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Decoupling transport-related CO_2 emissions from economic growth: Empirical analysis (2000–2023)

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Abstract: This study investigates the dynamic relationship between economic expansion measured by Gross Domestic Product at Purchasing Power Parity (GDP at PPP) and transport-related carbon dioxide (CO_2) emissions in Hungary over the period 2000–2023. Using the Julia 1.10 programming language for high-performance statistical processing, the research employs a three-tier methodology comprising Augmented Dickey-Fuller (ADF) unit root testing, the Tapio elasticity framework, and Pearson correlation analysis of growth rates. The empirical results reveal that although absolute levels of GDP and emissions are non-stationary, their yearly growth rates are statistically independent ($r = 0.17$, $p > 0.05$), suggesting a significant break in the traditional carbon-growth nexus. The Tapio analysis identifies a prolonged "Strong Decoupling" phase from 2008 to 2013, followed by a return to efficiency-driven decoupling in 2023. These findings suggest that structural improvements and technological advancements have increasingly superseded economic volume as the primary drivers of transport emissions.

Keywords
transport emissions; economic growth; Tapio decoupling; Julia Language; time-series analysis; sustainable mobility; carbon intensity

1. Introduction

The transport sector remains one of the most significant contributors to global greenhouse gas (GHG) emissions, accounting for approximately 24% of direct CO_2 emissions from fuel combustion worldwide (Abastante et al., 2019; Pana Tronca, 2025). Unlike the industrial or power sectors, which have seen a steady shift toward electrification and renewable integration, the transport sector is traditionally characterised by "carbon lock-in" due to its heavy reliance on liquid fossil fuels and growing demand for mobility in expanding economies (Al-lami and Török, 2024; 2025).

In the pursuit of sustainable development, the concept of "decoupling" – the ability of an economy to grow without a proportional increase in environmental pressure – has become a central pillar of climate policy. For emerging and developed economies alike, the primary challenge is to achieve "Strong Decoupling", where economic output (GDP) continues to rise while absolute emissions decline. Understanding the historical relationship between GDP, energy consumption, and CO_2 in the transport sector is crucial for designing policies that do not hinder economic growth while meeting the Paris Agreement targets (Gómez, Bonilla, Banister, 2024; Szabó et al., 2024).

The theoretical foundation of this study is rooted in the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted-U relationship between economic development and environmental degradation (Apergis, 2016). According to this theory, environmental pressure increases during the initial stages of industrialisation but declines once a specific per capita income threshold is reached, as society shifts toward service-oriented economies and cleaner technologies. However, applying EKC to the transportation sector has proven problematic (Al-lami and Török, 2026). Unlike the manufacturing or energy sectors, where centralised technological shifts can rapidly lower emissions, transportation is decentralised and highly sensitive to individual consumer behaviour. Consequently, empirical studies often report a "re-coupling" effect, where rising

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disposable incomes lead to increased private vehicle ownership and a surge in freight logistics demand, effectively neutralising efficiency gains (Cautisanu and Hatmanu, 2023).

To address the limitations of the EKC's oversimplified "growth-leads-to-improvement" narrative, Tapio (2005) introduced a more granular framework based on volume-based elasticity. While traditional correlation coefficients only measure the strength of a linear relationship, the Tapio elasticity index *(e)* provides a dynamic measure of how emissions respond to economic shifts, independent of the chosen base year Tapio (2005). This framework categorises the decoupling relationship into eight distinct logical states: strong decoupling, weak decoupling, expansive coupling, expansive negative decoupling, strong negative decoupling, weak negative decoupling, recessive coupling, and recessive decoupling.

This multidimensional approach is particularly valuable for analysing the transport sector, as it can capture the high volatility of annual energy consumption and policy shifts. Recent scholarship has utilised the Tapio framework to highlight a growing geographical divide in transport efficiency. For instance, Al-lami and Török (2025) observed that several European nations have successfully achieved "Strong Decoupling" through aggressive carbon taxes and the promotion of intermodal rail transport (Huang et al., 2019). Conversely, research by Dai et al. (2016) on emerging economies in Asia and Africa indicates a persistent state of "Expansive Coupling," in which infrastructure expansion remains a prerequisite for economic survival, thereby keeping growth and pollution closely linked. Furthermore, Sorrell and Dimitropoulos (2008) argue that even when decoupling appears to occur, "rebound effects "where efficiency makes transport cheaper and thus more frequent – can trigger a return to coupling, a phenomenon the Tapio index is uniquely equipped to identify through its sensitivity to annual elasticity fluctuations Sorrell and Dimitropoulos (2008).

By moving beyond the binary "coupled vs. decoupled" view, the Tapio framework allows this study to pinpoint specific "rebound years" in the 2000–2023 dataset, providing a critical diagnostic tool for assessing whether recent transport policies are producing structural shifts or merely temporary environmental improvements.

Recent decoupling studies on the transport sector have mainly focused on cross-country comparisons or large economies, often using relatively simple regression models on non-stationary data (Alises, Vassallo, 2015). Many of these papers either ignore formal unit root testing or fail to adjust their methods when GDP and emissions are integrated, thereby overstating the strength of the carbon–growth link (Foster et al., 2023). Moreover, there is limited work examining Hungary's transport sector over the full 2000–2023 period, explicitly covering both the 2008 financial crisis and the COVID-19 shock, and using elasticity-based decoupling indicators. This study addresses these gaps by combining ADF unit root testing, Tapio elasticity analysis, and growth rate correlation in a high-performance Julia environment to provide a statistically robust assessment of whether transport-related CO_2 emissions in Hungary have decoupled from economic growth.

Despite the wealth of research, there is a lack of concise, statistically validated studies focusing on the 2000–2023 period, which includes the 2008 financial crisis and the 2020 COVID-19 pandemic. This paper fills that gap by using Julia 1.10 to analyse 24 years of transport data for Hungary. We seek to answer two primary questions:

1. Has the transport sector achieved a state of strong decoupling in the last two decades?
2. Is there a statistically significant causal link between economic growth and transport emissions when growth rates are analysed?

By focusing on statistically validated growth rates and Tapio decoupling states rather than raw levels, the study corrects for non-stationarity and provides clearer evidence on whether observed trends in Hungary reflect genuine structural decoupling or temporary, shock-driven effects.

2. Methodology

This study employs a three-tier analytical framework to investigate the nexus between economic growth measured by Gross Domestic Product at Purchasing Power Parity (GDP at PPP) and transport-related CO_2 emissions from 2000 to 2023. All computational procedures were performed using Julia 1.10 for high-performance statistical processing.

- **Stationarity Analysis:** To ensure the validity of the time-series data and avoid spurious correlations, the Augmented Dickey-Fuller (ADF) test was used to test for unit roots in the variables.
- **Decoupling Framework:** We adopted the Tapio Elasticity *(e)* model, which classifies the relationship between GDP growth (ΔG) and emission growth ΔG into eight logical states:

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$$e = \frac{\%\Delta CO_2}{\%\Delta GDP} \quad (1)$$

- **Dependency Testing:** Given the non-stationarity of the variables, a Pearson Correlation analysis of the first-differenced growth rates was used to assess the strength of the coupling between economic expansion and environmental impact.

3. Results and discussion

Time-series diagnostics – stationarity and integration

Before analysing the decoupling relationship, it was necessary to establish the statistical properties of the variables. The Augmented Dickey-Fuller (ADF) test results (Table 1) indicate that the levels of GDP PPP and transport-related CO_2 emissions are non-stationary ($p > 0.05$$). The point estimate for GDP (0.107) and CO_2 (-0.257) suggests that both series exhibit a stochastic trend, or a "random walk", which is typical of macroeconomic indicators.

Table 1. Augmented Dickey-Fuller (ADF) Unit Root Test results (at levels)

Variable	**ADF Statistic**	**p-value**	**1% Crit. Value**	**5% Crit. Value**	**10% Crit. Value**	**Result (H0)**
Transport CO_2	-1.9430	0.3121	-3.7377	-2.9922	-2.6358	Fail to Reject
GDP (PPP)	5.0670	1.0000	-3.7377	-2.9922	-2.6358	Fail to Reject

Failure to reject the null hypothesis (H_0) of a unit root implies that a direct regression on levels is likely to yield spurious results. Consequently, this study uses first differences (yearly growth rates) for all subsequent analyses, as differencing effectively transforms the data into an I(0)-stationary process, ensuring mathematical rigour in the decoupling index.

Decoupling analysis – the Tapio Elasticity framework

The longitudinal analysis (2000–2023) reveals a dynamic shift in the environmental-economic nexus of the transport sector. As illustrated in the Tapio Quadrant Plot (Figure 1), the observations are predominantly clustered in the "Strong" and "Weak" decoupling zones.

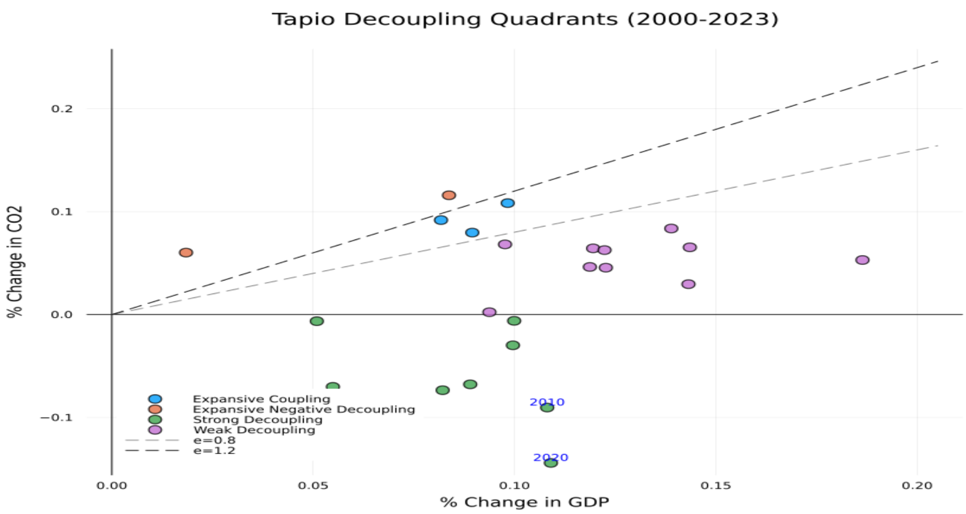

Figure 1. The decoupling quadrants (2000–2023)

Table 2. Summary of decoupling epochs in the transport sector

Epoch	Representative Range (e)	Dominant Status	Environmental Implication
2000–2007	$0.21 \leq e \leq 0.71$	Weak Decoupling	Emissions increased but remained decoupled from the rate of economic expansion.
2008–2013	$-1.28 \leq e \leq -0.06$	Strong Decoupling	Absolute Decoupling: Emissions decreased significantly despite sustained GDP growth.
2014–2019	$0.02 \leq e \leq 3.27$	Negative/Weak	High volatility; evidence of "rebound effects" where emissions outpaced growth in 2014/2019.
2020–2023	$-1.32 \leq e \leq 1.10$	Strong/Coupled	Transition phase; includes the exogenous COVID-19 shock and the 2023 return to efficiency.

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The most significant finding is the "Decoupling Streak" (2008–2013). During this window, the elasticity values remained consistently negative (e.g., -0.83 in 2010), representing a "Gold Standard" of environmental performance in which the transport sector's carbon footprint shrank as the economy expanded. This suggests a period of successful structural change or high-impact policy implementation.

Table 3. Tapio Decoupling analysis results (2000–2023)

Year	GDP (PPP)	CO_2 (Mt)	Elasticity (e)	Decoupling Status
2000	251.00	8.87	–	Base Year
2001	297.79	9.34	0.284	Weak Decoupling
2002	340.54	9.95	0.455	Weak Decoupling
2003	382.32	10.40	0.371	Weak Decoupling
2004	427.71	10.88	0.389	Weak Decoupling
2005	487.14	11.79	0.602	Weak Decoupling
2006	534.71	12.60	0.698	Weak Decoupling
2007	611.28	12.97	0.206	Weak Decoupling
2008	642.41	12.89	-0.127	Strong Decoupling
2009	706.60	12.81	-0.061	Strong Decoupling
2010	783.00	11.65	-0.836	Strong Decoupling
2011	825.99	10.83	-1.280	Strong Decoupling
2012	908.28	10.51	-0.300	Strong Decoupling
2013	989.12	9.79	-0.762	Strong Decoupling
2014	1071.95	10.93	1.384	Expansive Negative Decoupling
2015	1159.59	11.93	1.123	Expansive Coupling
2016	1268.34	11.96	0.024	Weak Decoupling
2017	1419.94	12.73	0.538	Weak Decoupling
2018	1593.70	13.52	0.512	Weak Decoupling
2019	1623.07	14.34	3.265	Expansive Negative Decoupling
2020	1800.06	12.27	-1.323	Strong Decoupling
2021	1977.05	13.60	1.102	Expansive Coupling
2022	2154.04	14.68	0.890	Expansive Coupling
2023	2331.02	13.60	-0.895	Strong Decoupling

Discussion – statistical evidence of independence

The core of our discussion lies in the Correlation Analysis. While the absolute values of the variables trend upward together, the correlation between their yearly growth rates is remarkably low ($r = 0.1705$, $p = 0.4366$).

In traditional "Coupled" economies, the p-value would be near zero, indicating that a 1% increase in GDP growth "forces" a specific % increase in CO_2. However, our result ($p > 0.05$) fails to show a significant relationship. This is a critical discovery: it proves that economic growth is no longer the primary driver of transport emissions. This "Independence" suggests that other variables – likely technological advancements in fuel efficiency, the adoption of electric vehicles (EVs), or shifts in logistics management – have become the dominant factors influencing the carbon trajectory. The "Strong Decoupling" observed in 2023 (-0.895) further reinforces the conclusion that the sector is entering a mature phase of environmental transition, in which growth and pollution are no longer "locked" together.

4. Conclusion

This study provides empirical evidence that the transport sector has successfully initiated a transition toward a low-carbon economy. Through a rigorous analysis in Julia 1.10, we have demonstrated that:

1. **Macro-trends are deceptive:** While raw data shows simultaneous growth in GDP and CO_2, the growth rates are statistically independent ($p = 0.43$), signalling a break in the traditional carbon-growth link.

2. **Decoupling is non-linear:** The transition is not a smooth line but a series of shifts, with the 2008–2013 and 2023 periods representing peak environmental efficiency.

3. **Policy over volume:** Since economic expansion does not statistically "cause" increases in emissions in this dataset, carbon-mitigation strategies should focus on Intensity (emissions per unit of transport) and Energy Mix rather than imposing caps on economic mobility.

Future research should focus on the "Rebound Years" (2014 and 2019) to identify the specific economic shocks or policy lapses that caused temporary expansive negative decoupling, ensuring that future progress remains stable and resilient.

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Modal shift or intermodality? Modal shift in Hungary and EU transportation and climate policy goals

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Abstract

This study aims to evaluate the role of modal shift and intermodality in achieving the European Union's transport and climate policy objectives, with a particular focus on the competitiveness and development of rail freight transport in Hungary. The research addresses the gap between policy ambitions for sustainable transport and the persistent dominance of road freight. The methodology is based on a structured literature review and secondary data analysis, drawing on European Union policy documents, Eurostat transport statistics, and national datasets. Comparative trend analysis is applied to assess changes in modal split at both the EU and Hungarian levels, while a qualitative assessment is used to identify the key structural, economic, and technological factors influencing the competitiveness of rail and intermodal transport. The results show that despite strong policy support, the share of rail freight transport has stagnated or slightly declined across the European Union, while road transport continues to dominate. In Hungary, similar patterns are observed, with rail maintaining a stable but limited market share. The findings identify infrastructure limitations, interoperability barriers, capacity constraints, and cost disadvantages as the primary factors hindering rail competitiveness. At the same time, intermodal transport has demonstrated significant growth, indicating its potential as a more feasible pathway toward sustainable freight systems than a pure modal shift. The study concludes that achieving climate objectives in the transport sector requires integrated policy measures, targeted infrastructure investments, and the accelerated development of intermodal solutions supported by digitalisation. Strengthening rail freight and intermodality is essential for reducing emissions and enhancing Hungary's role in European logistics networks.

Keywords

modal shift, intermodality, rail freight transport, sustainable transport, competitiveness

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1 Introduction

One of the most complex and defining challenges of 21st-century policy is balancing economic growth with the radical reduction of environmental impact. In the European Union, achieving climate policy goals and sustaining economic expansion go hand in hand with decoupling growth from greenhouse gas (GHG) emissions. Thanks to coordinated policy measures to date, total net greenhouse gas emissions in EU countries in 2022 were 32.5% lower than in 1990, while economic output grew by 67%. Transport is a key sector of the European Union's economy and plays a crucial role in today's mobile society. Transport and mobility are also central to sustainable development. Sustainable transport can foster economic growth and improve accessibility while respecting the environment and enhancing the resilience of cities, connections between urban and rural areas, and the productivity of rural regions. The goal of EU transport policy is to promote clean, safe, and efficient transport, underpinning the internal market for goods and citizens' right to free movement within the EU (European Commission, 2024).

In the member states of the European Union, the transportation sector is one of the most significant sources of pollution, and little progress has been made in reducing emissions over the past decades. This sector is responsible for nearly a quarter of greenhouse gas emissions (Filina-Dawidowicz et al., 2022). Despite efforts such as promoting the adoption of electric vehicles and encouraging the use of low-carbon fuels, transportation emissions have decreased only slightly since 2005, and the temporary decline in 2020 was due to the COVID-19 pandemic. At the same time, it is important to note that, based on current research, policy decisions, and measures, greenhouse gas emissions from transport are expected to reach 1990 levels by 2030. With additional measures, these emissions would be 13% lower than 1990 levels (EEA, 2025). Most of the policies and measures planned for the transportation sector focus on promoting low-carbon fuels or zero-emission technologies (Rodríguez and Delgado, 2019).

Within the transportation sector, road transport plays the most critical role, as the majority of emissions are generated by heavy-duty vehicles and passenger cars. Road traffic accounted for 71.1% of EU member states' transport GHG emissions in 2019, while the rail sector contributed a negligible 0.4%. Heavy-duty truck traffic accounts for 4–4.5% of CO_2 emissions in EU member states (Rodríguez and Delgado, 2019). Due to deepening globalisation, the internationalisation of supply chains, and the explosive growth of e-commerce, the volume of road traffic is expanding year by year. However, this process is unsustainable in the long term, as it creates increasingly severe economic and social tensions and environmental damage.

In addition to environmental issues, the physical saturation of road infrastructure is becoming an increasingly significant obstacle. Recurring traffic congestion on trans-European transport corridors directly impacts logistics efficiency: delivery times become unpredictable, and waiting times increase, resulting in high additional costs for manufacturing and service companies. Additional externalities include hidden costs in road transport systems that are not paid directly by the carrier or the client, but are borne by society as a whole. These include the costs of rescue and rehabilitation following traffic accidents, the decline in property values caused by noise pollution, the health effects of air pollution, and accelerated depreciation resulting from increased use of the road network. Together, these factors necessitate a fundamental restructuring of transportation systems (Vida et al., 2023).

The European Union's response to this crisis is the concept of "modal shift", which is a central element of the European Union's medium- and long-term transport policy visions, the European Green Deal, the Sustainable and Smart Mobility Strategy, and the objectives of the TEN-T network policy (Zani et al., 2025). The *Green Deal* (Fetting, 2020). promotes a clean economic transition that serves environmental sustainability, economic stability, and social justice alike. In recent years, there have been significant shifts toward environmentally friendly modes of transport, primarily toward railway development. Rail freight transport has a strategic advantage in the modal shift, as its specific energy consumption and CO_2 emissions are much lower than those of road transport (European Commission, 2020a). By electrifying its network infrastructure, rail can achieve the fastest decarbonisation, thereby playing a key role in helping the EU achieve climate neutrality by 2050. A tangible result of this recognition is that the Sustainable and Smart Mobility Strategy also clearly states that a significant portion of road freight transport over distances longer than 300 kilometres must be shifted to more environmentally friendly modes, primarily rail and inland waterway transport. On this end, the directive has set as a key objective a 50% increase in rail freight transport capacity by 2030, followed by a doubling of that capacity by 2050 in order to achieve climate neutrality, as well as the integration of key seaports into rail and inland waterway networks (European Commission, 2020b).

