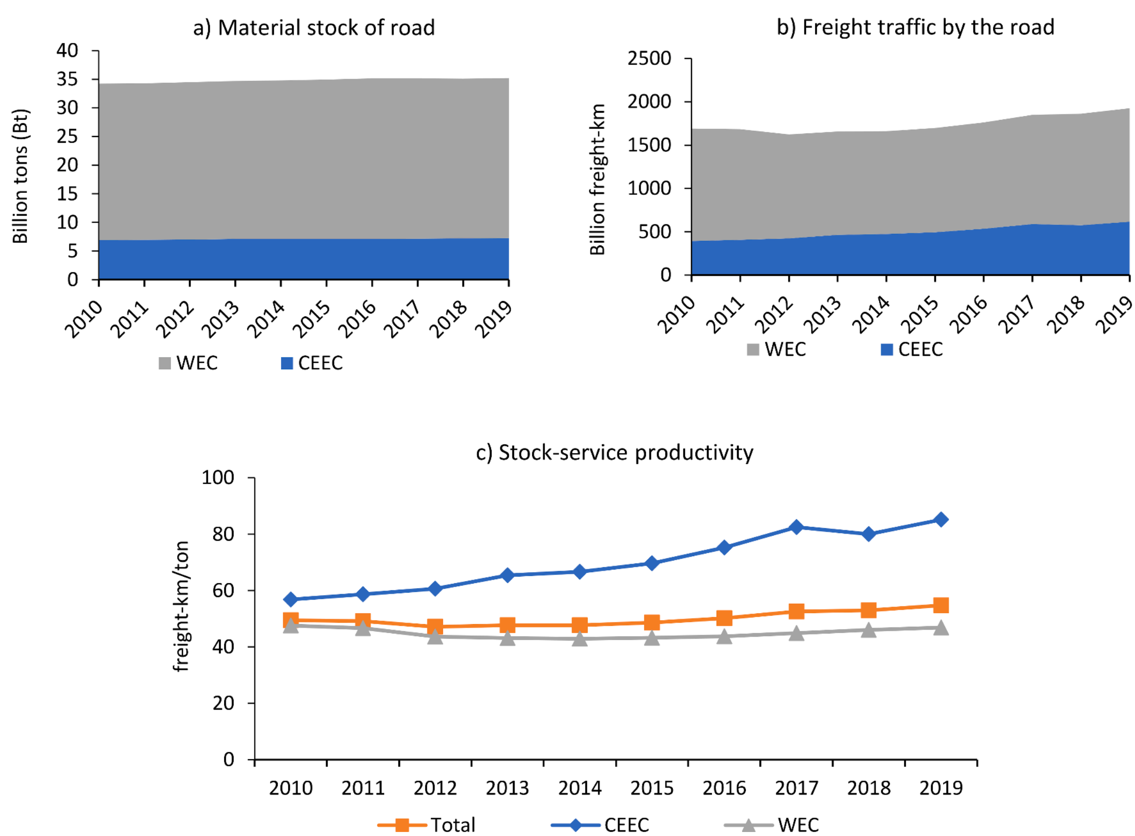


Fig. 2. The stock-service productivity of roads in CEEC and WEC; 2010–2019. (a) The volume of freight traffic by the road; (b) the materials stocked in roads; and (c) the stock-service productivity of roads. freight-km= freight-kilometers; freight-km/ton = freight-kilometers/ton.

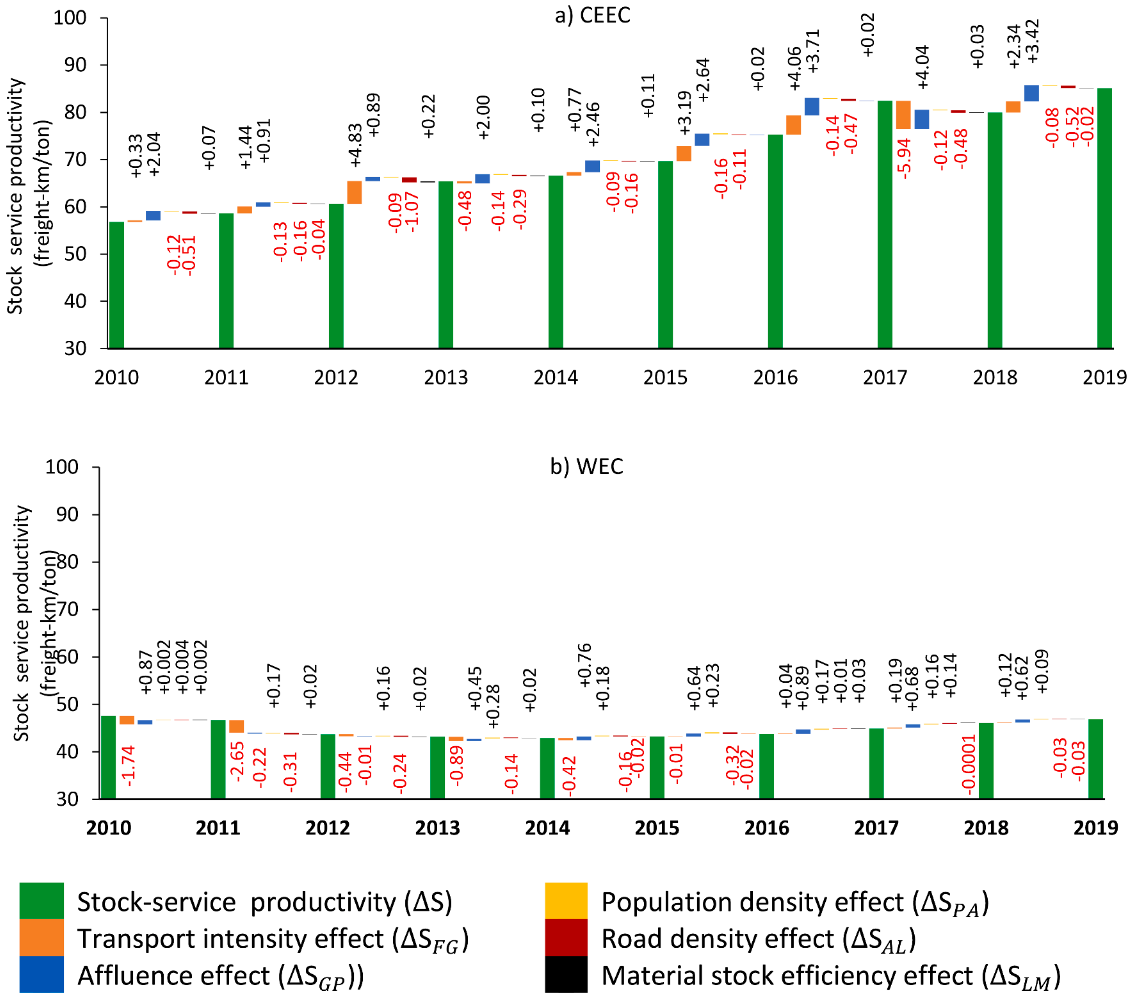


Fig. 3. Waterfalls of temporal decomposition on the year-by-year changes of stock-service productivity, 2010–2019; a) CEEC; b) WEC. Note that the vertical axis starts at 30 freight-km/ton to increase the overall readability.

Over the 2010–2019 period, stock-service productivity increased significantly by approximately 28 freight-km/ton in CEE (Fig. 3a), whereas showed little change in WE (Fig. 3b). In detail, changes in affluence were responsible for +21 freight-km/ton in CEE, four times higher than its amount of +5 freight-km/ton in WE. Affluence was thus the most significant contributor to both regions' stock productivity increase. The second most important effect is freight transport intensity, which had cumulative positive values of +11 freight-km/ton in CEE but a cumulative negative value of −6 freight-km/ton in WE respectively. The other effects (population density effect, road density, and material stock efficiency effect) had minor contributions to cumulative productivity values in both regions.

Freight transport intensity effect: From a year-by-year perspective, the CEE mainly experienced positive influences of freight transport intensity effect in most years (except for the 2013–2014 and 2017–2018) (Fig. 3a). These exceptions may have resulted from the economic slowdown that occurred in 2012 (EC, 2012) and the decline in freight traffic of CEE haulers in 2017 (CNR, 2020a), respectively. The 2013–2014 exception showed the slight influence of freight transport intensity in curbing the increase of the CEE stock-service productivity. Meanwhile, the 2017–2018 outlier showed the significant influence of freight transport intensity effects as its decline led to the unique reduction of CEE stock-service productivity. The WE countries also recorded negative impacts of freight transport intensity effect not only in one year but in the first half of the period (Fig. 3a). Together with the efforts to decouple growth in freight transport from growth in GDP, the economic slowdown in 2012 appears to be the primary reason for the decline of freight transport intensity in the WE from 2010 to 2016. In 2016, a clear exit from the crisis was already apparent since the WE road freight transport improved performances in domestic and bilateral activities (CNR 2018c). As of 2016, this effect showed positive impacts but little contribution for the remainder of the study period.

Affluence effect: The affluence effect was the dominant positive driver of changes in stock-service productivity in both European regions. The growth of per capita GDP enables people to consume more products, enhancing the groups of goods being carried for relatively long distances and feeding into the product supply chains. Notable exceptions were observed between 2011 and 2012 and 2012–2013 in WE. During these years, the decline in affluence due to the economic downturn contributed to the decline in stock-service productivity.

Population density effect: Fig. 3a shows that the population density effect was negative from 2010 to 2019, which shows that changes in the population density reduced CEE stock-service productivity, reflecting the drop in the inhabitants in the CEE regions during this period, meaning that the road stock was underutilized. Meanwhile, the changes in population density seem to be a promoter of the increase of stock-service productivity in the Western region, as its population density effect was positive from 2010 to 2019 (Fig. 3b). In both regions, the population density effect had a lower magnitude than other dominant effects (freight transport intensity and affluence) from 2010 to 2019. It means that for regions like CEE, where the population density slightly decreased, and WE, where population density grew slowly, population density change was a relatively insignificant driver for changes in stock-service productivity.

Road density effect:

In most years, the inverse parameter of road density appears as a main restraining factor in increasing stock-service productivity in the two regions. This inverse of road density indicates that increasing road density enhances stock-service productivity. Higher road network density allows more freight traffic in the areas.

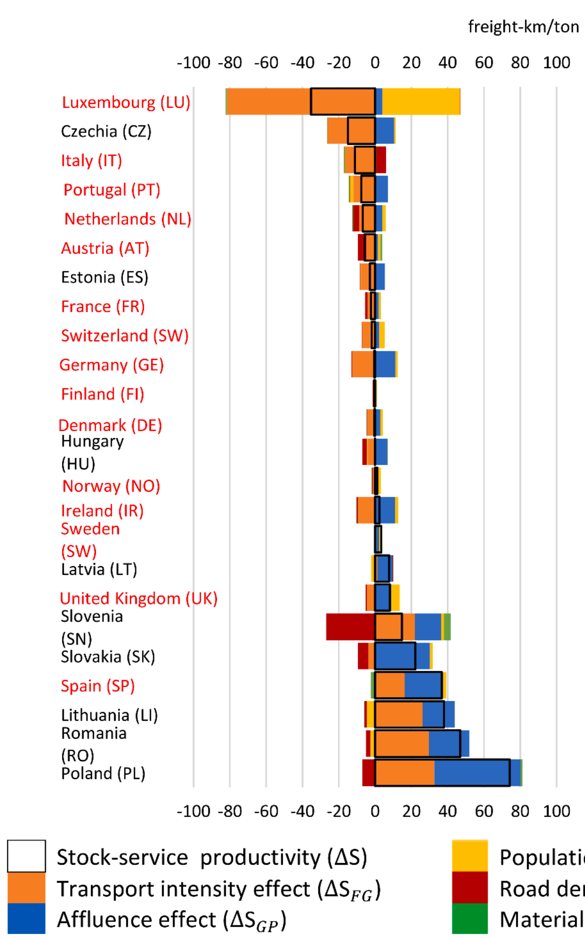
Material stock efficiency effect:

In this study, we considered the material stock efficiency ratio as the inverse of the material intensity ratio usually expressed in t/km. Material stock intensity measures the quantity of material used for constructing a single unit of road length. Quality infrastructure is a precondition for providing efficient transport services for freight movements. The material intensities of the roads we considered in this study (i.e., motorways, state roads, provincial roads, and communal roads; refer to Supporting Information S2 for details) highlight that the upper road category needs more materials per kilometer than the lower road categories. This difference results from the more demanding performance dictated by higher traffic and heavier transiting vehicles. Therefore, a lower $\frac{L}{MS}$ ratio corresponds to more material-intensive road classifications. As plotted in Fig. 4a and 4b, material stock efficiency had positive effects on stock-service productivity in most years but negative effects in some periods in the CEE (2011–2012, 2018–2019) and the second half of the study period in WE (2014–2019, except for 2016–2017). In these periods, the material stock efficiency of European regions slightly decreased, corresponding to the transition to more material-intensive road classifications, extending more motorway and state roads than provincial and communal roads. From 2010 to 2019, the motorway lengths expanded by 37%, while the communal road lengths rose only by 9% in the CEEC. In the WEC, the length of motorways increased by 6%, higher than the 4% expansion of communal roads, enhancing the roads carrying more traffic and heavier vehicles.

3.3. Temporal variation in the stock-service productivity in 24 European countries

The national road stock-service productivity for freight transportation varies from 10 to 231 freight-km/ton for 2010, 8 to 207 freight-km/ton for 2015, and 10 to 246 freight-km/ton for 2019. We grouped the 24 countries into different stock-service productivity clusters. Group I is a low stock-service productivity group, with annual productivity of 8–40 freight-km/ton. Group II is a medium stock-service productivity group, with annual productivity of 41–80 freight-km/ton. Group III is a high stock-service productivity group, with annual productivity of 81–120 freight-km/ton. Finally, group IV is an extra-high stock-service productivity group, with annual productivity of more than 120 freight-km/ton. The temporal variation in stock-service productivity by country in 2010, 2015, and 2019 is shown in Table 3.

During the 2010–2019 period, significant changes in stock-service productivity occurred at the national level, especially in CEE countries. Those countries with high and extra high stock-service



	Effects (freight-km/ton), 2010-2019					
	ΔS	ΔS_{FG}	ΔS_{GP}	ΔS_{PA}	ΔS_{AL}	ΔS_{LM}
LU	**-35**	-82	4	43	0	-1
CZ	**-15**	-26	11	1	0	0
IT	**-11**	-17	0	1	5	0
PT	**-8**	-12	7	-2	0	0
NL	**-7**	-9	4	2	-3	-1
AT	**-6**	-5	2	1	-5	1
ES	**-3**	-8	5	0	0	0
FR	**-2**	-4	2	1	-1	0
SW	**-2**	-7	2	3	0	0
GE	**-1**	-13	11	1	0	0
FI	**0**	-1	1	0	0	0
DE	**0**	-4	3	1	0	0
HU	**0**	-4	7	-1	-2	0
NO	**1**	-1	1	2	-1	0
IR	**2**	-10	11	2	-1	0
SW	**3**	1	1	1	0	0
LT	**8**	1	8	-2	0	0
UK	**8**	-5	9	5	-1	0
SN	**15**	22	15	2	-27	4
SK	**22**	-4	30	1	-6	0
SP	**37**	21	16	2	0	-2
LI	**38**	26	18	-5	-1	0
RO	**47**	30	22	-3	-2	0
PL	**74**	33	47	0	-7	1

Fig. 4. Cumulative effects for stock-service productivity in 24 European countries in the 2010–2019 period. The countries are ordered by the value of stock-service productivity from negative to positive value for the 2010–2019 period. Note that the black-lined bar is equal in space to the colored bars of the effects; Western European countries are in red.

