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Towards sustainable transport in Visegrád countries: Decomposition of emissions drivers and policy directions

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ABSTRACT

This study addresses a critical research gap in understanding the drivers of transportation emissions in Central Europe by applying the Kaya Identity and Logarithmic Mean Divisia Index (LMDI) methods. To analyze data from 2001 to 2021, the study identifies critical factors—economic growth, energy intensity, and population changes influencing emissions trends. It provides region-specific insights for aligning with EU climate targets. Findings reveal Poland's steepest emissions increase due to its coal dependency and rapid economic growth, underscoring the need for renewable energy and public transport electrification. Hungary and the Czech Republic exhibit relatively stable emission trends, indicating moderate success in energy efficiency measures and cleaner technologies. At the same time, Slovakia demonstrates a balanced approach to emission control through adequate investment in public transportation and renewable energy. The COVID-19 pandemic caused a temporary reduction in emissions across all four countries, illustrating the potential impact of large-scale economic shifts. Policy recommendations include targeted actions such as expanding electric vehicle infrastructure, incentivizing renewable energy, and enhancing multimodal transport options. Despite the study's valuable insights, limitations include reliance on aggregated data, assumptions of linear relationships, and the pandemic's short-term disruptions. Future research should explore more detailed data on transport modes and extend the timeframe to better understand complex interactions driving emissions. This study offers actionable guidance for reducing transportation emissions to support Central Europe's climate goals.

1. Introduction

The escalating levels of greenhouse gases (GHGs) pose severe environmental and public health risks across Europe, with climate change increasingly disrupting ecosystems, economies, and communities. In response, the European Union (EU) has committed to ambitious climate targets, including a 55 % reduction in GHG emissions by 2030 and carbon neutrality by 2050, under the framework

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of the European Green Deal. (EU Green Deal, 2021; Fiore et al., 2023). Central Europe—comprising Hungary, the Czech Republic, Poland, and Slovakia—faces unique challenges in contributing to these targets. The region exhibits a high dependence on fossil fuels, particularly in the road transport sector, which remains a significant source of CO_2 emissions and air pollution. This sector alone accounts for roughly 24 % of Europe's CO_2 emissions, and all this underscores the urgent need for sustainable policy interventions that are tailored to regional conditions (Kriswardhana and Esztergár-Kiss, 2024; Nazarko et al., 2022).

Sustainable transportation plays a critical role in this transition by aiming to reduce environmental impacts while preserving mobility that is efficient, affordable, and accessible (Haines and Scheelbeek, 2020). This involves advancing clean technologies—such as electric vehicles and public transit powered by renewable energy—improving urban planning, expanding public transportation, and promoting active mobility options like cycling and walking. Such integrated strategies are essential for reducing the carbon intensity of transportation, mitigating air pollution, and enhancing the overall quality of life in urban environments. Bridging the gap between current practices and EU climate objectives thus demands a multifaceted approach that addresses infrastructural, economic, and technological barriers while promoting sustainable transport systems (Kazancoglu et al., 2021).

However, the transition to a low-emission economy in Central Europe is complex, given each country's unique energy landscape. For instance, while Poland's heavy reliance on coal has led to more volatile emission trends, Hungary and the Czech Republic have seen more stable emission levels due to targeted energy policies (Jovanović et al., 2015). Understanding the specific factors driving CO_2 emissions in transportation is thus essential to creating effective, country-specific policies.

This study aims to analyze CO_2 emissions in Central Europe's transportation sector from 2001 to 2021, using the Kaya identity and Logarithmic Mean Divisia Index (LMDI) to isolate key factors influencing these emissions. The analysis will highlight the impact of carbon intensity, energy intensity, economic activity, and population growth, providing policymakers with insights into the main contributors to emissions.

The Kaya identity provides a systematic framework for analyzing the key drivers of CO_2 emissions by decomposing them into population, economic activity, energy intensity, and carbon intensity. When integrated with the Logarithmic Mean Divisia Index (LMDI) method, this approach becomes a powerful analytical tool for quantifying each factor's contributions to emissions changes over time. The LMDI method is advantageous because it can complete decomposition without residual terms, ensuring analytical consistency and interpretative clarity. This enables precise identification of the impact of specific drivers, such as economic growth, technological progress, and shifts in energy use, on emission trends (Abbes et al., 2021).

The four driving factors selected—population, economic activity (GDP), energy intensity, and carbon intensity—are grounded in both the structure of the transport-energy-emissions nexus and prior empirical evidence. These variables capture the most proximate contributors to emission levels and have been validated in numerous cross-national studies (Cansino et al., 2015; Khusna and Kusumawardani, 2021; Yang et al., 2020). While more granular "ground-floor" factors such as modal split, fuel composition, and vehicle efficiency are not explicitly disaggregated in this study, they are partially embedded within the terms of energy and carbon intensity. For instance, shifts toward electric mobility or modal transitions to rail would be reflected in improved energy and carbon intensity metrics over time.

These findings will support the development of regionally tailored strategies for reducing emissions, such as promoting public transport, encouraging electric vehicle adoption, and implementing stricter fuel standards aligned with EU climate goals. (Al-lami and Török, 2024; Marrero et al., 2021).

In conclusion, this research offers actionable insights to aid Central Europe's transition to a low-carbon transportation system, ultimately contributing to a sustainable future aligned with EU targets. By addressing the transportation sector's unique emissions drivers, Central Europe can set a precedent for effective emissions reduction, offering a model for sustainable transportation policies worldwide.

The structure of this paper is as follows: the introduction outlines the study's context and objectives, the literature review discusses relevant research, the methodology section details the data and methods used, the results section presents the findings, and the discussion and conclusion sections interpret the results and offer recommendations for policy and practice.