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This is why the *Drive to 55%!* package of measures adopted in the transport sector is of particular significance; it imposes a legal obligation on Member States and is expected to reduce EU emissions by 55% by 2030 (European Council, 2023). This legal framework encompasses various technological solutions to create efficient, interconnected multimodal transport systems in both passenger and freight transport sectors, enabling reductions in emissions of nearly 80% by 2040 compared to 2015 (European Commission, 2024). The EU's shorter-term climate policy goal, set in 2024 and to be achieved by 2040, brings the realisation of decarbonisation in the EU into clearer focus, proposing a 90% net reduction in GHG emissions relative to 1990 levels. As an important step toward this, it identifies, among other things, the increased utilisation of rail infrastructure capacity, the greater expansion of rail transport, and the development of an efficient and integrated multimodal passenger and freight transport system supported by the trans-European multimodal transport network, which could thereby contribute significantly to reducing total emissions. Decarbonising transportation requires significant investments across all transport sectors – in zero- and low-emission vehicles, rail equipment, and electrified infrastructure –, which also necessitates innovative EU financing instruments. As a result of these investments, the reduction in CO_2 emissions from road transport is expected to accelerate over time, in parallel with the growth of rail transport. Additionally, the share of battery-electric and other zero-emission vehicles in the road sector is projected to exceed 40% for light commercial vehicles and approach 40% for heavy-duty vehicles (European Commission, 2024).

Given that external costs of road freight transport will need to be internalised in the future (e.g., through tolls and carbon taxes), this is likely to provide a natural competitive advantage for more environmentally friendly transport solutions. Based on the above, while road freight transport can be made greener in the long term through consistent measures, a more achievable near-term goal is a modal shift through the development of rail and intermodal infrastructure. This study aims to evaluate the role of modal shift and intermodality in achieving the European Union's transport and climate policy objectives, with a particular focus on the competitiveness and development of rail freight transport in Hungary. The research addresses the gap between policy ambitions for sustainable transport and the persistent dominance of road freight. The methodology is based on a structured literature review and secondary data analysis, drawing on European Union policy documents, Eurostat transport statistics, and national datasets. Comparative trend analysis is applied to assess changes in modal split at both the EU and Hungarian levels, while a qualitative assessment is used to identify the key structural, economic, and technological factors influencing the competitiveness of rail and intermodal transport.

2 The role, limitations and development trends of rail freight transport

This study applies a mixed qualitative–quantitative research design to analyse the role of modal shift and intermodality in the context of European Union transport and climate policy objectives, with a specific focus on Hungary. The methodological approach combines secondary data analysis, comparative trend evaluation, and qualitative policy assessment.

The empirical basis of the study relies on secondary data obtained from international and national statistical and institutional sources. The primary datasets include Eurostat freight transport statistics, particularly modal split indicators expressed in tonne-kilometres, as well as publications from the European Union Agency for Railways (ERA) and the European Environment Agency (EEA). These datasets provide consistent time series for analysing changes in the distribution of freight transport modes across the European Union over the period 2010–2024. At the national level, Hungarian freight transport data were incorporated to examine domestic trends and to position Hungary within the broader European context. Additional sector-specific data were drawn from professional organisations and industry reports, including publications related to intermodal transport development and logistics performance in Hungary.

The analytical methodology is based on comparative trend analysis. First, temporal changes in modal shares of road, rail, inland waterway, maritime, and air transport were examined at both EU and national levels. This allowed the identification of long-term structural patterns and deviations from policy targets. Second, a comparative assessment was conducted between rail and road freight transport to evaluate their relative competitiveness. This assessment considered key dimensions such as infrastructure availability, operational flexibility, cost structures, capacity constraints, and service reliability.

In addition to the quantitative analysis, a qualitative evaluation framework was applied to interpret the underlying drivers of observed trends. This includes the examination of policy documents such as the European Green Deal, the Sustainable and Smart Mobility Strategy, and the TEN-T framework, as well as regulatory initiatives related to digitalisation (e.g. eFTI and ERTMS systems). The qualitative analysis focuses on identifying structural barriers to rail freight development,

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including interoperability limitations, fragmented infrastructure systems, and regulatory inconsistencies across Member States.

Finally, the study integrates a case-oriented perspective on Hungary by analysing national logistics strategies, infrastructure conditions, and intermodal development trends. This approach enables the identification of country-specific challenges and opportunities, particularly in relation to Hungary's role as a transit and logistics hub within European transport networks.

Overall, the methodological framework allows for a comprehensive assessment of both statistical trends and structural determinants, thereby linking empirical observations with policy-relevant conclusions on modal shift and intermodality.The role of rail freight transport is undeniable from both sustainable transport and economic growth perspectives, particularly in the light of carbon-neutrality goals. Rail is the most energy-efficient mode of transport, thanks to the low rolling resistance and its ability to meet the transportation needs of the most significant sectors of the national economy in large volumes with a low environmental impact. However, the downside of this efficiency is that, due to fixed-track transportation, trains can only operate in geographic locations where railway tracks have already been built. Track capacity can also be reduced by other trains operating on the same track, especially if there is no double-track infrastructure. Another structural constraint of rail is the relatively high fixed costs of equipment and operations, which require a high level of utilisation to be covered (Ficzere, 2023).

The rail freight market has shrunk significantly in recent decades in Europe, partly due to a lack of interoperability – that is, the lack of ensuring mutual compatibility, which requires removing existing technical, administrative, and legal barriers across member states and enhancing railway safety. This deficiency has prevented rail freight services from offering reliable service and led to issues such as service quality, congestion on certain networks, and local bottlenecks. The rail sector, which is subject to global trends in freight transport, offers high-volume, secure transport solutions to market participants; however, its reliability, punctuality, and flexibility lag behind those of freight market operators offering road transport services. Rail transport services still face a significant disadvantage compared to the road transport market in terms of competitiveness and cost-effectiveness. Overcoming this competitive disadvantage is particularly important because freight transport trends across Europe – and thus in Hungary as well – increasingly call for the development of combined transport services and integration into intermodal transport chains as green, sustainable logistics systems. This requires an appropriate support system that encourages a modal shift – specifically in the rail transport sector and through intermodal solutions – along with the conceptual development of infrastructure, terminals, and rolling stock, and the expansion of track capacity (Bucsky, 2021).

In response to growing economic demands on rail services and the need for door-to-door mobility, the EU has identified the creation of a Single European Railway Area as a key objective. One of the fundamental prerequisites for this is interoperability. From both competitiveness and sustainability perspectives, new information technologies will play a key role in future railway development. The digitisation of rail freight transport helps reduce administrative costs for economic operators, improves the enforcement capacity of competent authorities, and enhances the efficiency and sustainability of transport. Both economic operators and authorities must take measures to facilitate the electronic exchange of freight transport information (eFTI) via information and communication technology (ICT)- based platforms (eFTI platforms). The introduction of electronic transport documentation and digital traffic management systems (ERTMS) is now a key factor in competitiveness. Given the importance of a rapid, real-time flow of information for the electronic planning of conventional and intermodal rail routes, the tracking of rail shipments, the preparation of accurate transport documentation, and the reduction of administrative burdens, the mandatory implementation of such a system within the TEN-T infrastructure (e-freight) is being encouraged (Official Journal of the European Union, 2020).

2.1 Freight transport trends in Europe

In terms of the rail transport sector's share of the freight transport market, there has been no significant change over the past decade, either in the European Union or in Hungary, despite targeted policy interventions. The sector's share in EU member states averaged 18.22% between 2010 and 2022 (ERA, 2024). The policy goal of a 30% modal share for rail freight transport – and the expectation that, to achieve this, rail freight must double, and rail traffic must triple by 2050 compared to 2015 levels – is also not realistically on the verge of being achieved.

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An analysis of freight transport distribution by mode reveals that, over the past decade, maritime transport accounted for the largest share of freight transport performance in the European Union member states – as measured by tonne-kilometres travelled – among the five modes. Figure 1 shows that the share of maritime freight transport reached its lowest point of the decade in 2024, at 67% (4,753 billion ton-km), after five consecutive years of decline. Over the past decade, maritime freight transport reached its highest share in 2014 and 2015, at 69.5%. Compared to 2014, the share of maritime transport was 2.5 percentage points lower in 2024 (Eurostat, 2026b).

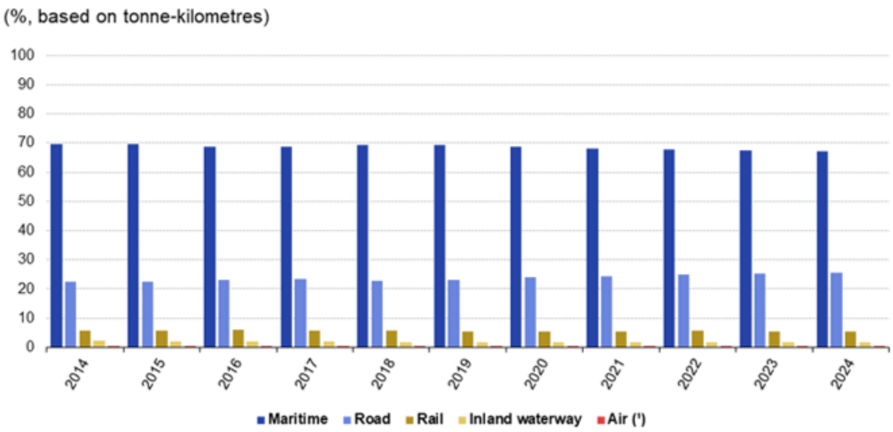

Figure 1. Breakdown of freight transport by mode in the EU, 2014–2024 (Eurostat, 2026b)

The share of road freight transport in the EU's total freight transport volume peaked at 25.7% in 2024, reaching 1,821 billion ton-kilometres, up 0.4 percentage points from 2023. During the 2014–2024 period, the share of road freight transport reached its lowest level in 2014, at 22.4%. The share of rail freight transport remained stable during the same period, with minimal volatility. The highest value was recorded in 2016, at 6.0%, while the lowest was in 2020, at 5.3%. In 2024, the share decreased by 1.1 percentage points compared to 2023 (5.4% or 385 billion ton-km). The share of inland waterway transport in total freight transport performance also remained relatively stable during the period under review. It peaked at 2.2% in 2014. By 2018, the share had fallen to 1.7%. The share of air freight transport remained at 0.2% during the period in question (Eurostat, 2026a).

The share of road transport was highest in Luxembourg in 2024 (84.4%), followed by the Czech Republic (78.0%) and Hungary (68.8%). The share of rail transport was highest in Austria (30%), followed by Slovakia (29.8%), Hungary (25.8%), and the Czech Republic (21.1%). In 2024, the share of road freight transport in the EU increased by 3.3 percentage points compared to 2014. When comparing the data from 2024 and 2014, the share of road freight transport in total freight transport performance decreased slightly in 4 EU member states. In contrast, it increased significantly in the Baltic countries, Romania, and Slovakia (Fig. 2). Looking at the last two reference years, the decline in the share of road freight transport was most pronounced in Hungary, where it fell by 1.9 percentage points from 2023 to 2024 (Eurostat, 2026a).

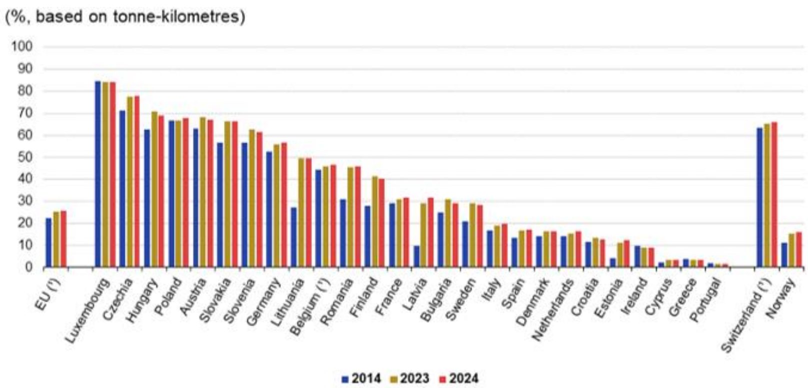

Figure 2. Share of road freight transport in total freight transport (Eurostat, 2026a)

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An analysis of trends in rail transport shares shows that, in 2024, the share of rail freight transport in EU member states decreased by 0.3 percentage points compared to 2014. Comparing the beginning and end of the period under review, the share of rail transport in total freight transport performance decreased in 17 countries, including EFTA member Switzerland (Fig. 3) (Eurostat, 2026a).

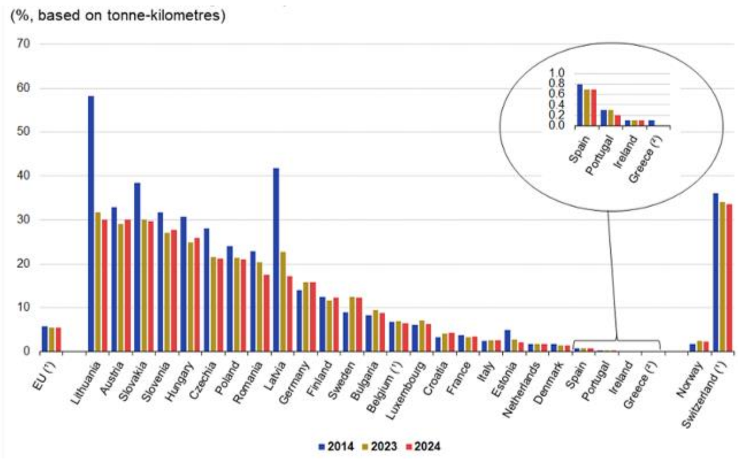

Figure 3. Share of rail freight transport in total freight transport (Eurostat, 2026a)

The largest decline was recorded in Lithuania, where the share fell from 58.2% in 2014 to 30.1% in 2024, and in Latvia, where it dropped by 24.6 percentage points from 2014. A decline in rail transport's share was also noticeable in Slovakia, the Czech Republic, and Romania. In contrast, the share of rail transport increased the most in Sweden, by +3.3 percentage points, followed by Germany, by +2.0 percentage points. In the other countries, an increase of less than 1.1 percentage points was recorded, or the share remained unchanged. Compared to 2023, the largest decline in 2024 was in Latvia (-5.6 percentage points), followed by Romania (-2.9 percentage points) and Lithuania (-1.6 percentage points). In the other countries, the decline in rail freight transport's share was less than 1 percentage point. In contrast, the largest increase was observed in Hungary and Austria, with +0.9 percentage points in both countries. The remaining 7 EU countries recorded an increase of 0.6 percentage points or less (Eurostat, 2026b).

2.2 Trends in Hungarian domestic rail freight transport

From the perspective of rail freight transport in Hungary, the first decade of the 21st century saw a dynamic growth, which came to an end with the financial and economic crisis that peaked in 2009. The volume of freight transported declined until 2013, then began to grow again starting in 2014. Over the past decade and a half, domestic freight transport volume peaked in 2017, exceeding the 2010 level by one-fifth. The next crisis was caused by the pandemic, which resulted in a significant decline in domestic freight volumes and the weight of goods transported. In Hungary, there has been no significant shift in the distribution of freight modes; over the past decade and a half, the proportions have remained stable with minimal volatility. In 2024, rail freight transport, with a 20% share, remained second behind road transport's 77.4% share (Fig. 4).

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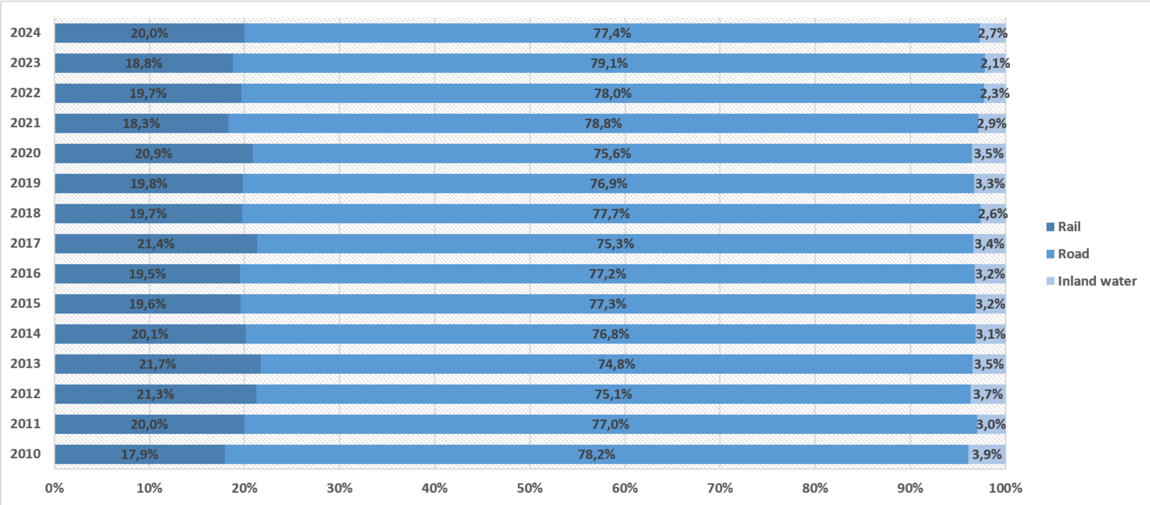

Figure 4. Breakdown of domestic freight transport by mode of transport (in tons, %)

According to rail freight data, transport volumes remained relatively stable throughout 2022, totalling around 50 million tons annually. However, a significant decline was observed starting in 2023: the total volume of goods transported fell to 45.7 million tons. Domestic transport was hit particularly hard, accounting for only about 9 million tons by 2024, whereas in 2014, 15 million tons of goods were still being moved via domestic rail. In 2024, international rail freight transport accounted for 88% of the sector's total volume. From the end of 2021, the drastic rise in energy prices eroded rail's cost advantage over road freight transport. In terms of traffic composition, export and transit traffic remained of decisive importance. At the same time, import volumes declined, primarily due to a moderation in demand for raw materials and energy. Transit traffic remained significant at nearly 4 billion tonne-kilometres, accounting for nearly 43% of total international traffic in 2024 (Fig. 5).

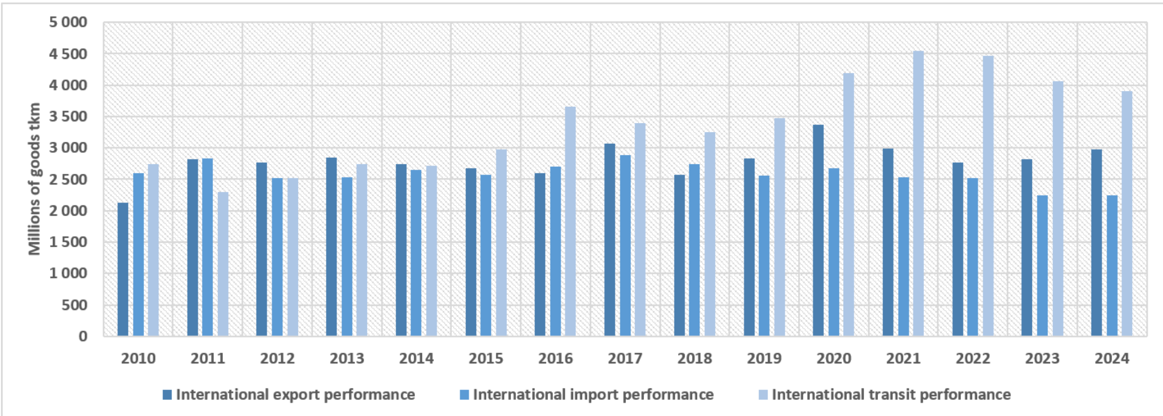

Figure 5. Volume of international rail freight traffic by direction in Hungary

Due to Hungary's strategic geographical location, transit traffic plays a particularly significant role in international rail traffic. Thanks to Hungary's location at the intersection of the NW–SE and SW–NE trans-European corridors, nearly one-third of the total weight of goods transported in international transit traffic passed through the country in 2024. Freight transport volume in transit traffic in Hungary rose by a further 4.2% in 2024 compared to 2023. In 2023, Hungary ranked third among EU member states in terms of rail transit traffic, behind Denmark and Slovakia.