Table 3
Temporal variation in stock-service productivity across the countries, 2010–2019; freight-km/ton = freight-kilometers per metric ton of road stock; Western Europan countries are in red.

Stock-service productivity	Range	2010	2015	2019
I (low)	8–40 (freight-km/ton)	Estonia, Latvia, Lithuania, Hungary, Romania, Denmark, Ireland, France, Austria, Finland, Sweden, Norway, Switzerland	Estonia, Latvia, Lithuania, Hungary, Denmark, Ireland, France, Austria, Finland, Sweden, Norway, Switzerland	Estonia, Latvia, Hungary, Denmark, Ireland, France, Austria, Finland, Sweden, Norway, Switzerland
II (medium)	41–80 (freight-km/ton)	Czech Republic, Italy, the Netherlands, Portugal, the United Kingdom, Germany	Czech Republic, Italy, the Netherlands, Portugal, the United Kingdom, Germany, Romania, Slovenia	Lithuania
III (high)	81–120 (freight-km/ton)	Poland, Slovenia		Romania, Slovenia
IV (extra-high)	>120 (freight-km/ton)	Spain, Luxembourg, Slovakia	Spain, Luxembourg, Slovakia, Poland	Spain, Luxembourg, Slovakia, Poland

productivities are late European developers with potential accumulation of material stocks in the future (Fishman et al., 2016), and the freight demands showed an upward trend (Nowakowska-Grunt and Strzelczyk, 2019). Romania, Slovenia, Slovakia, and Poland are all CEE countries that had a substantial amount of structural and investment funds (ESI funds) of the EU included in their program for 2007–2013 (Schroten et al., 2019), so they gained significant progress in terms of infrastructure development (Fig. S4a) (CNR, 2018b, 2019b, 2020c; ITF, 2022). The substantial foreign investment from other European countries has also helped strengthen those CEE economies in producing goods. Besides, with benefits from the geographical situation, these countries represent important trade routes (CNR, 2018b, 2019b, 2020c; ITF, 2022;). Due to their geographical positions, Spain and Luxembourg were also important operational bases for transport and logistics activities (CNR, 2018a, 2020b). In addition, Poland and Romania are the largest and most populous countries in the CEE region (Fig. S4e). Their demographic profiles are boosting the construction and distribution sectors in the market (ITF, 2022; CNR, 2020c). These factors explain the massive volume of freight transport in those countries from 2010 to 2019 (Fig. S4c). However, a "high" or "too high" stock productivity may indicate an overuse and perhaps insufficient material stock, culminating in overstressed roads and congestion. For example, Romania suffers from high road congestion and its unevenly developed road infrastructure (EC, 2019). On the other hand, despite the comparatively good infrastructure provision, road congestion is also a known issue in Spain and Luxembourg (EC, 2019).

Meanwhile, it should be noted that low- and medium-productivity countries are either economically emerging CEE countries or wealthy WE nations (Fig. S4d). Most CEE nations have experienced low availability and insufficient transport infrastructure quality (EC, 2019). On the other hand, WE nations have a more dense infrastructure. Their construction material inflows for infrastructure maintenance are almost twice that for infrastructure expansion (Wiedenhofer et al., 2015), while their material stocks have reached a saturated state (Fishman et al., 2016). Medium productivity Western countries (Italy, Netherlands, Portugal, United Kingdom, and Germany) are the EU's largest economies with high transport and logistics performance (Fig. S4c and S4d). Transport volume usually highly correlates with economic performance (CollERS, 2020). However, although these Western nations experienced negligible growth in the freight transport demand between 2010 and 2019 (Fig. S4c), their GDP clearly increased (Fig. S4d).

Countries at "an earlier stage of development are usually more dependent on the production and export of low-value primary products that have to be hauled over long distances" (McKinnon, 2015). As these countries develop, various factors such as industrialization, movement up the global value chain, and service sector growth tend to depress the level of freight transport intensity (McKinnon, 2015). Fig. S4f shows European countries' transport intensity performance according to each country's increasing per capita GDP in 2010, 2015, and 2019. We emphasize that those Western countries within the top countries based on per capita GDP in 2010, 2015, and 2019 had their transport intensity less than 0.1 freight-km/$US (except Spain and Luxembourg), indicating that the countries relying on freight transport play a smaller role in promoting national economic activity compared with other nations. The transport intensity of the CEE countries with relatively low per capita GDP is high, indicating the strength of freight transport in these nations and that it still plays a vital role in promoting economic development.

The low stock productivity can be attributed to different situations. First, the road material stock is used inefficiently, and it could accommodate more traffic without incurring congestion. Second, there is a natural delay between the growth of transported goods and material stock, meaning that the freight transport demand would not immediately follow the increase in road material stock in a given year. Third, road freight transport decreased as the volume of road freight transport shifted to less polluting modes of transport such as rail or inland waterways. This shift corresponded to the EU's transport sustainability targets and policies (EU, 2011). Several low-productivity Western countries (e.g., France) have exhibited a decline in road freight transport for many years (Nowakowska-Grunt and Strzelczyk, 2019).

3.4. National LMDI decomposition

Fig. 4 plots the changes in stock-service productivity and the relative influence of five factors based on the decomposition analysis. The spatial decomposition analysis shows that the regional trends are not uniform across all countries, and some have followed different trajectories.

In 2010–2019, all CEE countries resembled the regional trend of increasing stock productivity, with the Czech Republic and Estonia departing from this trend due to declining productivity, −15 freight-km/ton and −8 freight-km/ton, respectively (Fig. 4). Hungary and Latvia observed slight variance, with the cumulative contribution of all five effects being small, ranging from about 0 to +8 freight-km/ton. Meanwhile, significant increases in stock-service productivity have taken place in Slovenia (+15 freight-km/ton), Slovakia (+22 freight-km/ton), Lithuania (+38 freight-km/ton), Romania (+47 freight-km/ton), and Poland (+74 freight-km/ton). The freight transport intensity and the affluence effects were the dominant drivers of these significant increases in stock-service productivity. This observation implies these five countries' intense freight traffic activity and economic growth. According to historical reports by European National Roads Committee (CNR), the sectors of Slovakia, Slovenia, Lithuania, Romania, and Poland have had a significant presence in the European road freight market in recent years (CNR 2018c, 2020a).

Regarding WE countries, the changes in stock-service productivity in Luxembourg and Spain were significantly larger than in others. The stock-service productivity decreased by −35 freight-km/ton for Luxembourg while increasing by +37 freight-km/ton for Spain. In Luxembourg and Spain, freight transport intensity was the most important effect since its value was much more significant in cumulative value than the other effects. However, changes in freight transport intensity reduced Luxembourg's stock productivity but induced Spanish stock productivity.

Changes in stock-service productivity in other WE countries were negligible from 2010 to 2019. The effects of transport intensity and affluence change on these national stock productivities were insignificant, indicating that the freight transport intensity effect and affluence effect had little impact on the growth of their stock-service productivities. The transition to more service-oriented economies would explain this phenomenon; thus, their economic growth has become progressively detached from road transport demand (Alises and Vassallo, 2015). Also, there are efforts to shift freight from road to other transport modes, such as railways and inland waterways in Western countries (ITF, 2022). There are possible reasons for the variation in road freight transport intensity at the national level. However, identifying the detailed explanation behind the change in road freight transport intensity for each country is complicated work (Piecyk and McKinnon, 2010; Alises and Vassallo, 2015) and beyond the scope of our study.

The affluence effect had a positive value and was one of the dominant drivers of increased stock-service productivity in all European countries. It was consistent with the increases in personal income thanks to recovery from the 2012 economic slowdown. On the same cumulative basis, the three individual effects (population density effect, inverse of road density effect, and material stock productivity effect) have negligible values in stock productivity in most CEE and WE countries, except Slovenia and Luxembourg. In Slovenia, the inverted road density effect is the most important of all effects in reducing stock-service productivity, which alone reduces about −23 freight-km/ton of stock productivity in this country. As Slovenia's total length of roads increased by about 30% between 2010 and 2019, its road density increased considerably, and the mass of materials accumulated in roads. This result was a possible reason for the temporary decrease in Slovenian stock productivity, as the freight transport service had not increased immediately in the same period. In Luxembourg, the population density effect was the decisive factor for increasing +43 freight-km/ton stock-service productivity. Between 2010 and 2019, the size of the Luxembourg population increased by 22% (Fig. S4e). This rapid population growth is boosting the construction and distribution sectors which is particularly beneficial for road freight transport in Luxembourg (CNR, 2019a). Other European countries followed similar trends to their regions regarding the influences of changes in population density, road density, and material stock productivity. Due to slight inhabitant growth, population density change was a relatively insignificant driver of stock productivity on the national scale. From 2010–2019, the road network expanded at a low rate, and the proportion of high-material-intensive road types (e.g., motorways) was modest. These are possible reasons why population density, road density, and material stock productivity played relatively minor roles in changing stock productivity in European countries. The year-by-year cumulative effects of factors in stock service productivity in the 24 European countries are shown in section 6 of the supporting information.

3.5. Comparison of material stock productivity between service and economic perspectives

Stock productivity measures the usage efficiency of the accumulated materials. In other words, the more added value produced per unit of stocked material, the more-effective usage of existing stocks. There are now long-term studies of stock productivity from economic output perspectives on a national scale (Fishman et al., 2014; Miatto et al., 2021), global scale (Krausmann et al., 2017), and for specific materials (Xu et al., 2022). These publications, along with others that focus on stock productivity of specific sector from service perspective (Tanikawa et al., 2021; Haberl et al., 2021; Carmona et al., 2021; Miatto et al., 2021), support policy making for sustainable stock management. However, regarding specific sector like road freight transportation, transport authorities interested in meeting national or regional sustainability targets will emphasize metrics beyond mere productivities, such as congestion, safety, air pollution, and infrastructure degradation (Nguyen et al., 2019; Miatto et al., 2021; Carmona et al., 2021). Thus, to implement a productive yet sustainable materials use in the road transportation sector, policy makers should not only seek to improve "too low" stock productivity, but also seek to reduce the negative externalities deriving from "too high" stock productivity.

As illustrated in Fig. 4, with the exception of Luxembourg and Spain, other WE low- and medium-stock productivity countries show insignificant change during the 2010–2019 period, hinting the potential delays between the accumulation of road material stocks and the service obtained in these countries. The reduced growth of freight transport activity means less materials and energy consumption for the service realization and fewer emissions. This behavior is supposed to be good for the environment but the same cannot be automatically argued for an economic standpoint. To see whether the economy is being affected, we also considered the trends and patterns of stock productivity from an economic perspective. Fig. 5 shows a comparison between economic and service perspectives for stock productivity of CEE and WE regions during 2010 – 2019.

Measuring the material stock productivity based on economic output (GDP) and service-provisioning output (freight transportation) shows an inverse trend for the two European regions. For the CEE region, both stock productivity measures increased from 2010 until 2017. In 2018, the CEE service productivity, measured as Freight/MS, temporarily declined due to driver shortages but later grew in the trend of stock economic productivity (GDP/MS). For the WE region, from 2010 until 2014, the service-stock productivity (Freight/MS) decreased while the stock economic productivity (GDP/MS) increased. 2010–2014 was a real slowdown in the WE economies' road freight transport sector. Since 2014, stock-service productivity (Freight/MS) has been increasing, following the upward trend of MS economic productivity (GDP/MS). Stock-service productivity in the CEE region has increased since 2010. It almost doubled the WE productivity in 2019, but the WE stock economic productivity remained triple that of CEE during the whole period. Excluding Switzerland, our studied countries belong to the European Economic Area organization, which has the transport markets within being opened and harmonized (EEA 2022). Compared to CEE countries, WE countries are ahead in shifting the economic structure from goods to more services, optimizing transport networks, accessibility and supply systems, and technological changes in production processes (Sorrell et al., 2012; Ruijgrok, 2017). Besides, rail and inland waterways, presented as green solutions for limiting the negative environmental impact of road transport (EU, 2001, 2011), are more developed in WE than in CEE countries (Tomeš, 2017; Islam et al., 2016). Their rail freight market shares are significantly higher than those of their CEE counterparts (Tomeš, 2017). This modal shift to non-road options has helped reduce road overload so that a less considerable amount of road materials is needed to maintain the roads in service (Wiedenhofer et al., 2015; Schiller, 2007). Thus, the CEE region with the most stock-service productivity is not necessarily the one with the highest economic and environmental benefits. WE countries, especially those with medium stock-service productivities, are likely to meet better economic and environmental benefits than CEE counterparts.

With the specific values of service provision from material stock and showing insignificant changes in the period of study, WE countries (excluding Luxembourg and Spain) seem to have reached a level of sufficiency of stock-service productivity. The observations suggest that the medium productivity range between 40 and 80 freight km/ton is the "comfort zone" for achieving and balancing road stocks' economic benefits and environmental impacts. The contribution of road material stocks and their transport service to economic development, the satisfaction of human needs, and well-being have been discussed in recent work (Virág et al., 2022b). For benchmark, our average per-capita

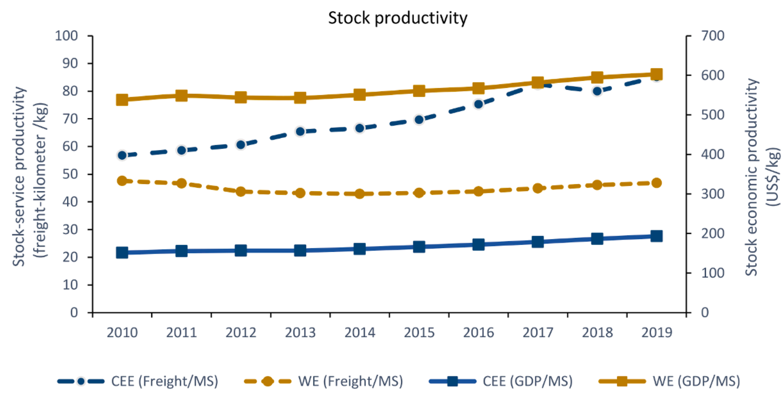


Fig. 5. Material stock productivity for ton-kilometer of freight traveled per ton of road stock (freight-km/ton) (left axis) and the gross domestic product (GDP) per metric ton of road infrastructure stock (US$/ton) (right axis).

material stock in road infrastructure is about 75 t/cap in WE countries, which is much lower than the level of resources (92–207 t/cap) needed to get sufficiency thresholds of high societies' well-being. Such a lower level was explained by the differences in the type of transport infrastructure (excluding rail infrastructure) and transport service provision (passenger movements instead of goods movements) between this study and Virág et al. (2022b).