2. Literature review

Rising global greenhouse gas (GHG) emissions, mainly from fossil fuel use in transportation, present significant climate challenges. Transportation is a crucial source of CO_2 emissions in Europe, especially in Central Europe—Hungary, the Czech Republic, Poland, and Slovakia—where energy-intensive industries and fossil-fuel-dependent transport complicate emissions reduction efforts. Economic growth patterns, fuel types, and energy efficiency levels shape emission trends in this region. Research employing the Kaya Identity and Logarithmic Mean Divisia Index (LMDI) methods has expanded our understanding of CO_2 emissions across various sectors, offering valuable insights into the factors that drive emissions and the impact of different mitigation strategies. These decomposition techniques are particularly relevant in Europe, where transportation significantly contributes to national CO_2 emissions. Despite substantial research in this field, relatively few studies have focused on the transportation sectors of Central Europe—Hungary, the Czech Republic, Poland, and Slovakia—where economic growth and energy policies are intricately linked to emission trends. This study addresses this gap using the LMDI method to analyze transportation emissions in this region, aiming to inform sustainable transport policies aligned with EU climate targets.

Several European studies have applied the LMDI method to analyze transportation emissions, focusing on specific countries and regions. For instance, they used an extended Kaya Identity and LMDI approach to assessing CO_2 emissions in Spain from 1995 to 2009, finding that economic activity and energy intensity significantly contributed to emissions increases effectively (Cansino et al., 2015). Similarly, O'Mahony (2013) utilized LMDI to decompose emissions in Ireland, revealing that economic growth and population size were significant drivers, while improvements in energy efficiency and renewable energy adoption helped mitigate emissions (O'Mahony, 2013). These studies underscore the complexity of transportation-related emissions and demonstrate the effectiveness of decomposition analysis in isolating the factors that influence emissions.

Central Europe presents a hybrid case between Eastern and Western Europe. While gradually aligning with EU climate policy frameworks, these countries still rely significantly on high-carbon energy sources—particularly coal, diesel, and natural gas—for transport and industry. Economic patterns in the region reflect a continued emphasis on manufacturing and heavy industry, both energy- and carbon-intensive sectors. Hungary and Poland, for example, rely heavily on road freight and private car use, while widespread public transport systems suffer from ageing infrastructure and underinvestment (Armeanu et al., 2019). Renewable energy penetration in transportation remains low across the region, and transitions to electric vehicles are proceeding more slowly than in Western Europe (Amin et al., 2020). For instance, a decomposition analysis of CO_2 emissions in Eastern European countries, including Hungary, showed that economic activity and fuel mix were primary contributors to emissions increases, with modal share and energy intensity also playing roles, albeit to a lesser extent (Abbes et al., 2021). Similarly, Dogan and Seker (2016) examined the impact of renewable and non-renewable energy on CO_2 emissions in Eastern European transport, advocating for increased integration of renewable energy to meet EU emission reduction targets (Dogan and Seker, 2016). In contrast, Western European nations such as Germany and France have more diversified and decarbonized energy portfolios driven by high renewable integration, stricter emissions regulations, and advanced transport electrification(Zhang et al., 2021). These structural differences necessitate region-specific strategies and underline the importance of context-aware emission decomposition.

Research specific to Central Europe remains limited but is expanding. Some studies have employed the LMDI method to examine transportation CO_2 emissions in Central European countries, including Hungary, the Czech Republic, Poland, and Slovakia. Brozyna et al. (2020) assessed the impact of economic activity on transportation emissions in the Czech Republic and Slovakia, concluding that fossil fuel dependence and limited renewable energy infrastructure pose critical challenges to emissions reduction (Brozyna et al., 2020). In Poland, Budzianowski (2012) analyzed the carbon intensity of energy production, linking emissions trends to the nation's reliance on coal, underscoring the need for cleaner energy transitions in the transportation sector (Dzikuć et al., 2021). These findings emphasize Central Europe's distinct energy and economic landscape, highlighting the importance of tailored approaches to emissions reduction that address each country's specific circumstances. Economic activity is the primary driver of CO2 emissions in Hungary. At the same time, improvements in energy efficiency have significantly mitigated these emissions, and population changes have a moderate impact, with minimal influence from carbon emission intensity (Al-lami and Török, 2024).

Table 1 summarizes the differences in energy structures and economic patterns across Eastern, Western, and Central Europe (focusing on Hungary, Poland, the Czech Republic, and Slovakia) and their impact on transport energy consumption and emissions.

Despite these valuable contributions, research on Central Europe's transportation sector has yet to comprehensively assess the region's emissions drivers using LMDI. Most studies focus on individual nations rather than analyzing the area, limiting our understanding of broader trends and the potential for coordinated policy strategies. This study fills this gap by applying the Kaya Identity and LMDI methods to examine CO_2 emissions drivers across Hungary, the Czech Republic, Poland, and Slovakia from 2001 to 2021. By analyzing the impacts of carbon intensity, energy intensity, economic growth, and population, this research provides a detailed decomposition of emissions within the region's transportation sector. These insights will support policymakers in developing region-specific strategies to meet EU climate objectives, addressing national and EU-level sustainability priorities.

In summary, while previous studies offer valuable insights into emissions dynamics within specific European countries, a significant research gap remains in examining transportation emissions drivers in Central Europe. This study responds to this gap, providing a comprehensive analysis to guide data-driven policies for reducing emissions in Hungary, the Czech Republic, Poland, and Slovakia.

3. Research methodology and data collection

This study employs the Kaya Identity and Logarithmic Mean Divisia Index (LMDI) method to decompose transport-related CO_2 emissions in Central Europe from 2001 to 2021. The analysis focuses on four key drivers—population, GDP, energy intensity, and carbon intensity—using harmonized data from reputable international sources to ensure consistency and comparability.

Table 1
Comparison of Energy Structures and Economic Patterns Affecting Transport Emissions in Europe.