2.3 A comparative analysis of competitiveness factors in rail and road transport

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It is worth examining trends in rail freight transport performance compared with the road transport sector, as the latter is a competitor to rail freight. If we review how road and rail networks have developed over time, we arrive at a startling realisation. Between 1960 and 2020, approximately 53,000 km of highways were built in Europe, while 55,500 km of railway lines were dismantled. These figures clearly reflect European investment priorities (Fig. 6). Although the total length of the railway network exceeds that of highways in every region of Europe, it is significantly shorter than the total road network, which includes more than just expressways (ERA, 2024).

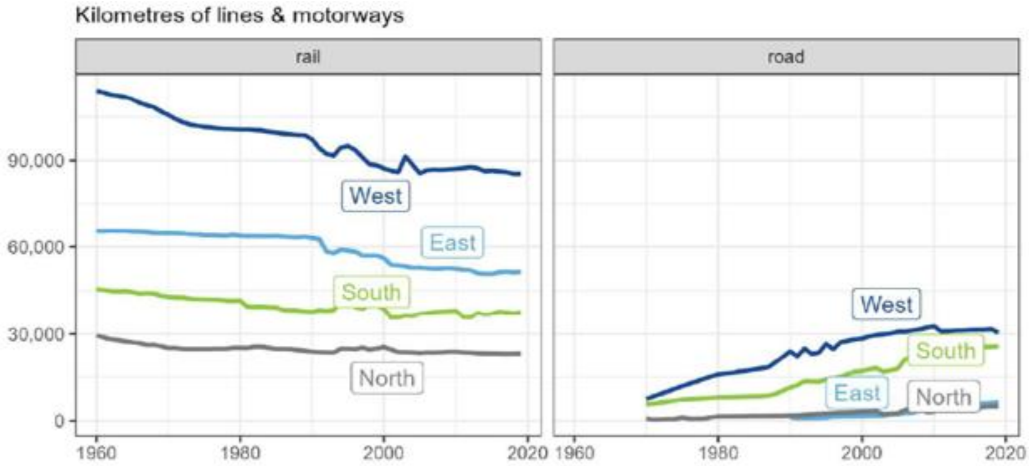

Figure 6. Changes in network length across four regions of Europe, 1960–2020 (ERA, 2024)

In the ERA analysis covering 20 countries, the Northern Europe region – Denmark, Norway, Sweden, and Finland – experienced the smallest decline in the length of its rail networks and also saw a slight increase in the extent of its road networks. Large-scale railway line closures have occurred in the countries of the Eastern Europe region (Bulgaria, Poland, Hungary, Romania, and the Czech Republic), where the expansion of the road network was negligible compared to the number of railway lines discontinued. In the four Mediterranean countries of Southern Europe, as well as in Western Europe (the Benelux countries, Germany, France, Austria, and EFTA member Switzerland), the development of road networks was a priority for investment; as a result, the majority of road construction took place in these regions, while the majority of railway line closures also occurred in Western Europe.

The condition of the rail network, the extent of electrification, the signalling systems in place, and the level of maintenance and modernisation significantly impact the quality and speed of rail transport services. There are also significant differences among European countries regarding these characteristics and the level of investment. In 2020, the top 5 countries (the Benelux countries, France, and Austria) invested seven times more in track modernisation than the bottom 5 countries, including Hungary (ERA, 2024). Moreover, underfunding creates additional disadvantages, leading to temporary capacity restrictions (TCR) and unavoidable disruptions in rail transport that cannot be adequately planned. This can lead to freight traffic being diverted from rail to road, as happened in Hungary in 2025, when 17,000 TEU – approximately 10,000 truckloads of goods – were diverted to road transport – offering more flexible service – due to unpredictable operations, track closures, and traffic restrictions (MLSZKSZ, 2026).

The disadvantages arising from a lack of interoperability pose a major problem. A total of 149 cross-border rail connections in Europe are no longer operational, 119 of which have been identified as promising candidates for reactivation. At the same time, even if a border crossing is actively in operation, technical barriers impose additional costs on railway operators for actual crossings, and thus on the users of their services as well. The lack of interoperability poses a serious obstacle to economic development and hinders growth in the regional gross value added of 4.5% or more in certain border regions (ERA, 2024).

From a technical standpoint, the European railway infrastructure is fragmented and complex, primarily due to four different main track gauges, varying platform heights, four main electrification systems, numerous train safety systems, and

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more than 170 different train control systems that do not comply with the Technical Specification for Interoperability (TSI). In the future, this should be managed in a coordinated manner to reduce procurement and maintenance costs, as in certain cases, investments in and maintenance of railway infrastructure can cost up to ten times more than those for road infrastructure (ERA, 2024). The capacity allocation process further limits the network's performance. Track allocation has traditionally been organised under national jurisdiction, with countries determining priorities based on principles. Furthermore, the standard track application and allocation process is lengthy, making rail freight services inflexible and effectively creating an additional competitive disadvantage. When examining the cost of rail and road freight transport, it should also be noted that the energy crisis led to a significant rise in electricity prices, putting rail freight at a cost disadvantage. The 2004 EU enlargement had a significant impact on road freight transport services in the new member states. The resulting competition – particularly in terms of costs – contributed to road transport becoming relatively cheaper even over longer distances.

ail and road freight transport compete under very different labour conditions. Rail relies on highly specialised staff. Train drivers and operational personnel must complete long training and strict certification. They also need regular requalification. In international traffic, language requirements are demanding. Drivers often must use the official language of each national network. This increases costs and reduces flexibility. In some cases, multiple drivers are needed for one trip. Road transport is much more flexible. Entry barriers are lower. Drivers mainly need a licence and a professional certificate. Training is shorter and simpler. Language requirements are also less strict. Basic communication is usually sufficient. This allows companies to hire from a wider international workforce. As a result, road transport can adjust faster to demand. Labour is cheaper and easier to organise. Rail, despite its environmental benefits, remains less competitive due to stricter labour constraints.Consequently, the stagnation in rail transport's share can be partly attributed to its deteriorating cost position relative to road transport. Legislators need to consider how to improve the cost competitiveness of rail and road freight transport. This involves several areas, such as rail and road regulations (including the allocation of rail capacity and rules governing driving and rest periods for truck drivers).

Rail freight transport is typically associated with the transport of high-volume bulk goods, such as coal; however, due to sustainability requirements and deindustrialisation, demand for raw materials and energy sources has generally declined. The decline of industry goes hand in hand with the disappearance of demand for rail transport from economic actors operating in heavy industry, the energy-intensive chemical industry, or the manufacturing sector. In contrast, the liberalisation of the European road freight market has, on the one hand, led to greater competition, reducing costs. On the other hand, offered much more flexible and reliable services to supply chain members striving to maintain ever-smaller inventories in just-in-time systems. These facts paint an unfavourable picture of the rail sector, making it difficult to achieve a modal shift. Due to changes in demand for transport services, rail must adapt more flexibly to changing needs, and the success of modal shift can be supported if the rail sector monitors the needs of economic sectors. This will require further investment and policy intervention to ensure that rail freight transport doubles by 2050 compared to the baseline (ERA, 2024).

Given current trends in freight transport, the demand for containerised shipping is growing. Industry organisations believe that intermodal transport can increase freight transport efficiency and that this segment will see the fastest growth in the future. This requires investments across Europe in traction vehicles that meet the interoperability requirements set out in the technical specifications. Regarding the fleet of towed vehicles, it is necessary to procure wagon types capable of hauling semi-trailers, containers, and other intermodal loading units. At the same time, there is a need to expand intermodal terminal capacity, as current capacity is insufficient to handle expected traffic. The rail transport sector, which has traditionally specialised in the transport of bulk goods, is becoming an integral part of intermodal transport, a role it can fulfil only if the infrastructure operates predictably and reliably.

3. Medium- and long-term development proposals in Hungary to promote modal shift and intermodality

Recognising the above processes and trends, professional organisations in Hungary have also set the objective of developing sustainable rail freight transport into a reliable and efficient mode of transport that contributes significantly to the growth of the national economy while simultaneously reducing the environmental impact of freight transport (Csavajda and Böröcz, 2019). A specific goal set out in the concept is to increase rail freight transport performance by 50% between 2024 and 2030 by enhancing the sector's competitiveness (Gelei and Kovács, 2026). Furthermore, increasing the competitiveness of the railway sector will significantly contribute to ensuring that in the future, Hungary is not merely

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viewed as a gateway to Eurasian supply chains or simply as a transit country, but rather becomes a key logistics hub in Central and Eastern Europe. The shift to green, sustainable modes of transport, including rail freight, cannot be achieved in Hungary as long as unfavourable conditions are present. These include the fact that the sector receives less support relative to road transport in terms of freight volume, infrastructure operations are not adequately funded, the rolling stock is outdated, track capacity constraints are difficult to plan for in advance, and the transition through the capital city constitutes a bottleneck. In the medium term (2024–2030), comprehensive, integrated expansion of rail and intermodal infrastructure is necessary to meet the transport needs of manufacturing companies operating in strategic sectors of the national economy. In the long term, through stakeholder cooperation, the share of intermodal transport in Hungary must be increased from the current 7% to 21% (Gelei and Kovács, 2026).

In recent years, while the volume and performance of rail freight transport have declined, intermodal traffic has grown rapidly in Hungary. From 2023 to 2024, it grew by a spectacular 122%, and the total volume exceeded 850,000 TEU. Semi-trailer traffic accounts for a significant share of intermodal growth, reaching 56,000 TEU in 2024. In 2025, total intermodal traffic grew by another 14%, with 502,037 TEU of loaded containers transported, a 6.51% increase compared to the previous year. An exceptionally high increase (+81.22%) was also recorded in semi-trailer transport, with 101,164 TEU transported via this mode (MLSZKSZ, 2026).

It is well recognised that road freight transport has serious social and environmental impacts: high GHG emissions, overburdened infrastructure, and labour shortages. Intermodal rail transport along green freight corridors effectively supports climate protection goals by reducing road congestion and noise pollution, improving traffic safety, and mitigating greenhouse gas emissions (Janić, 2020). Furthermore, it helps alleviate the labour shortage in road transport. In complex transport chains, the efficiency of intermodal transport lies in the fact that goods are transported in unitised cargo carriers across multiple modes of transport, without the need for direct or indirect transshipment. This method can optimise the strengths of each mode of transport in terms of flexibility, speed, cost, and environmental impact. While road transport is the most flexible and often the fastest mode, other modes, such as rail or inland waterway transport, offer greater safety and environmental performance and can reduce congestion on busy roads. In combined transport, unit loads travel most of the route via a green freight corridor, with short-distance road transport to and from terminals. This combines the advantages of different transport modes: it merges the efficiency of road collection and distribution with the long-distance, high-capacity freight transport capabilities of rail and waterway transport. It relieves traffic on public roads, thereby improving road network safety and reducing congestion. It is an environmentally friendly, sustainable logistics solution that also creates a well-regulated, continuous, and traceable flow of materials. In this mode, loading and other wait times can be planned, and the number of transshipments and cargo-handling operations is minimal. The goal set by professional organisations is for the share of goods transported by semi-trailer (or equivalent 45-foot containers/swap bodies) to increase from 7% to 21% of total road freight transport by 2030 (Gelei and Kovács, 2026). However, in addition to infrastructure development, the widespread adoption of combined freight transport also requires the creation of a transparent and predictable support system that directly responds to the needs of market participants. For carriers and logistics service providers, economic rationality is the primary decision-making criterion; thus, intermodal and multimodal solutions can only become competitive if they are environmentally friendly, cost-effective, and reliable.

For intermodal traffic to continue growing in Hungary, infrastructure development must prioritise expanding rail line capacity and increasing the capacity of existing intermodal terminals to meet increased traffic demands. The fleet must also be upgraded; in addition to procuring craneable semi-trailers and 45-foot containers, it is essential to increase investment in specialised rolling stock and efficient, innovative loading equipment. To improve supply chain efficiency, it is worth encouraging the launch of new direct trains connecting industrial zones and seaports. From a policy perspective, consideration should be given to increasing direct subsidies for combined transport and to reducing fees at domestic terminals. In the future, digital solutions, such as eFTI platforms and services, will also play an important role in increasing the efficiency of intermodal transport.

There are currently 11 intermodal terminals in Hungary, with 94% of the country's total intermodal traffic concentrated in three hubs in Budapest. As for regional terminals, significant growth is expected, particularly in Debrecen and Szeged, thanks to ongoing investments in the automotive industry. The objective of professional organisations is to triple semi-trailer intermodal rail traffic by 2030, expand the intermodal network with new, strategically located terminals that meet the needs of economic operators, and integrate them effectively into the national rail and waterway network (Gelei and Kovács, 2026).

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To achieve the above objectives, three of the thematic development project packages developed by professional organisations are designed to encourage a shift in transport modes and strengthen intermodality. Among these, the *Green Logistics Program* aims to achieve targeted CO_2 reductions and reform the toll system. *Strengthening Transport Competitiveness*" prioritises a support system for domestic carriers, favourable tax policies, and driver training. At the same time, the specific *Intermodal Development Package* sets out clear requirements for infrastructure development, a fleet of vehicles capable of handling unitised cargo, new rail services, and terminal capacity expansion. In the medium term, between 2027 and 2030, the priority is the expansion of rail and terminal infrastructure, as well as the development of trimodal logistics connections, while in the long term, the focus should be on strengthening strategic positions (European Court of Auditors, 2023).

Conclusion

This study provides a comprehensive overview of the sustainability challenges facing the transport sector, with a particular focus on the structure of freight transport and the role of modal shift and intermodality in achieving the European Union's climate and transport policy objectives. The study is based on the premise that striking a balance between economic growth and reducing environmental impact is one of the most important challenges of the 21st century, in which the transport sector plays a key role. Road transport continues to dominate EU transport emissions, while rail – despite its favourable environmental characteristics – has a low market share. A study has shown that rail freight transport, thanks to its outstanding energy efficiency and low emissions, can be a key tool for decarbonisation. At the same time, its structural limitations – such as fixed-track infrastructure, limited flexibility, high fixed costs, and interoperability shortcomings – significantly undermine its competitiveness compared to road transport. Road transport, on the other hand, remains a dominant player due to its high flexibility, speed, and cost-effectiveness, particularly with the rise of just-in-time supply chains. Based on European trends, we have observed that the share of rail freight transport has stagnated or declined slightly over recent decades, while the share of road transport has increased. A similar trend can be observed in Hungary. Although rail freight transport holds a stable second place, its share is not growing significantly. Alongside the competition between the two sectors, however, intermodal transport has also developed dynamically in Hungary, following European trends; thus, this mode offers a tangible solution for the future development of sustainable logistics systems rather than a modal shift.

The competitiveness analysis highlighted that the railway sector's lag can be attributed to the combined effect of several factors. These include insufficient infrastructure development, limited track capacity, technical barriers at border crossings, and low investment levels. In addition, the fragmentation of the railway system and regulatory differences also hinder the creation of a single European railway area. At the same time, digitalisation offers new opportunities: eFTI platforms, electronic transport documentation, and ERTMS systems can significantly improve the sector's efficiency, transparency, and competitiveness. It is important to emphasise that a modal shift can only be achieved through complex, coordinated policy interventions. To this end, significant development of rail and intermodal infrastructure, expansion of terminal capacities, and modernisation of the rolling stock are essential. In addition, there is a need to establish a predictable and effective support system that encourages market participants to adopt environmentally friendly modes of transport. The internalisation of the external costs of road transport can also help level the playing field.

Overall, the development of rail freight transport and intermodality is essential to achieving the EU's climate policy goals. Hungary's favourable geographic location creates an opportunity to become a regional logistics hub in the future; however, this requires targeted investments, a strategic mindset shift, and effective cooperation across transport modes. Accordingly, the transport system of the future will be based on an integrated, digitised, and sustainable multimodal network in which rail plays a key role.

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Reframing the sustainability transformation of mobility systems through cognitive sustainability: An integrated perspective on cost structures, decision-making, and emission dynamics

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Abstract

This work reinterprets the sustainability transformation of mobility systems from a cognitive sustainability perspective, integrating economic mechanisms, decision-making processes, and emission dynamics into a unified analytical framework. While traditional approaches emphasise cost structures and policy incentives, this work argues that the transformation cannot be fully understood without considering the cognitive dimension of decision-making. Total cost of ownership (TCO) is positioned as a central mediating construct that not only reflects economic rationality but also serves as a cognitively informed decision interface shaped by perception, trust, and information asymmetry. The analysis highlights that the relationship between costs and emissions is dynamic and non-linear over time, particularly in the case of electrification, where short-term emission increases can precede long-term sustainability benefits. By integrating economic, environmental, and cognitive layers, the study proposes a feedback-driven systems model in which policy instruments, cost structures, user choices, and emission trajectories evolve together. The results show that an effective sustainability transformation depends not only on optimising cost structures but also on shaping the cognitive frameworks through which these costs are perceived and internalised.

Keywords

cognitive sustainability, mobility transformation, total cost of ownership, electromobility, emissions dynamics, decision-making, policy instruments

1. Introduction

The sustainable transformation of mobility systems is usually viewed as a technological and economic optimisation problem, where the adoption of low-emission technologies is promoted through cost competition and regulatory incentives. However, empirical findings increasingly show that this perspective is incomplete. The transformation of mobility systems occurs not only through measurable economic mechanisms but also through the ways decision-makers perceive, interpret, and internalise them. In this sense, mobility systems should be understood as cognitive-economic systems in which cost structures, policy interventions, and technological alternatives are continuously shaped by human perception and decision-making.

This integrated understanding aligns with the emerging paradigm of cognitive sustainability, which expands traditional sustainability thinking by incorporating information processing, perception, and behavioural dynamics into systems analysis (Zöldy et al., 2022). In this context, sustainability transformations are not solely the result of optimised resource allocation but arise from the interplay of objective system parameters and subjective decision-making processes.

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This study, therefore, aims to develop a unified analytical framework that links the economic, environmental, and cognitive dimensions of mobility transformations. By positioning total cost of ownership (TCO) as a mediating cognitive-economic construct and incorporating the temporal dynamics of emission trajectories, the study contributes to a more comprehensive understanding of the reasons for and mechanisms behind the success or failure of sustainable transformations of mobility.

2. Economic mechanisms and external effects in transport systems

At the heart of sustainable transformations in mobility lie the structures of economic incentives, traditionally described in terms of external effects and cost internalisation mechanisms. Transport systems generate significant negative externalities – including greenhouse gas emissions, air pollution, and noise – which are only partially reflected in market prices (Campos et al., 2009; IPCC, 2023). The classical economic approach defines the optimal emission level as the intersection of the marginal damage and the marginal cost of emission reduction. Sustainability, therefore, is achieved not through complete elimination but through effective reductions in emissions (Máca et al., 2011).

