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Global transport emissions 1850–2020: Historical drivers and lessons for transport decarbonization

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ABSTRACT

This study analyzes global transport CO_2 emissions from 1850 to 2020 using the LMDI method, offering, for the first time, a decomposition over such a long timespan and global scope. Emissions are split into technological and demand-related drivers using a new dataset. Transport efficiency is divided into final-to-useful efficiency and useful energy intensity, a novel distinction. Key findings include: (1) efficiency improvements avoided 9067 Gt CO_2 by 2019, with peak impacts in 1950–1973 (-1.62 %/yr) and 2008–2020 (-3.63 %/yr), respectively; (2) these gains were insufficient to counter rising demand, which led to 8252 Gt CO_2 in cumulative emissions; (3) demand growth driven by GDP per capita, service intensity, and population accounted for 16 683 Gt CO_2 in 2019, with service intensity dominating in 1850–1913 (+3.97 %/yr) and GDP and population drivers peaking in 1950–1973 (+2.57 % and +1.83 %/yr); (4) keeping emissions at 2020 levels through 2029 would require electricity to supply 52 % of transport energy.

1. Introduction

The growing concern global warming has led to policies and investments to reduce CO_2 emissions, and the transport sector has received significant attention due to its 22 % share of global emissions in 2022 (IEA, 2022). Historically, the transport sector played an important role in human development, enabling countries to specialize in their comparative advantages, stimulating economic growth through access to fossil fuel energy, and facilitating the faster movement of people and goods (O'Rourke and Williamson, 1999). However, despite current efforts to decarbonize the transport sector, fossil fuels remain dominant. Reductions in CO_2 emissions can result from lowering transport demand, via changes in service intensity, income, or population, or improving energy efficiency and shifting to low-carbon fuels. Understanding the relative impact of these drivers is essential for effective policy design (Henriques and Borowiecki, 2017), and this can be achieved using decomposition methods, particularly the Logarithmic Mean Divisia Index (LMDI), which is favored for its theoretical rigor, flexibility, and perfect decomposition properties (Ang, 2004).

Although previous studies have examined the drivers of transport sector CO_2 emissions, few have conducted global decomposition analyses over long timescales reducing the ability to capture key historical transitions, such as periods of economic growth, shifts in

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energy use, and the emergence of new transport modes. Most prior research is also constrained by data availability, often focusing on short timeframes or single countries. Such national analyses overlook the global nature of CO_2 emissions and exclude the impact of international transport. Additionally, efficiency is often treated in aggregate, combining thermodynamic final–to–useful efficiency (e.g., diesel to mechanical work) with the use of that useful energy (e.g. mechanical work) to deliver transport services (e.g., passenger-km), which limits a detailed understanding of emission drivers. A global and long-term approach allows for a more comprehensive assessment of the factors driving emissions and the identification of opportunities for decarbonization.

This study applies LMDI decomposition methods to analyze global CO_2 emissions from the transport sector, separating technological and demand-related drivers over the long period from 1850 to 2020. A key methodological contribution is the disaggregation of efficiency into final-to-useful energy efficiency and useful energy intensity, allowing for a more detailed understanding of technological drivers. The analysis uses a new dataset that includes emissions, energy services, and modal intensities for water, rail, road, and air transport. The results are used to address the following questions:

1. How have the key drivers of transport CO_2 emissions evolved over the period 1850–2020?
2. What has been the quantitative contribution of each driver to total transport CO_2 emissions during this timeframe?
3. What insights do these historical trends offer for shaping future energy and climate policies?

The remainder of this paper is organized as follows: Section 2 provides a brief review of decomposition studies applied to the transport sector. Section 3 describes the LMDI method, its application in this study, and the dataset used. Section 4 presents and analyzes the main findings. Section 5 discusses key policy implications, and Section 6 concludes the paper.

2. Literature review

CO_2 emissions can be reduced by either decreasing overall transport demand and/or reducing CO_2 emissions per unit of transport service (e.g., passenger-km). Reduced transport demand could result from lower service intensity (transport services per unit of GDP), declining income per capita, or population decrease. On the other hand, reducing CO_2 emissions per unit of transport service could come from an increase in efficiency or the switch to low-carbon energy sources.

To better understand the relative contributions of these factors, decomposition methods are used to analyze historical trends in energy use and CO_2 emissions (Tsemekidi Tzeiranaki et al., 2023; Wu and Xu, 2014; Scholl et al., 1996; Lu et al., 2007; Kwon, 2005; Huang et al., 2019; Felício et al., 2024; Guan et al., 2008; Luukkanen and Kaivo-oja, 2002; Zhang et al., 2017). These are divided into two main branches: Index Decomposition Analyses (IDA) and Structural Decomposition Analyses (SDA) (Su and Ang, 2012). IDA has been the preferred method due to its flexibility and ease of use (Ang, 2004). In IDA, the Logarithmic Mean Divisia Index (LMDI) is recommended due to its solid theoretical foundation, adaptability, and easily interpretable results (Ang, 2004). IDA helpfully enables both additive and multiplicative formulations. Moreover, LMDI provides a perfect decomposition, i.e., no residual term exists.

Building on this, numerous studies have employed the LMDI method to isolate and evaluate the specific drivers behind transport-related CO_2 emissions (Kwon, 2005; Timilsina and Shrestha, 2009; Wang et al., 2011; Wu and Xu, 2014; Lu et al., 2017; Tsemekidi Tzeiranaki et al., 2023; Zhao et al., 2025; Li et al., 2019b). For example, in China's transport sector from 1985 to 2009, emissions grew at an average annual rate of 10.56 % (Wang et al., 2011). The study identifies per capita economic activity, population growth, and modal shifts as the main drivers of this increase while emission reductions were mainly associated with improvements in transport intensity (i.e., transport services per unit of GDP) and changes in fuel types within each transport mode. Similarly, the drivers of CO_2 emissions in the transport sector in 12 Asian countries during the 1980 to 2005 period were investigated. The results indicate that population growth, increasing per capita income, and increased transport energy intensity (final energy per GDP) were the main contributors to increased emissions while fuel switching, modal shifting, and changes in emission coefficients had minimal influence (Timilsina and Shrestha, 2009).

Among the various drivers identified in these studies, energy efficiency plays a particularly important role, yet its definition and measurement vary widely across the literature and deserve closer examination. Previous decomposition studies measured energy efficiency as kilometers traveled (Kwon, 2005; Wu and Xu, 2014), number of vehicles in use (Lu et al., 2007), or transport turnover (e.g., passenger-kilometer) (Scholl et al., 1996; Tsemekidi Tzeiranaki et al., 2023; Huang et al., 2019) per volume or energy content of fuel consumed. Using these metrics, it is not possible to differentiate emissions avoided due to improved engine efficiency or due to improvements in the utilization of transport (e.g., occupancy, speed, or aerodynamics). One way of accounting for these factors is to distinguish between active and passive systems, which correspond to the machine where the active conversion of energy occurs (e.g., internal combustion engine, where fuel is converted into mechanical work) and the structure where energy is delivered past its conversion to provide the service (e.g, a car, where mechanical work is converted into the service of passenger transport), respectively (Cullen and Allwood, 2010). Using this framework, energy efficiency can be divided into three components: the efficiency of extracting and converting natural resources into fuels delivered to end users, the efficiency of converting fuel into mechanical energy, and the efficiency of converting mechanical energy into transport services.

Studies applying decomposition methods to the transport sector have primarily focused on individual countries or regions, rather than on a global scale (Scholl et al., 1996; Kwon, 2005; Lu et al., 2007; Timilsina and Shrestha, 2009; Wang et al., 2011; Wu and Xu, 2014; Lu et al., 2017; Huang et al., 2019; Tsemekidi Tzeiranaki et al., 2023; Zhao et al., 2025; Li et al., 2019b) or focused on specific transport modes (Kwon, 2005; Zhao et al., 2025) or examined only passenger or freight services in isolation (Scholl et al., 1996; Lu et al., 2017). While such region or mode specific analyses are useful for assessing the effects of targeted policies, they often overlook the broader dynamics of global CO_2 emissions. In contrast, world-scale studies are essential to capture the aggregate risks and opportunities involved in emission reduction. Furthermore, country-level analyses miss the impacts of international circulation of goods and people, as emissions from international bunker fuels are excluded from national energy balances. In addition, due to historical data limitations, previous studies have generally been restricted to short time intervals (Tsemekidi Tzeiranaki et al., 2023; Wu and Xu, 2014; Scholl et al., 1996; Lu et al., 2007; Kwon, 2005; Huang et al., 2019), reducing their ability to identify structural changes associated with long-term economic growth, historical energy transitions, or the emergence of new transport modes, such as the introduction of air travel in the 1940s, all of which require a long-run perspective to fully understand.

In summary, studies that have applied decomposition methods for analyzing CO_2 emissions and energy use in the transport sector have often been constrained by limited temporal or geographic scope, narrow modal coverage, and simplified treatment of energy conversion processes. Few integrate passenger and freight services, account for the full chain from final to useful energy, or take a global and long-term perspective. This study provides a comprehensive, mode-inclusive, and global decomposition of transport emissions over an extended historical period, capturing technological and demand-side dynamics in detail.

3. Methods and data

The present section is divided into two parts. Section 3.1 describes the LMDI decomposition method and the decomposition factors used. Section 3.2 presents the data sources used to estimate world CO_2 emissions from transport and the respective decomposition factors.

3.1. LMDI decomposition

In decomposition analysis, an aggregate indicator is divided into several subcategories, which are determined by the product of different factors. The objective of the decomposition is to determine the influence of each factor on the total variation of the aggregate indicator (Ang, 2004).

In the present work, the aggregate indicator is the CO_2 emissions from the transport sector (V), which are divided into the sum of the CO_2 emissions from each transport mode (V_i), described by

$$\begin{aligned} V &= \sum_{i=1}^{m} V_i \\ &= \sum_{i=1}^{m} x_{1,i} \times x_{2,i} \ldots \times x_{7,i} \\ &= \sum_{i=1}^{m} \frac{1}{\eta_{fui}} \times \frac{m_{CO2i}}{Ef_i} \times \frac{Eu_i}{serv_i} \times \frac{serv_i}{serv} \times \frac{serv}{GDP} \times \frac{GDP}{pop} \times pop \\ &= \sum_{i=1}^{m} C_{fu\,i} \times CF_i \times UEI_i \times Cm_i \times SI \times GDPpc \times pop, \end{aligned} \tag{1}$$

where i denotes a transport mode, $x_{j,i}$ is a quantifiable variable, η_{fu} is the transport final-to-useful efficiency, Ef is the transport final energy use, Eu is the transport useful energy use, $serv$ is the transport energy service (passenger-km or ton-km), GDP is the world gross domestic product, and pop is the world population. The ratios presented in Eq. (1) are defined as the decomposition factors, described in Table 1.

The factors selected for the decomposition analysis are grouped into two main categories: technology-side and demand-side drivers. On the technology side, the key factors are the inverse of final-to-useful efficiency ($C_{fu\,i}$), the carbon emission factor (CF), and useful energy intensity (UEI), as all are related to the conversion of energy into transport services. The inverse of final-to-useful efficiency

Table 1
Factors used in the decomposition analysis, their mathematical expression, and a brief description.