4. Conclusions

In order to offer a new perspective on options for implementing productive yet sustainable stocked materials, this study presents an analysis of material stock productivity of roads in 24 European countries during the 2010–2019 period. Methodologically, this research applied the LMDI approach focusing on exogenous and endogenous drivers to analyze the changes in stock-service productivity at regional and national levels. Comprehensive analysis shows the regional and national differences in road stock productivity for freight transportation and the underlying drivers of productivity changes. We have connected all the influencing factors, namely freight transport intensity, affluence, population density, the inverse of road density, and material efficiency.

The results point toward an imbalance in the use of road capacities between Western and CEE countries. In the study period, WE countries had high economic and environmental benefits with modest stock-service productivity, and most of them are likely to reach sufficient service productivity. On the other hand, CEE countries stand out with roads that support high stock productivity rates but obtain lower economic benefits and require attention to the environmental impacts. In general, the road freight transport intensity and affluence were the most significant contributors to the change in stock-service productivity at the regional and national levels. However, there are exceptions, such as Luxembourg's population density and Slovenia's road density. Details of this research are expected to help deepen our understanding of the relations between stock and benefits obtained and thus be beneficial in policymaking for the transition to sustainable infrastructure at the national and European levels. Characteristics that are absent in the current discussion are the variation of productivity by road types and by freight sectors. More material-intensive road types can facilitate the distance of freight movements as motorways and state roads are likely to provide the service of long-distance freight movements. However, provincial and local roads service the "last mile" and local deliveries (these roads are especially relevant with the rise of internet shopping). Likewise, countries have unique economic structures, so the road freight transportation of the agriculture-forestry-fishing, industrial, and service sectors has demanded different volume ratios. Even though we considered road type characteristics and freight road intensity as driving factors of stock productivity, understanding more detailed components could increase the validity of our results.

Another caveat is that this study focuses only on road infrastructure in terms of freight transportation demand. Different modes of transport, such as railroads, could be potentially examined. Future research should also consider energy use and the material requirements for the construction and maintenance of road infrastructure. Investigating freight transport with the stock-flow-service nexus offers an option for reducing resource demand and environmental impacts. This study relies on national statistics of road networks and material intensities to derive material stock data. In European countries, national statistics related to road classification and road infrastructure networks are insufficient, especially concerning local roads. This limitation led to various interpolations of the missing data points. From the sustainability viewpoint, data constraints are some of the biggest challenges in material stock studies (Augiseau and Barles, 2017). Road policies are typically established and implemented by national and lower-level governments, such as state or local governments. These policies vary widely depending on the jurisdiction and may cover issues such as road design and construction, maintenance activities, traffic regulations, and vehicle standards. Therefore, we are of the opinion that a meaningful analysis of significance and policy implications would require a more extended time series and a more extensive literature review than is currently available. We hope our study despite covering only at 10-year period, will be the cornerstone to developing detailed datasets on the material stocks and flows of the European road network.

CRediT authorship contribution statement

Thi Cuc Nguyen: Conceptualization, Data curation, Writing – original draft. **Alessio Miatto:** Writing – review & editing. **Tomer Fishman:** Writing – review & editing. **Junbeum Kim:** Supervision, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.106961.

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SUPPORTING INFORMATION 1

1. **Material stocks of road**
   Bottom up accounting

We have applied the bottom-up approach (equation 1) for the estimation of construction materials stocked in roads in 24 European countries during 2010-2019 year period. We estimate materials stocked in four different road types: motorways, state roads, provincial roads, and communal roads. Different such types of road are based on the hierarchical road system and reported data of Eurostat.

$$\mathrm{MS}_{i,j,k}\ (t) = \mathrm{L}_{j,k}(t) \times \mathrm{I}_{i,j,k} \qquad \text{(Equation 1)}$$

Where:

$\mathrm{L}_{j,k}\ (t)$ is the total length of specific road category j in country k at year t.

$\mathrm{I}_{i,j,k}$ is the material intensity of material i in specific road category j in country k.

2. **Data:**

Road networks in 24 European countries are mainly collected from Eurostat (EU 2020). Missing data were yellow or organge cells. Yellow cells are those years which were taken from the European Road Federation (ERF 2022) . Organge cells are those years which were either interpolated for missing years in between or extrapolated using averaged rate of change from (Wiedenhofer et al. 2015). For Germany, the data of communal roads is unavailable on Eurostat. Approximately 430,000 km, or 2/3 of the total network, were last surveyed in 1993 and are usually not included in the official Eurostat statistics. We modified data and assumed based on the average of changes from (Wiedenhofer et al. 2015) .

Table S1: Length of Motorways of 24 European countries, kilometers (km), 2010-2019

Countries	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Czechia	734	745	751	776	776	776	1,223	1,240	1,252	1,276
Denmark	1,120	1,143	1,195	1,216	1,232	1,237	1,255	1,308	1,329	1,346
Estonia	115	115	124	140	141	147	145	154	154	161
Ireland	900	900	900	897	897	916	916	916	916	995
Spain	14,262	14,531	14,701	14,981	15,049	15,336	15,444	15,523	15,585	15,585
France	11,392	11,413	11,413	11,552	11,560	11,599	11,612	11,618	11,671	11,671
Italy	6,668	6,668	6,726	6,751	6,844	6,943	6,943	6,943	6,966	6,977
Latvia	0	0	0	0	0	0	0	0	0	0
Lithuania	309	309	309	309	309	309	314	324	324	403
Luxembourg	152	152	152	152	152	161	161	165	165	165
Hungary	1,477	1,516	1,515	1,767	1,782	1,884	1,924	1,937	1,982	1,723
Netherlands	2,646	2,651	2,658	2,666	2,678	2,730	2,756	2,758	2,755	2,790
Austria	1,719	1,719	1,719	1,719	1,719	1,719	1,719	1,719	1,743	1,743
Poland	857	1,070	1,365	1,482	1,556	1,559	1,637	1,637	1,637	1,676
Portugal	2,737	2,737	2,988	3,035	3,065	3,065	3,065	3,065	3,065	3,065
Romania	332	350	550	644	683	747	747	763	823	866
Slovenia	768	768	769	607	607	610	610	618	623	623
Slovakia	416	419	419	420	420	463	463	482	482	495
Finland	779	790	780	810	881	881	890	893	926	926
Sweden	1,971	1,957	2,004	2,044	2,088	2,119	2,118	2,132	2,132	2,133
Norway	381	393	392	420	450	480	500	523	599	1,008

Switzerland	1,406	1,415	1,419	1,419	1,429	1,440	1,447	1,458	1,462	1,462
United Kingdom	3,672	3,686	3,733	3,756	3,760	3,768	3,764	3,803	3,838	3,838
Germany	12,819	12,845	12,879	12,917	12,949	12,993	12,996	13,009	13,141	13,183

Table S2: Length of state roads of 24 European countries, kilometers (km), 2010-2019

Countries	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Czechia	6,255	6,254	6,250	6,250	6,233	6,245	5,807	5,825	5,818	5,826
Denmark	2,697	2,697	2,645	2,629	2,614	2,613	2,598	2,602	2,594	2,603
Estonia	16,385	16,397	16,469	16,490	16,584	16,597	16,594	16,605	16,608	16,609
Ireland	4,513	4,513	4,513	4,513	4,513	4,390	4,390	4,390	4,390	4,314
Spain	15,103	15,056	15,110	15,041	15,002	14,949	14,946	14,904	14,870	14,870
France	9,754	9,757	9,631	9,658	9,645	9,633	9,585	9,044	9,551	9,522
Italy	20,856	20,773	19,861	19,920	19,894	20,786	21,686	22,399	23,335	23,305
Latvia	20,150	20,119	20,115	20,093	20,150	20,093	20,073	20,047	19,990	20,015
Lithuania	20,958	20,949	20,934	20,945	20,943	20,940	20,930	20,927	20,915	20,835
Luxembourg	837	837	837	837	837	837	837	837	839	839
Hungary	30,151	30,183	30,177	31,760	31,802	30,041	30,062	30,069	30,088	30,128
Netherlands	711	697	697	715	710	2,549	2,584	2,599	2,628	2,668
Austria	9,959	10,003	10,009	2,187	2,187	473	489	489	489	489
Poland	18,606	18,801	19,182	19,296	19,293	19,293	19,388	19,410	19,403	19,451
Portugal	13,241	13,241	13,241	13,241	13,241	13,241	13,241	13,241	13,241	13,241
Romania	16,552	16,690	16,887	17,110	16,589	16,859	16,865	16,891	16,917	17,007
Slovenia	5,769	5,764	5,775	5,938	5,938	5,926	5,920	5,917	5,917	5,917
Slovakia	3,507	3,546	3,546	3,538	3,545	3,566	3,580	3,593	3,594	3,604
Finland	77,383	77,349	77,329	77,283	77,252	77,107	77,091	77,100	77,016	76,999
Sweden	13,504	13,515	13,600	13,647	13,603	13,574	13,576	13,565	13,557	13,556
Norway	10,496	10,574	10,581	10,562	10,608	10,666	10,695	10,683	10,713	10,753
Switzerland	384	384	390	392	394	383	393	397	397	397
United Kingdom	8,489	8,508	8,507	8,505	8,485	8,478	8,465	8,481	8,672	8,700
Germany	39,710	39,673	39,604	39,389	38,917	38,303	38,068	38,018	37,879	37,842

Table S3: Length of provincial roads of 24 European countries, kilometers (km), 2010-2019

Countries	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Czechia	48,763	48,743	48,715	48,736	48,739	48,717	48,727	48,692	48,674	48,666
Denmark	9,628	9,628	9,628	9,628	9,628	9,628	9,628	9,628	9,628	9,628
Estonia	23,514	23,647	23,901	23,939	23,955	23,833	23,944	23,970	24,002	24,060
Ireland	11,631	11,631	11,631	11,631	11,631	13,120	13,120	13,120	13,120	13,120
Spain	68,595	68,860	68,384	67,972	68,194	68,113	68,055	68,067	68,051	68,035
France	377,769	377,857	377,965	377,323	378,973	377,197	381,379	377,890	378,401	378,693
Italy	158,895	51,583	153,588	154,948	155,662	155,668	155,247	142,139	135,691	135,691
Latvia	30,742	30,649	30,453	30,493	30,439	30,183	30,169	30,088	30,147	29,975
Lithuania	60,864	61,653	62,923	63,214	63,782	63,684	62,485	63,076	64,334	63,848

Luxembourg	1,891	1,891	1,891	1,891	1,891	1,891	1,891	1,891	1,891	1,891
Hungary	167,939	169,263	170,249	171,549	172,255	172,957	174,599	178,809	181,230	188,551
Netherlands	6,812	6,794	6,719	6,650	6,551	7,738	7,759	7,757	7,745	7,813
Austria	23,680	23,654	23,642	33,651	33,652	33,637	33,644	34,025	34,174	34,174
Poland	154,634	156,219	154,202	153,787	153,923	154,201	153,865	153,757	153,497	153,675
Portugal	4,358	4,358	4,358	4,358	4,358	4,358	4,358	4,358	4,358	4,791
Romania	35,221	35,374	35,380	35,587	35,505	35,334	35,361	35,149	35,085	35,083
Slovenia	13,568	13,510	13,451	13,385	13,370	13,387	13,365	13,361	13,357	13,353
Slovakia	3,643	3,639	3,637	3,617	3,616	3,616	3,611	3,610	3,611	3,631
Finland	13,464	13,464	13,464	13,464	13,464	13,464	13,464	13,464	13,464	13,469
Sweden	157,384	157,459	158,046	157,281	157,241	157,227	157,227	157,227	157,221	157,281
Norway	44,281	44,287	44,317	44,382	44,291	44,497	44,541	44,622	44,639	44,696
Switzerland	18,040	17,997	17,983	17,896	17,916	17,868	17,852	17,831	17,816	17,772
United Kingdom	38,218	38,225	38,235	38,245	38,301	38,298	38,351	38,416	38,708	38,749
Germany	178,253	178,184	178,034	178,071	178,281	178,786	178,906	178,876	178,806	178,751

Table S4: Length of communal roads of 24 European countries, kilometers (km), 2010-2019

Countries	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Czechia	74,919	74,919	74,919	74,919	74,919	74,919	74,919	74,919	74,919	74,919
Denmark	70,363	70,429	70,495	70,561	70,627	70,646	70,705	70,817	70,840	70,900
Estonia	18,398	18,328	18,398	18,398	18,445	18,398	18,398	18,220	18,237	18,398
Ireland	78,958	78,958	78,958	78,958	78,958	80,472	80,472	80,472	80,472	80,548
Spain	67,827	67,439	67,400	67,368	68,040	67,605	67,038	68,223	67,332	66,147
France	651,202	651,491	666,343	673,290	681,485	687,789	699,224	704,999	704,151	704,201
Italy	68,267	72,018	73,555	74,420	73,290	74,719	73,591	74,734	69,098	67,927
Latvia	8,034	8,035	7,998	7,987	8,039	7,967	8,174	8,291	8,306	8,271
Lithuania	0	0	0	0	0	0	0	0	0	0
Luxembourg	0	0	0	0	0	0	0	0	0	0
Hungary	0	0	0	0	0	0	0	0	0	0
Netherlands	121,128	121,412	121,542	121,839	122,175	125,895	126,025	126,180	126,458	127,173
Austria	74,750	75,000	80,250	88,750	88,753	88,759	97,745	102,463	100,633	100,633
Poland	232,880	237,244	238,651	240,447	243,810	246,143	246,983	249,136	251,664	251,789
Portugal	65,638	65,638	65,638	65,638	65,638	65,638	65,638	65,638	65,638	65,638
Romania	30,613	31,639	31,918	32,190	32,585	32,980	33,107	33,296	33,409	33,435
Slovenia	18,773	18,805	18,797	32,031	32,041	32,050	32,091	32,078	32,061	32,087
Slovakia	35,759	35,762	35,766	35,787	35,777	36,814	36,817	36,811	37,497	37,479
Finland	27,685	28,973	28,899	29,477	29,557	28,011	29,516	30,454	31,018	31,638
Sweden	41,473	41,575	42,001	41,907	42,121	42,171	42,291	42,488	42,780	42,805
Norway	38,732	38,893	38,970	39,041	39,158	39,287	39,406	39,457	39,543	39,715
Switzerland	51,622	51,668	51,721	51,819	51,814	51,828	51,849	51,863	51,880	51,927
United Kingdom	343,989	343,992	344,531	345,070	345,190	345,274	346,254	346,455	345,918	346,404
Germany	522,145	522,667	523,189	523,713	524,236	524,761	525,285	525,811	526,336	526,863

3. **Material intensities of road**

The material intensities for the above-mention road categories are estimated based on the Standard Specifications for design of each country and on the literature review. According to report of the Joint Research Centre, European Commission, in Europe the main pavement layer type is the flexible asphalt one (Garbarino et al. 2016). For instance, the United Kingdom Road Administration has reported that in the United Kingdom, 96% of pavements are flexible. The Danish Road Directorate has reported that that 100% of all pavements are flexible and in the Netherlands 97% of all pavements are flexible. Stakeholders feedback confirmed that more than 95% of main pavement layer type in Europe are flexible (Garbarino et al. 2016). Therefore, this study focuses on only the flexible asphalt pavement for all of four road types: motorways, state roads, provincial roads, and communal roads. Figure S1 is the cross-section profile of the flexible asphalt pavement.