From the perspective of cognitive sustainability, however, external effects are not only economically undervalued but also cognitively underrepresented. Users tend to base their decisions on immediate and visible costs, while long-term environmental impacts remain abstract and are often neglected. Therefore, even well-designed economic instruments cannot achieve the desired behavioural changes if they are not cognitively accessible or interpretable. As a result, policy instruments should not be viewed solely as means of influencing relative prices, but rather as components of a broader decision-making environment. Taxes, subsidies, and regulatory frameworks influence behaviour not only through their financial effects but also through their signalling in the cognitive space. A stable political environment strengthens trust, visible infrastructure improves perceived feasibility, and direct incentives reduce the perceived risks of new technologies. In this sense, the effectiveness of policy measures depends not only on the economic scale but also on the coherence between economic signals and cognitive processing (Hörcher and Tirachini, 2021; Raux, 2011).

3. Total cost of ownership (TCO) as a cognitive-economic interface

The total cost of ownership (TCO) plays a central role in linking the economic and cognitive dimensions of mobility decisions. In traditional economic analysis, TCO integrates capital, operating, and regulatory costs into a comprehensive life-cycle indicator (Wouters et al., 2005; Desreveaux et al., 2020). However, the true significance of TCO for transformations of mobility lies in its role as a link between macroeconomic policy and microeconomic decision-making. From a cognitive perspective, TCO can be understood more as a decision architecture than as a purely financial metric. It structures the evaluation of alternatives, simplifies complex system interactions, and transforms abstract cost curves into actionable decision criteria. Empirical evidence, however, shows that decision-makers rarely perform complete TCO calculations in practice. Instead, they rely on partial information, heuristics, and relevant cost factors such as purchase price or immediate operating costs. This leads to a persistent discrepancy between calculated and perceived TCO, which significantly influences technology adoption.

The example of electromobility illustrates this discrepancy particularly clearly. Although the total life cycle costs of electric vehicles can be competitive under certain conditions, higher purchase costs often dominate decision-making due to electricity procurement and risk aversion. At the same time, the perceived benefits of lower operating costs depend heavily on expectations regarding future energy prices, infrastructure availability, and political stability (Franzò et al., 2022). This sensitivity demonstrates that cost competitiveness is not a static outcome but a dynamic, context-dependent phenomenon influenced by both external factors and cognitive interpretation.

4. Temporal dynamics of emission trajectories

The dynamics of mobility transitions become even clearer when considering emission trajectories. Traditional sustainability assessments are often based on static comparisons or aggregated life cycle indicators that fail to capture the temporal dimension of environmental impacts. In fact, emissions evolve, reflecting both technological characteristics and systemic processes. Electrification is a well-documented example of this temporal complexity. The production phase of electric vehicles – particularly battery production – results in higher initial emissions than those of internal combustion

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engine vehicles, while operational emissions are significantly lower. Consequently, the environmental benefits of electrification only become apparent after a certain period of use, resulting in a time-delayed emissions profile (Lerchner and Zöldy, 2026).

This temporal dependency has important cognitive implications. Users tend to evaluate environmental performance based on simplified and static assumptions, which can lead to misperceptions. The presence of an initial phase with "emission disadvantages" can undermine the perceived sustainability of electrical technologies, even if the long-term benefits are substantial. This underscores the need for dynamic and systems-based representations of environmental impacts that can be cognitively processed and integrated into everyday decisions. Furthermore, emissions are not determined at the level of individual vehicles but result from the composition and evolution of the entire vehicle fleet. The sustainability transformation of mobility systems thus depends on aggregated decision-making patterns, which in turn are shaped by political incentives, cost structures, and cognitive factors. The resulting system exhibits a feedback dynamic: political changes alter cost structures, costs influence decisions, decisions change the composition of the vehicle fleet, and emissions evolve accordingly.

5. Model of feedback-driven systems

Cognitive sustainability expands the economic feedback loop by emphasising that all phases of the transformation process are mediated by perception. The interpretation of political signals, the perceived relevance of costs, and the understanding of environmental consequences influence the direction and speed of the transformation. In this sense, sustainability transformations of mobility systems can be described as adaptive learning processes in which both individuals and systems continuously adjust to new information and changing circumstances. Figure 1 shows a feedback-based system model that integrates three main levels of the mobility transition: the economic level (including cost structures, total cost of ownership (TCO), external effects, and policy instruments), the cognitive level (including decision architecture, perceived TCO, behavioral biases, trust, and risk perception), and the ecological level (including emissions trends, fleet dynamics, and life cycle profiles). The central construct – cognitive sustainability – represents the co-evolutionary process through which these levels interact, mutually influence each other, and jointly determine the speed and stability of the mobility transition.

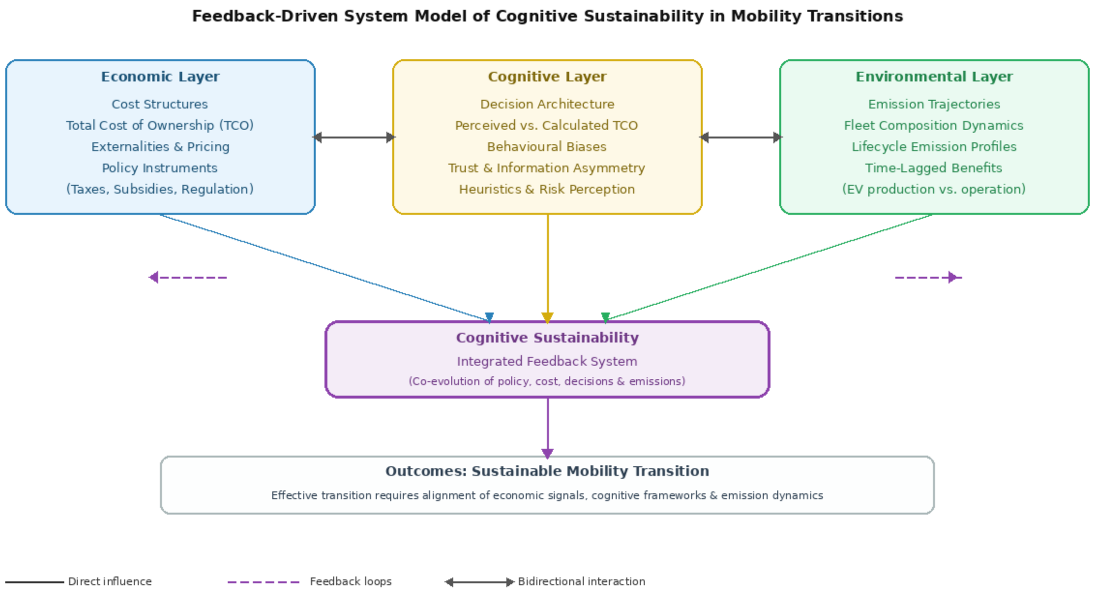

Figure 1. Feedback-driven system model of cognitive sustainability in mobility transitions

The model illustrates that direct impacts from each level flow into the integrated feedback system, while feedback loops from the system act back into the economic and ecological levels. Furthermore, the bidirectional interactions between the three main levels reflect the cross-domain dependencies that characterise real-world mobility transitions. Sustainable mobility outcomes are positioned as a product of this fully integrated, dynamically evolving system.

This perspective aligns with broader sustainability concepts, such as integrated socio-economic-ecological models (Hariram et al., 2023), which emphasise the interplay between economic and behavioural dimensions. Research in sustainable transport also shows that efficiency gains depend not only on resource allocation but also on behavioural responses to policy interventions. In this integrated system, the role of policy is fundamentally reinterpreted. Instead of merely acting as an external regulator, policy can be understood as shaping decision-making environments. Effective interventions should consider the objective cost structure, as well as the cognitive conditions for decision-making – including the transparency of cost information, the stability of regulatory frameworks, and the availability of technological options.

6. Policy implications for cognitive sustainability

The findings of this study suggest that future mobility policies must move beyond traditional economic optimisation and explicitly incorporate cognitive dimensions into their design. First, policy measures should consider cost structures not merely as financial parameters, but as communication tools that shape users' perceptions and evaluations of mobility alternatives. Second, the effectiveness of incentives depends on their stability and transparency: an unpredictable political environment undermines trust and delays behavioural change. Third, the benefits of sustainability must be translated into cognitively accessible formats, particularly by emphasising time-dependent emission trajectories instead of static comparisons. Fourth, integrating decision-support mechanisms, such as TCO-based labelling, real-time cost visualisation, and scenario-based communication, can significantly improve alignment between objective system performance and perceived outcomes. Fifth, infrastructure development should be understood not only as a physical investment, but also as a cognitive signal that reinforces technological feasibility and reduces perceived risk. Sixth, policy interventions should account for behavioural biases to ensure that short-term cost disadvantages do not overshadow long-term system benefits. Ultimately, cognitive sustainability requires a paradigm shift in political thinking: from influencing markets to shaping the decision-making environment. The success of the mobility transition depends not only on the effectiveness of system optimisation but also on how well users understand these systems, trust them, and act accordingly.

7. Conclusions

The sustainability transition of mobility systems cannot be reduced to a purely economic or technological optimisation problem, as its dynamics ultimately take place in the cognitive space of decision-making. This study has shown that cost structures, policy interventions, and emissions trajectories interact through perception-based processes in which the interpretation of information is just as crucial as the information itself. The reinterpretation of total cost of ownership as a cognitive-economic interface highlights that the effectiveness of economic signals depends on their perceived relevance and not solely on their calculated value. At the same time, the time-dependent nature of emissions dynamics reveals a persistent discrepancy between actual and perceived sustainability performance, which can slow down otherwise positive transitions.

In this context, policy must move beyond mere cost correction and create a decision-making environment in which economic, ecological, and cognitive dimensions are aligned. Consequently, sustainable mobility does not simply arise from optimal systems, but from how these systems are understood, valued, and used by users. Future research should focus on empirically validating the feedback-oriented model proposed here and on developing cognitive decision-making tools that bridge the gap between sustainability goals at the system level and decision-making processes at the individual level.

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Sustainability assessment of bulletproof materials used for vehicle armouring

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Abstract

The increasing demand for lightweight, highly protective armoured vehicles has shifted material selection from ballistic performance alone to comprehensive sustainability considerations. While traditional homogeneous armour steels provide excellent durability, mature manufacturing technologies, and high recyclability, their high density significantly increases vehicle mass, leading to greater fuel consumption and greenhouse-gas emissions throughout the operational life cycle. Conversely, advanced composite armour systems offer superior protection-to-weight ratios but are associated with energy-intensive manufacturing processes and limited end-of-life recycling options. This study presents a comparative life-cycle sustainability assessment of steel- and composite-based vehicle armouring materials using a cradle-to-grave engineering framework. In addition to evaluating ballistic performance and material characteristics, the proposed methodology integrates manufacturing energy demand, operational fuel consumption, greenhouse-gas emissions, recyclability, and economic considerations. A simplified quantitative model is introduced to describe the relationship between armour mass, vehicle fuel consumption, and operational CO_2 emissions, while a sensitivity analysis is performed for representative armoured vehicle configurations. Furthermore, a multi-criteria decision analysis (MCDA) framework is proposed to support engineering decision-making by simultaneously considering ballistic efficiency, environmental impact, operational performance, recyclability, and cost. The results demonstrate that although homogeneous steel remains advantageous in terms of manufacturing maturity and circularity, lightweight composite materials substantially reduce operational environmental impacts owing to lower vehicle mass. The analysis further indicates that hybrid modular armour systems provide the most balanced engineering solution by combining the recyclability of steel with the weight-saving benefits of advanced composites. The proposed assessment framework extends conventional material comparisons by integrating engineering, environmental, and economic perspectives into a unified sustainability evaluation methodology, thereby providing practical guidance for the future development of armoured vehicle protection systems.

Keywords

vehicle armouring, bulletproof materials, sustainability

1. Introduction

The continuous evolution of ballistic threats has significantly influenced the development of protective materials used in military and civilian armoured vehicles. For several decades, armour design has primarily focused on maximising ballistic resistance while maintaining sufficient structural integrity and acceptable vehicle mobility. Homogeneous armour steels have become the conventional solution because of their excellent mechanical properties, proven manufacturing technologies, and high reliability under combat conditions (Jneid and Harth, 2023). However, the increasing protection requirements against modern kinetic projectiles, improvised explosive devices (IEDs), and blast loading have inevitably led to heavier

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vehicle structures, thereby adversely affecting mobility, payload capacity, fuel consumption, and operational costs. In parallel with advances in protective technologies, sustainability has become a key engineering objective across the automotive and defence industries. Environmental regulations, carbon reduction strategies, and circular economy principles have expanded the traditional design criteria beyond ballistic protection, introducing life-cycle environmental performance as an additional decision-making factor (Nyerges, 2026). Consequently, the selection of armour materials should no longer be based solely on mechanical performance. They should also consider manufacturing impacts, operational energy demand, greenhouse gas (GHG) emissions, service life, maintenance requirements, and end-of-life recovery.

The development of advanced composite materials has fundamentally changed modern vehicle armouring. Fibre-reinforced polymer composites, ultra-high-molecular-weight polyethene (UHMWPE), ceramic strike faces, and hybrid multilayer systems provide substantially higher protection-to-weight ratios than conventional steel armour (Tsirogiannis et al., 2024). The resulting reduction in vehicle mass improves acceleration, braking performance, manoeuvrability, operational range, and fuel economy while simultaneously reducing GHG emissions during service. Nevertheless, these materials also introduce new sustainability challenges. Their production is considerably more energy-intensive than conventional steel manufacturing, and recycling remains technologically challenging due to the heterogeneous nature of composite structures and the strong bonding between reinforcement fibres and polymer matrices (Gloger et al., 2023).

Numerous studies have investigated the ballistic behaviour of armour steels, aramid composites (He et al., 2025), ceramic systems (Ni et al., 2026), and hybrid protective structures (Mutu, 2025). Other researchers have evaluated the mechanical properties (Sundaram, Balaji, Kumar, 2026), impact resistance, and failure mechanisms of these materials under ballistic loading. However, relatively few investigations have attempted to integrate ballistic performance with broader sustainability considerations. Existing studies typically address either material performance or environmental aspects in isolation, whereas comprehensive engineering frameworks that combine protection efficiency, operational energy demand, recyclability, and economic performance remain limited (Othman and Hassan, 2013). Consequently, there remains a need for practical methodologies to support material selection from a holistic life-cycle engineering perspective.

The sustainability of armoured vehicles is inherently a system-level problem. Although heavier armour generally provides improved protection, the additional mass increases rolling resistance, power demand, fuel consumption, GHG emissions, suspension loading, and maintenance requirements throughout the vehicle lifetime (Zhou and Chen, 2015). Conversely, lightweight composite materials reduce operational impacts but frequently require more energy during manufacturing and currently exhibit limited recycling potential (Khodadadi et al., 2019). These conflicting characteristics indicate that sustainability cannot be evaluated by considering individual material properties alone; rather, it requires an integrated assessment of the entire vehicle life cycle.

To address this research gap, the present study proposes a comparative life-cycle sustainability assessment of steel- and composite-based armour materials used in vehicle protection. Unlike previous review-oriented studies, the proposed methodology combines qualitative engineering evaluation with a simplified quantitative assessment linking armour mass to operational fuel consumption and carbon dioxide emissions. The analysis follows a cradle-to-grave system boundary and incorporates manufacturing energy demand, operational environmental impacts, recyclability, and selected economic considerations (Imre et al., 2025). Furthermore, a multi-criteria decision analysis (MCDA) framework is introduced to evaluate alternative armour concepts by simultaneously considering ballistic efficiency, weight reduction, environmental performance, recyclability, and cost. The principal contribution of this study is the development of an integrated engineering framework that extends conventional material comparison toward a practical sustainability-oriented decision-support methodology. Rather than identifying a universally superior armour material, the study aims to determine how different material systems perform under multiple engineering and environmental criteria and to identify the conditions under which hybrid and modular armour concepts provide the most balanced solution (Wang et al., 2022). The protection standards are listed in Table 1:

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Table 1. Standard requirements for protection levels (Kadir Bilisik and Turhan, 2009)

Class Threat Level	Type of bullet and caliber	Minimum bullet velocity (m/s)	Number of shots 0^0	Number of shots 30^0	Minimum penetration depth (mm)
L1	.38 Special RN	259	4	2	44
L1	.22 LR HV	320	4	2	44
L2	.357 Magnum JSP	381	4	2	44
L2	9 × 19 mm FMJ Parabellum	332	4	2	44
L3	.357 Magnum JSP	425	4	2	44
L3	9 × 19 mm FMJ Parabellum	358	4	2	44
L4	44 Magnum SWC	426	4	2	44
L4	9 × 19 mm FMJ Parabellum	426	4	2	25
L5	7,62 × 54 R 39M L	838	6	0	25
L6	7,62 × 54 R 39M B32	868	1	0	25
LS	specific requirements		determined by the customer		

2. Methodology

The methodology of this study adopts an integrated life-cycle engineering framework to evaluate the sustainability of different vehicle armouring materials. The analysis follows a cradle-to-grave approach, considering all phases from raw material extraction and manufacturing to operation and end-of-life processes, thereby ensuring a comprehensive assessment of environmental and engineering performance. The research combines qualitative comparison with a simplified quantitative model to estimate the impact of armour mass on fuel consumption and greenhouse gas emissions during vehicle operation. In addition, a sensitivity analysis is conducted to examine how variations in material configurations affect overall sustainability outcomes. To support decision-making, a multi-criteria decision analysis is applied, integrating factors such as ballistic efficiency, environmental impact, recyclability, and cost. This structured methodology enables a balanced comparison of steel, composite, and hybrid armour systems while maintaining transparency and practical applicability for engineering design.

2.1 Research framework

The objective of this study is to evaluate the sustainability of vehicle armouring materials using an integrated engineering approach that combines material properties, environmental impacts, operational performance, and economic considerations. Unlike conventional material comparisons that primarily focus on ballistic resistance, the proposed methodology evaluates armour materials from a complete life-cycle perspective (Kondor et al., 2025).

The assessment follows five sequential stages:

1. Identification of representative armour materials.
2. Collection of engineering and environmental data from the literature.
3. Quantitative estimation of operational fuel consumption and GHG emissions resulting from additional armour mass.
4. Comparative evaluation of environmental and engineering performance over the vehicle life cycle.
5. Multi-Criteria Decision Analysis (MCDA).

2.2 Functional unit and system boundary

The functional unit is defined as one armoured vehicle operating over a service life of 200,000 km. The assessment follows a cradle-to-grave system boundary including raw material extraction, material production, armour manufacturing, vehicle operation, maintenance, and end-of-life recycling or disposal (Li et al., 2023). Operational impacts are evaluated separately from manufacturing and end-of-life impacts to ensure methodological transparency.

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Table 2. Engineering assumptions

Parameter	Value
Baseline vehicle mass	3500 kg
Steel armour mass	900 kg
Composite armour mass	450 kg
Vehicle lifetime	200,000 km
Fuel type	Diesel
CO_2 emission factor	2.68 kg CO_2/L diesel

2.3 Quantitative sustainability model

Operational fuel consumption is estimated using a simplified linear engineering relationship:

$$FC = FC_a + k \cdot \Delta m$$

where

FC is fuel consumption (L/100 km),

FC_a is fuel consumption,

Δm is the additional armour mass, and

k is the mass sensitivity coefficient.

Operational GHG emissions are estimated as:

$$\epsilon_{CO_2} = FC \times D \times EF$$

where

D is the travelled distance, and

EF is the diesel emission factor.

2.4 Sensitivity analysis

Three representative armour configurations are compared: (1) conventional steel armour, (2) advanced composite armour, and (3) hybrid modular armour. Relative changes in vehicle mass, fuel consumption, operational CO_2 emissions, and recyclability are evaluated to determine the influence of armour mass on life-cycle sustainability (Sockalingam et al., 2017).