Factors	Formula	Description
$C_{fu\,i}$	$C_{fu\,i} = \frac{1}{\eta_{fu\,i}}$	Inverse of final-to-useful efficiency, aggregated by transport mode. Accounts for changes in the conversion of final energy (e.g., chemical energy of the fuel) into mechanical work (useful energy).
CF_i	$CF_i = \frac{m_{CO2i}}{Ef_i}$	The carbon emission factor is the mass of CO_2 emitted per unit of energy content in the final energy carrier. For fossil fuels, it is dependent on their chemical composition, while for electricity it varies with the energy mix and the efficiency of electricity production.
UEI_i	$UEI_i = \frac{Eu_i}{serv_i}$	Useful energy per unit of transport service (useful energy intensity). This factor is influenced by factors past the conversion devices, such as occupancy, aerodynamics, and speed.
Cm_i	$Cm_i = \frac{serv_i}{serv}$	Fraction of the energy service per transport mode regarding the transport energy service.
SI	$SI = \frac{serv}{GDP}$	Transport service demand per unit of GDP (service intensity).
$GDPpc$	$GDPpc = \frac{GDP}{pop}$	GDP per capita.
pop	-	Population.

is defined as $C_{fu\,i} = \frac{1}{\eta_{fu\,i}}$, where $\eta_{fu\,i}$ represents the efficiency with which final energy (e.g., fuel or electricity) is converted into useful energy, such as mechanical work. This efficiency is evaluated by transport mode. For example, in road transport, it reflects the ratio of total mechanical work delivered by vehicles (cars, buses, trucks, etc.) to the total final energy consumed (e.g., diesel, gasoline, ethanol). It captures the thermodynamic efficiency of the active conversion system, typically, the internal combustion engine. Useful energy intensity (UEI) is defined as the amount of useful energy required per unit of transport service (e.g., per passenger-kilometer or ton-kilometer). It reflects how efficiently useful energy is translated into transport service by the passive system, meaning all vehicle components other than the active conversion system which includes the chassis, body, wheels, and drivetrain, and is influenced by factors like aerodynamics, vehicle occupancy, rolling resistance, and average speed. By separating the technology-related drivers in this way, the analysis can distinguish whether emissions reductions result from: (1) improved conversion of final to useful energy ($C_{fu\,i}$), (2) changes in the carbon intensity of energy carriers (CF), or (3) improved utilization of useful energy by the passive system (UEI).

On the other hand, demand-side factors are directly related to economic activity and population growth. The demand-side factors are the fraction of energy service by transport mode (Cm_i), the service intensity (SI), GDP per capita ($GDPpc$), and population (pop). By choosing these factors, the effects of the increase in GDP per capita and population are separated from transport demand, enriching the analysis.

We divided the 1850–2020 timespan into six periods to characterize distinct patterns of economic growth and globalization levels, with important implications for world transport systems. We have followed Maddison economic phases of Western capitalist development until 1973 (Maddison, 2007), but divided them into shorter periods afterwards to capture the integration of emergent economies in world trade and the end of the Great Divergence. The 1850–1913 period is characterized by the emergence of industrialized transport systems, with the widespread expansion of railways and the steamship. This period captures the growth of the transport infrastructure during the first wave of globalization, which was marked by increasing trade liberalization, international division of labour and mass migration from the Old to the New world and was interrupted by the First World War. The 1913–1950 covers the period of global economic turbulence, disruption of global trade and rise in protectionism caused by the two world wars and the Great Depression. Except for the rise of automobile transport in this period (particularly in the US), these crises delayed the transport system development in the world. We chose to end in 1950, as many of the countries had then recovered from World War II. The 1950–1973 is the golden age period, characterized by cheap oil as an engine of economic growth, substantial increases in both GDP and energy per capita in the West and a Second Wave of Globalization following the Bretton Woods (1944) and GATT (1947) negotiations which were accompanied by the rapid expansion of road transport and shipping, which lasted until the 1973 oil shock. The 1973–1990 period is characterized by the oil shocks (1973, 1979) and its impact on world economy, the emergence of energy efficiency concerns and early environmental awareness and ends with the collapse of the Soviet Bloc. The year 1990 is also the baseline for greenhouse gas emission reduction targets under the Kyoto Protocol. The 1990–2008 period captures the effects of a third wave globalization that entered in full force in the 1990s with increasing integration of China and emerging economies in world trade and modern economic growth, which contributed to a steep increase in transport demand, particularly freight. The last period 2008–2019 reflects the aftermath of the global financial crisis, where there has been a plateau in world trade openness, and a growing influence of climate policy and electrification trends on the transport sector.

We applied the LMDI decomposition in both multiplicative and additive formulations (Ang, 2005). The multiplicative formulation was used to study the relative change of the decomposition factors during the epochs of growth to facilitate comparison between two distinct epochs. Furthermore, the additive formulation was used to determine the cumulative yearly change to assess the contribution of each decomposition factor over time.

In multiplicative decomposition, the ratio of total CO_2 emissions is decomposed between years 0 and T and given by

$$\begin{aligned}\frac{V^T}{V^0} = D_{tot} &= \prod_{j=1}^{7} D_j \\ &= D_{fu} \times D_{cf} \times D_{uei} \times D_{Cm} \times D_{si} \times D_{GDPpc} \times D_{pop},\end{aligned} \tag{2}$$

where D_j corresponds to the contribution of the decomposition factor j (listed in Table 1) to the relative change in CO_2 emissions. Each D_j can be calculated by

$$D_j = exp\left(\sum_i \frac{(V_i^T - V_i^0)/(ln\, V_i^T - ln\, V_i^0)}{(V^T - V^0)/(ln\, V^T - ln\, V^0)} \times ln\left(\frac{x_{j,i}^T}{x_{j,i}^0} \right) \right). \tag{3}$$

Eq. (3) is applied for the following epochs of growth: first globalization (1850–1913), deglobalization (1913–1950), second globalization (1950–1973), oil crisis (1973–1990), third globalization (1990–2008), post–global financial crisis (2008–2020). The epochs of growth present different lengths of time (ΔT), therefore, each D_j is transformed to annual growth rates (G_j) so that they are comparable. The conversion from D_j to G_j is given by

$$G_j = \frac{ln(D_j)}{\Delta T}. \tag{4}$$

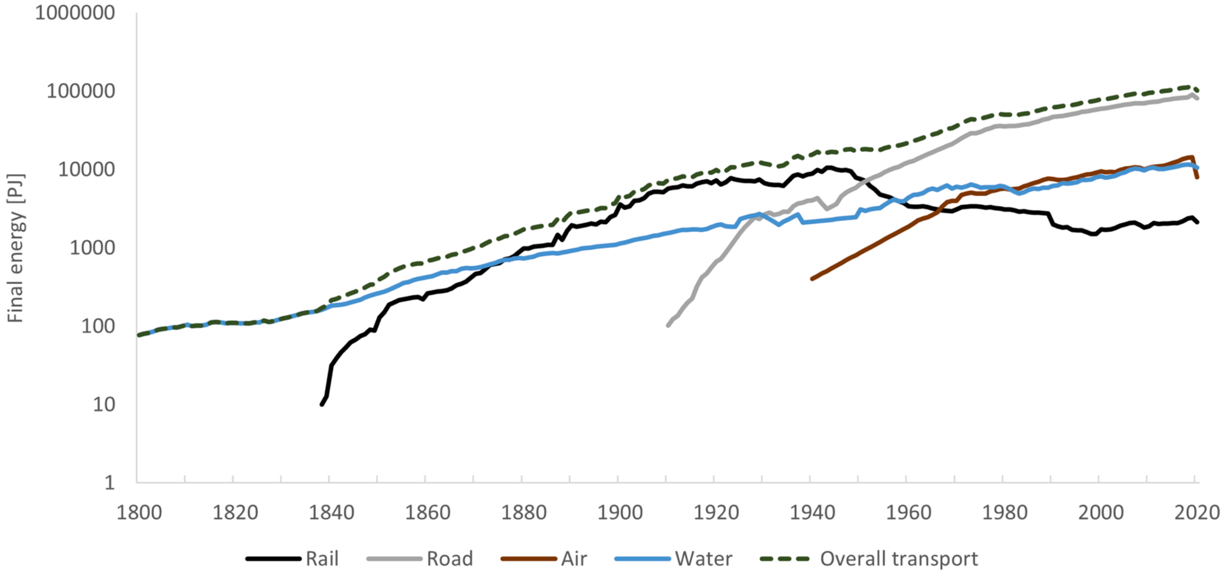

Fig. 1. World final energy use per transport mode: 1850–2020 (Tostes et al., 2024b).

The additive decomposition is formulated by

$$\begin{aligned} V^T - V^0 &= \Delta V_{tot} \\ &= \sum_{j=1}^{7} \Delta V_j \\ &= \Delta V_{fu} + \Delta V_{cf} + \Delta V_{uei} + \Delta V_{Cm} + \Delta V_{si} \\ &+ \Delta V_{GDPpc} + \Delta V_{pop}, \end{aligned} \tag{5}$$

where ΔV_j corresponds to the contribution of each factor j (listed in Table 1) to the relative change in the emissions of CO_2. Each ΔV_j is calculated by

$$\Delta V_j = \sum_i \frac{V_i^T - V_i^0}{ln\,V^T - ln\,V^0} \times ln\left(\frac{x_{j,i}^T}{x_{j,i}^0}\right). \tag{6}$$

Then, the cumulative change of CO_2 emissions per driving factor (Cc_j) is obtained as

$$Cc_j^{T+1} = Cc_j^T + \Delta V_j^T. \tag{7}$$

3.2. Data

3.2.1. Long-run energy use and CO_2 emissions

Applying decomposition methods requires extensive and detailed datasets. To support this analysis, a comprehensive long-run global dataset of final and useful energy use by transport mode was developed (Tostes et al., 2024b). As shown in Fig. 1, this dataset captures the evolution of final energy consumption across different transport modes. Using these energy data, CO_2 emissions were then estimated by multiplying the final energy values by the corresponding carbon emission factors, as presented in Fig. 2.

For fossil fuels, the IPCC (IPCC, 2006) provides carbon emission factors which were assumed to be constant through time. For other petroleum products (OPP), we considered the emission factor of liquefied petroleum gases, which is the most abundant among OPP. Indirect emissions from electricity were accounted for using the time series of carbon emission factors (Pinto et al., 2023). Biofuels were assumed to have an emission factor of zero, under the assumption that the carbon emitted in their combustion is captured by growing biomass (life cycle emissions are beyond the scope of this work). The carbon emission factor used for each fuel is shown in Fig. 2. The carbon emission factor for each transport mode (CF_i) was calculated by summing the emissions from all energy carriers, obtained by multiplying the final energy use by their respective carbon emission factors, and then dividing by the total final energy use of that mode.

3.2.2. Energy service and intensities

Passenger and freight energy services of rail transport were obtained for the whole period (1850–2020) of study from the literature (Tostes et al., 2024a). For the remaining transport modes, energy service was estimated separately for two periods: 1850–1990 and

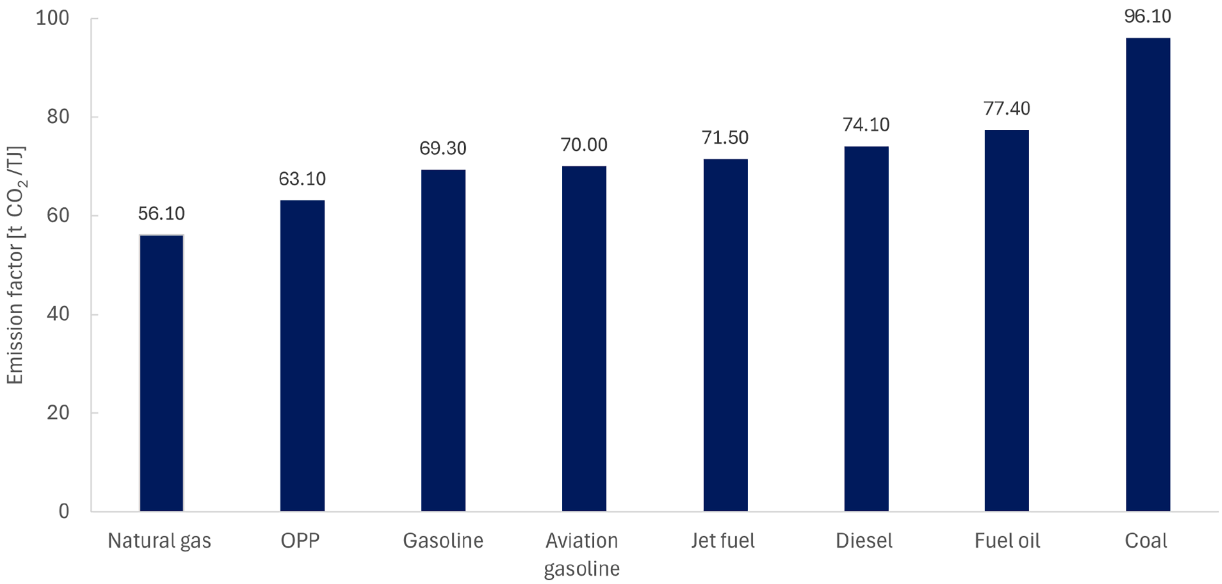

Fig. 2. Carbon emission factors in tonnes of CO_2 per TJ from the different energy carriers listed by the IPCC (IPCC, 2006).