Category	Central Europe Visegrád Group	Western Europe	Eastern Europe (Non-EU)
Energy Structure	Fossil-fuel dominant; limited clean energy in transport(Yan et al., 2024).	High renewable integration; strong grid support for EVs	High fossil fuel dependency, slow reform, and weak grids (Davey, 1987).
Transport Emissions	Growing emissions due to economic growth and freight activity; road-dominated (Suproń and Łącka, 2023)	Lower emissions per GDP; clean, electrified public transport	High emissions intensity, outdated vehicles and inefficient systems
Economic Impact	Rapid post-EU growth; rising energy intensity in transport (Al-lami and Török, 2025a)	Service-driven economies, efficient logistics, and public mobility	Volatile growth; limited investment in clean transport
Decarbonization Progress	Moderate progress; strong EU funding support	Advanced policies: EVs, low-emission zones, modal shifts	Minimal; hindered by politics and infrastructure gaps

3.1. Yoichi Kaya and Log-Mean Divisia Index (LMDI)

The research methodology presented here uses the Logarithmic Mean Divisia Index (LMDI) method to decompose the Yoichi Kaya identity for analyzing CO_2 emissions and energy consumption trends in Central Europe's transportation sector. The Yoichi Kaya identity offers a framework for understanding the drivers of CO_2 emissions. At the same time, the LMDI method facilitates the decomposition of changes in emissions and energy consumption into various contributing factors. This approach dissects aggregate figures to identify the primary sources of carbon emissions within the transportation sector of specific nations. The method provides precise decomposition without residual factors, achieved with a limited number of time-series variables. The decomposition formula is based on the Kaya identity developed by Yoichi Kaya, allowing for a detailed breakdown of carbon emissions.

$$CO_2 = (C/EC)*(EC/G)*(G/P)*P \tag{1}$$

Where: C: CO_2 emissions [$MtCO_2$], EC = energy consumption [MJ], G = gross domestic product [USD]; P = population [inhabitant].

Eq. (1) can help determine the drivers of CO_2 emissions by breaking down CO_2 emissions into various drivers, namely carbon intensity (C/EC) [$MtCO_2$ /Mtoe] of energy use, energy intensity (EC/G) [Mtoe/USD], GDP per capita (G/P) [USD/inhabitant], and population (P) [inhabitant]. The Kaya identity applies primarily to broad evaluations of a nation or region. However, it is used to scrutinize specific industrial sectors and energy varieties. According to the decomposed equations in (Ang and Liu, 2007; Liu et al., 2021; Solaymani, 2019; Wang et al., 2011). Based on Eq. (1), we reframe the Kaya identity as:

$$C = \sum_{ij} CO2_{ij}^{t} = \sum_{ij} \frac{C}{EC} \times \frac{EC}{G} \times \frac{G}{P^{t}} \times P = \sum_{ij} E_i LMA \tag{2}$$

Where:

$\frac{C}{EC}$ = Carbon intensity from fuel (E_i) [$MtCO_2$ /Mtoe]

$\frac{EC}{G}$ = Energy intensity (L) [Mtoe/USD]

$\frac{G}{P^t}$ = GDP per capita (M) [USD/inhabitant]

P = Population effect (A) [inhabitant]

From Eq. (1 and 2) above, the three ratios on the right side of the equation are from the transport sector. Next, the Logarithmic Mean Divisia Index (LMDI) method will be utilized to break down CO_2 emissions and energy consumption changes into various contributing factors, as the Yoichi Kaya identity outlines. This approach will dissect the shift in CO_2 emissions within the transportation sector from the base year 2001 to the target year 2021, revealing the influences of six distinct factors as expressed in Eq. 3.

$$\Delta C_{tot} = C_{i\ j}^{t} - C_{i\ j}^{0} = \Delta C_{ECIE} + \Delta C_{EIE} + \Delta C_{GDPE} + \Delta C_{POPE} \tag{3}$$

From Eq. (3), ΔC total is the total change in CO_2 between the current year and the base year. ΔC_{CEIE} is the change in carbon emissions intensity effect. ΔC_{EIE} Is the change in energy intensity effect, change in the GDP effect ΔC_{GDPE}. population effect (ΔC_{POPE}). Each factor's effect on the right-hand side of Eq. (3) can be calculated according to the general (LMDI) formulation. We employed the Logarithmic Mean Divisia Index (LMDI) for the calculations due to its ability to provide perfect decomposition without residuals and its robustness in handling zero and negative values, ensuring accurate and consistent results for each contributing factor to CO_2 emissions. This precision and flexibility make LMDI ideal for analyzing the driving characteristics of CO_2 emissions in the transportation sector across different nations (Chen and Yang, 2015; Raza and Lin, 2020; Tu et al., 2019).

$$\Delta C_{ECIE} = \sum_{i} \frac{C_{ij}^{t} - C_{ij}^{0}}{\ln C_{ij}^{t} - \ln C_{ij}^{0}} . \ln\left(\frac{E^{t}}{E^{0}}\right) \tag{4}$$

$$\Delta C_{EIE} = \sum_{i} \frac{C_{ij}^{t} - C_{ij}^{0}}{\ln C_{ij}^{t} - \ln C_{ij}^{0}} . \ln\left(\frac{L^{t}}{L^{0}}\right) \tag{5}$$

$$\Delta C_{GDPE} = \sum_{i} \frac{C_{ij}^{t} - C_{ij}^{0}}{\ln C_{ij}^{t} - \ln C_{ij}^{0}} . \ln\left(\frac{M^{t}}{M^{0}}\right) \tag{6}$$

$$\Delta C_{POPE} = \sum_{i} \frac{C_{ij}^{t} - C_{ij}^{0}}{\ln C_{ij}^{t} - \ln C_{ij}^{0}} . \ln\left(\frac{A^{T}}{A^{0}}\right) \tag{7}$$

Where J represents the transport sector, i represents the fuel type, namely oil, gas, renewable, and waste, and t represents the time (in this study, t = 2001 to 2021). Eq. (4) to calculate the carbon emission intensity effect (ΔC_{ECIE}), Eq. (5) to calculate the energy intensity effect (ΔC_{EIE}), Eq. (6) to calculate the economic activity effect (ΔC_{GDPE}), and Eq. (7) to calculate the population effect ΔC_{POPE}.