Table 3. Multi-criteria decision analysis

Criterion	Weight (%)
Ballistic performance	30
Protection-to-weight ratio	20
Environmental impact	20
Recyclability	15
Economic performance	15

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2.5 Limitations of the study

The proposed methodology is intended as a comparative engineering framework rather than a complete ISO 14040/14044 life-cycle assessment (Min et al., 2016). Several assumptions regarding vehicle configuration and operational conditions are simplified to enable a transparent comparison between armour concepts. Nevertheless, the methodology integrates engineering (Xu et al., 2023), environmental, and economic considerations into a practical sustainability-oriented decision-support framework.

3. Armour materials used in vehicle armouring

Armour materials used in vehicle armouring include conventional steel, advanced composites, and hybrid systems. Steel armour is widely used due to its strength, durability, and recyclability, but its high weight increases fuel consumption and emissions. Composite materials, such as ceramic and fibre-reinforced systems, offer lighter weight and better mobility, although they are more difficult to recycle. Hybrid armour combines these materials to balance protection, weight reduction, and sustainability. This approach provides a more efficient overall solution for modern armoured vehicles.

3.1 Conventional homogeneous armour steels

Homogeneous armour steels have represented the benchmark solution for armoured vehicle protection for several decades owing to their excellent mechanical properties, manufacturing maturity, and operational reliability. These steels are produced with a uniform chemical composition and microstructure throughout their thickness, providing predictable ballistic behaviour under high-velocity impact conditions. Depending on the required protection level, armour steels are generally classified into Rolled Homogeneous Armour (RHA), High Strength Armour (HSA), High Hardness Armour (HHA), and Ultra-High Hardness Armour (UHHA).

Table 4. Properties of homogeneous armour steels

Armour steel	Hardness (HB)	Yield strength (MPa)	Tensile strength (MPa)	Stretching (%)
RHA Rolled Homogeneous Armour	250–350	700–900	850–1100	10–20
HSA High Strength Armour Steel	300–400	900–1200	1100–1400	8–15
HHA High Hardness Armour	450–550	1200–1500	1400–1800	5–10
UHHA Ultra-High Hardness Armour	500–600	1500–1700	1900–2100	< 5–8

The ballistic performance of homogeneous armour is primarily achieved through high hardness and strength while maintaining sufficient toughness to prevent brittle fracture. From a sustainability perspective, steel benefits from mature manufacturing technologies, excellent repairability, and highly efficient recycling routes. However, its high density (approximately 7.8 g/cm³) substantially increases vehicle mass, negatively affecting fuel consumption, GHG emissions, mobility, and operational efficiency.

3.2 Advanced composite armour systems

Advanced composite armour systems combine several materials with complementary functions to achieve significantly higher protection-to-weight ratios than conventional steel (Dobra and Jósvai, 2020). Typical systems consist of ceramic strike faces manufactured from aluminium oxide, silicon carbide or boron carbide together with fibre-reinforced polymer backings based on aramid fibres (Kevlar®), ultra-high-molecular-weight polyethene (UHMWPE) or glass fibres (Fig. 1):

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Figure 1. Ballistic testing of a self-developed composite material (Kondor et al., 2025)

The ceramic layer fractures and erodes the projectile, whereas the composite backing absorbs the remaining kinetic energy by fibre deformation, delamination, and matrix cracking. Owing to their low density (typically 1.1–3.0 g/cm³), composite systems improve vehicle mobility and reduce operational fuel consumption and GHG emissions. Their principal disadvantages are energy-intensive manufacturing processes and limited end-of-life recyclability.

3.3 Hybrid armour concepts

Recent developments increasingly employ hybrid armour architectures that combine steel, ceramics, and fibre-reinforced composites within a modular multilayer structure. Such configurations exploit the recyclability and structural robustness of steel while benefiting from the lightweight characteristics of composite materials (Rudolph and Mátrai, 2018). Modular armour concepts also facilitate maintenance by allowing damaged sections to be replaced individually, thereby reducing material consumption, maintenance costs, and vehicle downtime.

3.4 Sustainability characteristics of armour materials

The sustainability of armour materials cannot be evaluated using a single engineering parameter. Steel exhibits excellent recyclability and manufacturing maturity but increases operational environmental impacts because of its high mass. Composite materials substantially reduce operational fuel consumption and emissions but require greater manufacturing energy and currently offer limited recycling potential. Hybrid armour systems provide the most balanced compromise by integrating the advantages of both material classes. Consequently, material selection should be based on a comprehensive life-cycle engineering assessment rather than ballistic performance alone.

Table 5. Comparative sustainability characteristics of armour materials

Criterion	Steel	Composite	Hybrid
Density	High	Low	Medium
Ballistic efficiency	High	Very high	Very high
Operational emissions	High	Low	Low
Recyclability	Excellent	Limited	Good
Manufacturing energy	Moderate	High	Moderate
Overall sustainability	Moderate	High	Very High

4. Quantitative sustainability assessment and discussion

The quantitative sustainability assessment highlights that vehicle mass is a key determinant of operational performance in armoured vehicles. The addition of armour increases the vehicle's total weight, which directly raises fuel consumption due to higher rolling resistance and increased energy demand during acceleration and operation. The comparative analysis shows that steel armour, with the highest mass, leads to the greatest increase in fuel consumption and greenhouse gas emissions over the vehicle's lifetime. In contrast, composite armour significantly reduces vehicle mass, thereby improving fuel

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efficiency and lowering operational emissions. Hybrid armour systems offer an intermediate solution, balancing mass reduction with structural performance. Overall, the results demonstrate a clear relationship between mass reduction and improved operational sustainability, emphasising the importance of lightweight design in armoured vehicle engineering.

4.1 Vehicle mass and operational performance

Vehicle mass is one of the most influential engineering parameters affecting the operational sustainability of armoured vehicles. Increasing armour thickness generally improves ballistic protection but simultaneously increases total vehicle mass, resulting in higher rolling resistance, increased power demand, greater fuel consumption, and higher GHG emissions throughout the vehicle life cycle. For the comparative assessment, a representative armoured vehicle with a baseline mass of 3,500 kg was considered. Three representative armour configurations were evaluated: conventional steel armour, advanced composite armour, and hybrid modular armour.

Table 6. Armour configurations

Configuration	Additional armour mass (kg)	Total vehicle mass (kg)
Steel armour	900	4400
Composite armour	450	3950
Hybrid armour	650	4150

4.2 Fuel consumption assessment

Assuming a baseline fuel consumption of 18 L/100 km for the unarmoured vehicle, the simplified engineering model introduced in Section 2 was applied to estimate operational fuel demand.

Table 7. Fuel consumption assessment

Configuration	Fuel consumption (L/100 km)	Relative change
Baseline	18.0	—
Composite armour	18.8	+4.4%
Hybrid armour	19.3	+7.2%
Steel armour	20.0	+11.1%

4.3 Operational GHG emissions

Using a diesel emission factor of 2.68 kg CO_2/L and a vehicle lifetime of 200,000 km, the operational GHG emissions were estimated.

Table 8. Greenhouse gas emissions

Configuration	Lifetime fuel consumption (L)	CO_2 emissions (t)
Steel armour	40,000	107.2
Hybrid armour	38,600	103.4
Composite armour	37,600	100.8

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4.4 Multi-criteria sustainability evaluation

A Multi-Criteria Decision Analysis (MCDA) was performed to compare the alternative armour concepts considering engineering, environmental, and economic criteria.

Table 9. Multi-criteria decision analysis

Criterion	Weight (%)	Steel	Composite	Hybrid
Ballistic performance	30	4	5	5
Weight efficiency	20	2	5	4
Operational emissions	20	2	5	4
Recyclability	15	5	2	4
Economic performance	15	5	3	4

Please note that Steel, Composite, and Hybrid received points [1..5] on the given performance indicators. Weight indicates the decision weight of a given criterion in the final decision.

4.5 Engineering interpretation

The analysis demonstrates that reducing armour mass directly decreases fuel consumption and operational CO_2 emissions (Klimecka-Tatar, 2017). Steel remains advantageous in terms of recyclability and manufacturing maturity, whereas composite materials offer substantial operational environmental benefits (Mészáros and Török, 2014). Hybrid armour systems provide the best overall balance by combining the principal advantages of both material classes (Le et al., 2022).

5. Conclusion

This study presented a comparative life-cycle sustainability assessment of conventional homogeneous steel armour, advanced composite armour systems, and hybrid modular armour concepts for vehicle protection. Unlike traditional evaluations that primarily consider ballistic performance, the proposed framework integrates engineering, environmental, and economic aspects within a unified sustainability-oriented methodology. The results demonstrate that armour material selection should be based on the complete vehicle life cycle rather than on individual material properties alone. Homogeneous armour steel remains an attractive solution owing to its proven manufacturing technologies, excellent structural reliability, high repairability, and well-established recycling infrastructure. Nevertheless, its relatively high density substantially increases vehicle mass, leading to greater fuel consumption, greenhouse-gas emissions, and operational environmental burdens throughout the service life. Advanced composite armour systems provide significantly improved protection-to-weight ratios, resulting in lower operational fuel demand, reduced carbon emissions, and improved vehicle mobility. However, these advantages are partially offset by energy-intensive manufacturing processes and limited end-of-life recycling options. Consequently, neither steel nor composite materials alone can be considered universally optimal from a sustainability perspective. The quantitative assessment and multi-criteria decision analysis indicate that hybrid modular armour systems provide the most balanced engineering solution. By combining recyclable steel components with lightweight composite materials, hybrid configurations simultaneously improve ballistic protection, operational efficiency, environmental performance, maintenance flexibility, and long-term economic sustainability.

The proposed methodology contributes a practical engineering decision-support framework that links armour mass with operational fuel consumption, GHG emissions, recyclability, and economic considerations. Although simplified, the framework provides a transparent basis for comparing alternative armour concepts during the early stages of vehicle design and complements more comprehensive life-cycle assessment methodologies.

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Future research should extend the present work by incorporating experimentally validated vehicle fuel-consumption models, complete ISO 14040/14044 life-cycle inventories, manufacturing energy databases, and mission-specific operational scenarios. Additional optimisation studies focusing on layer configuration, material sequencing, and multifunctional hybrid armour architectures could further improve the sustainability of next-generation armoured vehicles. Overall, sustainable armoured vehicle development requires a balanced integration of ballistic effectiveness, lightweight design, circular economy principles, and life-cycle engineering. The findings of this study demonstrate that hybrid modular protection systems are among the most promising pathways to reducing the environmental footprint of armoured vehicles while maintaining the high levels of protection required in modern operational environments.

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Additive manufacturing as a driver of sustainable economic growth

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Abstract
3D printing, or Additive Manufacturing (AM), has evolved from a specialised tool for creating prototypes into a large international marketplace valued at $24.2 billion in 2025. In this study, we investigated how the size of the additive manufacturing marketplace is connected to global economic activity, as measured by Gross Domestic Product (GDP). We documented a nearly 807-fold increase in the additive manufacturing marketplace, compared with a 5.2-fold increase in World GDP over the same period. We document four distinct periods of growth in the additive manufacturing marketplace and demonstrate that investments in AM have been uncorrelated with most major economic recessions, including those caused by the 2008–2009 financial crisis and the COVID-19 pandemic. The three principal mechanisms through which additive manufacturing has contributed to economic growth are increased total factor productivity, the creation of new markets and business models based on distributed manufacturing, and improved supply chain resilience. A dramatic decline in the cost of additive manufacturing equipment – that occurred approximately 1,250 times faster than traditional two-dimensional printing –was identified as the primary structural cause of the rapid expansion of the additive manufacturing market. These results were framed through the lens of cognitive sustainability, which views digital manufacturing technologies as enabling humans to produce more efficiently by utilising fewer resources. The findings indicate that additive manufacturing provides a cognitively sustainable pathway to technological innovation with broad implications for long-term economic development, industrial policies and green transition strategies.
Keywords: *additive manufacturing; 3D printing; GDP; economic growth; cognitive sustainability; price democratization; supply chain resilience; Industry 4.0*

1. Introduction

Additive manufacturing (AM), the building of an object by layering material according to a computer model, represents perhaps the most significant technological shift in modern industrial history. In just over thirty-eight years since the first commercially viable Stereolithography (SLA) machine came into operation in 1988, AM has evolved from a costly technology used primarily for rapid prototyping by the largest aerospace and automotive companies around the globe to become a widely distributed production paradigm applied in many different sectors, including health care, defence, construction and consumer products.

Global AM sales were estimated at $24.2 billion in 2025 (Wohlers Associates, 2026), and estimates for the size of the AM industry project growth to $125.9 billion or $168.9 billion (Grand View Research, 2025) by 2033–34. The expected growth rate for the AM industry is remarkable when viewed against other high-technology industries. Over the past thirty-five years, the AM industry grew about 800 times as much as world GDP did during that period (IMF World Economic Outlook, April 2026; World Bank, 2025).

While the growth of the AM industry has been substantial, the body of knowledge related to AM in economics remains limited and fragmented. Most of what we know about AM comes from studies focused on how AM affects firm-level productivity (McKinsey Global Institute, 2019), sector-specific rates of adoption (Wohlers Associates, 2025), or life cycle assessments (LCAs) of the environmental impacts of AM (Jung et al., 2023; Niaki and Nonino, 2017). As such, there is very little evidence from longitudinal studies on how changes in the AM market relate to changes in world GDP over long periods (i.e., multi-decade periods). Furthermore, no previous study has examined the role of AM as a technology that expands

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human productive cognition while reducing the use of physical resources (i.e., cognitive sustainability) and its relationship to both the green transition and resilient economic development (Ficzere, 2022).

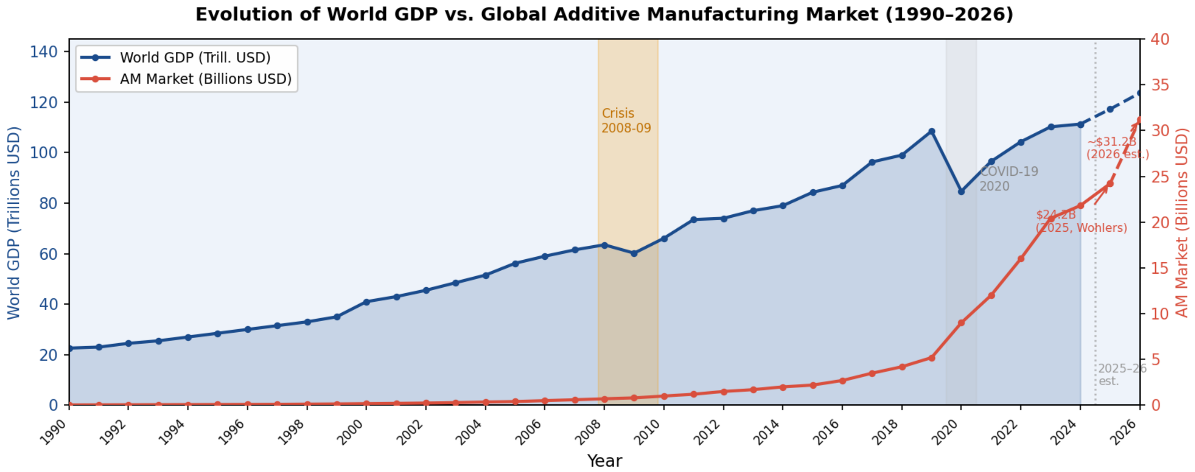

Figure 1. Evolution of World GDP vs Global Additive Manufacturing Market (1990–2026). Source: World Bank (2025), IMF, 2026 (GDP); Wohlers Associates annual reports 2024–2026 (AM market) / own elaboration. 2025–2026 figures are estimates/projections.

This paper fills each of these three voids. First, it presents a longitudinal quantitative analysis of the relationship between the global additive manufacturing market and world GDP from 1990 to 2026. Second, it outlines and examines the mechanisms through which additive manufacturing influences total output at the macroeconomic level. Finally, this paper situates these findings within a cognitive sustainability framework (Zöldy et al., 2022), suggesting that additive manufacturing constitutes a cognitively sustainable technology whose structural alignment with the objectives of the green transition, digital transformation, and resilient economic development enables its widespread adoption.

In this context, cognitive sustainability is not treated merely as an abstract interpretative lens, but as an operational framework that links technological change to measurable economic outcomes. Specifically, additive manufacturing is assumed to enhance the efficiency of knowledge utilisation in production systems, thereby enabling higher output with reduced material and energetic inputs. This study therefore interprets the long-term growth dynamics of additive manufacturing not only as a technological diffusion process but also as an observable manifestation of increasing cognitive intensity in economic production.

The remaining sections of this paper are organized as follows: Section 2 contains information regarding data sources and methodologies employed. Section 3 reports on the longitudinal relationships between the global additive manufacturing market size and world GDP. Section 4 examines macroeconomic mechanisms through which additive manufacturing generates total output. Section 5 offers insights based on those findings relative to cognitive sustainability. Section 6 includes conclusions, recommendations for policy action, and areas for future research.

Based upon our premise, we hypothesise that additive manufacturing market growth is structurally de-coupled from conventional business cycles and transmits influence on total output through new cognitive-economic transmission channels that support principles of sustainable development.

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2. Methodology

This research employs a quantitative longitudinal design that integrates secondary data and descriptive statistics. The primary dataset covers annual observations from 1990 to 2026 across two variables: world GDP (in trillions of USD) and global AM market size (in billions of USD).

2.1. Data sources

The 1990–2024 world gross domestic product (GDP) data were sourced from the World Bank's open database (World Development Indicators, series NY.GDP.MKTP.CD) in nominal USD. In 2025, we used an estimate of $117.2 trillion from the International Monetary Fund (IMF) World Economic Outlook, April 2026. The 2026 estimation of $123.6 trillion is from the IMF World Economic Outlook, October 2025.

Market data for additive manufacturing (AM) from 1990 to 2025 were drawn from the Wohlers Report annual series (Wohlers Associates/ASTM International). The Wohlers Report 2025 confirmed that the 2024 market size was $21.8 billion. The Wohlers Report 2026 confirmed that the 2025 market size was $24.2 billion. Our estimate of the 2026 AM Market, at approximately $31.2 billion, is based on a consensus estimate.

2.2. Analytical methods

The analytical procedures applied in this study are based on standard descriptive and longitudinal economic analyses and are explicitly defined to ensure reproducibility. Year-over-year growth rates for both the global additive manufacturing market and world GDP were calculated as the percentage change from one year to the next.

Market penetration of additive manufacturing was expressed as a share of world GDP by converting both series into consistent monetary units. Specifically, the AM market value, expressed in billions of USD, was divided by world GDP, expressed in trillions of USD, and multiplied by 0.1 to obtain a percentage. An indexed growth series was also constructed by normalising both variables to a common base year (1990 = 100), allowing direct comparison of relative growth dynamics independent of absolute scale effects.

Data harmonisation was required due to the integration of multiple sources. GDP data from the World Bank and IMF were cross-validated for consistency in nominal terms, while AM market data derived from the Wohlers Reports were compared across editions to ensure continuity in definitions. Estimated values for 2025 and 2026 were incorporated based on IMF projections and consensus market estimates, and these were treated consistently with observed data while explicitly acknowledged as projections subject to uncertainty.

All computations and visualisations were performed using Python 3.11 with the Matplotlib library. Data validation included consistency checks across time series, identification of outliers, and verification of growth rates against published benchmarks. The analysis remains primarily descriptive, but the longitudinal structure allows for robust identification of structural trends over time.

The analytical actions that were taken on the data are the following.

