




Decoupling transport-related CO₂ 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 (CO₂) 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 These findings suggest that structural improvements and technological advancements have increasingly superseded economic volume as the primary drivers of transport emissions.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 CO₂ 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 CO₂ 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



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 CO₂ 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 CO₂ 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:



$$e = \frac{\% \Delta CO_2}{\% \Delta GDP} \tag{1}$$

- **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 CO₂ emissions are non-stationary ($p > 0.05$). The point estimate for GDP (0.107) and CO₂ (-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 (H ₀)
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 (H₀) 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.

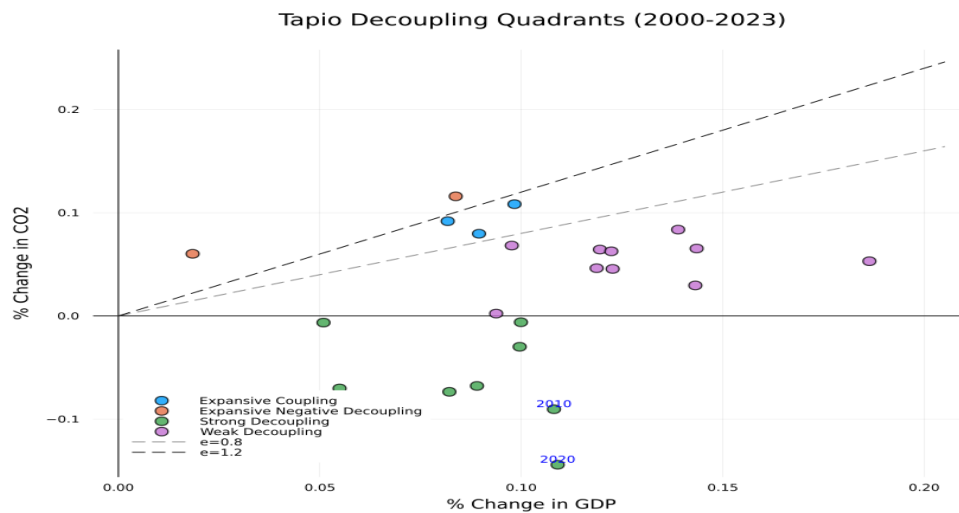


Figure 1. The decoupling quadrants (2000–2023)

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.



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 CO₂. 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 CO₂, 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.



References

- Abastante, F., Corrente, S., Greco, S., Ishizaka, A., Lami, I. M. (2019). A new parsimonious AHP Methodology: Assigning priorities to many objects by comparing pairwise few reference objects. *Expert Systems with Applications*. 127, 109–120. DOI: <https://doi.org/10.1016/j.eswa.2019.02.036>
- Alises, A., & Vassallo, J. M. (2015). Comparison of road freight transport trends in Europe. Coupling and decoupling factors from an Input–Output structural decomposition analysis. *Transportation Research Part A: Policy and Practice*, 82, 141–157. DOI: <https://doi.org/10.1016/j.tra.2015.09.013>
- Al-lami, A., Török, Á. (2024). Decomposition of carbon dioxide (CO₂) emissions in Hungary: A case study based on the Kaya Identity and LMDI Model. *Periodica Polytechnica Transportation Engineering*. 53(1), 7–15. DOI: <https://doi.org/10.3311/PPtr.37552>
- Al-lami, A., Török, Á. (2025). Assessing the driving forces of carbon dioxide emissions of the transport sector in Central Europe. *Transportation Research Interdisciplinary Perspectives*. 31, 101428. DOI: <https://doi.org/10.1016/j.trip.2025.101428>
- Al-lami, A., Török, Á. (2026). Economic growth and transport emissions: Testing the environmental Kuznets curve in Austria and the Netherlands. *Transportation Research Procedia*. 93, 71–76. DOI: <https://doi.org/10.1016/j.trpro.2025.11.011>
- Apergis, N. (2016). Environmental Kuznets curves: New evidence on both panel and country-level CO₂ emissions. *Energy Economics*. 54, 263–271. DOI: <https://doi.org/10.1016/j.eneco.2015.12.007>
- Cautisanu, C., Hatmanu, M. (2023). A study of the decoupling of economic growth from CO₂ and HFCs emissions in the EU27 countries. *Energies*. 16(14), 5546. DOI: <https://doi.org/10.3390/en16145546>
- Dai, S., Zhang, M., Huang, W. (2016). Decomposing the decoupling of CO₂ emission from economic growth in BRICS countries. *Natural Hazards*. 84(2), 1055–1073. DOI: <https://doi.org/10.1007/s11069-016-2472-0>
- Foster, V., Dim, J. U., Vollmer, S., & Zhang, F. (2023). Understanding the challenge of decoupling transport-related CO₂ emissions from economic growth in developing countries. *World Development Sustainability*, 3, 100111. DOI: <https://doi.org/10.1016/j.wds.2023.100111>
- Gómez, A. P., Bonilla, D., & Banister, D. (2024). Decoupling transport-CO₂ emissions: Mexico, Spain and The USA: A trend analysis. *Transportation Research Part D: Transport and Environment*, 137, 104510. DOI: <https://doi.org/10.1016/j.trd.2024.104510>
- Huang, F., Zhou, D., Wang, Q., Hang, Y. (2019). Decomposition and attribution analysis of the transport sector's carbon dioxide intensity change in China. *Transportation Research Part A: Policy and Practice*. 119, 343–358. DOI: <https://doi.org/10.1016/j.tra.2018.12.001>
- Pana Tronca, L. (2025). Climate and transport planning: A messy junction. *European Transport Studies*. 2, 100025. DOI: <https://doi.org/10.1016/j.ets.2025.100025>
- Sorrell, S., Dimitropoulos, J. (2008). The Rebound Effect: Microeconomic Definitions, Limitations and Extensions. *Ecological Economics*. 65(3), 636–649. DOI: <https://doi.org/10.1016/j.ecolecon.2007.08.013>
- Szabó, Z., Szalmáné Csete, M., Sipos, T. (2024). Spatial econometric analysis of carbon dioxide emission – European case study. *Promet – Traffic & Transportation*. 36(2), 193–202. DOI: <https://doi.org/10.7307/ptt.v36i2.436>
- Tapio, P. (2005). Towards a theory of decoupling: Degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. *Transport Policy*. 12(2), 137–151. DOI: <https://doi.org/10.1016/j.tranpol.2005.01.001>