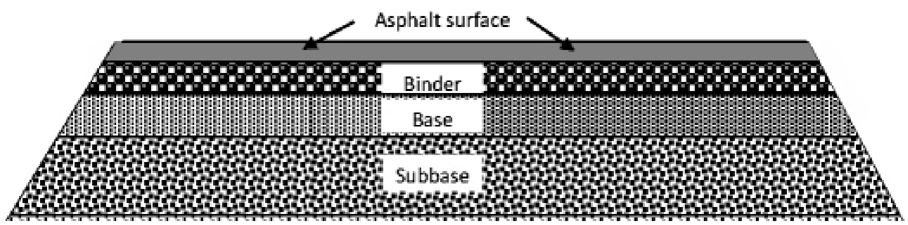


Figure S1: Flexible pavement profile (adapted from (Garbarino et al. 2016))

Pavement design approach for flexible pavements in 24 European countries and calculation method are shown in Table S5.

Table S5: Calculation method and sources of typical pavement structures in 24 European countries

Regions	Countries	Calculation method	Source
Central and Eastern European countries (CEEC)	**Czech**	Due to the lack of reliable material intensity data for Czech, we assumed that Czech material intensities are average of values of neighbouring countries's material intensity according to similar topography roughness. Topography roughness is low for flat countries and high for mountainous ones.	(Braconier et al. 2013)
	Estonia	Due to the lack of reliable material intensity data for Estonia, we assumed that Estonian material intensities are average of values of neighbouring countries's material intensity according to similar topography roughness. Topography roughness is low for flat countries and high for mountainous ones.	(Braconier et al. 2013)
	Latvia	The pavement structures are collected from literature data of LCA road pavements in Latvia	(Riekstins et al. 2019)
	Lithuania	The pavement structures are collected from literature data of LCA road pavements in Lithuania	(Vaitkus et al. 2010)
	Hungary	The pavement structures are taken from OECD report	(OECD 2005)
	Poland	The pavement structures are taken from OECD report	(OECD 2005) (Złotowska et al. 2021)
	Romania	The pavement structures are collected from literature data of LCA road pavements in Romania	(Dumitrescu et al. 2014)

Regions	Countries	Calculation method	Source
	Slovenia	The road thickness layers are collected and estimated from the Fladvad et al. 2017.	(Fladvad et al. 2017)
	Slovakia	The road thickness layers are collected and estimated from the Fladvad et al. 2017.	(Fladvad et al. 2017)
Western European countries (WEC)	**Denmark**	The pavement structures are taken from OECD report (OECD 2005)	(OECD 2005)
	Ireland	Due to the lack of reliable material intensity data for Ireland, we assumed that its material intensities are average of values of neighbouring countries's material intensity according to similar topography roughness. Topography roughness is low for flat countries and high for mountainous ones.	(Braconier et al. 2013)
	Spain	The road thickness layers are collected and estimated from the Fladvad et al. 2017.	(Fladvad et al. 2017)
	France	The French pavement design method for road pavements is described in the French standard NF-P 98-086	NF P 98-086 (2011)
	Italy	The only official reference document available on pavement is a pavement catalogue, “CATALOGO DELLE PAVIMENTAZIONI STRADALI”, published in 1994 by the National Research Council (CNR). The catalogue was developed using the design method described in the “AASHTO Guide for Design of Pavement Structures”	(CNR, 1995)
	Luxembourg	Due to the lack of reliable material intensity data for Luxembourg, we assumed that its material intensities are average of values of neighbouring countries's material intensity according to similar topography roughness. Topography roughness is low for flat countries and high for mountainous ones.	(Braconier et al. 2013)
	Netherlands	The pavement structures are taken from OECD report (OECD 2005)	(OECD 2005)
	Austria	The road thickness layers are collected and estimated from the Fladvad et al. 2017.	(Fladvad et al. 2017)
	Portugal	The pavement structures are taken from OECD report (OECD 2005)	(OECD 2005)
	Finland	The pavement structures are taken from OECD report (OECD 2005)	(OECD 2005)
	Sweden	Regulations from the Swedish Transport Administration are specified in the TRVK Väg	(Trafikverket, 2011)
	Norway	The pavement structures are taken from OECD report (OECD 2005)	(OECD 2005)
	Switzerland	The road thickness layers are collected and estimated from the Fladvad et al. 2017.	(Fladvad et al. 2017)
	United Kingdom	Current pavement design guidance in UK is regulated by Highway Agency’s (HA’s) as Design Manual for Roads and Bridges. It provides the procedure of standard design methods in detail	(Highways Agency, 2006); (Thom, 2008)
	Germany	The pavement design procedure is specified in RStO 2012	(FGSV, 2012)

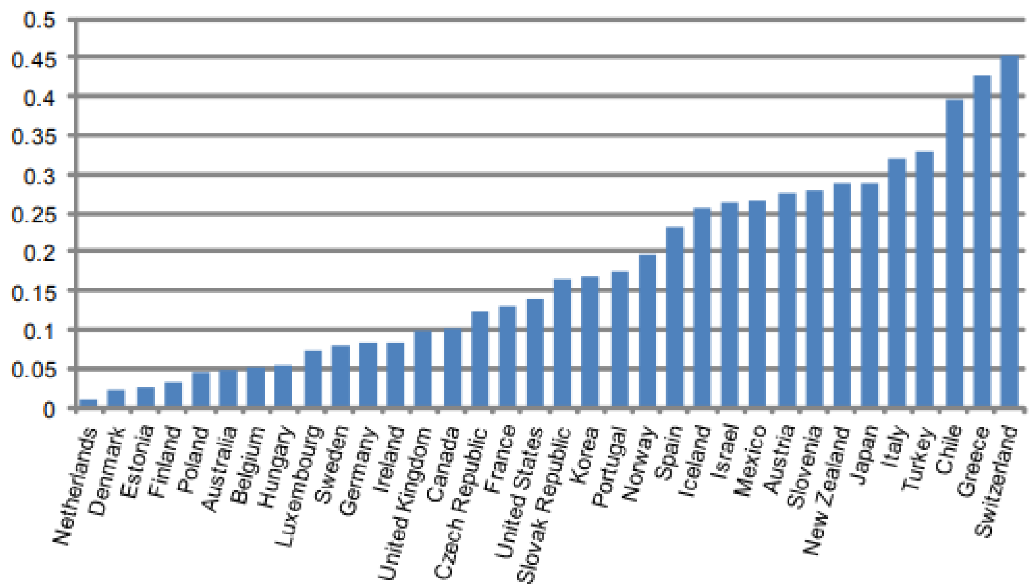


Figure S2: Roughness of topography (Braconier et al. 2013)

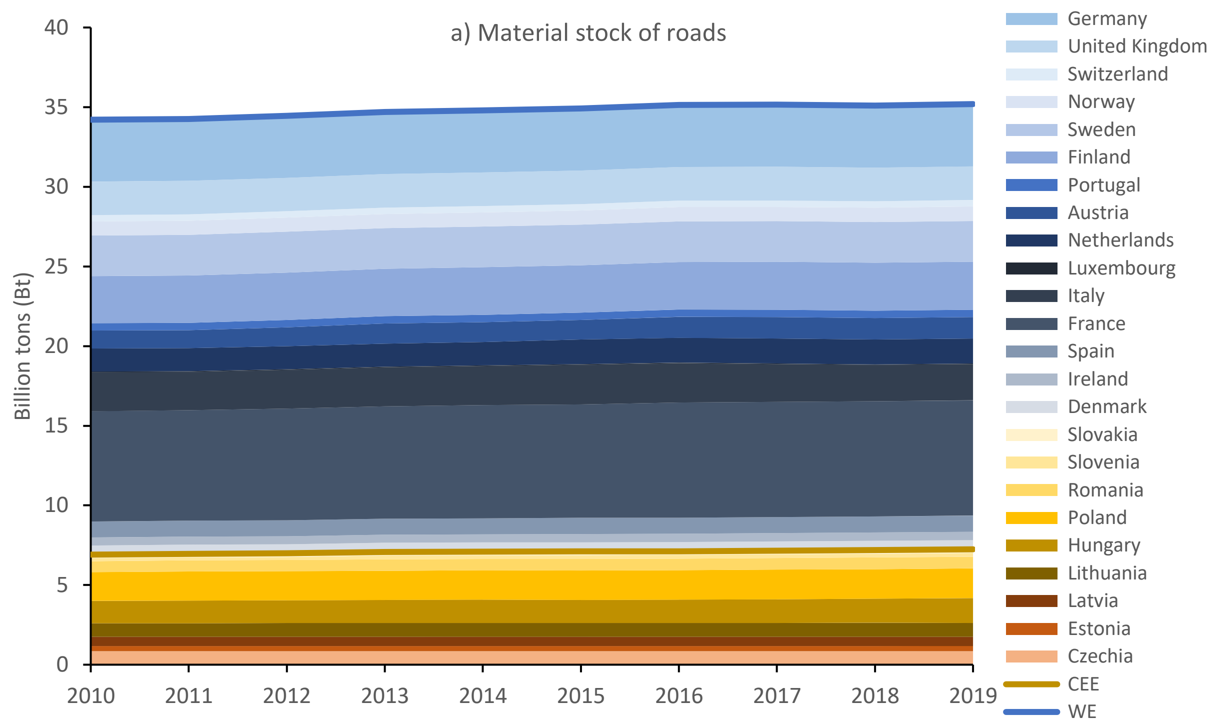
Table S6: The material intensities of road types in the 24 European countries (t/km)

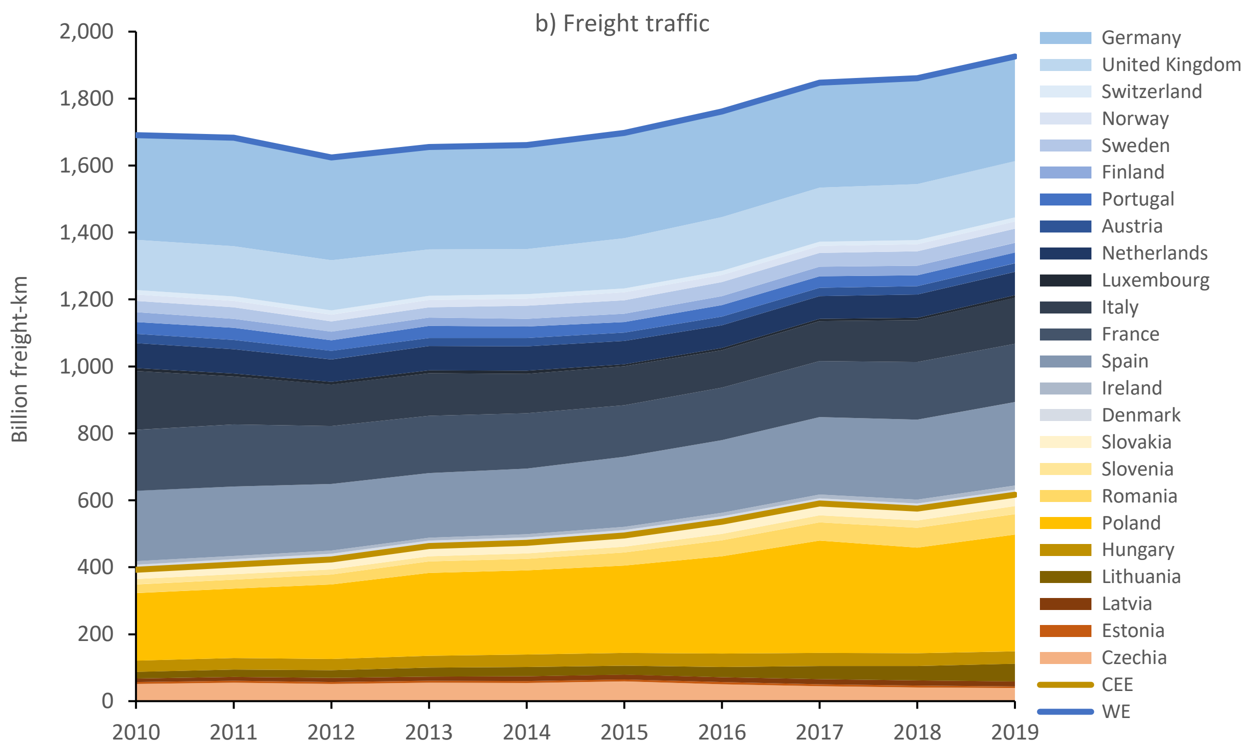
Regions	Countries	Motorways	State roads	Provincial roads	Communal roads
Central and Eastern European countries (CEEC)	**Czechia**	14,019	9,953	7,762	5,297
	Estonia	28,653	21,033	16,122	9,707
	Latvia	23,466	11,122	10,013	6,582
	Lithuania	19,576	14,529	8,775	5,738
	Hungary	11,215	8,615	6,757	3,775
	Poland	10,528	7,708	5,650	3,306
	Romania	15,715	11,672	8,644	6,288
	Slovenia	9,429	6,643	4,713	4,088
	Slovakia	12,340	8,072	5,494	4,725
Western European countries (WEC)	**Denmark**	17,841	12,922	10,519	5,906
	Ireland	12,027	8,830	6,642	4,785
	Spain	13,465	8,972	5,494	4,400
	France	14,071	10,318	7,735	5,738
	Italy	21,618	12,794	9,338	8,157
	Luxembourg	19,537	14,861	11,661	9,617
	Netherlands	31,430	20,472	14,607	10,363
	Austria	22,456	14,372	10,219	9,438
	Portugal	13,903	9,508	5,807	4,082
	Finland	39,465	29,143	21,725	13,538
	Sweden	27,858	18,508	12,107	8,019
	Norway	20,662	14,551	10,688	6,444
	Switzerland	17,165	11,893	6,750	4,838
	United Kingdom	13,968	9,588	7,789	4,857

	Germany	10,086	8,072	5,494	4,713

Table S7: Material stocks of 24 European countries (Million tons)