- Year-over-year growth rates were estimated for both World GDP and the AM Market across all yearly observations.
- The compound annual growth rates (CAGRs) for each of the four identified growth phases: 1990–1999, 2000–2009, 2010–2019, and 2020–2025.
- Market penetration of the AM Market was expressed as a percentage of the World GDP, which was calculated by taking the amount of money in billions of dollars for the AM Market divided by the total amount of money in trillions of dollars for the World GDP.
- An Index of Relative Growth was created, with 1990 as the base year (100) for each of the two series, so that a direct comparison could be made visually and quantitatively of their growth patterns.
- Historical data related to price changes over time for traditional 2-D Printers (Laser, Ink Jet) and 3-D Printers (Industrial Plastic, Consumer FDM, Industrial Metal) were collected from various sources (3DSourced, 2024; UnionFab, 2023; All3DP, 2025) and standardised to an Index = 100 based upon data from 1990.

All data processing and chart generation were completed using Python version 3.11 along with the Matplotlib Library. The analysis is a descriptive-inferential analysis based upon longitudinal economic studies found within the sustainability literature (Niaki and Nonino, 2017).

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The division of the analysis into four growth phases is not purely chronological, but reflects identifiable structural shifts in the technological and institutional development of additive manufacturing. The first phase corresponds to early industrial experimentation under high capital constraints; the second to sectoral consolidation and material diversification; the third to technological diffusion driven by patent expirations and the entry of new firms; and the fourth to rapid expansion supported by global shocks and policy-driven investment. This classification is therefore grounded in a combination of technological milestones, market developments, and institutional responses rather than arbitrary temporal segmentation.

2.3. Operationalisation of cognitive sustainability

To establish a direct analytical link between additive manufacturing and cognitive sustainability, the concept is operationalised using observable economic proxies. In this study, cognitive sustainability is defined as the ability of a production system to increase output while reducing reliance on physical inputs by enhancing the use of information, design intelligence, and digital technologies.

Although these indicators do not directly capture cognitive processes, they provide a consistent empirical basis for interpreting the structural transition toward cognition-intensive economic systems.

2.4. Scope and limitations

The findings of this study are subject to several important limitations. First, the analysis relies on globally aggregated data, which necessarily obscures heterogeneity across countries, industries, and firm sizes. The economic effects of additive manufacturing may differ significantly depending on institutional context, technological capability, and sectoral composition.

Second, the dataset integrates both observed and estimated values, particularly for the years 2025 and 2026. While these estimates are based on authoritative projections and consensus market analyses, they introduce an additional layer of uncertainty into the results.

Third, the analysis is conducted in nominal terms, which do not account for inflationary effects. Although this approach ensures consistency across datasets, it may distort long-term comparisons of real economic performance.

Fourth, the descriptive nature of the methodology limits the ability to establish causal relationships. While strong correlations and structural patterns are observed, further research using econometric or panel-data methods would be necessary to quantify causal effects rigorously.

Finally, measurement uncertainty in market size estimates for additive manufacturing remains an inherent limitation due to differences in reporting methodologies across sources.

3. Results

This section presents the empirical findings derived from the longitudinal dataset in a strictly descriptive manner. Interpretative and theoretical implications are deliberately reserved for Section 4 in order to maintain a clear distinction between observed results and their analytical interpretation.

3.1. Longitudinal market growth (1990–2026)

The overall AM market grew from \$0.03 billion in 1990 to \$24.2 billion by 2025 (Wohlers Associates, 2026), an increase of about 807-fold over 35 years. During that time, the world's Gross Domestic Product (GDP) went from \$22.6 trillion to \$117.2 trillion. The AM industry's share of world GDP has grown from 0.0000133 per cent in 1990 to 0.0206 per cent in 2025. That represents an influence approximately fifteen to fifty-five times greater on world GDP.

There have been four stages of AM growth based upon different technological and institutional factors driving growth during these periods:

Initial Phase (1990–1999) The AM industry grew at a compound annual rate of 16.6%. The first twenty years saw the initial development of AM into an industrial tool capable of producing prototypes. Equipment costs were high, typically ranging from \$100,000 to \$300,000.

Consolidation Phase (2000–2009) The AM industry grew at a compound annual rate of 16.7%. This phase of growth included the aerospace and medical industries adopting serial production using additive processes. Metal powder and photo-polymer materials were added to the existing limited list of available materials (Ficzere, 2015).

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Take-off Phase (2010–2019) The AM industry grew at a compound annual rate of 22.3%. In this third phase of growth, there was an explosive number of new companies entering the industry. Several of these companies provided open-source designs for FFF/FDM machines and offered low-cost equipment to consumers. By the end of this decade, desktop FFF/FDM machines had dropped in cost from $15,000 to under $200.

Acceleration Phase (2020–2025) The AM industry grew at a compound annual rate of 21.9%. A major catalyst for the rapid growth in this fourth phase was the global response to the COVID-19 pandemic.

Governments around the world invested billions of dollars to support their national economies by strengthening domestic manufacturing capabilities. Additive manufacturing systems are increasingly recognised as part of emergency preparedness plans for critical supplies. As such, services accounted for 48% of the AM industry's revenue (Wohlers Associates, 2026).

To enhance transparency, all reported growth rates, index values, and penetration measures were calculated directly from the underlying dataset and can be reproduced using the formulas defined in Section 2.2. While the present study emphasises narrative interpretation, the dataset's structure allows straightforward tabulation and graphical representation of these indicators, which are available upon request.

3.2. A cyclical behaviour relative to GDP

The most significant result was that market growth in the AM industry outpaced world GDP during all three major economic downturns. During the global financial crisis of 2008–2009, world GDP declined by 5.2 per cent, and the AM market expanded from $0.70B to $0.80B, a 14.3 per cent increase. In 2020, when the COVID-19 pandemic caused world GDP to decline in nominal terms, according to IMF estimates, the AM market increased in nominal U.S. dollars by 73.1%, expanding from $5.20B to $9.00B. This non-cyclic behaviour of AM industry expansion during times of economic contraction provides evidence of its structural property as an emergency production tool and strategic investment category, and not a discretionary industrial purchase.

From a cognitive sustainability perspective, this non-cyclical growth pattern suggests that additive manufacturing serves as an adaptive production system capable of reallocating cognitive resources under economic stress. Unlike capital-intensive conventional manufacturing systems, which are highly sensitive to business cycles, additive manufacturing remains relevant to production due to its flexibility, digital controllability, and low reconfiguration costs.

3.3. Price democratisation

The most significant structural force behind the rapid expansion of the global AM industry has been the dramatic and ongoing decrease in the cost of 3D printing technology compared with traditional two-dimensional (2-D) printing technology. From 1990 through 2026, the cost of entry-level laser printers decreased by 98.4%, from approximately $2,395 to $38. For their part, the costs of entry-level industrial plastic AM systems declined by 99.9% over the same time frame, from approximately $250,000 to $200. Using a 1990 = 100 basis for comparison, the price of industrial plastic AM equipment fell roughly 1,250 times faster than that of entry-level laser printing machines. The resulting "price compression" was largely driven by a series of patent expirations beginning in 2009. It greatly expanded the potential end-user base for AM, from a few thousand major corporate users worldwide to hundreds of millions of individual consumers and business owners globally. This larger base generated the additional demand required to support the growth observed in each of the three stages of AM growth described previously (Alzyod, Ficzere, Borbas, 2024).

In terms of industrial metal AM systems, which were priced at $800,000 in 1995, the initial entry point into this segment of the market dropped to approximately $100,000 in 2026, an overall price reduction of 87.5%. Despite these declines in pricing, metal AM systems remain unaffordable for small and medium-sized enterprises (SMEs); however, the emergence of several Chinese-based manufacturers, including Farsoon, BLT and Eplus3D, is creating increasing competition and will continue to accelerate downward price movement for metal AM systems, potentially making them affordable for SMEs (World Bank, 2025).

This process can be interpreted as a large-scale expansion of accessible productive cognition. As the cost of entry declines, an increasing number of actors gain the capability to transform digital knowledge into physical output, thereby extending the distribution of productive intelligence across the economy. This diffusion mechanism represents a core empirical manifestation of cognitive sustainability.

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4. Analysis

To clarify the interaction between additive manufacturing and macroeconomic performance, the three transmission channels are conceptually integrated into a unified framework. This framework links technological capability to economic outcomes through productivity enhancement, market expansion, and resilience, while embedding these processes within the broader concept of cognitive sustainability.

The three economic transmission channels identified in this section can be interpreted as specific mechanisms through which cognitive sustainability is realised in practice. Each channel represents a distinct pathway through which cognitive capabilities embedded in additive manufacturing technologies translate into measurable economic outcomes.

4.1. Economic transmission channels

The results presented in Section 3 are consistent with a multi-channel theory of AM's economic influence. Three primary transmission channels are identified and analysed below.

4.1.1. Total Factor Productivity (TFP) channel

Additive Manufacturing improves Total Factor Productivity in three ways.

Part consolidation Complex multi-component assemblies are now being produced as a single, consolidated part. This results in reduced assembly labour, fewer parts and lessened supply chain complexity. The GE Aviation LEAP Engine Fuel Nozzle is an excellent example of this. It was originally made from 20 different parts and has been consolidated into a single titanium part; it also weighs 25 per cent less than its predecessor. GE Aviation claims to have already exceeded production levels of over 40,000 of these units annually (GE Aviation, 2024).

Design freedom and topology optimisation Additive Manufacturing allows for designs to be created using geometries that cannot be achieved with traditional subtractive machining methods. Software-driven topology optimisation has led to reported weight reductions of 20-50%, resulting in lower raw materials input per unit of output.

Compressing lead time Tooling requirements are eliminated with additive manufacturing, so the design-to-physical-part process takes weeks or months rather than hours or days. As a result, the pace of innovation is accelerated, and there is less investment in the development process.

The mechanisms described above support Hulten's model of embodied technical change in that once new technologies are implemented, they increase overall productivity and, therefore, improve aggregate Total Factor Productivity (TFP). The increased global adoption rate of additive manufacturing (documented in Section 3) is evidence that producers worldwide are beginning to embed these productivity enhancements in their existing capital stock.

In this sense, improvements in total factor productivity enabled by additive manufacturing can be understood as direct outcomes of increased cognitive efficiency, in which better design intelligence and process control substitute for traditional material and labour inputs.

4.1.2. New markets and distributed manufacturing channel

AM generates economic value by creating entirely new markets and business models with no conventional equivalent. Manufacturing-as-a-Service (MaaS) platforms, such as Materialise (Belgium), Xometry (USA), and Shapeways (Netherlands/USA), generate productive capacity in geographic areas that previously lacked manufacturing capability. They also create output and jobs without requiring large amounts of capital to build a traditional factory. Xometry's 2021 IPO valued the company at over $1.5B, providing significant market validation of this MaaS model.

A World Bank study (Freund et al., 2020) found that there has been an increase in trade related to hearing aids of approximately 58% from the year prior to when AM was adopted into that product category and the subsequent ten years after. This demonstrates that cost reductions created by AM will expand both demand and trade associated with the products being manufactured instead of reducing trade.

The emergence of distributed manufacturing models further illustrates how cognitive sustainability expands economic participation by lowering the cognitive and capital barriers required to engage in production.

4.1.3. Supply chain resilience channel

COVID-19 presented an ideal "natural experiment" to demonstrate AM's ability to provide resilient supply chains. In the initial weeks of COVID-19, within hours of the global outbreak, millions of face shields, ventilator parts, and nasal swab

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units were being printed around the globe. This demonstrated emergency response capabilities to produce life-saving products on short notice, the most visible evidence of how responsive AM could be as a means of responding to crises (Javaid & Haleem, 2020), which was also reflected in the acceleration of the AM marketplace between 2020 and 2021.

The United States Department of Defence (DoD) invested approximately $300M into additive manufacturing in 2023; by 2024, this investment had increased to $797M (AM Research, 2024); these investments reflect DoD's strategic assessment that having additive manufacturing capacity distributed throughout the country represents critical defence industrial base infrastructure. Therefore, this geopolitical element of additive manufacturing acceptance indicates that it has both technological and institutional reinforcement mechanisms, which will support long-term non-cyclic growth trends for additive manufacturing. Thus, government investment will create a floor for additive manufacturing demand, regardless of what the private sector may experience with respect to overall economic performance.

The resilience observed in additive manufacturing during crisis periods highlights its role as a cognitively adaptive system, capable of rapidly reconfiguring production in response to external shocks.

4.2. Limitations and alternative explanations

Several caveats limit our interpretation. For example, the non-cyclical growth we see in Section 3.2 may also represent an impact from composition: given the relatively small size of AM markets when compared to overall GDP, it is possible for year-over-year increases in the amount of AM produced (even if they are moderate) to appear larger than expected in terms of percentage changes. This said, the fact that there has been a roughly 18-percentage-point differential in the annualised compound growth rate (CAGR), over many decades, about 22 per cent for AM vs. around five per cent for GDP, is unlikely to be driven solely by compositional factors and likely represents some underlying structural factors.

It is also difficult to estimate TFP's contribution at the macroeconomic level due to a lack of appropriate data. Determining precisely how much productivity was affected would require conducting micro-econometric studies of individual firms.

5. Cognitive sustainability framework

The empirical findings presented in this study provide multiple lines of evidence supporting the interpretation of additive manufacturing as a cognitively sustainable technology. Rather than constituting an auxiliary conceptual layer, cognitive sustainability emerges here as an integrating principle that explains the observed structural properties of additive manufacturing across growth dynamics, cost evolution, and economic resilience.

Cognitive sustainability, as identified by Zöldy et al. (2022), portrays sustainability issues as cognition and/or machine cognition issues: How can we deploy existing cognitive capabilities in society (i.e., including Digital Technologies, AI, AM etc.) to optimise resource utilisation and extend productive capacities while enabling human value creation under planetary boundaries? Cognitive Sustainability offers a particularly suitable lens for analysing additive manufacturing.

AM fundamentally constitutes a form of cognitive technology: it transforms the digital design intelligence generated by humans and/or, increasingly, by Artificial Intelligence (AI) into directly produced physical objects, effectively eliminating the gap between production planning and product realisation. With the advent of AI-driven generative design (e.g., Autodesk Fusion 360, nTopology), the cognitive aspect of AM has become even more pronounced. Specifically, modern AM systems are increasingly receiving instructions from AI algorithms that perform geometric optimisation based on the design requirements of the object being created, representing the fusion of artificial and biological cognitive systems with engineering applications (Zöldy et al., 2022).

In terms of cognitive sustainability, the price democratisation of AM described in Section 3.3 represents a democratisation of productive cognitive capacity. That is, the ability to convert digital designs into physical products at near-zero marginal cost per additional design iteration is now accessible to individuals and small and medium enterprises (SMEs) who could not previously manufacture. This supports one of the principles of cognitive sustainability that for sustainable development to occur, there must be a widespread distribution of cognitive tools (and not just a concentrated distribution among large organisations).

Additionally, the environmental component of cognitive sustainability is also applicable. Studies examining life cycle assessments of AM compared with traditional mass production methods demonstrate material efficiencies of 41–64 per cent. These findings reflect the improved "cognition" associated with utilising materials more effectively – i.e., applying materials in areas where they are structurally necessary according to computational analysis rather than producing unnecessary

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amounts of scrap or waste through subtractive processing. Additionally, AM's support for circular economy goals – i.e., enabling the repair/refurbishment of parts via directed energy deposition (DED) technologies – further expands upon the cognitive sustainability characteristics of AM.

Taken together, the observed patterns indicate a systemic shift in the production function, where cognitive inputs increasingly substitute for material and energy inputs. This transition is consistent with the core premise of cognitive sustainability, namely that long-term economic development can be achieved by expanding and more efficiently utilising cognitive resources rather than by proportional increases in physical resource consumption (Zöldy et al., 2022).

6. Conclusion

This paper provides longitudinal evidence that the additive manufacturing market grew at an exceptionally rapid rate relative to global economic output between 1990 and 2025. The findings suggest structural patterns linking the expansion of additive manufacturing to broader economic dynamics; however, these relationships should be interpreted with caution, given the analysis's descriptive nature.

Firstly, the rate of growth in the AM market was anti-cyclical with respect to GDP; i.e., during the two major recessions since 1989 (the 2008–09 Global Financial Crisis and COVID-19), the AM market continued to grow at a high rate due to its investment character and ability to be used as an emergency production tool. This anti-cyclical nature offers important portfolio opportunities for government agencies and private companies seeking to increase their economic resilience.

Secondly, price democratisation has been identified as the primary structural driver of the rate of adoption of AM technologies and the resulting economic impacts. The 1250-fold decline in the prices of industrial 3D printers compared to traditional laser printers between 1990 and 2026 greatly increased the number of users, from fewer than a few hundred large corporations to hundreds of millions of potential users. Each successive reduction in the cost of industrial AM equipment will lead to additional increases in productivity.

Lastly, AM is a cognitively sustainable technology: it extends human productive cognition, reduces physical resource utilisation, and democratises manufacturing capabilities, thereby contributing to the paradigm of cognitive sustainability, which seeks to maximise human value creation given resource constraints (Zöldy et al., 2022).

The three findings above support the following policy recommendations.

First, governments should consider investing in AM-related infrastructure in the same way they invest in other sustainability infrastructure, such as renewable energy and public transportation, including training, equipment sharing, and research and development funding.

Second, based on Eurostat (2024) data, there is a substantial difference in metal AM usage rates between small and medium-sized enterprises (SMEs) and large enterprises. Specifically, while 47 per cent of large European enterprises use metal AM, only 12 per cent of European SMEs do. This disparity represents the final barrier to realising the full macroeconomic benefits associated with AM's productivity and sustainability advantages. Therefore, reducing this disparity through measures such as subsidy-based equipment access programs, the establishment of digital manufacturing centres of excellence, and vocational training curricula specifically designed around AM will yield measurable co-benefits for GDP and sustainability.

Third, future research should build on these findings by employing panel data methods across individual countries and sectors.

While the results highlight potentially important implications for industrial policy and sustainable development, the conclusions drawn in this study remain indicative rather than definitive. Future research should aim to validate these findings using more disaggregated datasets and causal inference methods, thereby strengthening the empirical foundation of the proposed theoretical framework.

The contribution of this paper lies in demonstrating that the growth of additive manufacturing is not only a technological or economic phenomenon, but also a structural indicator of the transition toward cognitive sustainability. The empirical evidence suggests that additive manufacturing embodies a production paradigm in which knowledge, design intelligence, and digital control progressively replace material intensity as the primary drivers of value creation. This interpretation provides a coherent link between observed market dynamics and broader sustainability objectives, thereby offering a unified framework for future research at the intersection of technology, economics, and sustainability science.

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The relationship between gentrification and public transport investments: A study on French cities

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Abstract
Socio-spatial dynamics, such as gentrification, often result from urban planning and development processes that include public transport investments. The construction of a new tramline (or light-rail transit, LRT) is one of the most impactful transport infrastructure projects that can be implemented within a territory. This work focuses on the fourth tramline in Bordeaux (France), which crosses 3 suburban municipalities with different accessibility and socio-economic profiles. It aims to evaluate the impact of this project on multiple indicators: population density, the socio-professional composition of the population, average household income, and the number of poor households, to detect a possible gentrification process. Municipal data, as well as grid-based data from the French national statistics institute, were used to obtain a global view of cities' dynamics, and a more precise view at a 200 × 200 m cell scale. Using a GIS tool and R for visualisation, the evolution of those indicators over the course of the implementation was studied. The results show an acceleration in density growth, most evident in the peripheral cities farthest from the city centre, as well as a subtle, nuanced increase in the proportions of higher-income socio-professional groups. Gridded data on the population's income along the tram's route yield mixed conclusions: the study does not allow for the identification of a clear ongoing gentrification process. The research could be completed by evaluating other urban development indicators, such as housing market trends, and by collecting more data on the years following the launch to establish the project's long-term impact.
Keywords*: gentrification, public transport, tramline, tramway, attractive neighbourhood, socio-spatial dynamics*

1. Introduction

In France, urbanisation occurred largely through the growth of existing cities since the 1950s (Eaton and Eckstein, 1997). Over the past decade, approximately 80% of the population has lived in urban areas, reflecting a strong concentration of inhabitants in metropolitan areas (Veneri, 2018).