1990–2020. Regarding the first period, 1850–1990, we estimated freight and passenger energy service of water (sailing and motor), air, and road transport based on the passenger-km and ton-km per capita from the OECD (OECD, 2000).

For the period 1970–2020, we estimated the energy service differently for each transport mode. In road transport, the OECD database (OECD, 2017a,b) provides data of passenger-km and ton-km for several countries. These countries were aggregated in geographical regions (see Table A.1 in Appendix A), for which passenger-km and ton-km per capita were calculated. World passenger-kilometers and ton-kilometers were then calculated by multiplying each region's population by its estimated per capita service and summing the results across all regions.

For water transport, in the period 2000–2020 we summed data for energy service from coastal and inland navigation from the OECD (2023b,a) with the international navigation data from the UNCTAD (United Nations, 2022). Linear interpolation was applied for the period 1990–2000 due to the absence of a consistent and comparable dataset. While more advanced methods, such as transformer or ensemble-based approaches, can offer improved estimates, their effectiveness relies on large, high-quality datasets. Given the limited availability of historical data for this period, simpler methods like linear interpolation were considered more appropriate and robust. Since water transport has historically been used far more for freight than for passengers, it was assumed to be exclusively dedicated to freight in this analysis (OECD, 2000). Data on global air passenger energy service (i.e., passenger-kilometers traveled) for the period 1990–2020 were obtained from published data (Airlines for America, 2023). Corresponding data for global freight energy service (i.e., ton-kilometers traveled) over the same period were sourced from the World Bank (2024). Detailed passenger and freight energy service values are provided by Figs. B.1 and B.2 in Appendix B.

The final energy intensity was estimated using the same method for all the transport modes assessed in this work. Since the energy service is divided into passenger and freight, energy intensity should also be divided into these two end-uses. However, the final energy estimations for all transport modes are not separated by end-use. To solve this issue, we estimated the ratio between passenger and freight intensities, also known as turnover volume equivalent (V_e) (Tostes et al., 2024a; Liu and Lin, 2021). We collected several data points of final energy and carbon intensities (these are expected to be proportional modes) and calculated their ratio (see Table 2). Since water transport was considered to be used entirely for freight transport, there was no need to determine its V_e.

We estimated $V_e = 0.6$ and $V_e = 0.1$ for road and air transport, respectively. Passenger (EI_p) and freight (EI_f) energy intensities were calculated for each year (t) using the equations proposed by Tostes et al. (2024a):

$$EI_f(t) = \frac{Ef(t)}{pkm(t) \times V_e + tkm(t)}, \tag{8}$$

$$EI_p(t) = \frac{EI_f(t)}{V_e}. \tag{9}$$

The passenger and freight final energy intensities are available in Figs. B.3 and B.4 in Appendix B. Useful energy intensity (UEI_i) was determined by multiplying final energy intensity by the respective final-to-useful efficiency.

3.2.3. GDP and population

Maddison Project Database 2023 (Bolt et al., 2023) provides world GDP data at constant 2017 international dollars every 20 years between 1850–1940, every 10 years between 1940–1990, and yearly after 1990. Missing values from the period 1850–1990 were determined by linear interpolation. Population data were directly taken from Our World in Data (Mathieu and Rodés-Guirao, 2022).

Table 2
Final energy or carbon intensities from previous studies and their respective ratio (V_e).

Mode	Passenger	Freight	Ratio (V_e)	Source
Road	2.6 MJ/pkm	2.6 MJ/tkm	1.00	(Gilbert and Perl, 2010)
Air[a]	2.0 MJ/pkm	23.0 MJ/tkm	0.09	(Gilbert and Perl, 2010)
Air[b]	2.3 MJ/pkm	9.9 MJ/tkm	0.23	(Gilbert and Perl, 2010)
Road	1.8 MJ/pkm	3.0 MJ/tkm	0.60	(European Environment Agency, 2020)
Air	1.8 MJ/pkm	43.7 MJ/tkm	0.04	(Gragg, 2023)
Road	1.8 MJ/pkm	2.9 MJ/tkm	0.63	(Gragg, 2023)
Road	1.7 MJ/pkm	1.2 MJ/tkm	1.42	(Borysov et al., 2019)
Road	25.0 gCO_2/pkm	35.0 gCO_2/tkm	0.71	(Mendiluce and Schipper, 2011)
Road	2.0 MJ/pkm	5.0 MJ/tkm	0.4	(Kiang and Schipper, 1996)

[a] Domestic
[b] International

4. Results

The present section is divided into three parts. Section 4.1 explores the evolution of world transport CO_2 emissions. Section 4.2 answers the first research question while analyzing the historical evolution of the decomposition factors. Section 4.3 answers the second research question based on the LMDI decomposition results. The dataset with the results from this paper is available on Zenodo (Tostes et al., 2025).

4.1. CO_2 emissions

Fig. 3 shows the CO_2 emissions per transport mode. Water, road, and air transport present an increasing trend from 1850–2020. There were a few exceptions, such as in 2020 when emissions decreased due to the COVID-19 pandemic. Emissions from rail transport present a different trend, as emissions peaked in the 1940s. After that, rail transport saw a decrease in emissions until the 1990s, when emissions resumed rising (Tostes et al., 2024a). Overall transport emissions increased by 550-fold from 1850–2019.

4.2. Factors influencing CO_2 emissions

Fig. 4 shows the evolution of the final-to-useful efficiency per transport mode (Tostes et al., 2024b). According to this study, rail transport has experienced the greatest improvement in final-to-useful efficiency, primarily driven by the transition from steam trains to diesel and electric alternatives. From 1850 to 1910, water transport saw a decline in final-to-useful efficiency as sailing ships were being replaced with steamships. After the 1910s, the final-to-useful efficiency has generally increased across all transport modes,

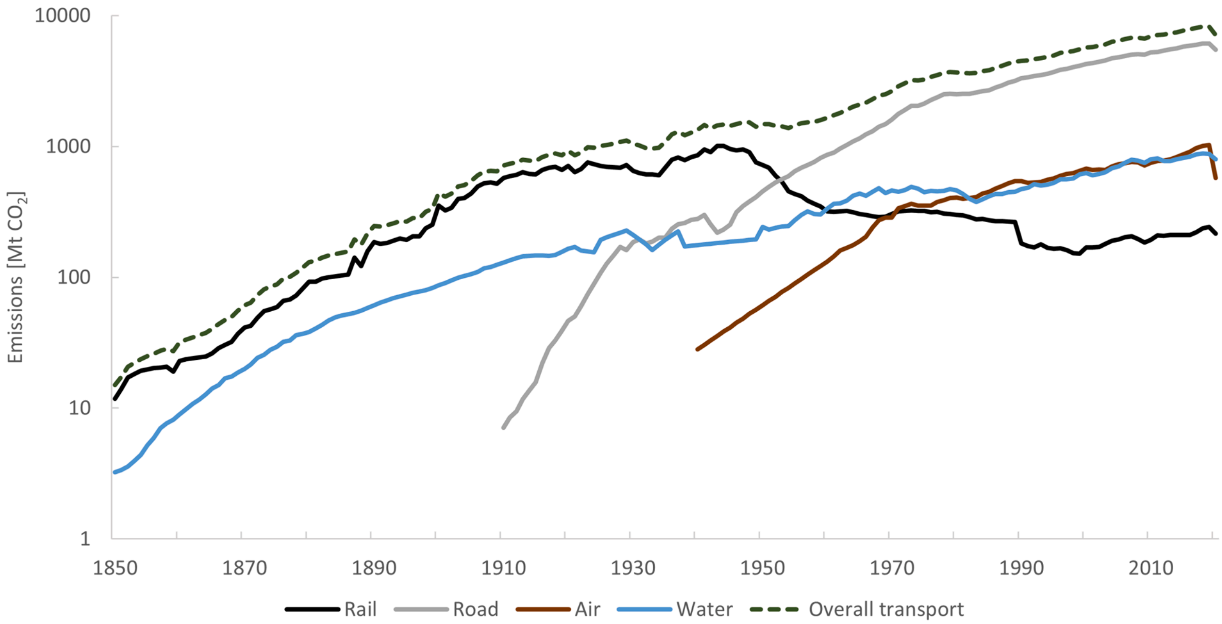

Fig. 3. World CO_2 emissions per transport mode: 1850–2020.

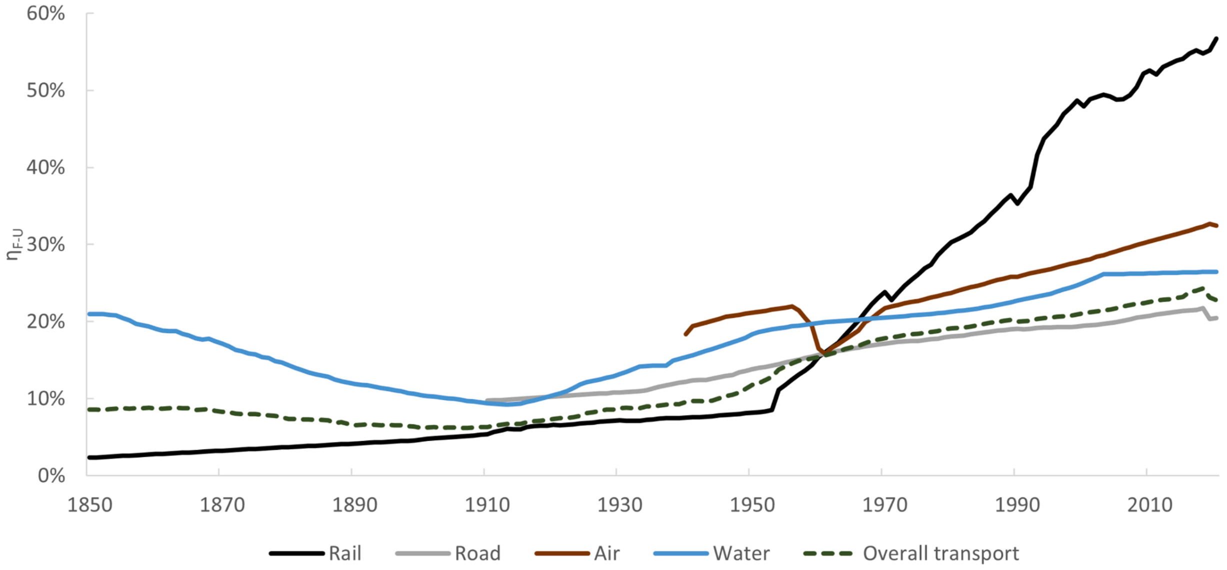

Fig. 4. World final-to-useful efficiency (η_{fu}) per transport mode: 1850–2020. Retrieved from Tostes et al. (2024b).

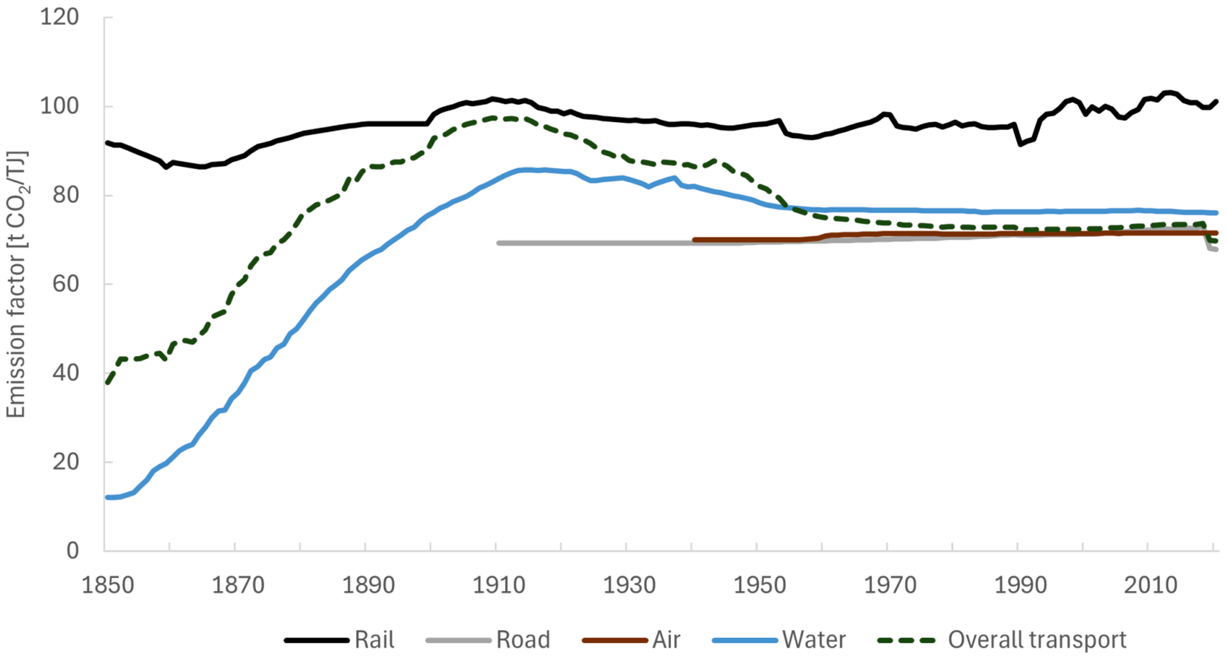

Fig. 5. World carbon emission factor (CF) per transport mode: 1850–2020.

apart from the shift from piston engines to jet engines in air transport in the 1960s. Overall, the final-to-useful efficiency of transport increased by 2.7-fold from 1850–2019. At present, the final-to-useful efficiency of rail transport is the highest among all modes, at approximately 50 % followed by air transport at around 30 %, water transport slightly above 20 %, and road transport below 20 %.