Regions	Countries	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Central and Eastern European countries (CEEC)	**Czechia**	848	848	848	848	848	848	850	850	850	850
	Estonia	521	522	524	525	526	525	526	525	526	526
	Latvia	585	584	581	581	582	578	579	579	579	577
	Lithuania	845	851	862	865	870	869	859	864	875	871
	Hungary	1,411	1,421	1,427	1,453	1,458	1,449	1,460	1,489	1,506	1,553
	Poland	1,796	1,823	1,823	1,828	1,841	1,850	1,853	1,859	1,866	1,868
	Romania	695	705	712	720	716	721	722	722	724	726
	Slovenia	186	186	186	239	239	239	239	239	239	239
	Slovakia	222	223	223	223	223	228	228	229	232	232
Western European countries (WEC)	**Denmark**	570	570	570	574	574	574	575	577	577	577
	Ireland	506	506	506	506	506	522	522	522	522	523
	Spain	1,003	1,006	1,006	1,007	1,011	1,012	1,011	1,017	1,013	1,013
	France	6,919	6,922	7,007	7,044	7,104	7,126	7,224	7,225	7,230	7,232
	Italy	2,452	2,413	2,434	2,455	2,454	2,479	2,477	2,374	2,280	2,280
	Luxembourg	38	38	37	37	37	38	38	38	38	38
	Netherlands	1,452	1,455	1,456	1,458	1,461	1,556	1,559	1,561	1,564	1,574
	Austria	1,129	1,132	1,181	1,252	1,252	1,227	1,312	1,360	1,345	1,345
	Portugal	457	457	461	461	462	462	462	462	462	462
	Finland	2,961	2,978	2,976	2,984	2,988	2,962	2,983	2,996	3,003	3,011
	Sweden	2,543	2,544	2,558	2,550	2,551	2,552	2,553	2,555	2,557	2,558
	Norway	883	886	887	888	889	894	896	897	900	911
	Switzerland	400	400	401	401	401	401	401	401	401	401
	United Kingdom	2,101	2,101	2,105	2,108	2,109	2,109	2,114	2,116	2,118	2,121
	Germany	3,890	3,892	3,893	3,895	3,895	3,896	3,897	3,899	3,901	3,903


a) Material stock of roads
Billion tons (Bt)
40
35
30
25
20
15
10
5
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Germany
United Kingdom
Switzerland
Norway
Sweden
Finland
Portugal
Austria
Netherlands
Luxembourg
Italy
France
Spain
Ireland
Denmark
Slovakia
Slovenia
Romania
Poland
Hungary
Lithuania
Latvia
Estonia
Czechia
CEE
WE


b) Freight traffic
Billion freight-km
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Germany
United Kingdom
Switzerland
Norway
Sweden
Finland
Portugal
Austria
Netherlands
Luxembourg
Italy
France
Spain
Ireland
Denmark
Slovakia
Slovenia
Romania
Poland
Hungary
Lithuania
Latvia
Estonia
Czechia
CEE
WE

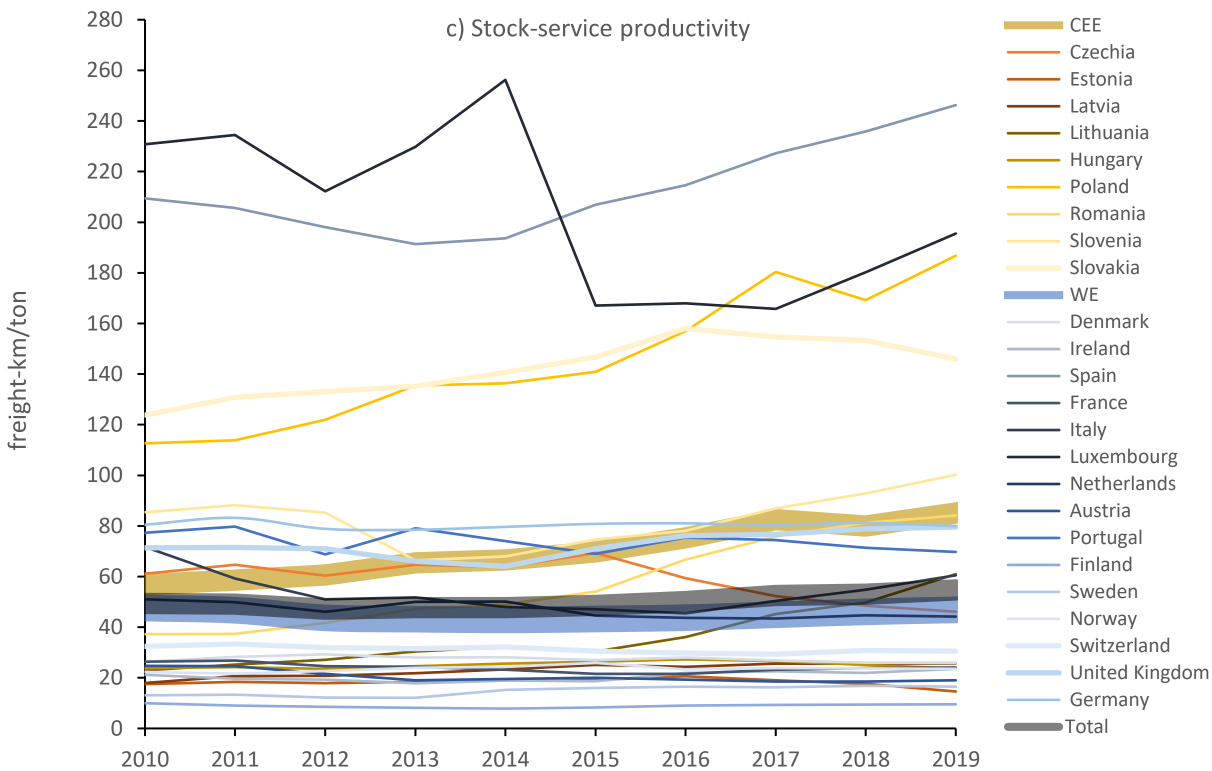


Figure S3: The stock service productivity of roads in CEEC and WEC; 2010–2019. (a) the materials stocked in roads; (b) the volume of freight traffic by the road; and (c) the stock-service productivity of roads. freight-km= freight-kilometers; freight-km/ton = freight-kilometers/ton.

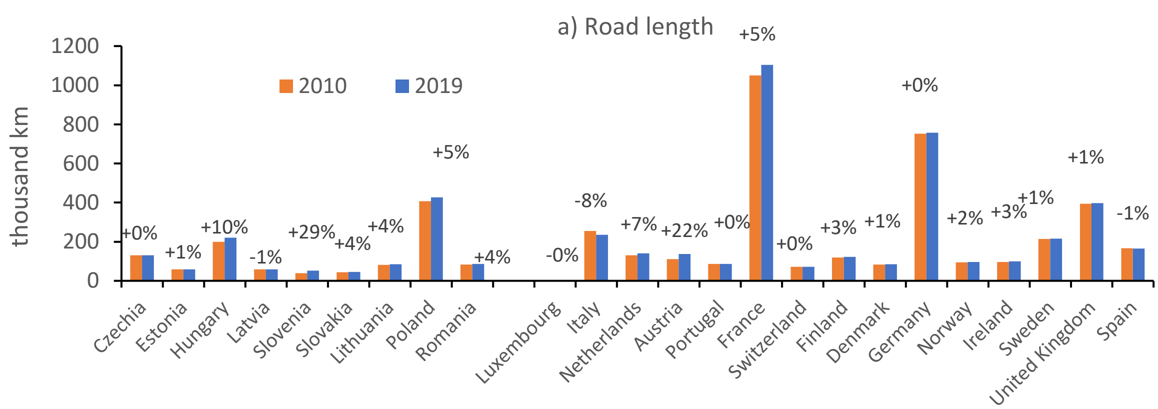
4. Stock service productivity:

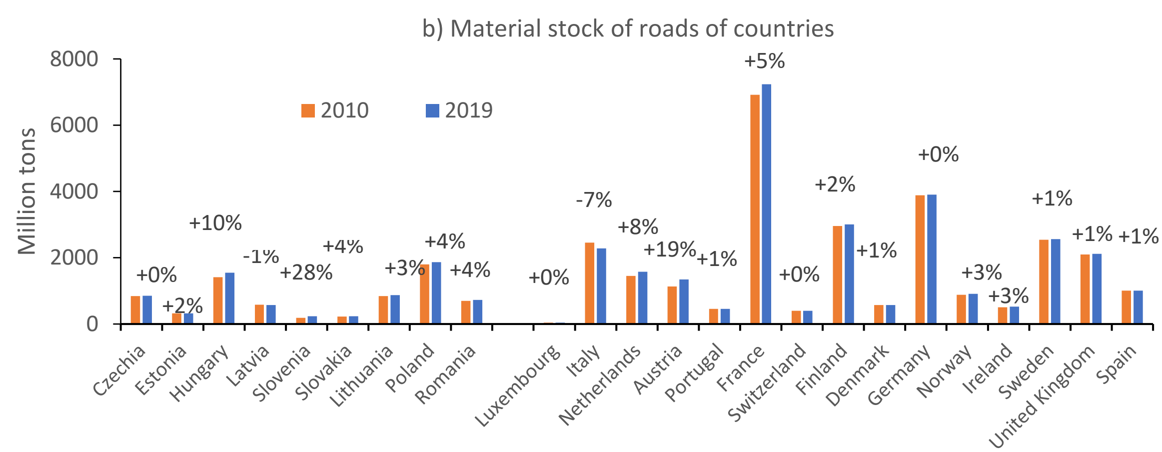
Table S8: Stock service productivity of 24 European countries, freight-km/ton (freight-kilometers/ton)

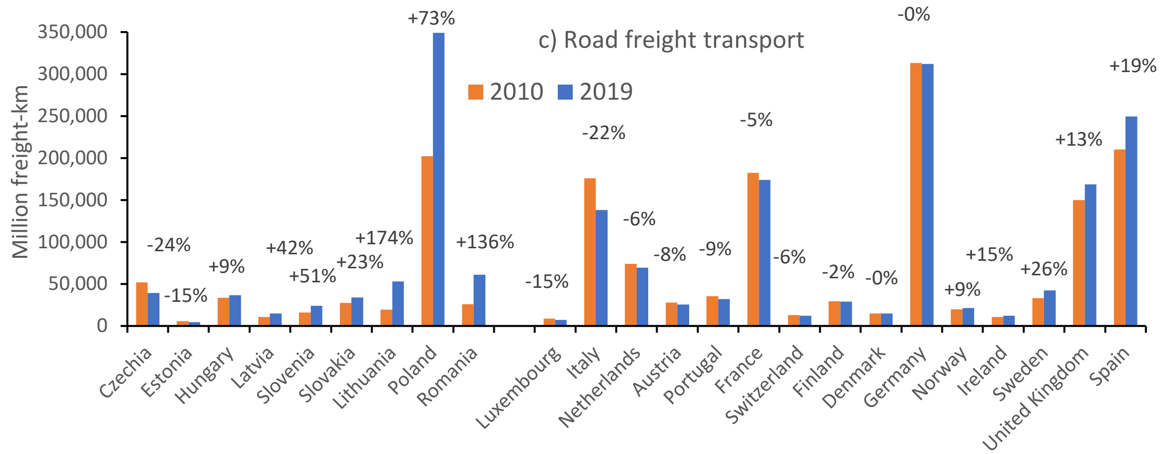
Regions	Countries	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Central and Eastern European countries (CEEC)	Czechia	61	65	60	65	64	69	59	52	48	46
	Estonia	17	18	18	18	19	19	21	19	18	15
	Latvia	18	21	21	22	23	25	24	26	26	26
	Lithuania	23	25	27	30	32	30	36	45	50	61
	Hungary	24	24	24	25	26	26	27	27	25	24
	Poland	113	114	122	135	136	141	157	180	169	187
	Romania	37	37	42	47	49	54	67	76	81	84
	Slovenia	85	88	85	66	68	75	78	87	93	100
	Slovakia	124	131	133	135	141	147	158	155	153	146
Western European	Denmark	26	28	29	28	28	27	28	27	26	26
	Ireland	21	20	19	18	19	19	22	23	22	24
	Spain	209	206	198	191	194	207	215	227	236	246

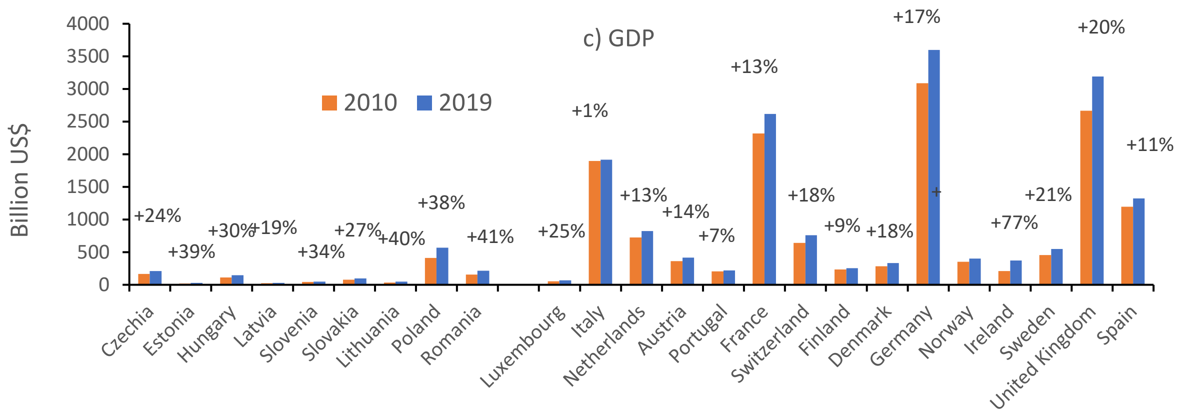
countries (WEC)	**France**	26	27	25	24	23	22	22	23	24	24
	Italy	72	59	51	52	48	47	45	50	55	61
	Luxembourg	231	234	212	230	256	167	168	166	180	196
	Netherlands	51	50	46	50	50	45	44	43	45	44
	Austria	25	25	22	19	20	20	19	19	19	19
	Portugal	77	80	69	79	74	69	75	74	71	70
	Finland	10	9	9	8	8	8	9	9	9	10
	Sweden	13	13	12	12	15	16	17	16	17	16
	Norway	22	22	23	24	24	26	23	24	24	24
	Switzerland	32	33	32	32	32	31	30	29	31	31
	United Kingdom	71	71	71	66	64	71	76	77	79	80
	Germany	80	83	79	79	80	81	81	80	81	80