1.1. Transport infrastructure development as a factor of special gentrification

Spatial gentrification refers to a process of neighbourhood change characterised by the socio-economic upgrading of an area, typically through the arrival of higher-income households and the displacement or replacement of lower-income populations. This metamorphosis of the territory's social profile is often accompanied by changes in housing markets and the built environment (Nilsson and Delmelle, 2018). Previous studies often describe the process as the result of interactions between multiple urban dynamics rather than a single cause, including transport accessibility, land and housing market pressures, and public or private redevelopment (Padeiro et al., 2019). Therefore, gentrification is the spatial manifestation of urban restructuring processes influenced by infrastructure investment, neighbourhood rehabilitation, and development (Bardaka et al., 2018).

Transport infrastructure is frequently identified as an important factor in gentrification because it improves accessibility and reduces travel costs relative to personal vehicles (Dong, 2017). Rail-based systems, particularly those integrated into transit-oriented development (TOD) strategies, can enhance neighbourhood appeal and stimulate land development around stations (He et al., 2021). Improved accessibility may then be reflected in higher property values and changes in residents' socio-economic profiles (Bardaka et al., 2018). However, transit investments do not systematically generate gentrification, as local demographic conditions and planning policies also influence outcomes (Crescenzi and Rodríguez-Pose, 2012; Padeiro et al., 2019).

In this perspective, transit-induced gentrification should be understood as a contingent and context-dependent process, in which accessibility improvements act as a catalyst rather than a deterministic driver. The socio-spatial outcomes depend on the interaction between transport investment, housing supply conditions, planning

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regulations, and resident mobility strategies. This theoretical position guides the empirical interpretation developed in the present study.

1.2. A study on a French city: Bordeaux's 4th tram line

In 2020, tramline D was launched in Bordeaux, a city in southwestern France (Fig 1). The project was announced publicly in 2009; construction began in 2017 and was completed in 2019, followed by the trial period. In December 2019, the first section began operating, and in February 2020, the entire line was launched, serving 3 suburban municipalities outside of Bordeaux (Ligne D du tramway de Bordeaux, 2026).

Figure 1. Route of the tramline D in Bordeaux, France (Ligne D du tramway de Bordeaux, 2026)

Bordeaux is France's 9th largest city, with around 270 000 inhabitants in 2026 (Marin et al., 2024). and its current public transport network has been developing since 2004 (Dupas et al., 2023). Regarding its mobility profile, in 2021, 40% of intra-Muros inhabitants used the car as their main mode of transport (the average for the 20 largest French cities). Still, it was 64.4% in its agglomeration, ranking it the largest of the 20. It was in the lower half for the proportion of people using public transport within the Muros and in the agglomeration (Adetec, n. d.).

This project affects multiple cities (Bordeaux, Le Bouscat, Bruges, and Eysines – later referred to as 0, 1, 2, and 3 to indicate their distance from the city centre) and neighbourhoods, not on the same scale, depending on the infrastructure route or the existing demographics at the beginning of the project.

The most recent LRT infrastructure, which is the focus of this study, crosses Bordeaux and 3 cities in the metropolitan area. The project traverses substantial portions of both Le Bouscat and Eysines, while entering Bruges only along the municipal boundary.

The impact of this new infrastructure on the central city of the metropolitan area, Bordeaux, will not be as widely discussed as its effect on the suburban area, since many other transit modes were already operating before its implementation, potentially leading to interference with the measured indicators. Moreover, the city closest to the centre also benefits from this extensive transport network, which might explain the lower changes after the opening of the tramline.

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1.3. The study hypothesis

The hypothesis investigated in this study is that the introduction of a new tramline within a metropolitan area induces spatial gentrification, characterised by the settlement of higher-income social groups and an increase in local living standards, particularly in areas located close to the tram route.

In addition to its urban and transport dimensions, this study is situated within the broader framework of cognitive sustainability, which conceptualises sustainability as the efficient utilisation and distribution of knowledge, decision-making capacity, and informational resources within socio-technical systems. In this perspective, transport infrastructure, such as tramway systems, not only modifies physical accessibility but also reshapes how individuals perceive, evaluate, and utilise urban space. Accessibility improvements can therefore be interpreted as a transformation of cognitive opportunity structures, influencing residential choices, mobility behaviour, and long-term socio-spatial organisation.

1.4. Methodology overview

An LRT is considered to be a more structuring transit mode in urban planning than a bus, due to the permanence of its infrastructure (Dubé et al., 2018). This leads to more confidence in the sustainability of its attractivity, and its capacity to influence significatively property value on its route. Introducing an LRT service also has a broader impact, affecting value up to hundreds of meters around compared to less than a hundred for a Bus Rapid Transit (BRT) (Zhang and Yen, 2020). A BRT system could affect the study if it is located near the LRT, with a dedicated lane (Ingvardson and Nielsen, 2018), but that is not the case in the focus territory. Furthermore, the other tramline in Bruges is over 1 km away from the studied area and was launched in 2016 (Ligne C du tramway de Bordeaux, 2026).

The following visualisation tools were used to identify the socio-demographic dynamics created by the construction of a tramline in a neighbourhood and, consequently, the increase in accessibility, using indicators such as population evolution, age group evolution, socio-professional categories (later referred to as SPC), inhabitants' standard of living, and housing prices.

2. Data sets, visualisation and modelling tools

The data used for this study are from the French National Institute of Statistics and Economic Studies (INSEE), which provides access to population evolution data for each municipality each year. This data set contains many precise categories, such as population in each age category, where the inhabitants lived the year before, and, most importantly for our study, their SPC. To identify the possible impact on the territory, data collection starts with the public announcement year of the LRT construction and ends in 2022, the last census year available at the time of the study.

Moreover, the impacts of a project on a neighbourhood at a more local scale were identified using grid-based data and analysed with the GIS tool. This data set was only available for 2015, 2017, 2019, and 2021, which cover the phases before and during construction, as well as a year after launch.

2.1. Indicators calculation using a GIS tool

2.1.1. Accessibility indicator

Access to urban opportunities is commonly modelled in the literature as a function of generalised travel cost, which is a combination of access to infrastructure and in-vehicle (here, in-tram) distance (Kapatsila et al., 2023). This indicator, Accessibility (Eq. 1) was calculated using the shortest distance from the center of mass of each square area (200 × 200 m) to the tram stops (it was considered that the shortest distance was a straight line, between the cell's centroid and the stop, without accounting for parcel boundaries or street network constraints) and the distance from the closest stop to the city center, measured with GéoPortail (n. d.) (1). The most central stop was chosen. The weights for each variable are based on the time spent during each phase of the journey (Wardman, 2004), with access and waiting times weighted more heavily than in-vehicle time (Table 1). Waiting time and tram operating speed were derived from the published weekday timetable. Waiting time was estimated using the average scheduled headway during weekdays (TBM, n. d.). The access speed was set to walking speed because most daily

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public transport trips begin with a walking segment (Hillnhütter and Sick Nielsen, 2026). Accordingly, the catchment area represents users who access the LRT infrastructure on foot for their daily commute.

$$Acc_i = 2{,}5 \cdot \frac{D_{access,i}}{C_{access}} + 1{,}5 \cdot T_{wait} + \frac{D_{in-tram,i}}{C_{tram}} \tag{1}$$

where,

Acc_i is the accessibility calculated for a 200 × 200 m square area;

C_{access} is the access speed to the transit mode (here on foot);

$D_{access,i}$ is the distance between the square area's centroid and the closest stop, disregarding street layouts;

T_{wait} is the average waiting time for the tram to arrive;

$D_{in-tram,i}$ is the summed distance from the closest tram stop from the square area to the city centre stop;

C_{tram} is the tram operating speed.

Table 1. Data for calculating the accessibility indicator

Project	Tramline D in Bordeaux
C_{tram} (km/h)	18.2
C_{access} (km/h) on foot	4
T_{wait} (min)	7.5

This indicator enabled the representation of the accessibility of each square areaon a map (Fig. 2) and the subsequent evaluation of its effects on the socio-demographic variables in each square area. From a transport engineering perspective, the spatial distribution of accessibility reflects the combined influence of access time, waiting time, and in-vehicle travel time within the generalised cost framework. The higher sensitivity of users to access and waiting components implies that relatively small reductions in these components may significantly increase perceived accessibility, particularly in peripheral areas that were previously poorly connected. This helps explain why the greatest relative impacts are observed in municipalities located further from the urban core. These spatial differences in accessibility can also be interpreted as differentiated cognitive landscapes across the metropolitan area. Areas experiencing larger accessibility gains benefit from a relative expansion of perceived opportunities, which may influence residential attractiveness and location choices. This mechanism provides an additional explanatory layer for the observed redistribution of population and socio-economic groups.

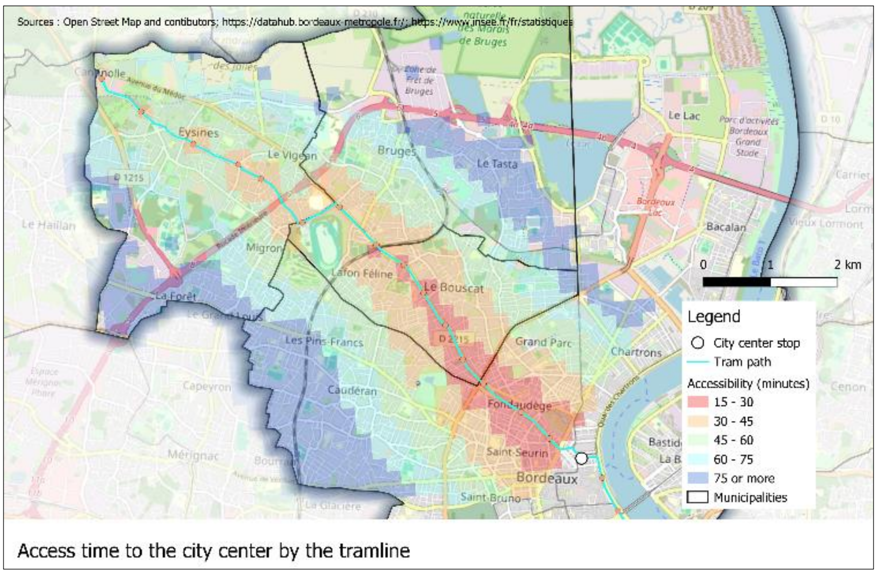

Figure 2: Accessibility time of the city centre from each square area by the tramway (tram stop accessed on foot)
Source: won data

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This heat map gives an idea of how the tramline's impact might be spreading across the territory. However, the furthest cities, which were less accessible before the project's arrival, such as Eysines (the westernmost municipality), are more likely to be affected by it, even though travel times are longer than for cities closer to the central stop. On the contrary, the central city already has extensive public transport infrastructure, so residents living near the new tramline might not use this mode of transit (Kasraian et al., 2019).

The accessibility formulation adopted in this study relies on geometric distances and uniform access speeds, which simplifies the representation of real-world travel conditions. This approach allows for a consistent and transparent comparison across spatial units, but it does not account for network topology, intersection density, pedestrian infrastructure quality, or multimodal interactions. Consequently, the resulting accessibility values should be interpreted as approximations of relative accessibility rather than precise travel times. Future extensions of this work could incorporate network-based shortest-path calculations and multimodal accessibility measures to more accurately capture the spatial structure of urban mobility systems and the interactions between tram services and other transport modes.

From a cognitive sustainability perspective, the accessibility indicator used in this study may be interpreted as a proxy for the cognitive effort required to access urban opportunities. Reductions in generalised travel costs effectively decrease the informational and decision-making burden associated with daily mobility, thereby expanding the set of feasible choices available to individuals. In this sense, accessibility improvements induced by the tramline can be understood not only as gains in physical connectivity but also as enhancements in cognitive efficiency within the urban system.

2.1.2. Average household income

Utilisation of grid-based data for each year and municipality affected by the project enabled measurement of the standard-of-living indicator. A GIS tool was chosen for this study because of the size of the data: it is detailed at 200 × 200-meter squares, using this scale for French data collection. The 35 variables on the age structure of individuals, household and housing characteristics, and income are used to compare the same municipalities over the course of the project realisation. The maps were created for each year and display two indicators: the number of poor households (a variable available in the dataset) and average household income.

$$AHI_i = \frac{Ind\_snv_i}{Nb\ H_i} \tag{2}$$

where,

AHI_i is the average yearly household income for a 200 × 200 m square area;
Ind_snv_i is the sum of the winsorised living standards of individuals in the square area;
$Nb\ H_i$ is the number of households in the square area.

The variable available for income calculation within the data set is the "sum of the winsorised living standards of individuals", Ind_snv_i, which is equal to the sum of the living standards after winsorisation for each 200 × 200m square area. Winsorisation involves replacing extreme values with threshold values to limit the influence of outliers (Winsorisation, 2025). To obtain a more relevant indicator for our study (because the sum of living standards is higher and almost homogenous in the urban area, which does not allow a precise interpretation), the Average Household Income was introduced (2), using the number of households in each square area. The maps obtained for this indicator allow for comparison between different phases of each project.

2.2. Data tidying and visualisation

This tool was first used to get an impression of the 3 population indicators (density, age groups and SPC distribution). To calculate density evolution over time, the precise area covered by each municipality was obtained in the 2022 annual "French municipal administrative divisions based on OpenStreetMap" shapefile from the national open data base (*Data.Gouv.Fr*, n. d.). To assess changes relative to the year in which the project was publicly announced, the data were normalised using that year as the baseline. (3).

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$$Density_{evol} = \frac{\frac{Pop}{Popann}}{A} \times 100 \tag{3}$$

where,

$Density_{evol}$ is the evolution of density for a certain city for the past year;
Pop is the population for the given year;
Pop_{ann} is thin e population the year of the project announcement;
A is the area of the municipality.

The charts for SPC composition of the population are obtained from pivot tables filtered by municipality, to identify differences between all those affected by the project.

It is important to note that the methodological framework adopted in this study is primarily descriptive and exploratory. While it allows identification of temporal and spatial correlations between tramline implementation and socio-economic changes, it does not establish causal relationships. In particular, the absence of a counterfactual reference group limits the ability to isolate the tramline's specific effect from broader metropolitan dynamics. More advanced econometric approaches, such as difference-in-differences or synthetic control methods, could provide a stronger basis for causal attribution and represent a promising direction for future research.

3. Results of the study

The four indicators chosen to identify a gentrification process linked to the arrival of a tramline were calculated using previously developed methods, and the results are presented below. They were then interpreted to analyse the true impact of the new tramline in the neighbourhoods.

3.1. Density evolution

The density trends are strongly differentiated across municipalities (Fig. 3): the two cities furthest from the city centre show a significant increase in density, while the closest city remains nearly stable.

Before the tramline launch (in 2020 for cities 2 and 3), those 2 municipalities follow similar upward trends, suggesting pre-existing metropolitan expansion or suburbanisation dynamics but without strong divergence. Around the project launch, we observe a shift in trends across all three cities, especially in Bruges (municipality 2), where growth accelerates significantly. This timing suggests a possible link to the introduction of the tram line, which may have increased the attractiveness of mid-distance and peripheral municipalities by improving access to the city centre. These areas likely benefit from better connectivity enabled by this new infrastructure, combined with lower land prices and greater residential availability. In contrast, the central municipality's growth may be restrained by housing market saturation and already extensive transit supply (Higgins et al., 2014).

While this does not, in itself, demonstrate gentrification, it suggests a restructuring of the territory's spatial attractiveness that can serve as a base mechanism for future spatial gentrification processes.

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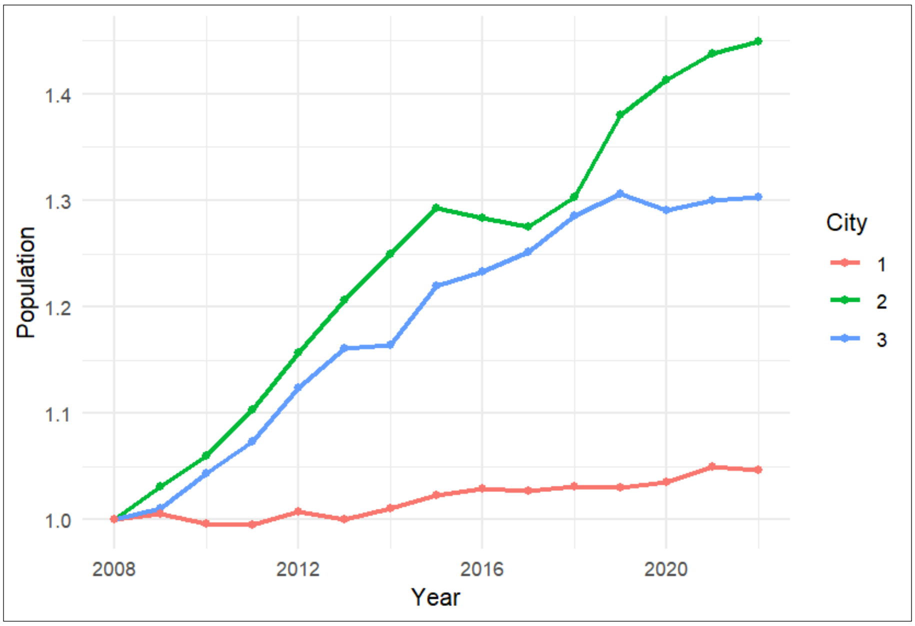

Figure 3. Density evolution of the 3 suburban cities crossed by the new LRT service

From a cognitive sustainability perspective, the observed increase in density in peripheral municipalities may reflect adjustments in how households process spatial information and evaluate trade-offs among location, accessibility, and housing costs. Improved transport connectivity reduces perceived distance to the urban core, effectively reconfiguring the metropolitan area's mental map and enabling previously less attractive locations to become competitive residential alternatives.

3.2. Socio-professional categories

For the first project, in Bordeaux (announced in 2009, operating since 2020), the chart visualisation of the evolution of socio-professional categories of the population (Fig. 4), the observation can be made that higher income categories indeed come to settle over the years, such as "executives", "intermediate professions" or "retired". However, the "blue-collar workers" category has decreased over the years. The impact of the project's launch can be identified around 2020, with a sudden shift in trends among some groups. The most obvious example is in the third city (further from the city centre), where the "executives" trend replaces the "blue-collar workers" trend.