Fig. 5 shows the carbon emission factor by transport mode. Air and road transport present reasonably constant emission factors since both transport modes have been almost exclusively dependent on oil products. As sailing ships do not release CO_2 in their usage, their substitution led to a sharp increase in the emission factor of water transport. Currently, rail transport has the highest carbon emission factor, at approximately 100 t CO_2 per TJ, whereas the emission factors for all other transport modes are around 70 t CO_2 per TJ.

Figs. 6 and 7 show the useful energy intensity per transport mode for freight and passenger transport, respectively. Energy use in water transport was assumed to be entirely allocated to freight since water transport has been mainly used for international trade of goods (OECD, 2000). For both transport purposes, useful energy intensity presents an overall declining trend, with a few exceptions

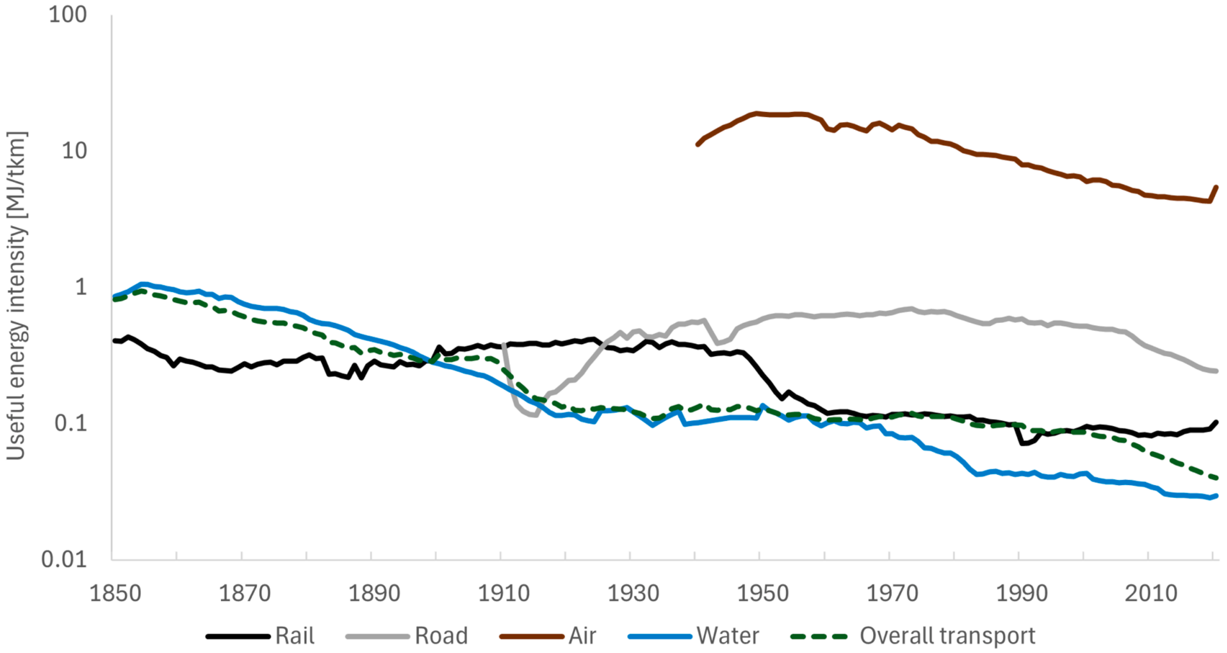

Fig. 6. World useful energy intensity (UEI) per freight transport mode (log-scale): 1850–2020.

which are mainly related to periods when speed and power were privileged over fuel savings. At the end of the 19th century and beginning of the 20th century, rail transport presented an increase in useful energy intensity due to the increase in speed (Tostes et al., 2024a). Road transport also presented an increasing trend in its development, as the power of engines was increasing and strict speed regulations were only implemented in the 1970s (Splitter et al., 2016).

The overall decline in useful energy intensity observed in Figs. 6 and 7 is a positive result regarding emissions savings, as apart from the increase in final-to-useful efficiency, the transport sector has become more efficient in converting useful energy into energy service. Among freight modes, water transport currently exhibits the lowest useful energy intensity at 0.03 MJ/tkm, followed by rail at 0.10 MJ/tkm, road at 0.24 MJ/tkm, and air which is by far the least efficient at 5.44 MJ/tkm. For passenger transport, rail again performs best at 0.10 MJ/pkm, followed by road at 0.15 MJ/pkm and air at 0.54 MJ/pkm.

Figs. 8 and 9 show the fraction of freight and passenger service per transport mode. For freight, water transport has been the most important transport mode, followed by rail. Even though air transport has been increasing over the last decades, its relative importance to freight transport is still very low. Regarding passenger transport, rail was the most relevant mode until the 1910s, when road transport started to grow its share. In 2020, road transport represented 93 % of passenger energy service. Unlike in freight transport, air transport constitutes a significant share of passenger energy service, ranging from 12 to 10 % in the period 2000–2020.

Fig. 10 shows the evolution of freight and passenger energy service per unit of GDP, with freight service intensity increasing approximately 30-fold, from 0.037 to 1 tkm per 2017 international dollar, and passenger service intensity rising 320-fold, from 0.002 to 0.629 pkm per 2017 international dollar, between 1850 and 2019. This sharp growth indicates that transport services have expanded significantly faster than economic output, pointing to diminishing returns, where additional transport activity yields progressively smaller gains in GDP.

As shown in Fig. 11, GDP per capita grew roughly 11-fold during the same period. When combined with the increase in service intensity, this implies that per capita passenger transport service increased about 3000-fold (from approximately 3 to 10,146 tkm/capita/year), while per capita freight transport service rose approximately 225-fold (from around 54 to 12,326 pkm/capita/year). Furthermore, the global population increased sixfold, amplifying the total demand for transport services even further.

4.3. LMDI: upward and downward drivers of CO_2 emissions

Fig. 12 shows the results for the multiplicative LMDI divided into the epochs of growth (decomposition results in table format are available in Appendix A). In these radar plots, each factor G_j represents the annual growth rates of CO_2 emissions that would occur if only factor j varied while the others remained constant. If $G_j > 0$, factor j is a upward driver of emissions, while if $G_j < 0$, factor j is a downward driver of emissions. In addition, the first three factors (clockwise) are the technology-side factors and the remaining four are the demand-side factors. Under each graph is the value of the actual annual growth rate of transport CO_2 emissions (G_{tot}).

During the first globalization period, 1850–1913, $G_{tot} = 6.49\,\%/\text{yr}$, its highest value among all epochs. The first globalization is marked by the abundant use of coal products replacing traditional renewable energy sources (e.g., from wind to coal power in water transport and from wood to coal in rail transport). This shift resulted in the carbon emission factor contributing to the rise in CO_2

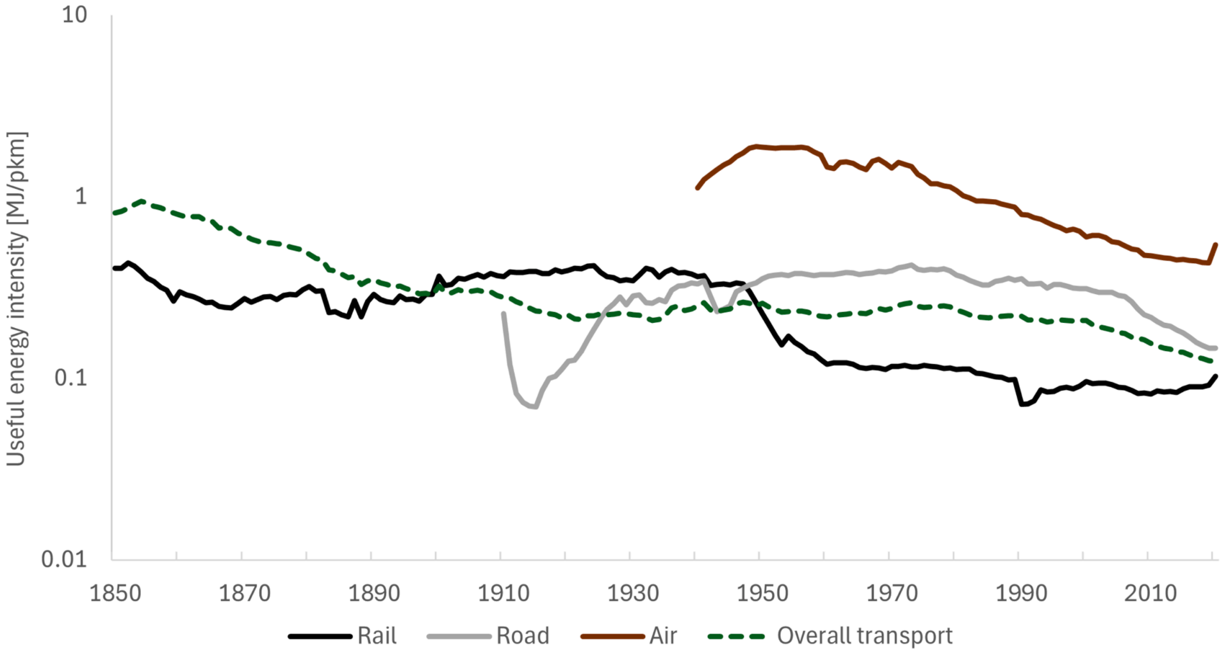

Fig. 7. World useful energy intensity (UEI) per passenger transport mode (log-scale): 1850–2020.

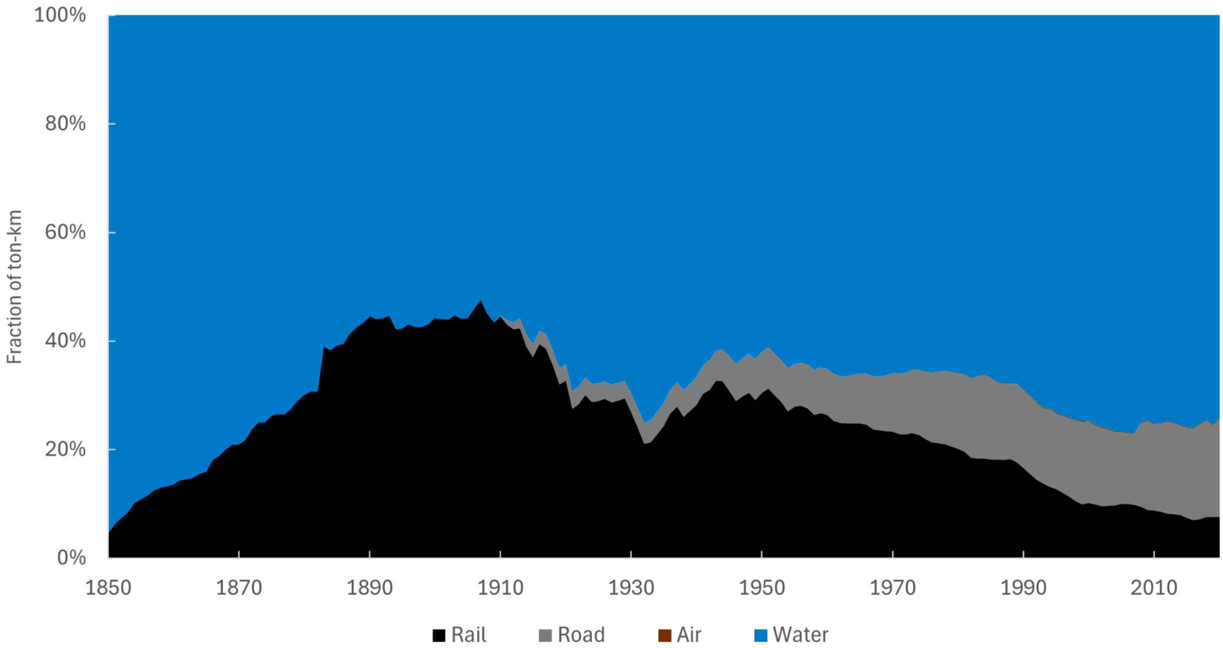

Fig. 8. Fraction of freight energy service (Cm) by transport mode: 1850–2020.

emissions ($G_{cf} = 0.73\,\%/\text{yr}$). During this period, the increase in service intensity was the main upward driver of emissions, followed by the choice of transport mode, GDP per capita, and population. The final-to-useful efficiency and the useful energy intensity were the two factors that contributed to avoiding emissions, as the efficiency of steam technology progressed in addition to transport optimizations (e.g., smoother tracks, schedule optimization).