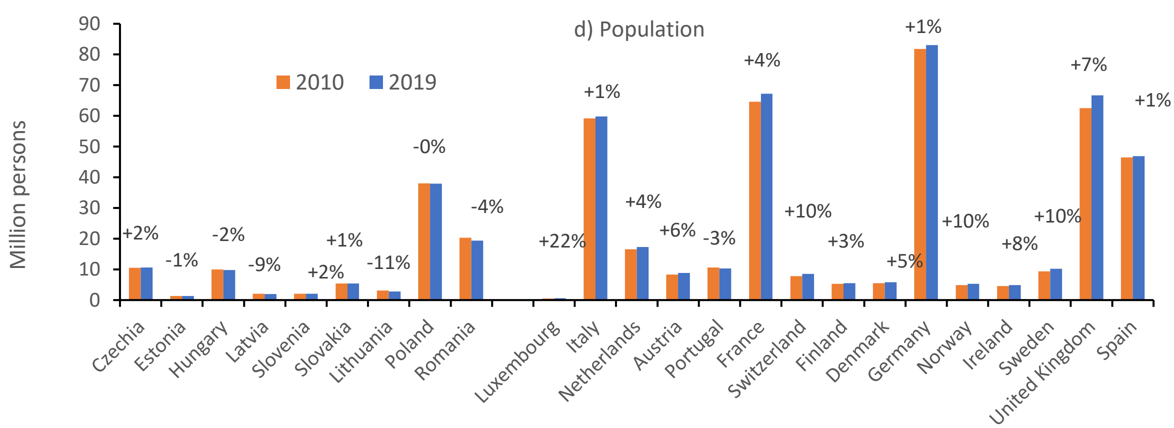
5. Changes in socio-economic and material stocks indicators in 24 European countries






c) Road freight transport
2010
2019
Million freight-km
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
-24%
-15%
+9%
+42%
+51%
+23%
+174%
+73%
+136%
-15%
-22%
-6%
-8%
-9%
-5%
-6%
-2%
-0%
-0%
+9%
+15%
+26%
+13%
+19%
Czechia
Estonia
Hungary
Latvia
Slovenia
Slovakia
Lithuania
Poland
Romania
Luxembourg
Italy
Netherlands
Austria
Portugal
France
Switzerland
Finland
Denmark
Germany
Norway
Ireland
Sweden
United Kingdom
Spain


c) GDP
2010
2019
Billion US$
4000
3500
3000
2500
2000
1500
1000
500
0
+24%
+39%
+30%
+19%
+34%
+27%
+40%
+38%
+41%
+25%
+1%
+13%
+14%
+7%
+13%
+18%
+9%
+18%
+17%
+77%
+21%
+20%
+11%
Czechia
Estonia
Hungary
Latvia
Slovenia
Slovakia
Lithuania
Poland
Romania
Luxembourg
Italy
Netherlands
Austria
Portugal
France
Switzerland
Finland
Denmark
Germany
Norway
Ireland
Sweden
United Kingdom
Spain


d) Population
2010
2019
Million persons
90
80
70
60
50
40
30
20
10
0
+2%
-1%
-2%
-9%
+2%
+1%
-11%
-0%
-4%
+22%
+1%
+4%
+6%
-3%
+4%
+10%
+3%
+5%
+1%
+10%
+8%
+10%
+7%
+1%
Czechia
Estonia
Hungary
Latvia
Slovenia
Slovakia
Lithuania
Poland
Romania
Luxembourg
Italy
Netherlands
Austria
Portugal
France
Switzerland
Finland
Denmark
Germany
Norway
Ireland
Sweden
United Kingdom
Spain

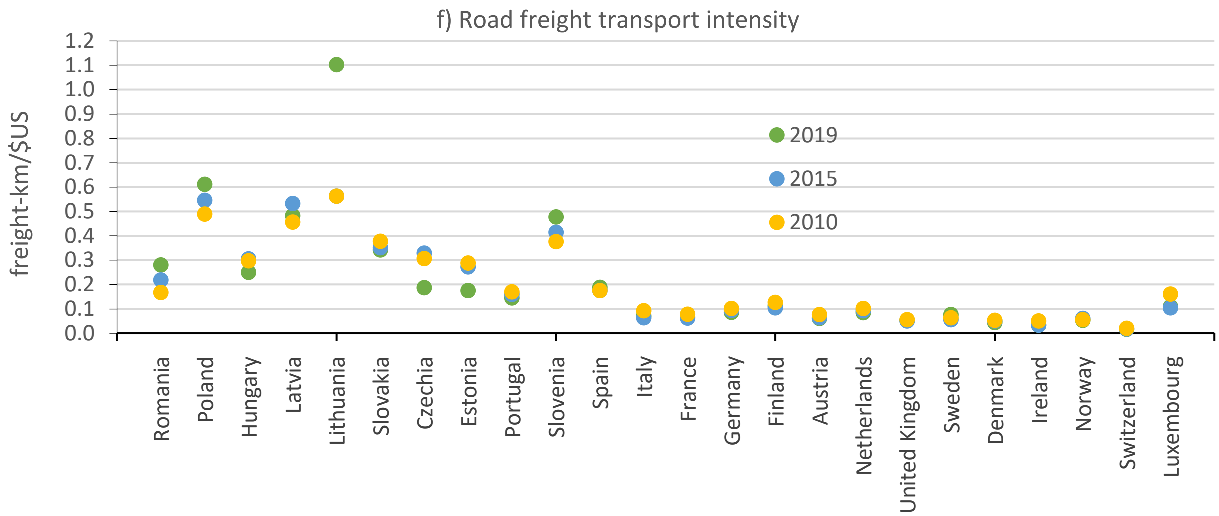
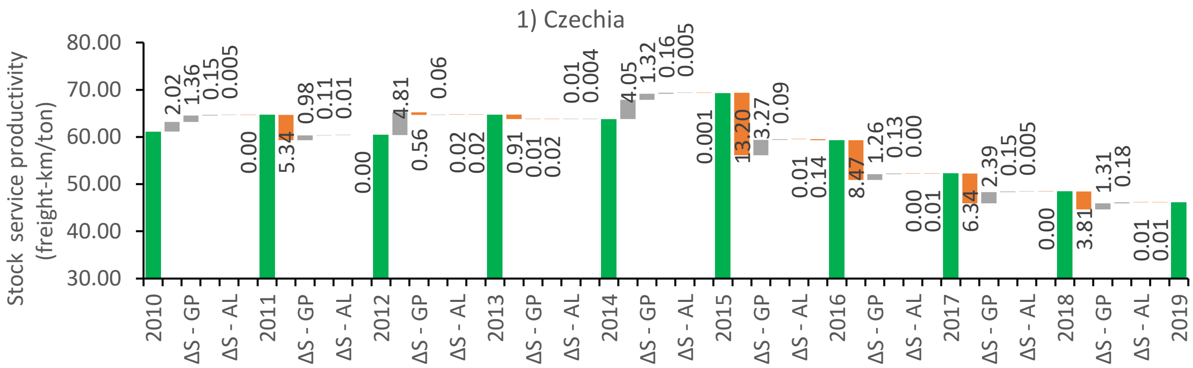
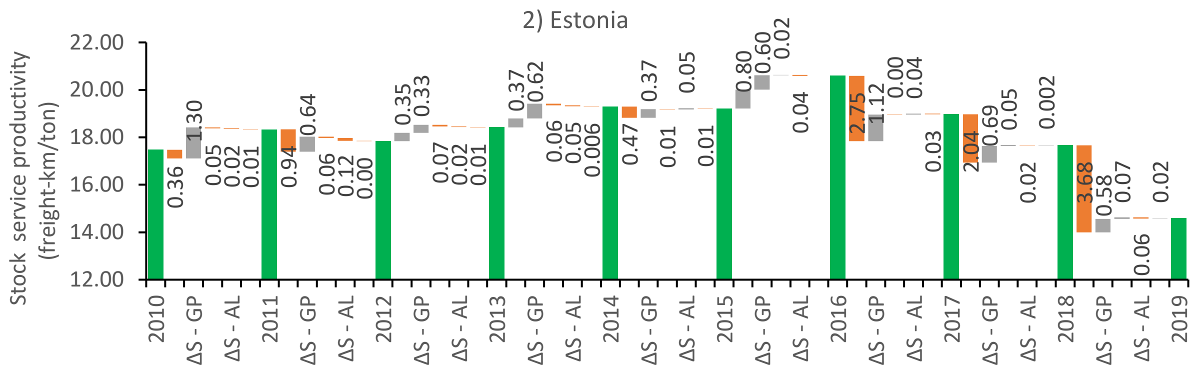


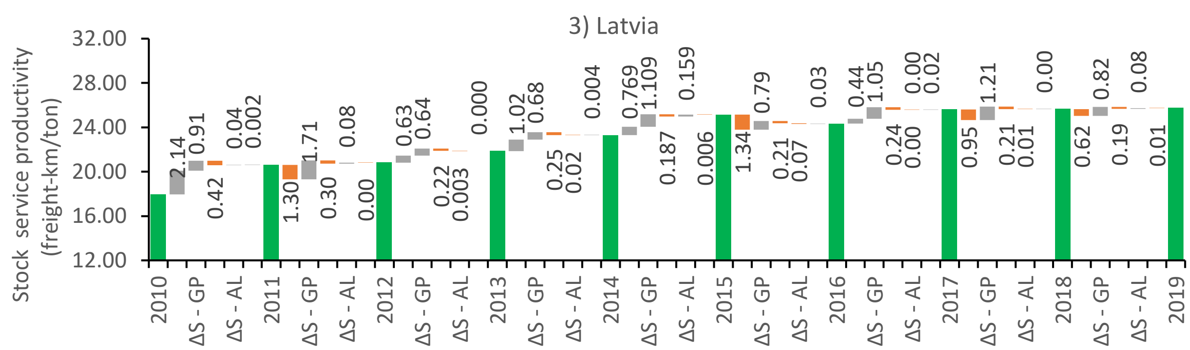
Figure S4. (a) Road lengths by countries; (b) Material stocks of roads by countries; (c) Volume of freight transport by road by countries; (d) Gross Domestic Product of countries; (e) Population by countries, (f) Road freight transport intensity according to the increasing per capita GDP of each countries. Note: in figures 4a, b, c, d, and e: countries are listed from left to right in the horizontal axis according to their belonged CEE and WE regions; in SI figure 4f, countries are listed from left to right in the horizontal axis according to the increasing per capita GDP of each country.

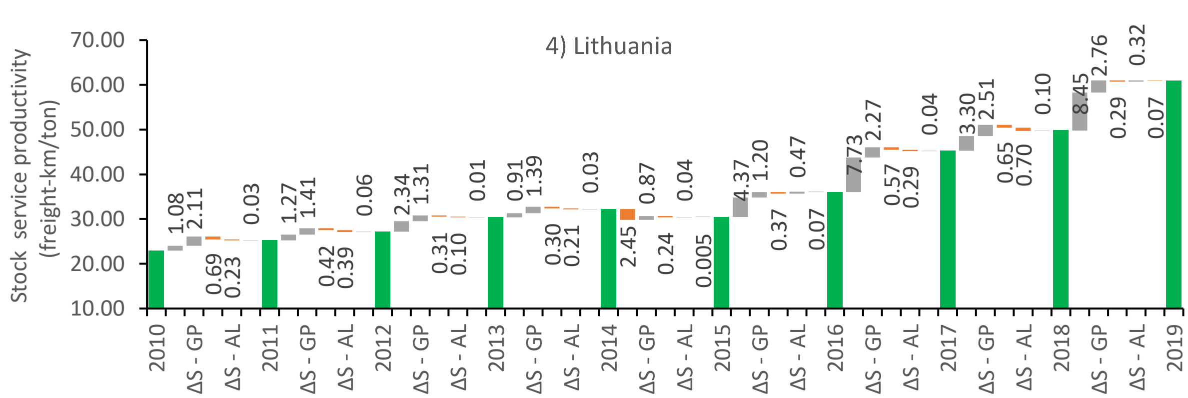
6. **The year-by year cummulative effects of factors in stock service productivity in the 24 European countries, 2010-2019.**

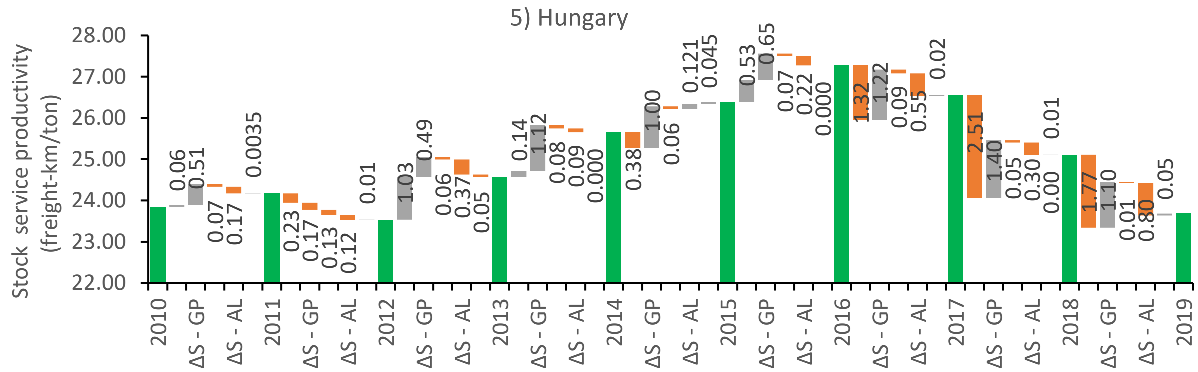
The year-by year cummulative effects of factors in stock-service productivity in the 24 European countries, 2010-2019.

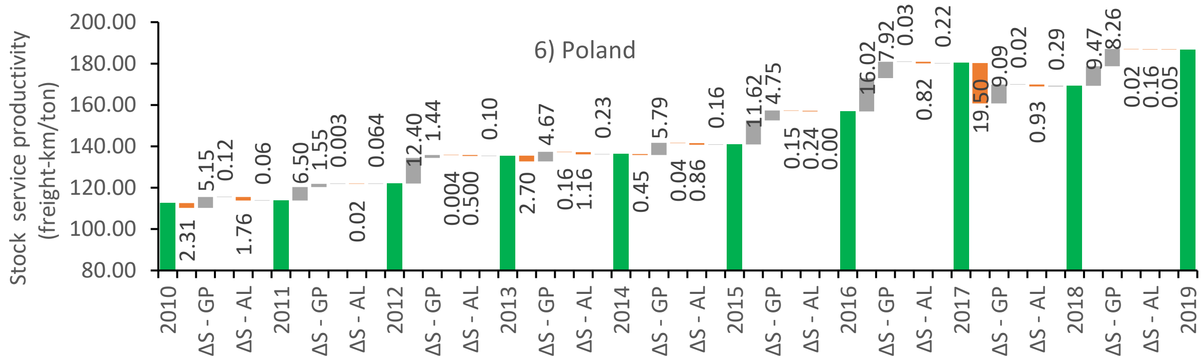









5) Hungary
Stock service productivity (freight-km/ton)
28.00
27.00
26.00
25.00
24.00
23.00
22.00
0.06
0.51
0.07
0.17
0.0035
0.23
0.17
0.13
0.12
0.01
1.03
0.49
0.06
0.37
0.05
0.14
1.12
0.08
0.09
0.000
0.38
1.00
0.06
0.121
0.045
0.53
0.65
0.07
0.22
0.000
1.32
1.22
0.09
0.55
0.02
2.51
1.40
0.05
0.30
0.00
0.01
1.77
1.10
0.01
0.80
0.05
2010
ΔS - GP
ΔS - AL
2011
ΔS - GP
ΔS - AL
2012
ΔS - GP
ΔS - AL
2013
ΔS - GP
ΔS - AL
2014
ΔS - GP
ΔS - AL
2015
ΔS - GP
ΔS - AL
2016
ΔS - GP
ΔS - AL
2017
ΔS - GP
ΔS - AL
2018
ΔS - GP
ΔS - AL
2019