3.2. Data collection and study area

The study employs time-series data from 2001 to 2021 from reputable international databases to ensure reliability and cross-country comparability. Specifically, CO_2 emissions and energy consumption data for the transport sector are obtained from the

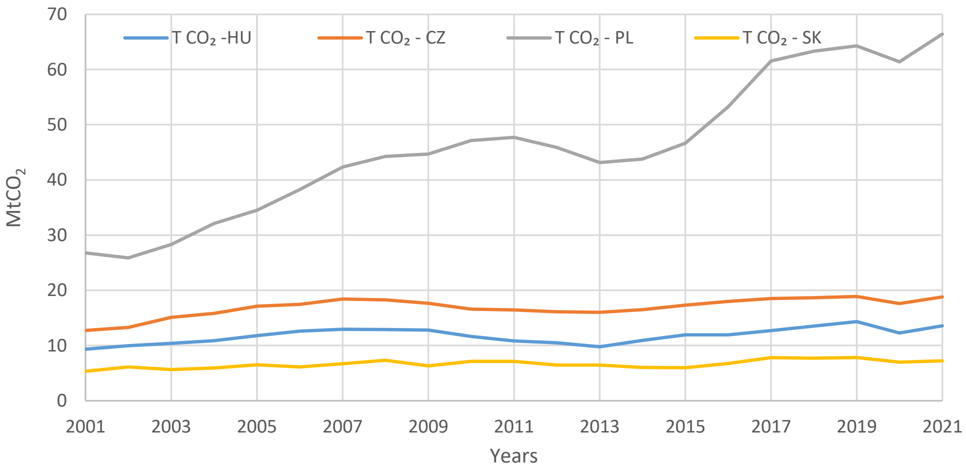

Fig. 1. Yearly total CO_2 emissions.

International Energy Agency (IEA). At the same time, GDP and population figures are sourced from the World Bank, Eurostat, and the International Association of Public Transport (UITP). To ensure temporal consistency and compatibility, all datasets were harmonized by aligning units, aggregating transport-specific indicators, and interpolating minor data gaps where necessary.

The analysis applies the Index Decomposition Analysis (IDA) framework using the Logarithmic Mean Divisia Index (LMDI) method. LMDI is particularly well-suited for this type of decomposition as it yields complete results without residuals, enabling a precise attribution of emission changes to underlying driving factors (Ang, 2005) (Ang and Liu, 2001). Moreover, LMDI facilitates consistent aggregation of subgroup effects, making it ideal for comparative cross-national analysis over time. (Spiessens and Debois, 2010). This methodological approach enhances the transparency and replicability of our findings.

4. Results and discussion

4.1. Analysis of ΔCO_2 emissions from 2001 to 2021

Fig. 1 and Table 2 show the analysis of CO_2 emissions from 2001 to 2021 in central Europe, which provides significant insights into the trends and fluctuations in emissions driven by transportation activities in the targeted countries. Fig. 1 shows the analysis of yearly total CO_2 emissions in the transport sector from 2001–2021 and reveals distinct trends and significant variations among these countries.

In Hungary, CO_2 emissions gradually increased from 9.34 $MtCO_2$ in 2001 to a peak of 14.34 $MtCO_2$ in 2019, followed by a drop to 12.27 $MtCO_2$ in 2020 due to the COVID-19 pandemic and a slight recovery to 13.599 $MtCO_2$ in 2021. This upward trend reflects

Table 2
Yearly Changes in CO_2 Emissions Effects (Mt ΔCO_2) Across Central Europe (2002–2021).

Year	Hungary	Czech Republic	Poland	Slovak Republic
2002	0.61	0.544	−0.916 ↓	0.8 ↑
2003	0.453	1.831 ↑	2.416	−0.511
2004	0.481	0.726	3.793 ↑	0.296
2005	0.91	1.3	2.419	0.581
2006	0.804	0.307	3.746	−0.399
2007	0.372	0.96	4.068*	0.58
2008	−0.084 ↓	−0.152	1.951	0.635 ↑
2009	−0.079 ↓	−0.627 ↓	0.411	−1.005 ↓
2010	−1.158 ↓	−1.032 ↓	2.43	0.831
2011	−0.819 ↓	−0.129	0.606	−0.034
2012	−0.324	−0.33	−1.85	−0.651
2013	−0.713 ↓	−0.139	−2.696 ↓	0.007
2014	1.135	0.508	0.613	−0.417
2015	1.003	0.806	2.863	−0.092
2016	0.027	0.686	6.605 ↑	0.77
2017	0.769	0.534	8.284 ↑	1.06 ↑
2018	0.797	0.133	1.779	−0.069
2019*	0.814	0.219	0.971	0.101
2020*	−2.068 ↓	−1.30 ↓	−2.91 ↓	−0.84 ↓
2021	1.329 ↑	1.243 ↑	5.045 ↑	0.263

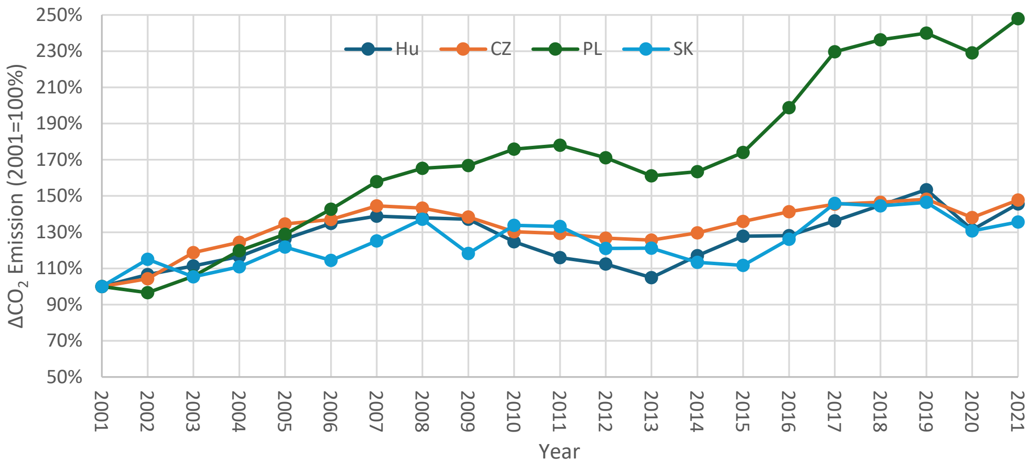

Fig. 2. ΔCO_2 in the centre of Europe.