In 1914, the Great War began, marking the end of the first globalization period. The following deglobalization period would last until around 1950. During this epoch, motorized road transport also started to develop. Surprisingly, the introduction of road transport contributed to avoiding emissions ($G_{mode} = -0.41\,\%/\text{yr}$), since steam trains were the previous main transport mode, which emitted large amounts of CO_2 per unit of service (Tostes et al., 2024a). In terms of emission factor, gasoline, the most dominant fuel

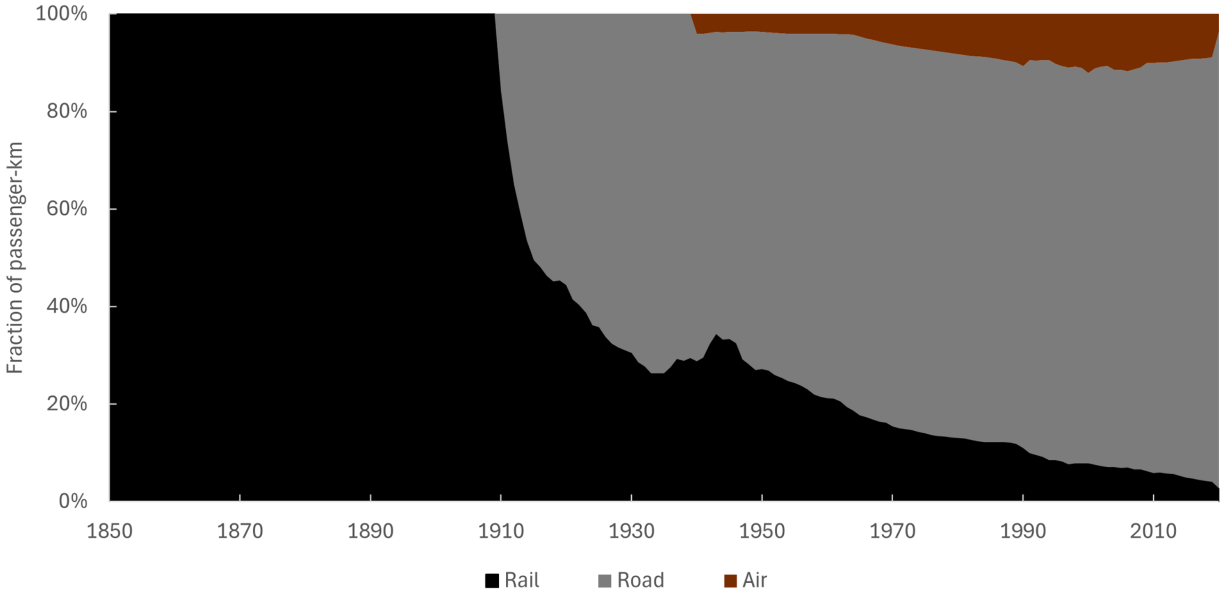

Fig. 9. Fraction of passenger energy service (Cm) by transport mode: 1850–2020.

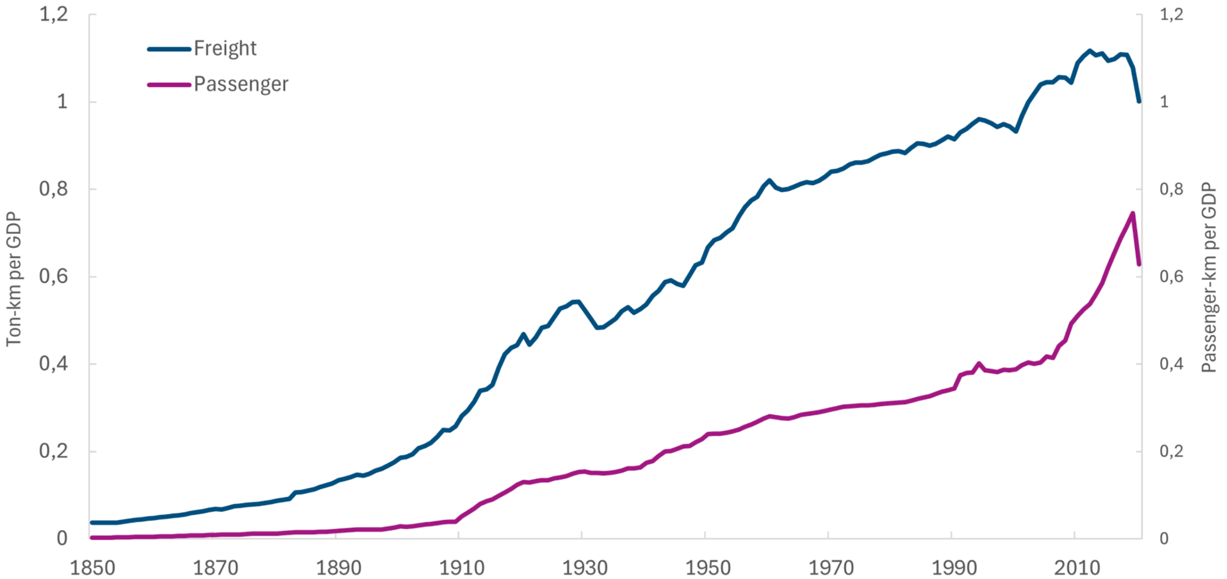

Fig. 10. World energy service intensity (SI) of freight and passenger transport: 1850–2020.

in road transport at the time, emits 69.3 t CO_2 per TJ, while coal emits 96.1 t CO_2 per TJ (IPCC, 2006). For this reason, introducing gasoline-fueled vehicles slightly contributed to avoiding emissions ($G_{cf} = -0.1\,\%/\mathrm{yr}$). On the demand side, out of the four factors, only the growth rate of population increased when compared to the first globalization period. All these factors combined led to $G_{tot} = 1.71\,\%/\mathrm{yr}$, the lowest among all epochs.

Between 1950 and 1973, the second globalization period followed by World War II resulted in extremely high CO_2 emission growth rates ($3.45\,\%/\mathrm{yr}$), approximately two times the rates observed during the deglobalization period. This epoch is marked by the intensive use of oil products, almost fully replacing coal in the transport sector. On the demand side, all four factors contributed to the rise in emissions. GDP per capita and population were the most relevant drivers at the time ($G_{GDP\ pc} = 2.57\,\%/\mathrm{yr}$, $G_{pop} = 1.83\,\%/\mathrm{yr}$), as a consequence of the rapid economic growth before the oil shocks and the baby boom phenomena after the war. The final-to-useful efficiency was the main downward driver of emissions, mainly due to the substitution of steam trains for diesel and electric ones, the increasing share of diesel usage in road vehicles (diesel engines present a higher efficiency), and the rise in the efficiency of existing technologies such as motor ships and gasoline-vehicles ($G_{fu} = -1.62\,\%/\mathrm{yr}$). As oil products were the main energy carriers across all transport modes, the emission factor's contribution to transport emissions was almost null ($G_{cf} = 0.01\,\%/\mathrm{yr}$).

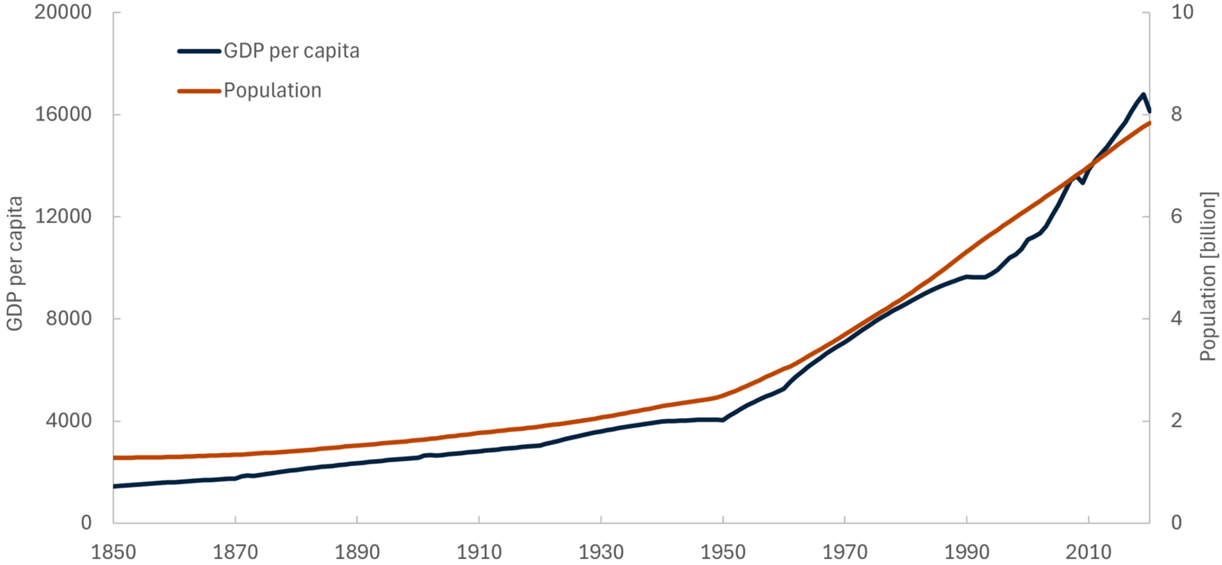

Fig. 11. World GDP per capita ($GDPpc$) and population (pop): 1850–2020 (Bolt et al., 2023; Mathieu and Rodés-Guirao, 2022).