6) Poland
Stock service productivity (freight-km/ton)
200.00
180.00
160.00
140.00
120.00
100.00
80.00
2.31
5.15
0.12
1.76
0.06
6.50
1.55
0.003
0.02
0.064
12.40
1.44
0.004
0.500
0.10
2.70
4.67
0.16
1.16
0.23
0.45
5.79
0.04
0.86
0.16
11.62
4.75
0.15
0.24
0.00
16.02
7.92
0.03
0.82
0.22
19.50
9.09
0.02
0.93
0.29
9.47
8.26
0.02
0.16
0.05
2010
ΔS - GP
ΔS - AL
2011
ΔS - GP
ΔS - AL
2012
ΔS - GP
ΔS - AL
2013
ΔS - GP
ΔS - AL
2014
ΔS - GP
ΔS - AL
2015
ΔS - GP
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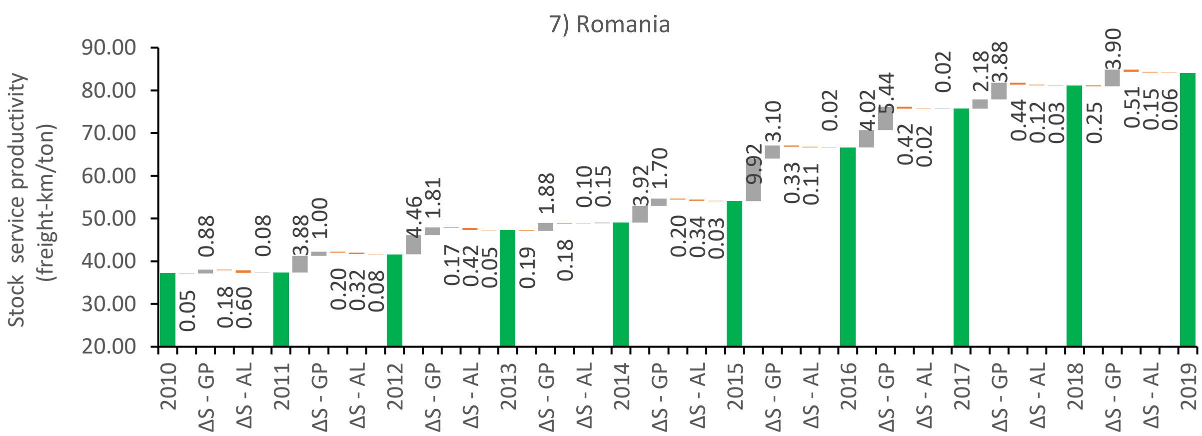
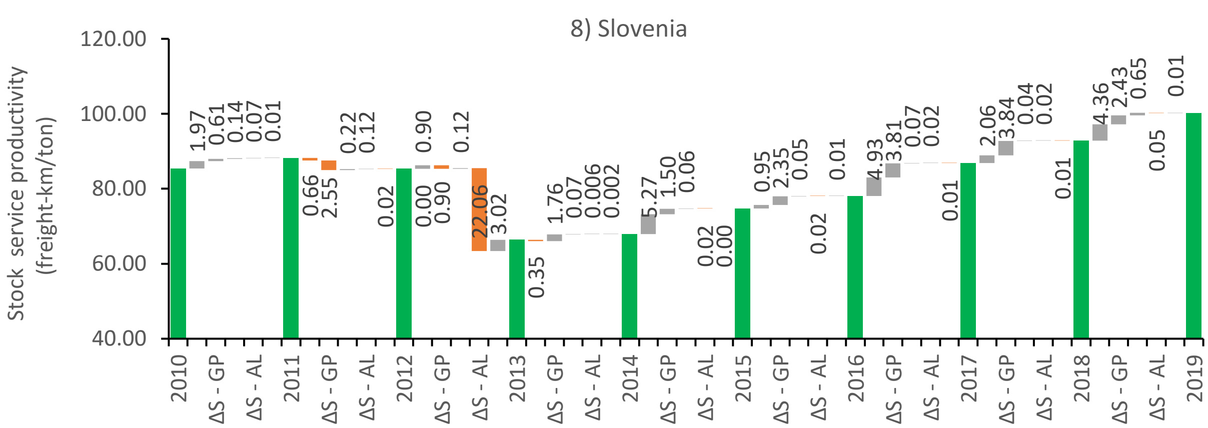
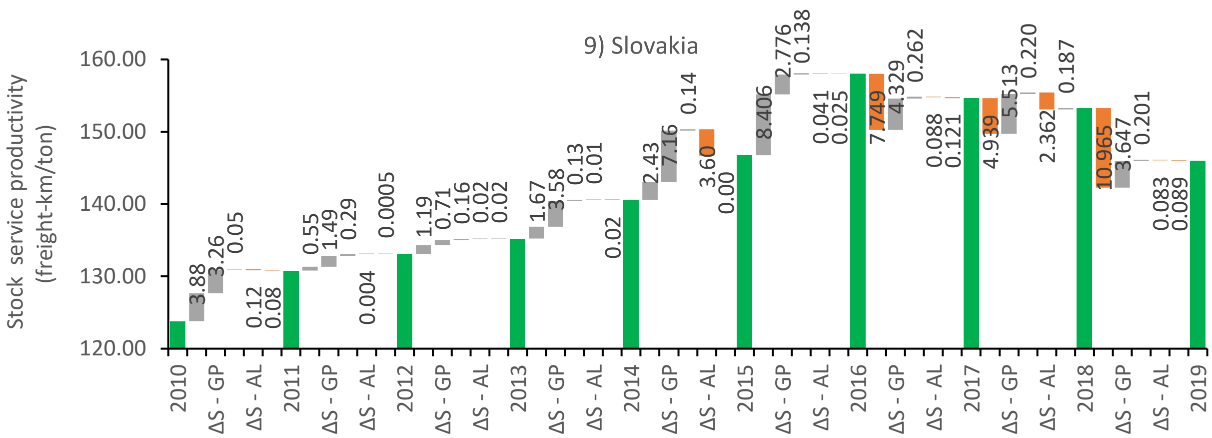
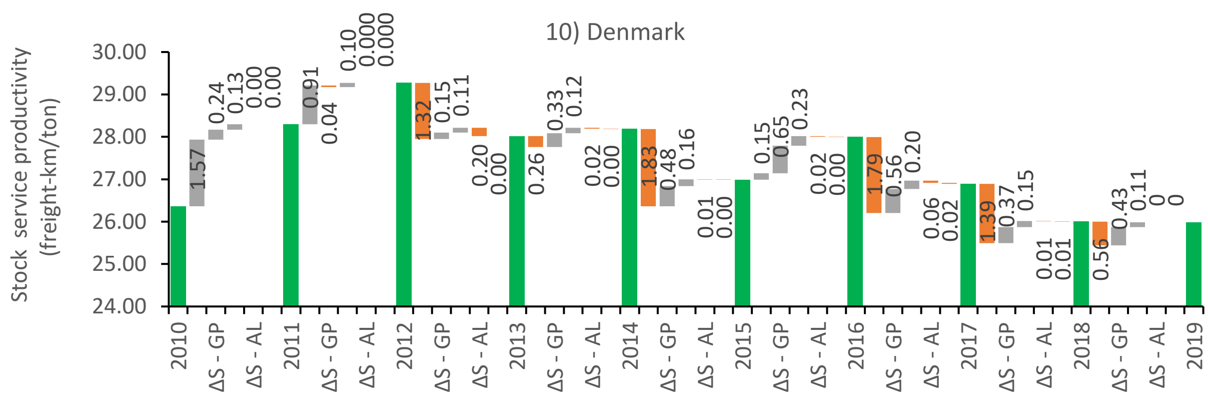
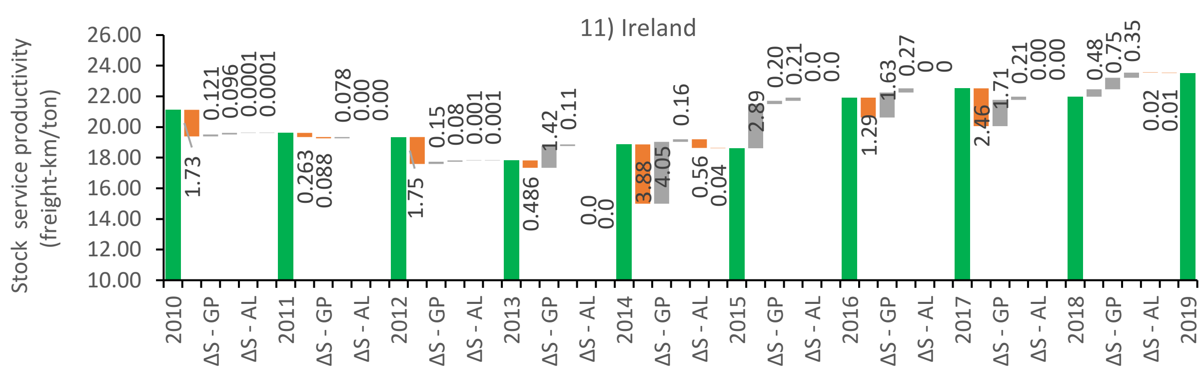
2016
ΔS - GP
ΔS - AL
2017
ΔS - GP
ΔS - AL
2018
ΔS - GP
ΔS - AL
2019

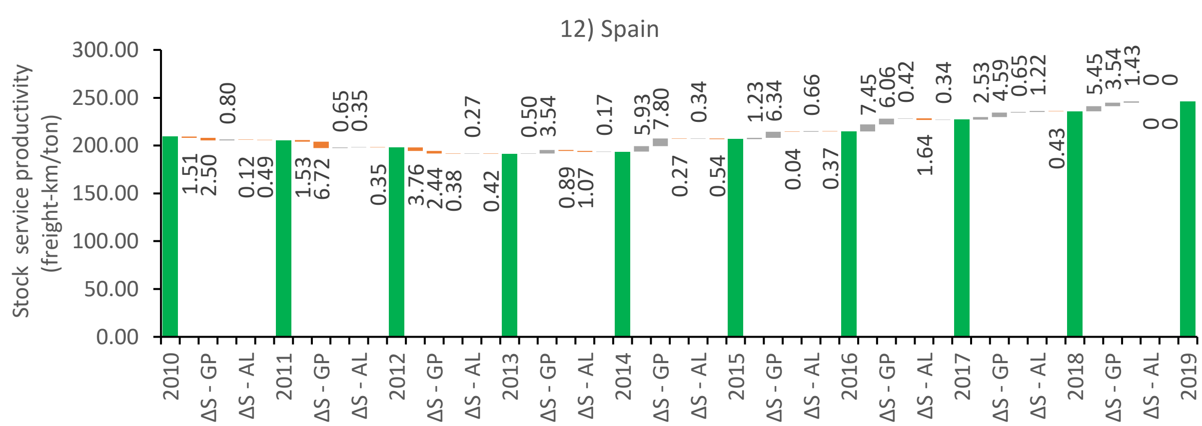

7) Romania
Stock service productivity (freight-km/ton)
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
0.05
0.88
0.18
0.60
0.08
3.88
1.00
0.20
0.32
0.08
4.46
1.81
0.17
0.42
0.05
0.19
1.88
0.18
0.10
0.15
3.92
1.70
0.20
0.34
0.03
9.92
3.10
0.33
0.11
0.02
4.02
5.44
0.42
0.02
0.02
2.18
3.88
0.44
0.12
0.03
0.25
3.90
0.51
0.15
0.06
2010
ΔS - GP
ΔS - AL
2011
ΔS - GP
ΔS - AL
2012
ΔS - GP
ΔS - AL
2013
ΔS - GP
ΔS - AL
2014
ΔS - GP
ΔS - AL
2015
ΔS - GP
ΔS - AL
2016
ΔS - GP
ΔS - AL
2017
ΔS - GP
ΔS - AL
2018
ΔS - GP
ΔS - AL
2019

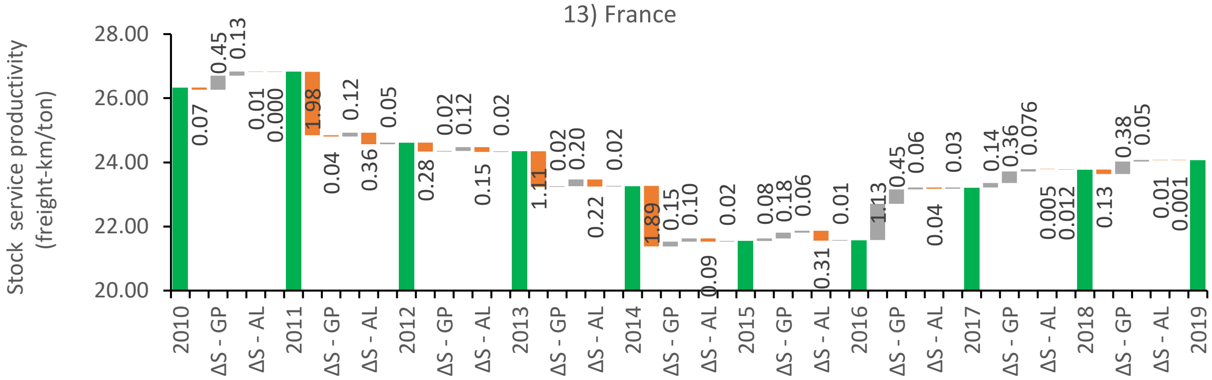

8) Slovenia
Stock service productivity (freight-km/ton)
120.00
100.00
80.00
60.00
40.00
1.97
0.61
0.14
0.07
0.01
0.66
2.55
0.22
0.12
0.02
0.00
0.90
0.90
0.12
22.06
3.02
0.35
1.76
0.07
0.006
0.002
5.27
1.50
0.06
0.02
0.00
0.95
2.35
0.05
0.02
0.01
4.93
3.81
0.07
0.02
0.01
2.06
3.84
0.04
0.02
0.01
4.36
2.43
0.65
0.05
0.01
2010
ΔS - GP
ΔS - AL
2011
ΔS - GP
ΔS - AL
2012
ΔS - GP
ΔS - AL
2013
ΔS - GP
ΔS - AL
2014
ΔS - GP
ΔS - AL
2015
ΔS - GP
ΔS - AL
2016
ΔS - GP
ΔS - AL
2017
ΔS - GP
ΔS - AL
2018
ΔS - GP
ΔS - AL
2019

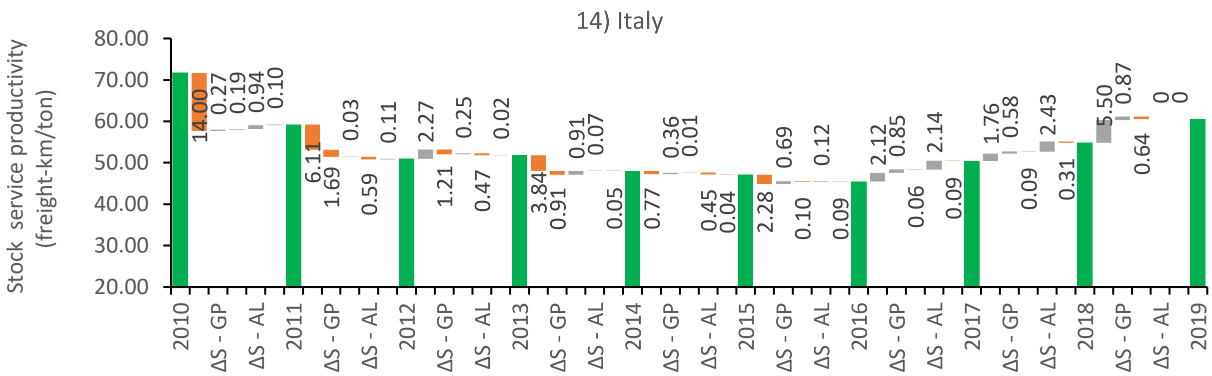

9) Slovakia
Stock service productivity (freight-km/ton)
160.00
150.00
140.00
130.00
120.00
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019