increasing transport activity and economic growth despite efforts to improve fuel efficiency and reduce emissions. The Czech Republic exhibited a steady rise in emissions from 12.75 $MtCO_2$ in 2001–18.89 $MtCO_2$ in 2019, with a decrease to 17.59 $MtCO_2$ in 2020 due to the pandemic and an increase to 18.83 $MtCO_2$ in 2021. This consistent increase highlights the challenges in curbing emissions amidst growing transport demands and economic development. Poland showed the most significant increase, with emissions rising from 26.80 $MtCO_2$ in 2001–66.43 $MtCO_2$ in 2021. The steep rise, particularly after 2010, reflects the country's heavy reliance on road transport and the challenges in transitioning to more sustainable transport modes. The Slovak Republic exhibited relatively moderate increases in emissions, starting from 5.345 $MtCO_2$ in 2001 and rising to 7.251 $MtCO_2$ in 2021, with fluctuations mirroring regional trends impacted by economic activities and the pandemic. Overall, the data indicate that all four countries have experienced increases in transport sector CO_2 emissions over two decades, driven by economic growth and increased transport activity. However, the COVID-19 pandemic caused a temporary reduction in emissions across all countries. Poland's significant rise in emissions underscores the need for urgent policy interventions to promote sustainable transport solutions. At the same time, the more gradual increases in Hungary and the Slovak Republic suggest some success in mitigating emissions growth.

Fig. 2 presents the yearly changes in CO_2 emissions, with 2001 set as the baseline year (100 %). In Hungary, CO_2 emissions exhibited relatively stable fluctuations around the baseline, with slight increases and decreases but no extreme variations. Emissions increased by approximately 14 %, peaking at 114 % of the 2001 levels in 2008, as indicated by a ΔCO_2 effect of 0.61 in 2002, rising to 0.91 in 2005. A notable decrease occurred in 2010 with a ΔCO_2 effect of −1.158, followed by a period of recovery and stability, maintaining around 110–120 % of the 2001 levels by 2021. This stability suggests balanced economic growth coupled with consistent emission control measures, including improvements in energy efficiency and the adoption of renewable energy sources. The Czech Republic experienced more pronounced fluctuations. Between 2001 and 2007, emissions increased by around 30 %, reaching 130 % of the 2001 level. This is reflected in the ΔCO_2 effect, rising from 0.544 in 2002–1.831 in 2003 and stabilizing around 1.3 in 2005. Afterwards, emissions decreased slightly but remained relatively high, fluctuating between 120 % and 130 % until 2019, when they again reached approximately 135 % (with a ΔCO_2 effect of 1.243 in 2021). These spikes are linked to robust economic growth and industrial activities, particularly during the global economic boom before the 2008 financial crisis. Despite efforts to modernize industry and adopt cleaner technologies, variability remains due to the dependence on industrial output. Poland exhibited the highest variability in CO_2 emissions. From 2001–2007, emissions increased dramatically, peaking at about 160 %. By 2019, emissions had surged to 230 % of the 2001 levels. The ΔCO_2 effect data show significant increases, from −0.916 in 2002–4.068 in 2007 and a peak of 8.284 in 2017. However, in 2020, emissions dropped significantly to approximately 140 %, with a ΔCO_2 effect of −2.91, likely due to the COVID-19 pandemic, which led to reduced industrial activities and energy consumption (IEA, 2020). The high variability is driven by Poland's heavy reliance on coal for energy production, which causes substantial fluctuations in emissions linked to economic activity. The Slovak Republic displayed relatively stable emissions with minor fluctuations. Emissions increased modestly, reaching around 120 % of the 2001 levels by 2008, reflected in a ΔCO_2 effect of 0.8 in 2002, rising to 0.581 in 2005. A notable dip occurred in 2009, reflecting the global financial crisis's impact, with emissions falling to around 105 % (ΔCO_2 effect of −1.005 in 2009). Following this dip, emissions gradually recovered, fluctuating between 110 % and 120 % of the 2001 levels by 2021, as indicated by a ΔCO_2 effect of 0.263 in 2021. This stability suggests effective policy measures and economic stabilization efforts, indicating a balanced economic growth and emission control approach. (Mohammed et al., 2021) showed that the industrial sector is the primary source of CO_2 emissions, contributing significantly to overall emission levels. (Guven et al., 2020), Emphasized that economic structure and manufacturing output significantly affect CO_2 emissions, further reinforcing the connection between economic activity and emission levels.