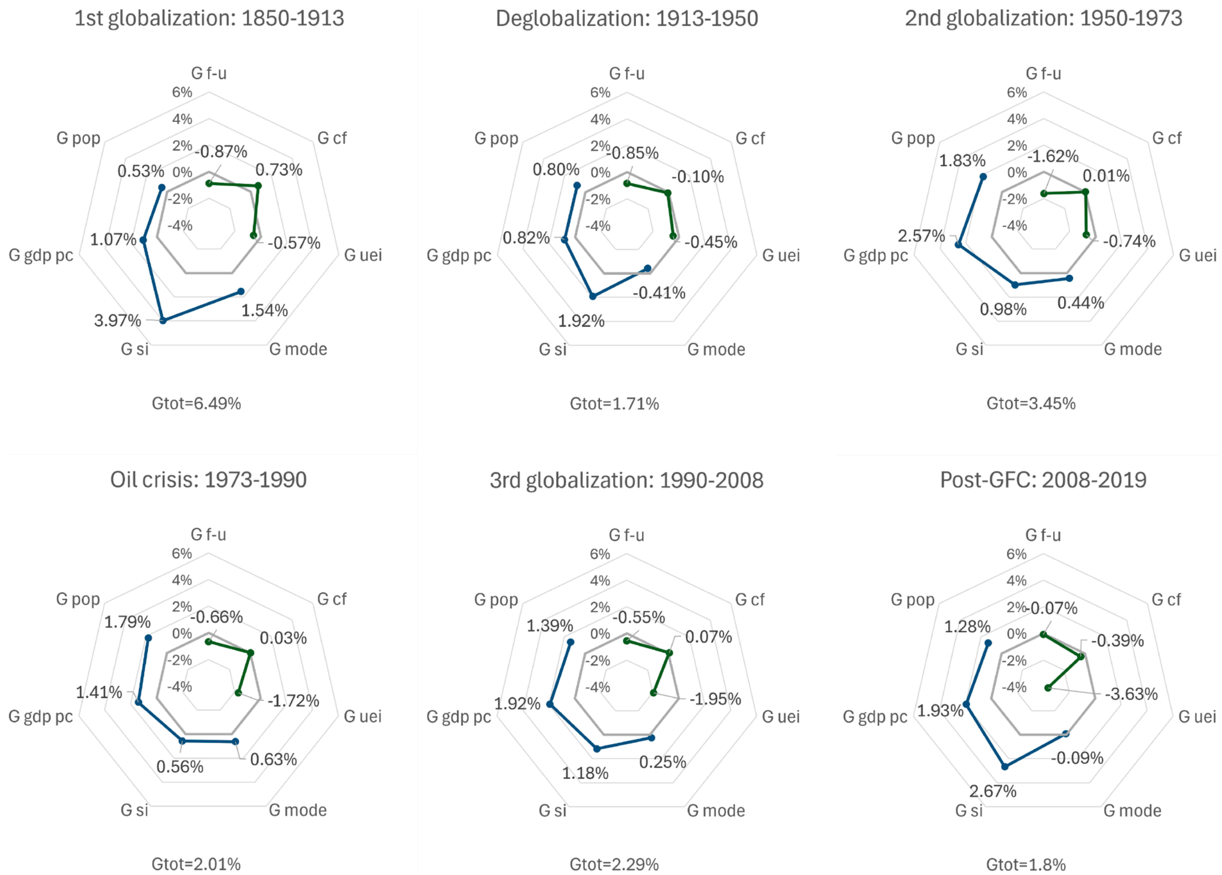

Fig. 12. Multiplicative LMDI decomposition results in annual growth rates for the epochs of growth. The green and blue dots represent the technology and demand-side factors, respectively. GFC: Global Financial Crisis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

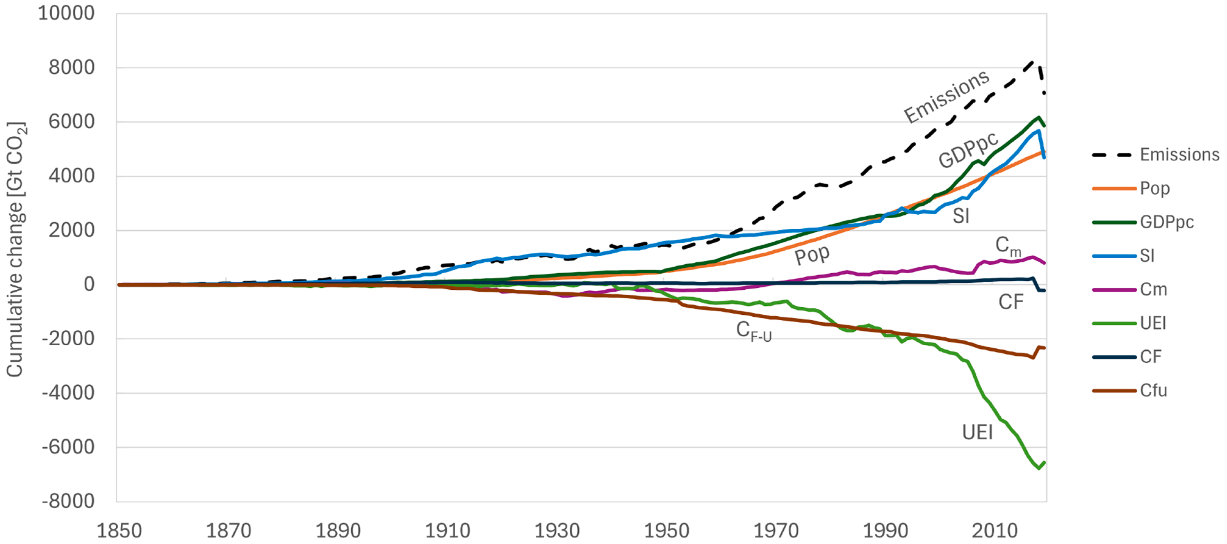

Fig. 13. Cumulative change in CO_2 emissions from world transport by driving factor.

Despite the oil shocks in the 1970s, transport emissions presented an average growth rate of 2.01 % during the period 1973–1990. Service intensity had its lowest growth rate ($G_{si} = 0.56\,\%/\text{yr}$), which resulted in population and GDP per capita being the main upward drivers of emissions. As air transport became more popular, the choice of transport mode contributed to increased emissions ($G_{mode} = 0.63\,\%/\text{yr}$). On the technology side, G_{cf} remained very close to 0 (almost no influence on emissions), while final-to-useful efficiency and useful energy intensity kept contributing to avoiding emissions ($G_{fu} = -0.66\,\%/\text{yr}$, $G_{uei} = -1.72\,\%/\text{yr}$). These improvements are likely related to the rising environmental concerns regarding transport, which led to the increase in the share of diesel-fueled vehicles (work at higher efficiencies), the ban of tetraethyllead from gasoline, improvements in spark and air-to-fuel ratio control, and the implementation of speed regulations in the USA (Splitter et al., 2016).

The following period 1990–2008 is marked by the beginning of the third globalization until the global financial crisis. G_{fu} increased to −0.55 %, which shows that final-to-useful efficiency started to increase at lower rates. In the subsequent period (2008–2019), G_{fu} increased further to -0.07 %. As there are theoretical limits to this factor, it is expected that gains in efficiency diminish in the future, unless there is a major shift in technology (e.g., electrification). On the other hand, useful energy intensity was the main downward emission driver ($G_{uei} = -1.95\,\%/\text{yr}$). This reduction in useful energy intensity is probably linked with several improvements, such as higher occupancy rates (e.g., more public transportation), downsize and downspeed of light-duty vehicles (Splitter et al., 2016), and optimization of the passive system. Demand-side factors kept driving emissions upward, led by GDP per capita, population growth, and service intensity.

Lastly, the period 2008–2019 encompasses the more recent years covered in this study after the global financial crisis. During these years, GDP per capita and population maintained similar growth rates compared to the previous period ($G_{GDP\ pc} = 1.93\,\%/\text{yr}$, $G_{pop} = 1.28\,\%/\text{yr}$). Service intensity was the main upward emission driver, reaching 2.67 % annual growth rate. This result highlights that up to the last decade, transport services increased at higher rates that GDP. On the technology side, useful energy intensity presented its lowest annual growth rate ($G_{uei} = -3.63\,\%/\text{yr}$). Even though final-to-useful efficiency has been contributing less to avoiding emissions, other energy utilization improvements beyond the conversion of fuel into mechanical work led to a decrease in useful energy intensity, which became an extremely important downward driver of emissions.

Fig. 13 shows the cumulative change per driving factor from 1850 to 2020. While in Fig. 12 the D_j coefficients express the impact of each factor at specific periods, Eq. (7) shows the cumulative importance of each factor. Curves below zero correspond to downward emission drivers, and curves above zero represent upward emission drivers. The dashed curve represents the actual emissions from the transport sector, which correspond to the sum of the remaining curves. The final-to-useful efficiency was the main downward driver of emissions until the 1990s, when the useful energy intensity surpassed it. In 2020, these two factors together avoided 8890 Gt CO_2.

The carbon emission factor (CF) is the least influential factor on CO_2 emissions. Despite significant transitions in energy carriers throughout history, these changes did not substantially impact emissions.

The choice of transport mode, Cm was a downward emission driver until the 1970s, after which it became a upward emission driver. This result indicates that, despite all the technological improvements across all transport modes, the preference for carbon-intensive transport modes has led to an increase in emissions.

The main upward drivers of emissions were service intensity (SI), GDP per capita ($GDPpc$), and population (pop), all of which experienced sharp growth from 1850 to today. If it was for these factors alone, emissions would have been 2.2 times higher in 2020. Service intensity (SI) was the main upward driver until the 1980s, after which GDP per capita ($GDPpc$) and population (pop) surpassed it.

Table 3
Multiplicative LMDI decomposition results in annual growth rates for the epochs of growth.

	G_{fu}	G_{cf}	G_{uei}	G_{mode}	G_{si}	$G_{GDP\ pc}$	G_{pop}	G_{tot}
1850–1913	−0.87 %	0.73 %	−0.57 %	1.54 %	3.97 %	1.07 %	0.53 %	6.49 %
1913–1950	−0.85 %	−0.10 %	−0.45 %	−0.41 %	1.92 %	0.82 %	0.80 %	1.71 %
1950–1973	−1.62 %	0.01 %	−0.74 %	0.44 %	0.98 %	2.57 %	1.83 %	3.45 %
1973–1990	−0.66 %	0.03 %	−1.72 %	0.63 %	0.56 %	1.41 %	1.79 %	2.01 %
1990–2008	−0.55 %	0.07 %	−1.95 %	0.25 %	1.18 %	1.92 %	1.39 %	2.29 %
2008–2019	−0.07 %	−0.39 %	−3.63 %	−0.09 %	2.67 %	1.93 %	1.28 %	1.80 %

Table 3 synthesizes the influence of each decomposition factor on transport CO_2 emissions across historical periods. The final-to-useful efficiency showed its greatest emissions reduction during 1950–1973 (−1.62 % per year), but its impact diminished significantly in 2008–2020 (−0.07 % per year). The carbon emission factor increased emissions most sharply in 1850–1913 (+ 0.73 % per year), when coal replaced traditional renewables, while the only significant decrease occurred during 2008–2019 (−0.39 % per year) due to a shift to gasoline. Useful energy intensity had its strongest emissions-reducing effect in 2008–2020 (−3.63 % per year), reflecting improvements in vehicle design and energy use, and the weakest in 1913–1950 (−0.45 % per year). The modal share factor contributed most to reducing emissions in 1913–1950 (−0.41 % per year) due to the increase in road share but increased them during 1973–1990 (+ 0.63 % per year) as air travel expanded. On the demand side, service intensity had the greatest upward pressure in 1850–1913 (+ 3.97 % per year) and the least in 1973–1990 (+ 0.56 % per year). GDP per capita contributed most to emissions growth during the economic boom of 1950–1973 (+ 2.57 % per year) and least in the interwar and WWII era (+ 0.82 % per year). Population growth had its highest impact between 1950–1973 (+ 1.83 % per year) and its lowest in 1850–1913 (+ 0.53 % per year).

5. Discussion

This section analyzes the evolution of CO_2 emissions in the transport sector and their driving factors, revealing important insights for future energy policies. Despite notable progress in improving both final-to-useful energy efficiency and useful energy intensity, these gains have not been sufficient to offset the growing demand for transport. Historical energy transitions in the transport sector have consistently resulted in increased final energy consumption, regardless of improvements in final-to-useful efficiency (Tostes et al., 2024b). However, since 1990, reductions in useful energy intensity have had a stronger mitigating effect on CO_2 emissions than in any previous period, contributing to a decline in average emissions of 3.6 %/year despite the overall growth in emissions. Unlike improvements in final-to-useful efficiency, which are limited by thermodynamic constraints and contributed most to an average emissions decline of 1.6 %/year between 1950 and 1973, reductions in useful energy intensity are not subject to such limits. They can be driven by behavioral shifts, such as increased use of shared mobility, offering a promising potential for further progress. For future policies to succeed in reducing CO2 emissions, either technological improvements should increase drastically to match the demand growth, or policies should start prioritizing demand-side factors, namely in reducing individual transport demand (Brand et al., 2020).

The increase in transport demand was driven by three main factors: service intensity, GDP per capita, and population. Service intensity had the greatest impact between 1850 and 1913, contributing to an average emissions increase of 4 %/year, and again between 2008 and 2019, contributing 2.7 %/year. In contrast, population growth and rising GDP per capita had the greatest impact between 1950 and 1973, contributing to emissions increases of 1.8 %/year and 2.6 %/year, respectively. These results reveal that while population growth partially contributes to the increased service demand, individual transport demand (the combined effect of GDP per capita and service intensity) is the primary upward driver of emissions. As the cost of transport declines and GDP per capita increases, transport becomes more affordable and people tend to increase their transport needs. However, over shorter time periods, in specific regions and for certain transport modes, transport intensity has been observed to decline (Zhu et al., 2020; Wang et al., 2011). Tackling individual transport demand, through for example behavioural shifts, is important for future transport policies.