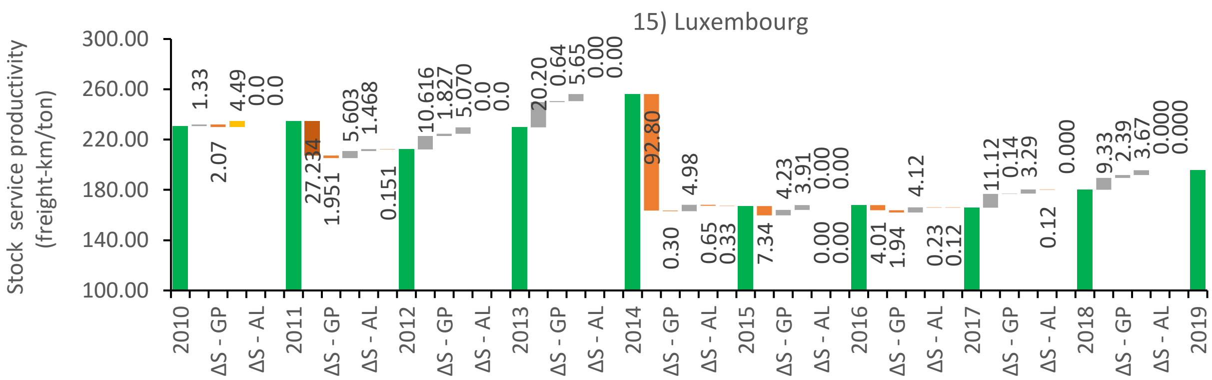

10) Denmark
Stock service productivity (freight-km/ton)
30.00
29.00
28.00
27.00
26.00
25.00
24.00
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019

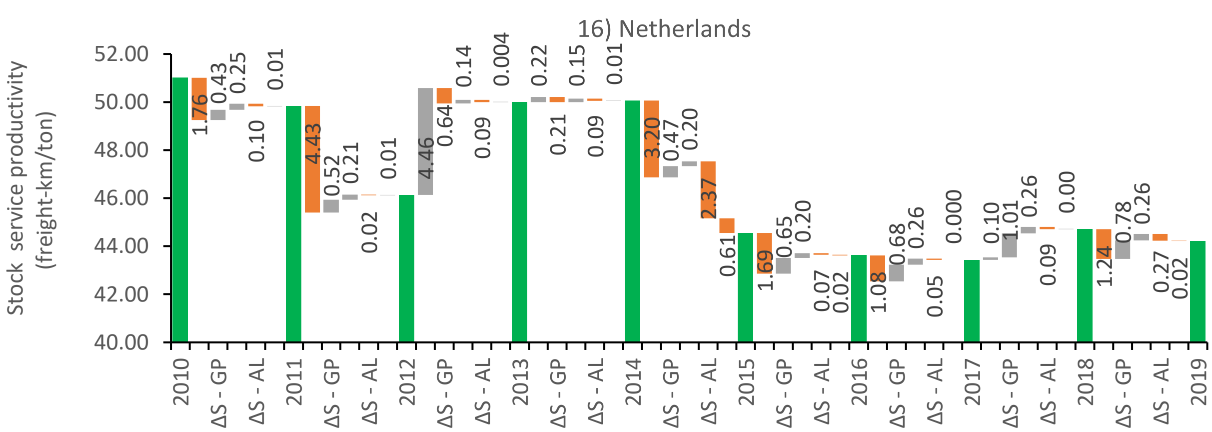

11) Ireland
Stock service productivity (freight-km/ton)
26.00
24.00
22.00
20.00
18.00
16.00
14.00
12.00
10.00
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019

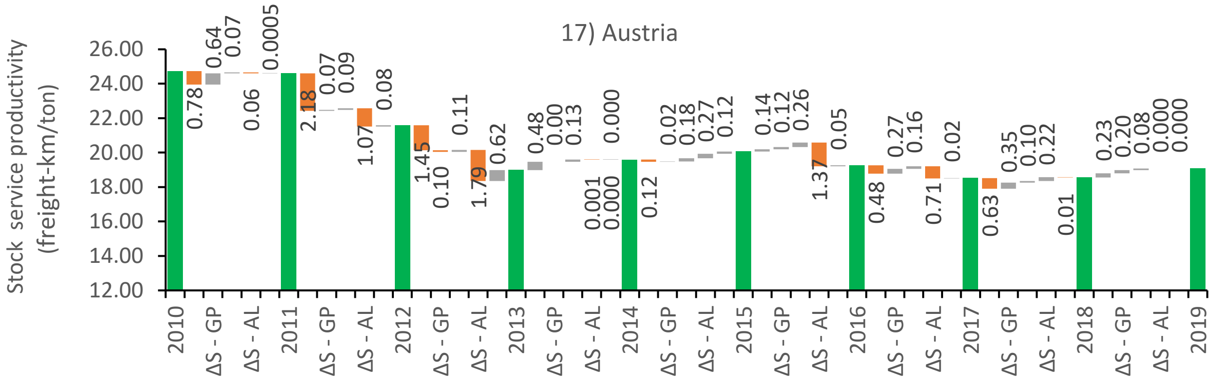

12) Spain
Stock service productivity (freight-km/ton)
300.00
250.00
200.00
150.00
100.00
50.00
0.00
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019

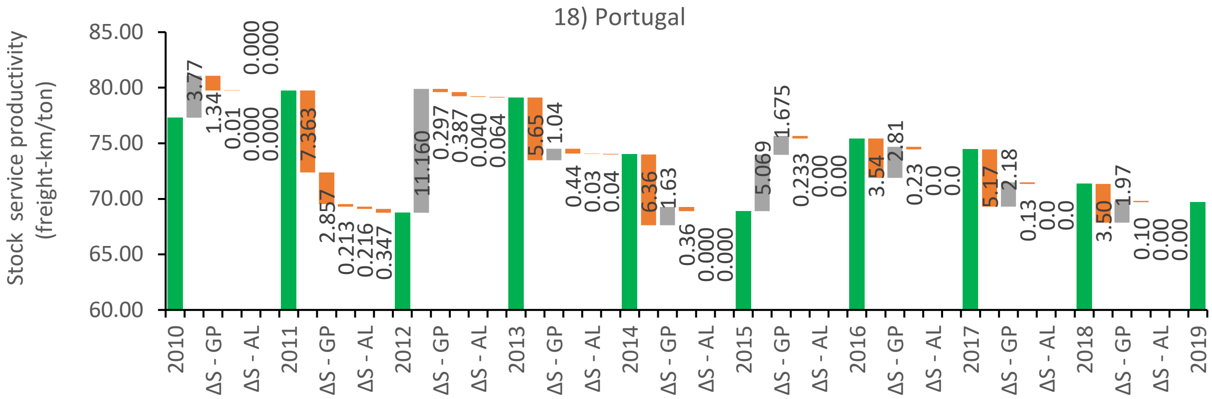

13) France
Stock service productivity (freight-km/ton)

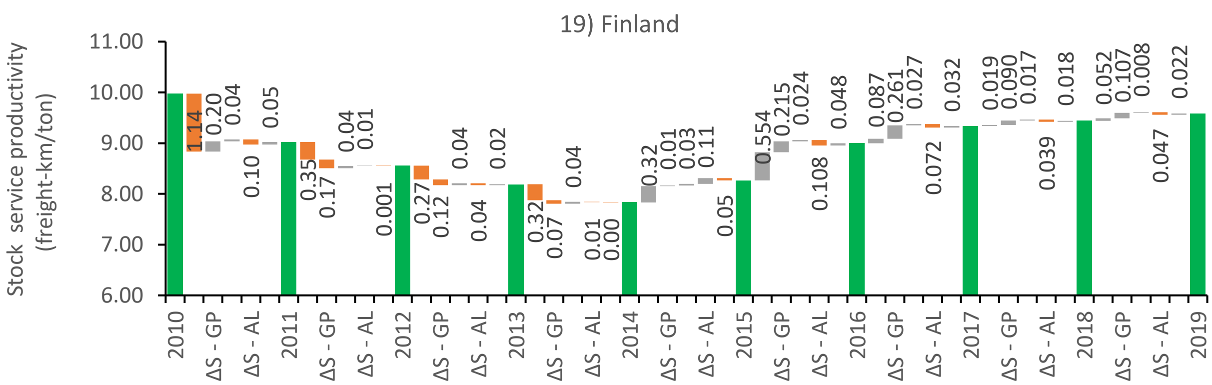

14) Italy
Stock service productivity (freight-km/ton)

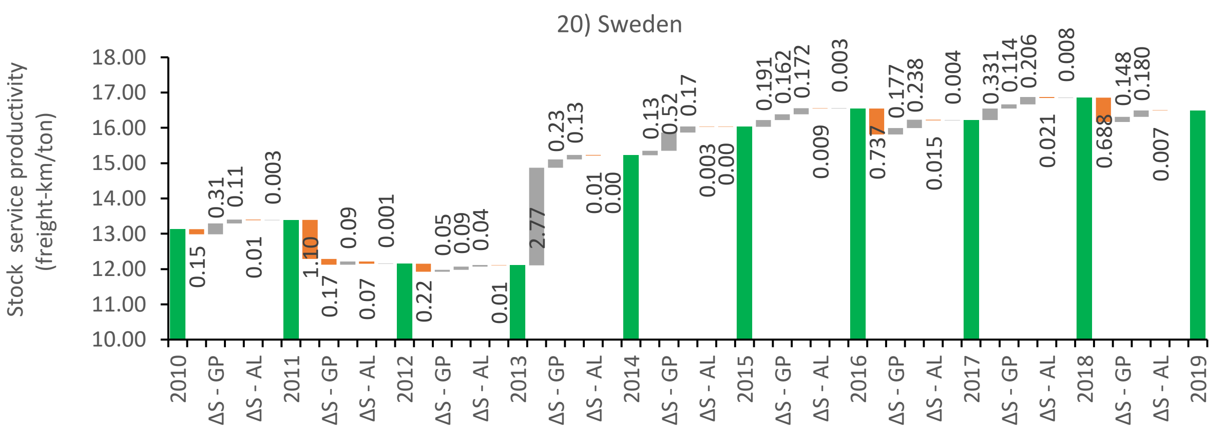

15) Luxembourg
Stock service productivity (freight-km/ton)


16) Netherlands
Stock service productivity (freight-km/ton)


17) Austria
Stock service productivity (freight-km/ton)
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019


18) Portugal
Stock service productivity (freight-km/ton)
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019


19) Finland
Stock service productivity (freight-km/ton)
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019


20) Sweden
Stock service productivity (freight-km/ton)
2010 ΔS - GP ΔS - AL 2011 ΔS - GP ΔS - AL 2012 ΔS - GP ΔS - AL 2013 ΔS - GP ΔS - AL 2014 ΔS - GP ΔS - AL 2015 ΔS - GP ΔS - AL 2016 ΔS - GP ΔS - AL 2017 ΔS - GP ΔS - AL 2018 ΔS - GP ΔS - AL 2019

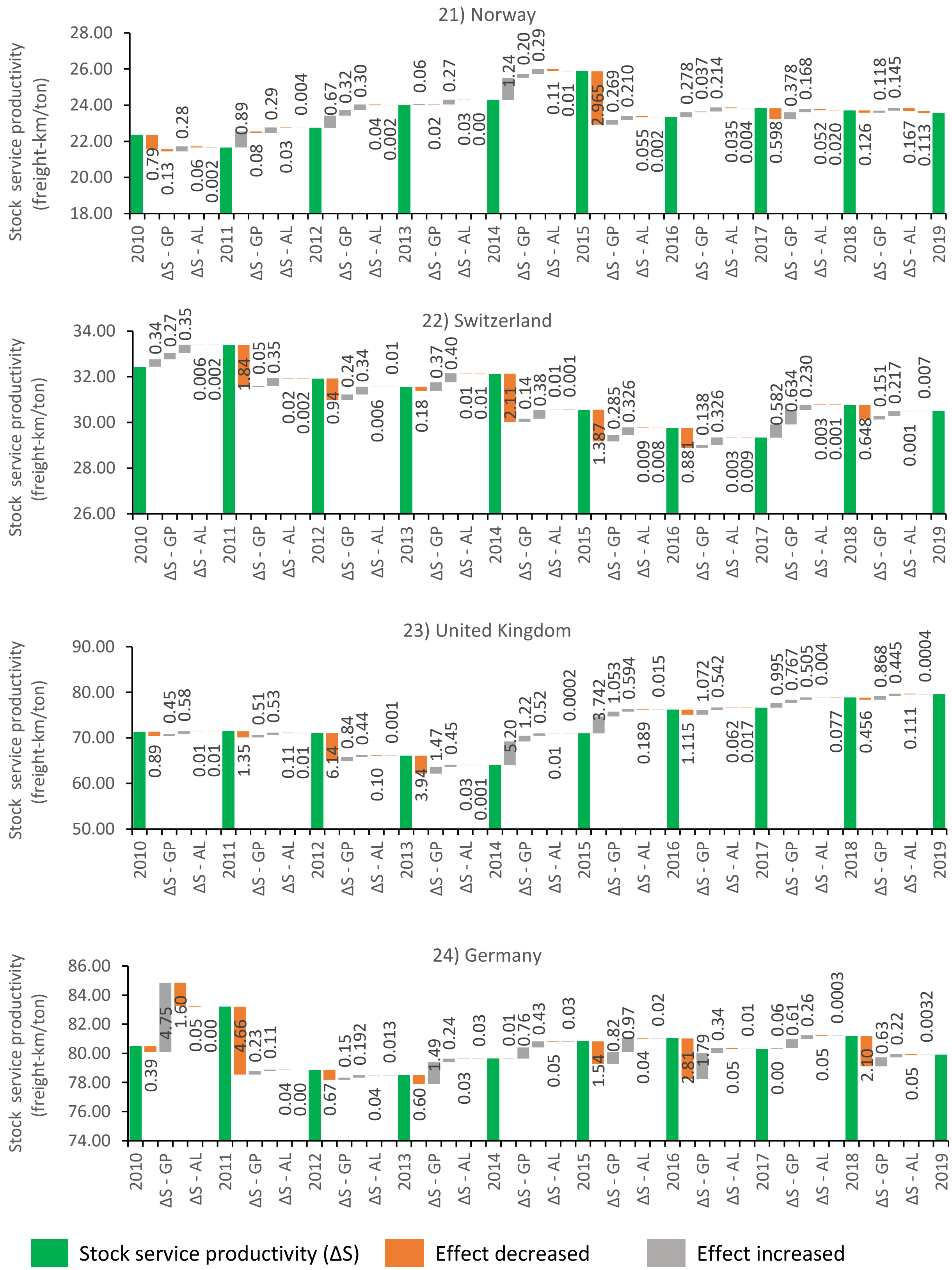


Figure S5: The year-by year cummulative effects of factors in stock service productivity in the 24 European countries, 2010-2019;

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