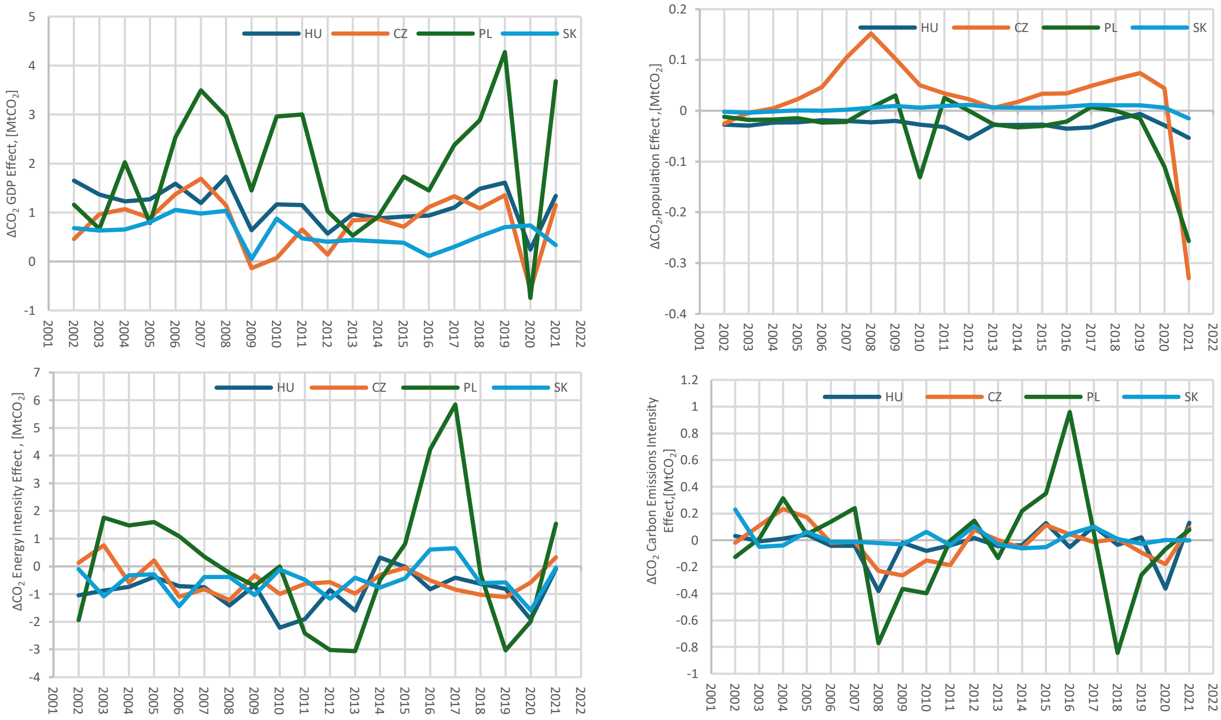

Fig. 3. Yearly driving factors for CO_2 emissions.

4.2. Trend analysis of historical driving factors of ΔCO_2 emissions

Fig. 3 illustrates the analysis of the yearly driving factors for CO_2 emissions from 2001 to 2021 for Hungary, the Czech Republic, Poland, and the Slovak Republic, based on the Kaya Identity and the Logarithmic Mean Divisia Index (LMDI) models. The factors considered include the effects of GDP, population effect, energy intensity effect, and carbon emissions intensity effect.

The ΔC_{GDPE} Effect reveals significant variability among the four countries. Poland exhibited the highest fluctuations, with emissions peaking at around 4.07 $MtCO_2$ in 2007 and 8.28 $MtCO_2$ in 2017, indicating periods of strong economic growth driven by industrial expansion and reliance on coal energy. In contrast, Hungary and the Czech Republic showed more moderate changes, with Hungary's peak at 1.73 $MtCO_2$ in 2008 and the Czech Republic peaking at 1.83 $MtCO_2$ in 2003. The Slovak Republic also experienced notable spikes, reaching 1.06 $MtCO_2$ in 2017, reflecting similar industrial growth patterns. The drastic drop in Poland from 2020 to −2.91 $MtCO_2$ highlights the impact of the COVID-19 pandemic, which caused significant reductions in industrial activities and energy consumption.

Table 3
Yearly Contributions to (Mt ΔCO_2) Factors by Region.

Region	Factors	2006	2011	2016	2021
Hungary	ΔCO2 GDP	7.22	5.55	4.47	5.61
	ΔCO2POP	−0.12	−0.12	−0.18	−0.14
	ΔCO2 EIE	−3.87	−6.68	−3.17	−3.71
	ΔCO2 CEIE	0.04	−0.52	0.01	−0.13
Czech Republic	ΔCO2 GDP	4.58	3.27	3.77	4.32
	ΔCO2POP	0.03	0.42	0.11	−0.11
	ΔCO2 EIE	−0.36	−3.85	−2.53	−3.20
	ΔCO2 CEIE	0.46	−0.81	0.18	−0.18
Poland	ΔCO2 GDP	7.38	13.51	6.17	11.95
	ΔCO2POP	−0.09	−0.09	−0.12	−0.35
	ΔCO2 EIE	3.81	−2.72	−2.13	2.55
	ΔCO2 CEIE	0.36	−1.23	1.62	−0.98
Slovakia	ΔCO2 GDP	3.64	3.32	1.89	2.40
	ΔCO2POP	−0.01	0.03	0.04	0.02
	ΔCO2 EIE	−3.05	−2.31	−2.32	−1.99
	ΔCO2 CEIE	0.19	−0.04	0.00	0.08

The ΔCO_2 Population Effect generally shows less pronounced fluctuations across countries, reflecting more stable population growth rates. The Czech Republic peaked at around 0.17 $MtCO_2$ in 2006, followed by a gradual decline. Hungary and the Slovak Republic maintained relatively steady levels, with slight variations indicating minimal population-driven changes in emissions. Poland's population effect showed some fluctuations, especially in 2019. The ΔC_{POPE} showed a significant drop from −0.0109 $MtCO_2$ to −0.256 $MtCO_2$ in 2021, which referred to a population drop in 2021, according to the World Bank database (Matysiak and Nowok, 2007). However, it remained relatively stable overall, reflecting that population growth had a less significant impact on emissions than economic activities and energy use. The ΔCO_{2EIE} presents notable differences among the countries. Poland again shows considerable variability, with peaks reaching approximately 6.61 $MtCO_2$ in 2016 and 8.28 $MtCO_2$ in 2017, indicating fluctuations in energy efficiency and industrial energy consumption. The Czech Republic and Hungary exhibited minor fluctuations, with peaks at 1.83 $MtCO_2$ in 2003 for the Czech Republic and around 1.16 $MtCO_2$ in 2005 for Hungary. The Slovak Republic had moderate changes, peaking at 1.06 $MtCO_2$ in 2017, reflecting variations in energy use efficiency over time. The ΔCO_{2CEIE} shows that Poland experienced significant changes, peaking at 1.16 $MtCO_2$ in 2017 and reflecting fluctuations in the carbon intensity of energy production, primarily due to its coal dependence (Al-lami and Török, 2025b; Budzianowski, 2012). Hungary and the Czech Republic exhibited more stable trends, with minor fluctuations, indicating steady improvements in reducing carbon intensity. The Slovak Republic showed notable variations, with a peak at 1.06 $MtCO_2$ in 2017, suggesting efforts to manage carbon emissions intensity while maintaining industrial growth.