The carbon emission factor is the most stable among the coefficients considered in the present study. It contributed to an average annual increase in emissions of 0.7 % between 1850 and 1913, and to an average annual decrease of 0.4 % between 2008 and 2019. The transport sector has been heavily dependent on fossil fuels leading to that stability. Even rail transport that was partially electrified presents a reasonably stable emission factor (Fig. 5). World electricity generation still relies on fossil fuels, therefore CO_2 emissions are not necessarily avoided, depending on the final-to-useful efficiency of electric and internal combustion motors. Tackling the carbon emission factor requires great investments, as a shift in energy resources and technologies is necessary. For hard-to-decarbonize segments such as aviation and shipping, this transition particularly relies on the development and large-scale deployment of low-carbon fuels like hydrogen and biofuels. While electrification is the dominant decarbonization pathway for road and rail transport, hydrogen becomes essential for international shipping, and advanced biofuels are critical for long-haul aviation (Speizer et al., 2024).

Another way to avoid emissions is to create incentives for less carbon-intensive transport modes. However, this has not been the case historically. Instead, this factor has generally contributed to increased emissions, resulting in an average annual rise of 1.5 % between 1850 and 1913. Although the choice of transport mode has occasionally helped reduce emissions, there have been few strong incentives to increase the share of environmentally friendly options. As a result, this factor continues to contribute to rising emissions, despite its potential to mitigate them. In contrast to reducing the carbon emission factor or improving final-to-useful efficiency, reducing CO_2 emissions by choosing more sustainable transport modes is not dependent on the development of new technology but rather on social and economic incentives for consumers to pursue other modes (Sporkmann et al., 2023).

Although urbanization and behavioral or cultural shifts are important drivers of transport-related CO_2 emissions, they were not explicitly analyzed in this study. Urbanization and increasing density can contribute to lower per capita and total CO_2 emissions over time (Li et al., 2019a, 2022). Likewise, behavioral changes, such as increased telecommuting, reduced air travel, and greater reliance on public and active transport, have demonstrated measurable impacts on transport emissions (Kraft-Todd et al., 2025). However, the influence of urbanization and behavioral or cultural shifts are indirectly reflected in analysed factors such as service intensity, useful energy intensity, and transport mode.

Based on the evolution of the decomposition factors analyzed in this study, we calculated the share of electricity required to offset the expected increase in transport demand in 2029 (see Appendix C). The projected GDP growth of 37.6 % from 2020 to 2029 (International Monetary Fund, 2024), combined with a 2 % annual increase in service intensity, would result in a 61 % rise in transport CO_2 emissions. To keep transport sector CO_2 emissions at 2020 levels, electricity would need to supply 64 % of the sector's final energy use by 2029 under Scenario A, where useful energy intensity remains unchanged. In Scenario B, where useful energy intensity continues to decline at 2 % annually, the required electricity share falls to 52 %. Assuming a 2029 electricity mix of 50 % renewables and 50 % natural gas (IEA, 2024), the sector's carbon intensity would drop from 69.7 t CO_2/TJ in 2020 to 62.4 t CO_2/TJ in Scenario B and 60.8 t CO_2/TJ in Scenario A. The primary challenge is not decarbonizing electricity, which already reached a 40 % share of renewables and nuclear in 2024 (IEA, 2024), but accelerating transport end-use electrification and using other low-carbon alternatives such as hydrogen and biofuels. Electricity made up only 1 % of the sector's final energy use in 2020 and just 1.3 % in 2024 (IEA, 2022), highlighting the significant effort required to avoid emissions growth. Additionally, even under the more favorable Scenario B, where useful energy intensity improves steadily, the transport sector would consume roughly 37 % of global electricity production by 2029, placing substantial pressure on renewable electricity generation (Enerdata, 2024).

The main limitation of our study, which is inherent to the fact that it is a global study, is that it does not differentiate between developing and developed regions, which present distinct challenges in terms of decarbonizing transport. In emerging or developing economies, rapid urbanization and motorization accompanied by increases in income can lead to congested and inefficient transport systems. Limited financing, lack of suitable power infrastructures and an over reliance in cost-competitive domestic fossil fuels in the power system due to national economy considerations can reduce the potential of transport decarbonization. On the other hand, emerging and developing economies can leapfrog conventional transport models, provided that sustainable policy and investments are supported. Notably, China has positioned itself as a global leader in the production and adoption of EVs by pursuing a heavily subsided state-led industrial policy (IEA, 2025).

Developed regions, such as the European Union or the US and Japan, have established patterns of private vehicle use, with car ownership rates higher than 500 cars per 1000 inhabitants (Abdul-Manan et al., 2022). They have the financial capacity to adopt decarbonization strategies such as fleet electrification, the expansion of active mobility infrastructure, and the enforcement of strict emissions regulations. However, they also deal with challenges. For example, many European countries have a strong policy framework and an increasingly decarbonized power system and climate-friendly urban and domestic policies which support the decarbonization of road transportation, but the growth of domestic and international aviation emissions as personal income rises constitutes a challenge (European Environment Agency EEA, 2024). In the US, there are still strong infrastructural, behavioural, and institutional lock-ins such as automobile-centered urban design, preference for driving large cars and an institutional framework which favours incumbent fossil fuel interests and poses significant barriers to low-carbon transitions (Seto et al., 2016). Thus, emerging and developing countries face the challenge of limited financial resources but also the opportunity to direct transportation infrastructure investments toward less CO2-intensive modes. While developed nations have (a) the challenge of overcoming entrenched interests and built-out transportation infrastructure and (b) the opportunity to use behavioural changes to support transitions.

6. Conclusion

This work explored the different factors associated with world transport CO_2 emissions during the period 1850–2020 by performing an LMDI decomposition, in both additive and multiplicative formulations, which enabled the identification of their upward and downward drivers. Moreover, transport efficiency was divided into final-to-useful efficiency and useful energy intensity, a novel distinction in transport decomposition studies that allows a deeper understanding of emissions driving factors. To perform the decomposition analysis, a novel dataset was developed comprehending CO_2 emissions, energy service, and intensities of world water, rail, road, and air transport. Our main results are:

- The final-to-useful efficiency and the useful energy intensity are the main downward emission drivers, combined have avoided 9067 Gt CO_2 in 2019. Gains in final-to-useful efficiency had its greatest impact between 1950–1973, reducing emissions by 1.62 % per year, while reductions in useful energy intensity contributed most during 2008–2020, with a decrease of 3.63 % per year.
- These downward drivers were not able to balance the increase in transport demand, resulting in cumulative transport emissions reaching 8252 Gt CO_2 in 2019;
- Transport demand has been driven mainly by GDP per capita, service intensity, and population, all of which currently contribute with similar shares and together accounted for 16 683 Gt of CO_2 emissions in 2019. Service intensity exerted the strongest upward pressure during 1850–1913 (+ 3.97 % per year), while GDP per capita and population growth contributed most during the postwar economic boom of 1950–1973, at + 2.57 % and + 1.83 % per year, respectively.

- To keep emissions at 2020 levels in 2029, with constant energy intensity, electricity must account for 64 % of the transport sector's energy mix. The necessary share drops to 52 % if useful energy intensity continues declining at 2 %/yr.

Our results provide useful inputs for scenario development and evaluation, as they show how the contribution of decomposition factors to CO_2 emission changes has evolved over time. However, future projections should avoid overreliance on historical trends, as these may reflect past technological and structural constraints that differ significantly from the changes required for deep decarbonization. If the contribution of decomposition factors to CO_2 emission changes in future scenarios diverges significantly from historical patterns, this may signal the need for strong policies, technological breakthroughs, or behavioral shifts. In this context, the long-term analysis of decomposition factors that are summarized in Table 3 offers valuable empirical insights that can help assess the plausibility of future emissions scenarios. These factors can serve as a critical tool for designing or evaluating pathways to decarbonization. Our results suggest that future policies should prioritize addressing demand-side factors, namely reducing the link between GDP and transport services. Additionally, since the carbon emission factor and the choice of transport mode have had the least influence on transport emissions historically, addressing them presents a valuable opportunity.

CRediT authorship contribution statement

Bernardo Tostes: Writing – original draft, Methodology, Formal analysis, Conceptualization; **Sofia T. Henriques:** Writing – review & editing, Conceptualization; **Matthew Kuperus Heun:** Writing – review & editing, Conceptualization; **Paul E. Brockway:** Writing – review & editing, Conceptualization; **Tânia Sousa:** Writing – review & editing, Supervision, Conceptualization.

Data availability

The results from this paper is available on Zenodo (Tostes et al., 2025).

Acknowledgments

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Appendix A. Auxiliary tables

Table A.1
Countries considered in each geographical region used to determine energy service by road transport.

Countries	Region
Angola, Burkina Faso, Botswana, Cameroon, Cabo Verde, Algeria, Egypt, Ethiopia, Ghana, Guinea, Kenya, Libya, Morocco, Madagascar, Mozambique, Namibia, Niger, Nigeria, Sudan, Somalia, South Sudan, Chad, Tunisia, Tanzania, Uganda, South Africa, Zambia, Zimbabwe	Africa
Albania, Andorra, Armenia, Austria, Belgium, Bulgaria, Bosnia and Herzegovina, Belarus, Switzerland, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Liechtenstein, Lithuania, Luxembourg, Latvia, Monaco, Moldova, North Macedonia, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Slovenia, Sweden, Ukraine	Europe
Argentina, Bolivia, Brazil, Barbados, Chile, Colombia, Dominica, Dominican Republic, Ecuador, Guyana, Jamaica, Mexico, Panama, Peru, Paraguay, Uruguay, Venezuela	Latin America
Canada, USA, Mexico	North America
Australia, New Zealand	Oceania
Bangladesh, China, Hong Kong, Indonesia, India, Japan, Cambodia, Korea, Rep., Sri Lanka, Myanmar, Mongolia, Malaysia, Nepal, Pakistan, Philippines, Singapore, Thailand, Vietnam	South and East Asia
Afghanistan, United Arab Emirates, Azerbaijan, Georgia, Iran, Islamic Rep., Iraq, Israel, Jordan, Kazakhstan, Lebanon, Oman, Qatar, Russian Federation, Saudi Arabia, Syrian Arab Republic, Tajikistan, Turkiye, Uzbekistan, Yemen, Rep.	West Asia

Appendix B. Auxiliary graphs

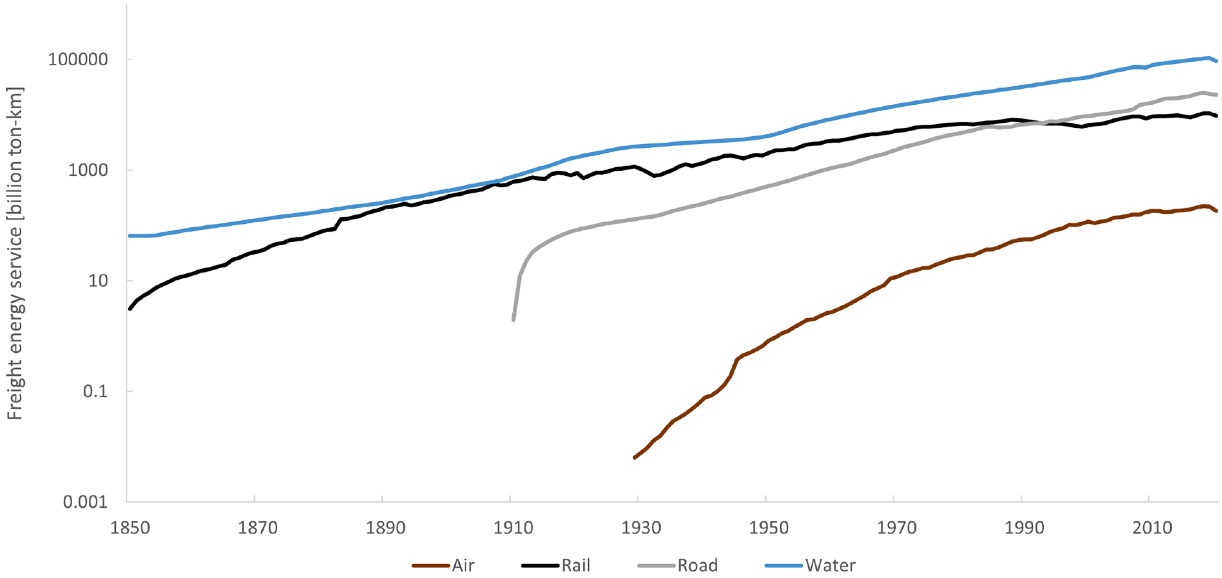

Fig. B.1. World freight energy service per transport mode: 1850–2020 (log scale).