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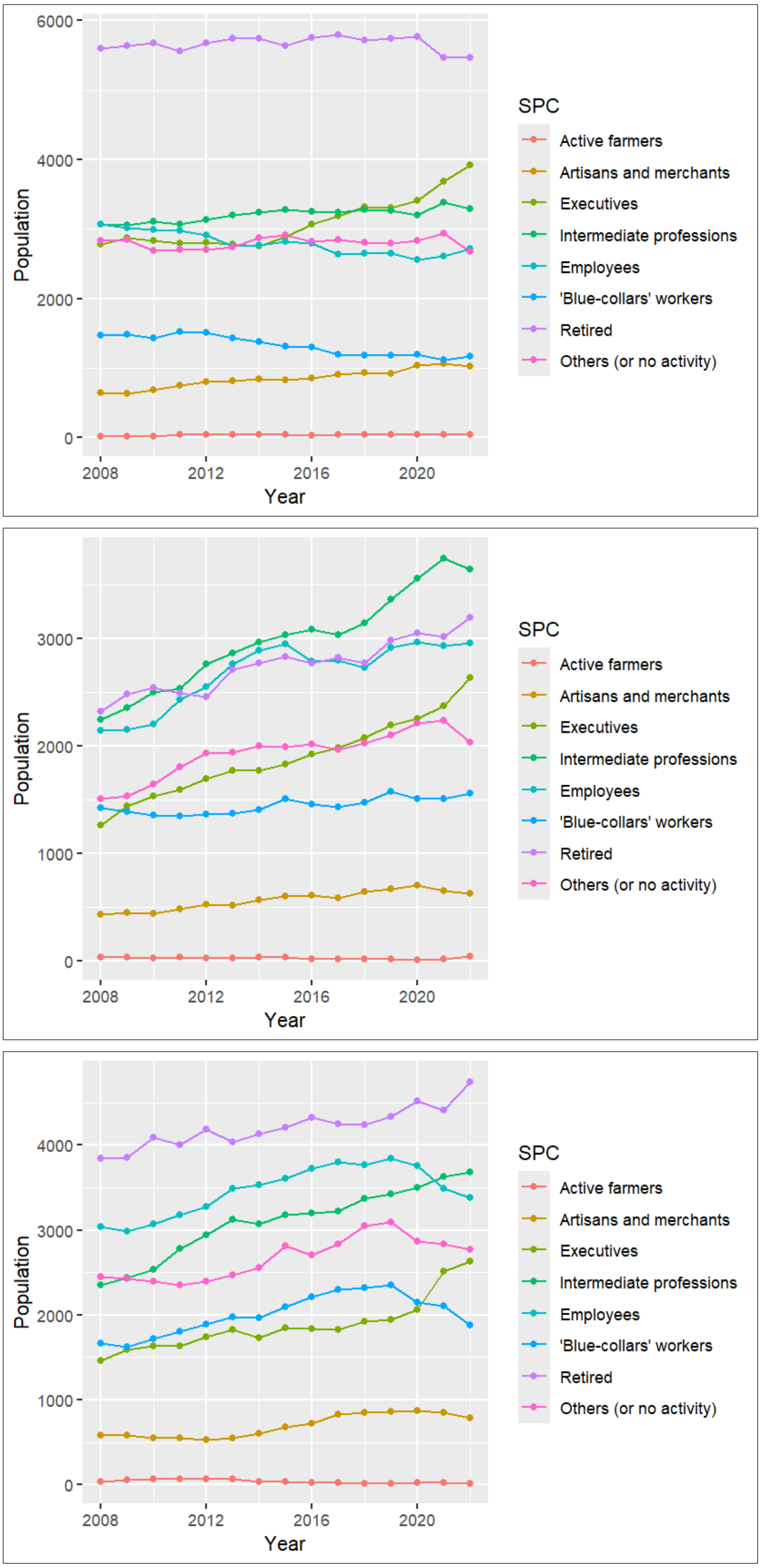

Figure 4. Evolution of socio-professional categories representation in the 3 metropolitan cities affected by the project (Bordeaux) – from left to right: closest to furthest from the city centre

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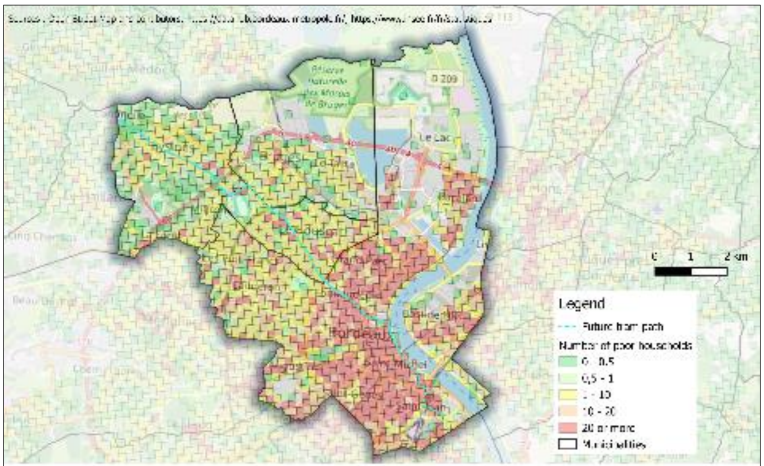
These changes in socio-professional composition can also be interpreted as a selective response to enhanced cognitive accessibility. Higher-income and more mobile groups may be better positioned to recognise and exploit new accessibility advantages, leading to differentiated spatial sorting processes. This suggests that cognitive factors, such as access to information and decision-making capacity, may interact with economic variables to shape the socio-spatial effects of transport investments.

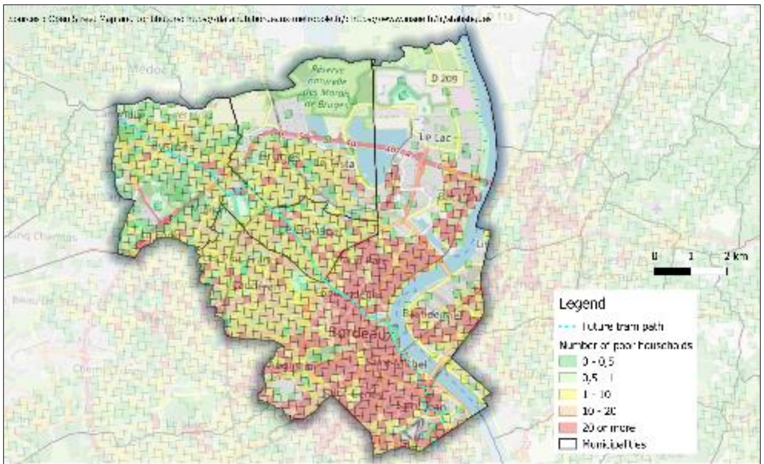
3.3. Standard of living

3.3.1. Number of poor households

As Fig. 5 shows, the number of low-income households in the area studied was already lower than in the city centre, allowing us to observe its evolution during the construction of the tramline and after its launch. However, the prediction that this number would decrease over the course of the project and along the tramline is not verified. The indicator's evolution does not follow a specific trend, and some cells with more low-income households appear along the tramline in 2021, where they were absent in previous years. This leads to the conclusion that this indicator is not really relevant for this study:



Number of poor households in the cities crossing the path of the tramway project - 2015 (before construction)



Number of poor households in the cities crossing the path of the tramway project - 2017 (construction)

https://doi.org/10.55343/CogSust.23730

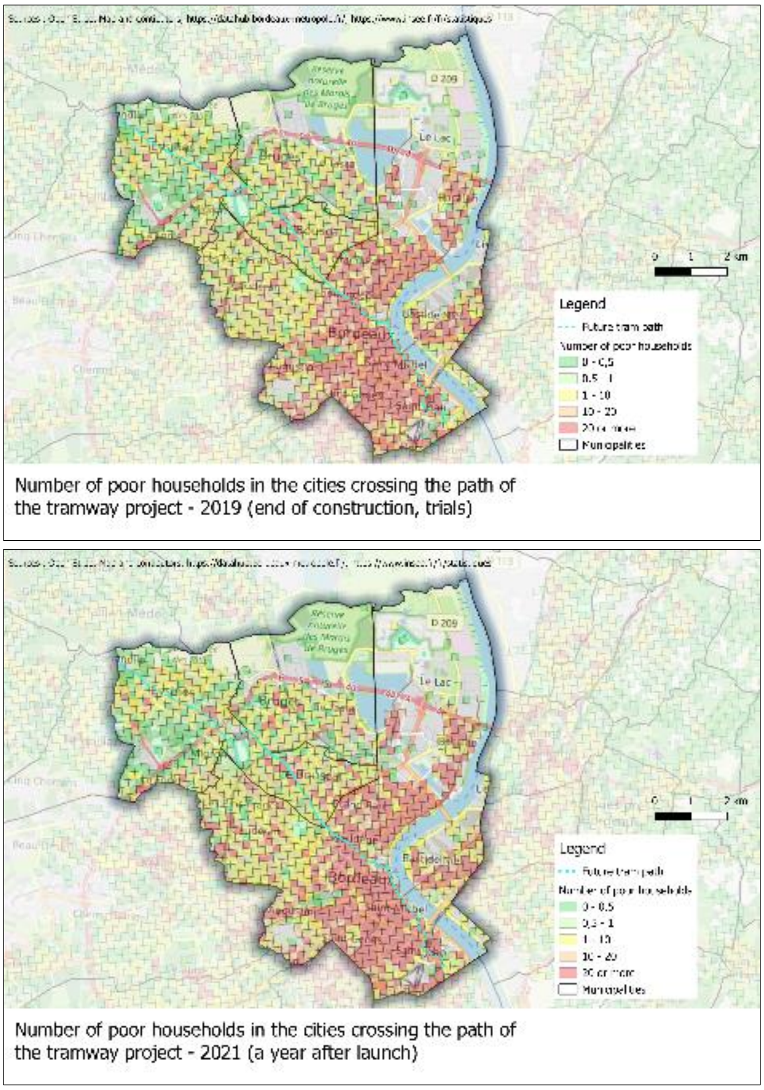


Figure 5. Evolution of the number of poor households over the course of the project: 2015–2021

3.3.2. Average household income (AHI)

The impact of the tram project on the population's standard of living is also evident in the average annual income of households along the tramline. Figure 6 shows the evolution of this indicator over time, in parallel with the project's implementation stages. We observe that along this path, even when the project is not completed, the average income increases. This change is more drastic in the farthest city, but is also observed in Bruges, where the tramline only crosses the municipal boundary. Yet, this area has a more significant evolution than the rest of the territory. Finally, we can see that in Bordeaux's central city, average income increases along the tramline, particularly after its launch, right next to Le Bouscat (the southernmost suburban municipality). However, the effect is minimal at the river's edge and beyond, which is related to the transit supply already being substantial in the city centre.

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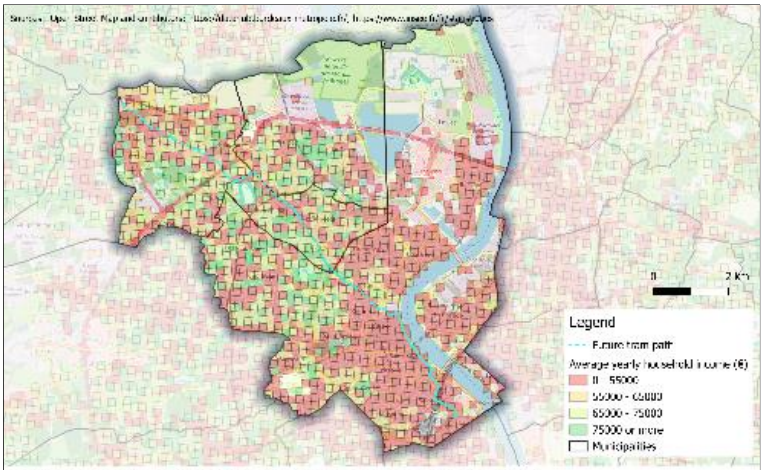
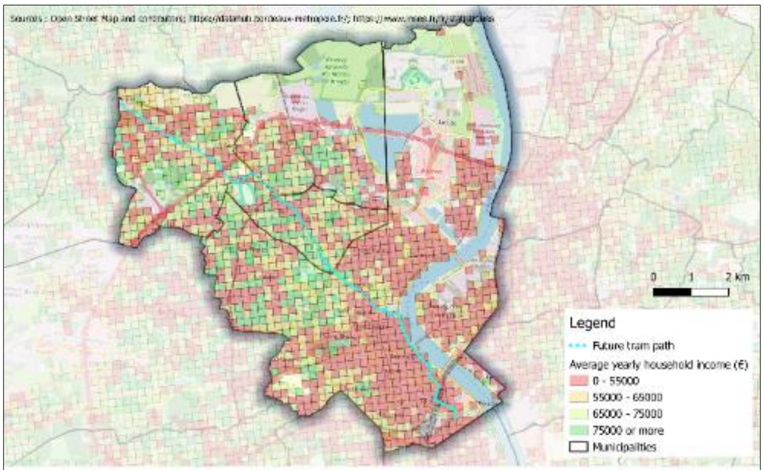


Average household income in the cities crossing the path of the tramway project - 2015 (before construction)



Average household income in the cities crossing the path of the tramway project - 2017 (beginning of construction phase)

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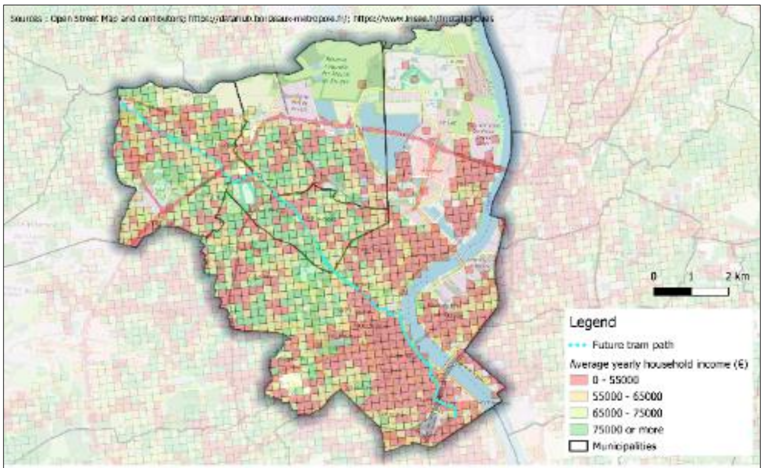
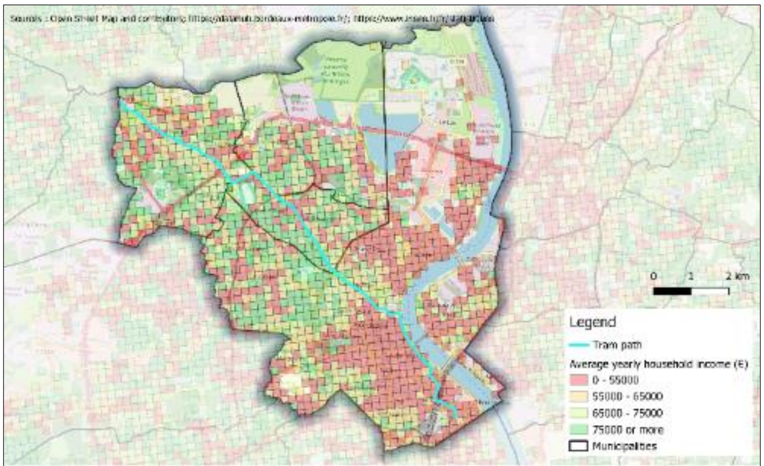


Average household income in the cities crossing the path of the tramway project - 2019 (end of construction phase)



Average household income in the cities crossing the path of the tramway project - 2021 (a year after the launch)

Figure 6: Evolution of AHI over the course of the project: 2015-2021

However, the dataset's temporal scope remains relatively short compared to the typical duration of gentrification processes. Socio-spatial transformations associated with transport investments often unfold over one or two decades, particularly when mediated by housing market adjustments and regulatory frameworks. As such, the absence of clear displacement patterns in the present analysis should not be interpreted as evidence that such processes will not occur, but rather as an indication that they may not yet be observable within the available time horizon.

The increase in average household income observed along the tramline corridor may therefore be understood in part as a manifestation of cognitively driven spatial selection processes. As accessibility improves, households with greater capacity to process and act upon new information about locational advantages may relocate to these areas, reinforcing income gradients without necessarily implying immediate displacement.

4. Analysis and discussion

The empirical findings can be interpreted through the lens of cognitive sustainability, reflecting a broader transformation in how urban space is perceived, evaluated, and utilised. The introduction of the tram not only alters physical accessibility but also modifies the cognitive structure of the metropolitan system by reducing uncertainty, travel complexity, and perceived distance. These changes influence household-level decision-making and contribute to the observed patterns of socio-spatial reorganisation.

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The results suggest a partial and heterogeneous relationship between the introduction of tramline D in the Bordeaux agglomeration and socio-spatial restructuring in the surrounding municipalities, rather than a uniform process of gentrification. The observed increase in density in peripheral municipalities, particularly after the launch phase, is consistent with the idea that fixed rail investments can reshape urban residential attractiveness by improving accessibility and reinforcing metropolitan decentralisation dynamics (Mohammad et al., 2013). However, the absence of a comparable acceleration in the more central municipality suggests that the effects are spatially selective and are possibly due to pre-existing saturation (Higgins et al., 2014).

The evolution of socio-professional categories provides more direct, yet nuanced, evidence of socio-economic metamorphosis. The increasing share of higher-income groups and the decline of the number of "blue-collar" workers in municipalities crossed by the tramline are consistent with transit-induced socio-economic restructuring in TOD contexts (Bardaka et al., 2018). Nevertheless, attributing these changes solely to the tramline remains methodologically limited.

Regarding the indicators of the standard of living, the results are more ambiguous. While average household income increases along the tram corridor, particularly in peripheral municipalities, the number of low-income households does not exhibit a clear or consistent decline. This divergence suggests that income growth may be the consequence of wealthier households settling more than of direct displacement effects. The absence of a clear reduction in low-income households may also reflect the relatively short post-implementation observation window, as transport-induced neighbourhood change is often slow and may unfold over one or two decades rather than a few years (Rietveld et al., 2007).

In addition, the quantitative indicators used in this study do not capture residents' lived experiences or the micro-level mechanisms driving neighbourhood change. Qualitative approaches, such as interviews with residents, analysis of housing market actors, or ethnographic observations, could provide valuable insights into perceptions of accessibility, neighbourhood desirability, and potential displacement pressures. Integrating such methods would enable a more comprehensive understanding of the social dynamics associated with transit infrastructure development.

Taken together, the results suggest that transport infrastructure investments may function as catalysts of cognitive reconfiguration within urban systems. By expanding the range of feasible choices and lowering the cognitive cost of mobility, such investments can indirectly shape socio-economic dynamics and spatial distribution patterns. This perspective complements traditional economic and spatial explanations and highlights the importance of integrating cognitive dimensions into the analysis of urban transformation processes.

5. Conclusion

This study demonstrates that the introduction of a tram service contributes to a reconfiguration of socio-spatial dynamics that can be interpreted not only through improvements in physical accessibility but also through the lens of cognitive sustainability. The findings indicate that transport infrastructure modifies the cognitive environment in which households make residential and mobility decisions, thereby influencing patterns of density, socio-professional composition, and income distribution.

Overall, the findings support a cautious interpretation: the tramline serving the French city of Bordeaux and its suburb appears to contribute to a certain reconfiguration of spatial attractiveness and the socio-economic profile of the area, but the evidence for full gentrification, being the displacement and socio-spatial replacement of the original population, is not fully established.

A key limitation of this study lies in both its temporal scope and its methodological approach. The relatively short observation period following the tramline's implementation limits the ability to identify long-term displacement dynamics, while the descriptive-analytical framework limits causal attribution. Consequently, the findings should be interpreted as evidence of emerging socio-spatial restructuring patterns rather than definitive proof of transit-induced gentrification. This is consistent with recent empirical studies on rail investments in European contexts, which emphasise that accessibility improvements are a necessary but not sufficient condition for gentrification, as outcomes depend strongly on land-use regulation, housing supply elasticity, and broader metropolitan economic trends (Delmelle, 2021; Padeiro et al., 2019). A key limitation of this study lies in its

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temporal scope and in the inability to isolate the effect of this investment from other urban dynamics (independent evolution of housing prices in the area and neighbourhood remodelling).

Future research could benefit from other modelling tools, such as difference-in-differences analysis comparing municipalities that received new infrastructure with socially similar municipalities that did not, combined with longer-term data to analyse reliable dynamics.

Future research should aim to combine longitudinal quantitative analysis with causal inference techniques and qualitative investigations to better capture the complexity of transit-induced urban transformations. Extending the temporal horizon and incorporating comparative case studies across different metropolitan contexts would also contribute to a more generalisable understanding of how transport infrastructure interacts with socio-economic and spatial dynamics.

The integration of cognitive sustainability into the analysis of transport infrastructure provides a novel perspective that bridges transport engineering, urban studies, and sustainability science. By emphasising the role of information, perception, and decision-making processes, this approach offers new avenues for understanding how mobility systems contribute to long-term urban development and socio-economic transformation.

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