Table 3 shows that GDP consistently contributed to CO_2 increases in Hungary, peaking at 7.22 Mt in 2006 and remaining significant at 5.61 Mt in 2021. Energy intensity (EIE) was the most important mitigating factor, reducing emissions by −6.68 Mt in 2011 and −3.71 Mt in 2021. Contributions from CEIE were marginal, fluctuating between 0.04 Mt in 2006 and −0.13 Mt in 2021, while population changes consistently had a minimal impact, with values like −0.12 Mt in 2006 and −0.14 Mt in 2021.

GDP was also a major driver of CO_2 emissions in the Czech Republic, contributing 4.58 Mt in 2006 and 4.32 Mt in 2021. Energy intensity played a key role in reducing emissions, with contributions of −3.85 Mt in 2011 and −3.20 Mt in 2021. CEIE's impact was minor, ranging from 0.46 Mt in 2006 to −0.18 Mt in 2021, while population effects remained negligible, with a slight positive contribution of 0.42 Mt in 2011 and a negative impact of −0.11 Mt in 2021.

Poland displayed the most significant GDP-driven CO_2 increases, contributing 13.51 Mt in 2011 and 11.95 Mt in 2021. Energy intensity, however, showed inconsistencies, reducing emissions by −2.72 Mt in 2011 but increasing them by 2.55 Mt in 2021. CEIE's impact fluctuated, contributing positively (1.62 Mt in 2016) and negatively (-0.98 Mt in 2021), while population changes had minor effects, such as −0.09 Mt in 2006 and −0.35 Mt in 2021.

Slovakia exhibited the smallest GDP contributions among the four countries, decreasing values from 3.64 Mt in 2006–2.40 Mt in 2021. Energy intensity consistently reduced emissions, with stable contributions like −3.05 Mt in 2006 and −1.99 Mt in 2021. CEIE's impact was negligible, fluctuating slightly around zero (e.g., 0.19 Mt in 2006 and 0.08 Mt in 2021), while population changes were minimal, such as 0.03 Mt in 2011 and 0.02 Mt in 2021.

The data indicate that economic growth is the primary driver of CO_2 emissions variability, especially in Poland, due to its heavy reliance on coal. Economic downturns, such as the 2008 financial crisis and the 2020 COVID-19 pandemic, resulted in significant reductions in CO_2 emissions across all countries due to decreased industrial activities. The population effect on emissions was relatively stable, showing minor impacts compared to economic and energy intensity effects. Energy efficiency improvements and carbon intensity reductions were more pronounced in Hungary and the Czech Republic, reflecting successful policy implementations and technological advancements, and all of this meets with the main findings of other researchers. The Czech Republic and Slovakia could achieve reductions in energy consumption and greenhouse gas emissions through effective energy policies.(Brozyna et al., 2020). Promoting energy efficiency and developing green economy sectors can help lower CO_2 emissions in post-communist economies. However, increases in GDP per capita and life expectancy tend to contribute to higher emissions.

4.3. Cross-sectional comparison of CO_2 emission drivers in central Europe

To supplement the time-series analysis, this section compares CO_2 emissions and their underlying drivers across Hungary, the Czech Republic, Poland, and the Slovak Republic in selected benchmark years: 2001, 2010, and 2021. These years were chosen to reflect important economic and policy milestones: the pre-EU accession period, the aftermath of the global financial crisis, and the onset of post-pandemic recovery combined with tightened EU decarbonization targets.

4.3.1. CO_2 emissions per capita and emissions intensity

In 2001, Poland recorded the highest CO_2 emissions per capita (~8.4 tCO_2/capita), mainly due to its coal-dominated energy mix and energy-intensive industry. Hungary and Slovakia, in contrast, had significantly lower emissions (~5.2 and 5.8 tCO_2/capita, respectively), reflecting more diversified energy systems and smaller industrial sectors.

By 2010, while emissions had declined in all four countries, the emissions intensity of GDP (tCO_2 per $1000 GDP) diverged. The Czech Republic and Poland continued to show higher intensity due to slower improvements in energy efficiency. At the same time, Slovakia achieved notable decoupling, thanks in part to the restructuring of its industrial base and investments in cleaner energy technologies.

By 2021, all four countries exhibited progress, but Poland remained an outlier in carbon intensity due to continued reliance on coal (accounting for ~70 % of electricity generation in 2021), (IEA, 2023). Hungary showed the most substantial alignment with EU emissions reduction pathways, supported by declining oil consumption in transport and targeted electric vehicle incentives.(Table 4)

Importantly, periods of economic contraction, notably the 2008 global financial crisis and the COVID-19 pandemic, coincided

Table 4
Key Drivers Based on LMDI Decomposition (2021 Cross-Section).

Country	GDP per capita effect	Energy intensity effect	Carbon intensity effect	Population effect
Hungary	↑ (positive growth)	↓ (strong reduction)	↓ (moderate)	~ stable
Czech Republic	↑	↓	↓	~ stable
Poland	↑	↓ (slight)	↑ (coal dominant)	↑ (modest)
Slovakia	↑	↓	↓	↓ (slight)

Note: Arrows indicate the direction of contribution to total CO_2 emissions change.

with sharp drops in GDP effects across all countries, reinforcing the strong link between macroeconomic cycles and emissions. While all four countries are bound by EU climate and energy targets, their trajectories diverge due to differing energy mixes, industrial structures, and policy effectiveness. This underscores the necessity of tailored national strategies to achieve carbon neutrality, particularly for Poland, which requires significant structural transformation, and for Slovakia, which needs to strengthen its policy frameworks. By contrast, Hungary and the Czech Republic appear better positioned to consolidate their emissions reductions through continued investments in clean technologies and energy efficiency.