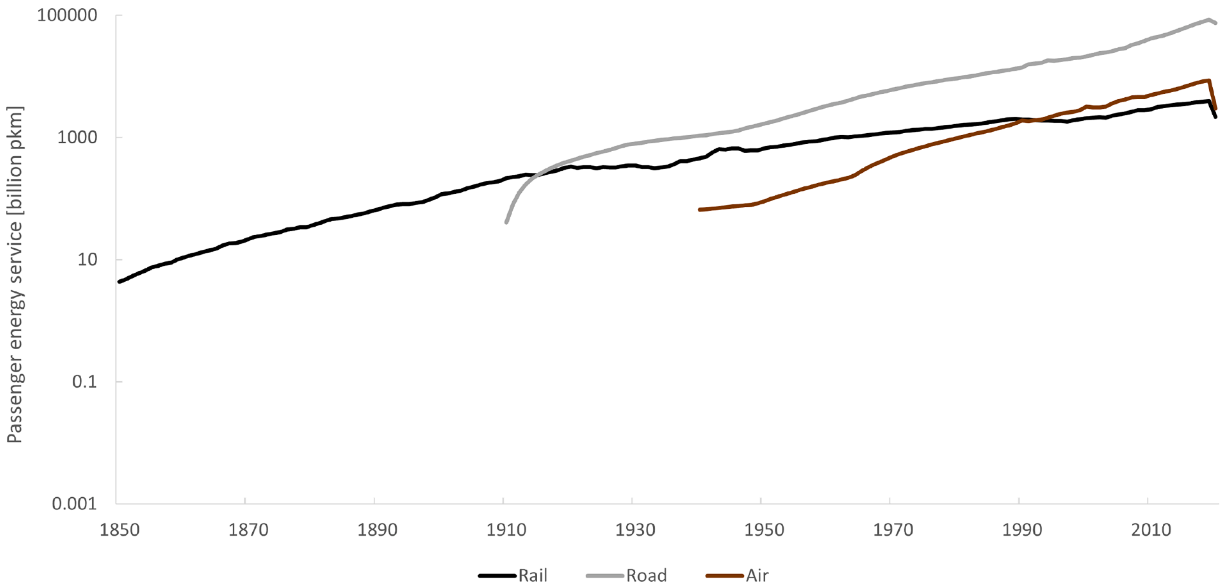

Fig. B.2. World passenger energy service per transport mode: 1850–2020 (log scale).

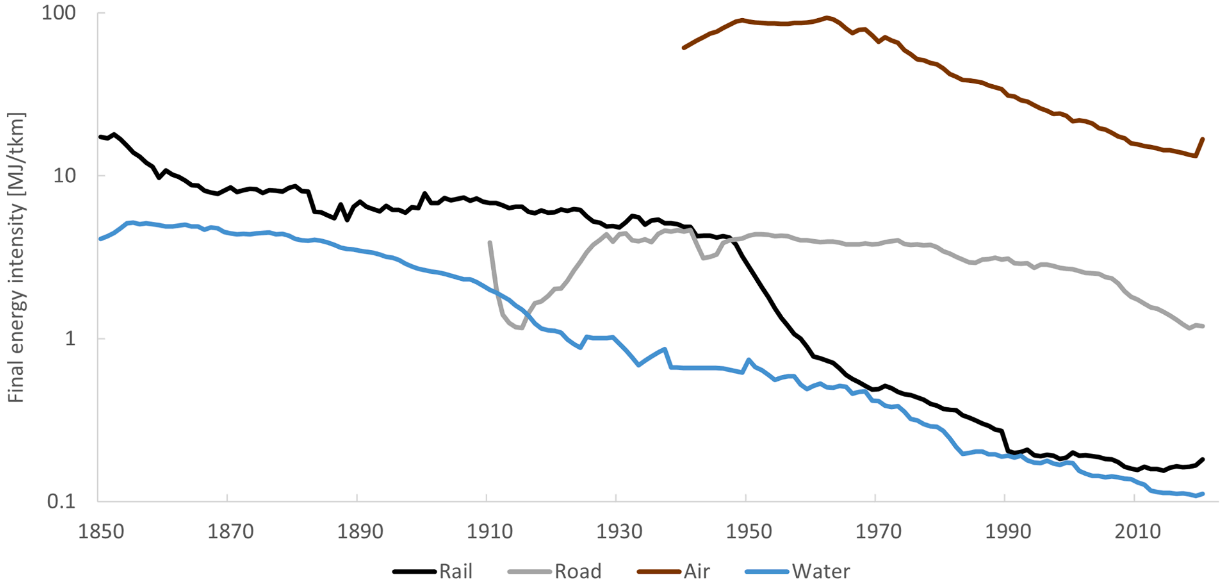

Fig. B.3. World final energy intensity of freight transport: 1850–2020 (log scale).

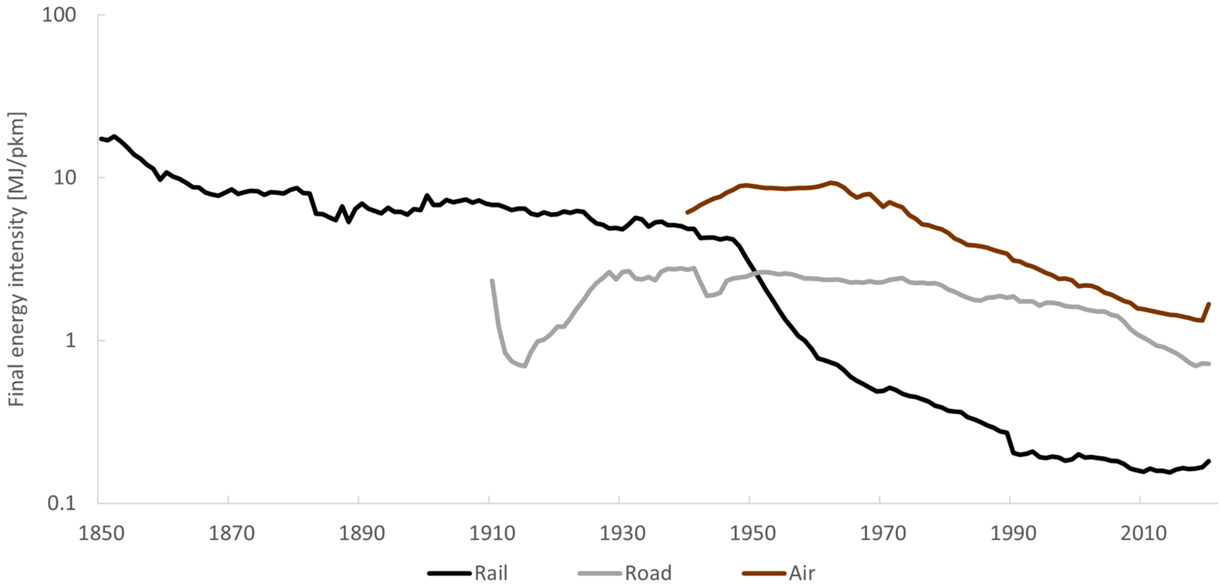

Fig. B.4. World final energy intensity of passenger transport: 1850–2020 (log scale).

Appendix C. Auxiliary calculations

According to the International Monetary Fund, GDP is expected to increase by 37.6 % from 2020 to 2029. Assuming freight and passenger service intensity will keep increasing with a 2 % annual growth rate, transport energy service ($serv$) will increase by

$$\frac{serv_{t=2029}}{serv_{t=2020}} = 1.376 \times (1.02)^9 = 1.644. \tag{C.1}$$

To compensate for the emissions that will occur due to the increase in transport demand, there should be a reduction in the final-to-useful efficiency, carbon emission factor, and/or useful energy intensity of service. We considered two scenarios: A) constant useful energy intensity and B) -2 % annual growth rate in useful energy intensity. We opted to work with these two scenarios since we could not predict if the current negative growth rates would be sustained. For scenario A, the necessary reduction to offset the increase in transport demand should be in the final-to-useful efficiency and/or carbon emission factor (carbon emission factor of useful energy, EF_u)

$$\frac{EF_{u,\,t=2029}}{EF_{u,\,t=2020}} = 1/1.644 = 0.608. \tag{C.2}$$

The $EF_{u,\,t=2020}$ can be calculated by

$$EF_{u,\,t=2020} = \left.\frac{EF_{Transp.}}{\eta_{Transp.}}\right|_{t=2020}. \tag{C.3}$$

By combining Eq. (C.2) with Eq. (C.3) and replacing $EF_{Transp.} = 69.72$ t CO_2/TJ and $\eta_{Transp.} = 23\,\%$, both for $t = 2020$, $EF_{u,\,t=2029}$ is given by

$$EF_{u,\,t=2029} = 0.608 \times \left.\frac{EF_{Transp.}}{\eta_{Transp.}}\right|_{t=2020} = \frac{0.608 \times 69.72}{0.23} = 184.30 \tag{C.4}$$

Since the increase in the final-to-useful efficiency of individual technologies is limited in the future we assumed the final-to-useful efficiencies for individual technologies were constant (aggregate transport final-to-useful efficiency might change due to the mix of technologies used). To simplify our calculations, we assumed only two technologies were in place: gasoline (Gas. V.) and electric vehicles (Elec. V.). The $EF_{u,\,t=2029}$ can be written as a weighted average of these two technologies

$$\begin{aligned} EF_{u,\,t=2029} &= (1-x) \times EF_{u,\,Gas.} + x \times EF_{u,\,Elec.} \\ &= (1-x) \times \frac{EF_{f,\,Gas.}}{\eta_{Gas.\,V.}} + x \times \frac{EF_{f,\,Elec.}}{\eta_{Elec.\,V.}} \end{aligned} \tag{C.5}$$

where x is the fraction of electricity in the final energy mix. Assuming the world electricity mix in 2029 is half renewable and half produced with natural gas ($EF_{f,\,Nat.\,gas} = 56.1$ t CO_2/TJ) with an efficiency of 50 % ($\eta_{Nat.\,gas}$) (Pinto et al., 2023), the carbon emission factor of electricity can be determined by

$$EF_{f\ Elec} = \frac{EF_{Nat.\,gas}}{\eta_{Nat.\,gas}} \times 0.5 + 0 = 56.1. \tag{C.6}$$

By substituting in Eq. (C.5), $EF_{u,\,t=2029} = 184.3$ t CO_2/TJ, $EF_{f,\,Gas.} = 69.3$ t CO_2/TJ, $\eta_{Gas.\,V.} = 17.7\,\%$, $EF_{f\ Elec} = 56.1$ t CO_2/TJ, and $\eta_{Elec.\,V.} = 80.8\,\%$, x can be determined by

$$x = \frac{EF_{u,\,t=2029} - EF_{f,\,Gas.}/\eta_{Gas.\,V.}}{EF_{f,\,Elec}/\eta_{Elec.\,V.} - EF_{f,\,Gas.}/\eta_{Gas.\,V.}} = 0.64. \tag{C.7}$$

The calculation was repeated for scenario B (-2 % growth rate in useful energy intensity). In this scenario, the share of electricity drops to 52 % of the final energy used in transport.

Scenario A assumes that 64 % of the electricity used has an emission factor of 56.1 t CO_2/TJ, and the remaining 36 % has an emission factor of 69.3 t CO_2/TJ, resulting in an aggregated emission factor of 60.8 t CO_2/TJ. In contrast, Scenario B uses 52 % electricity at 56.1 t CO_2/TJ and 48 % at 69.3 t CO_2/TJ, leading to a higher aggregated emission factor of 62.4 t CO_2/TJ.

To sum up, according to our calculations and assumptions, to compensate for the increase in emissions resulting from the increase in transport demand, in 2029, in scenario A electricity should be 64 % of the final energy used in transport, and in scenario B 52 %.

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