5. Policy implications based on the results and discussion

The LMDI decomposition analysis revealed that GDP growth is the dominant driver of CO_2 emissions across all four countries, with energy intensity (EIE) and carbon emissions intensity (CEIE) being key mitigating factors. Population effects were generally negligible. This section translates these findings into actionable policy strategies, emphasizing targeted interventions aligned with each country's specific emission-driving mechanisms.

5.1. Poland: Decarbonizing energy and transport to curb GDP and CEIE effects

Strong GDP-driven characteristics characterize Poland's emissions profile, which increases and fluctuates in energy and carbon intensity, mainly due to its continued dependence on coal and energy-intensive industries (OCED, 2022).

- Accelerate the Shift from Coal: The decomposition shows high CEIE values, indicating carbon-intensive energy production. Policies should enforce a phase-out of coal through stricter carbon pricing, feed-in tariffs for renewables, and subsidies for solar, wind, and bioenergy deployment.
- Transport Electrification: Poland's GDP growth drives transport demand. Electrifying public transit fleets and expanding intercity electric rail can mitigate GDP-related emissions while reducing CEIE.
- EV Incentives for Private Users: EIE Fluctuations highlight energy use inefficiencies. Broader EV adoption (tax incentives, grants, EV charging networks) can improve EIE and CEIE by displacing internal combustion engines.

5.2. Hungary: Strengthening energy efficiency and sustainable urban transport

Hungary demonstrated moderate GDP impacts and relatively stable and improving energy intensity, indicating the importance of maintaining and expanding efficiency gains.

- Upgrade Fuel Efficiency Standards: The EIE effect was the primary emission-reducing driver in Hungary. Introducing higher vehicle efficiency standards and promoting electric buses can build on this positive trend.
- Multimodal and Active Transport: GDP growth correlates with increased vehicle use. Promoting urban cycling, walking, and affordable public transport can reduce the GDP effect by shifting demand away from high-emission modes.
- Expand EV Infrastructure: Minor but persistent CEIE values suggest the potential to reduce carbon intensity further by encouraging EVs and decarbonizing the electricity mix.

5.3. Czech Republic: Technology innovation and industry decarbonization

The Czech Republic showed consistent GDP-driven emission increases and moderate EIE and CEIE values, suggesting the need for industrial modernization and clean technology.

- Support for Clean Vehicles and R&D: Stable but moderate CEIE values imply potential for faster adoption of cleaner technologies. Subsidizing EVs, hydrogen vehicles and supporting local EV production can reduce emissions intensity.
- Industrial Energy Efficiency Grants: Given the correlation between GDP and emissions, promoting industrial energy audits, smart grids, and cogeneration technologies can significantly cut EIE.
- Rail Electrification: Rail is crucial for freight. Electrifying rail transport can lower both CEIE and GDP-related emissions from the logistics sector.

5.4. Slovak Republic: Consolidating gains through green infrastructure

Slovakia displayed lower GDP effects and moderate reductions in EIE and CEIE, suggesting that while progress has been made, policies must support continued decarbonization amid future economic growth.

- Sustain Public Transport Investment: As EIE reductions were consistent, further expanding urban and interurban public transport can lock in these gains.
- Integrate Renewable Fuels in Transit: To lower CEIE, Slovakia can pilot biofuels and hydrogen in municipal fleets and incentivize renewable-powered train services.
- Urban Active Mobility Programs: With minimal population effect, emissions mitigation should focus on reducing GDP-related travel through pedestrian zones and cycling corridors.

5.5. Regional cooperation and EU support

- Knowledge Exchange on EIE and CEIE Reduction: Countries with strong EIE reductions (e.g., Hungary, Slovakia) should share regional technical know-how and policy frameworks.
- Leverage EU Funding Mechanisms: EU instruments like Horizon Europe and Connecting Europe Facility can fund EV corridors, clean freight logistics, and innovative mobility infrastructure.
- Align with EU Transport Emission Standards: Tightening vehicle CO_2 limits and enforcing low-emission zones in cities can support uniform CEIE reductions across the region.

6. Conclusions

The analysis of transportation-related CO_2 emissions in Central Europe—specifically in Hungary, the Czech Republic, Poland, and Slovakia—reveals significant variations in emission trends driven by economic growth, energy dependency, and policy effectiveness. Poland's heavy reliance on coal has led to a steep rise and high variability in emissions, highlighting the urgent need for policies focused on renewable energy transition and transport electrification. Conversely, Hungary and the Czech Republic have shown more stable emission patterns due to moderate success in implementing energy efficiency standards and adopting cleaner technologies. However, further efforts are needed to promote multimodal and public transport options. With relatively stable emissions, Slovakia has demonstrated a balanced approach to economic growth and emission control, underscoring the value of sustained investments in public transport and renewable energy. Tailored policy interventions, such as incentivizing electric vehicle adoption, improving public and active transport infrastructure, and enhancing industrial energy efficiency, are crucial for each country to mitigate transportation emissions effectively. Moreover, regional cooperation and alignment with EU climate targets can help these countries leverage knowledge-sharing opportunities and access funding for large-scale sustainable transport initiatives. By addressing their unique challenges, Central European countries can collectively work toward a low-carbon future, contributing to the EU's goal of reducing emissions and achieving climate neutrality by 2050.

This study has several limitations. First, it relies on aggregated data from sources like the International Energy Agency and the World Bank. Differences in data collection methods across countries may lead to inconsistencies and affect comparability. Using the Kaya Identity and LMDI methods assumes linear relationships, which may overlook complex interactions between factors like economic growth and fuel transitions. The timeframe of 2001–2021 includes disruptions, such as the COVID-19 pandemic, that may not reflect long-term trends.

Additionally, focusing on Hungary, the Czech Republic, Poland, and Slovakia limits the generalizability of findings to other European regions. The lack of detailed data on specific transport modes restricts the ability to assess each mode's impact on emissions. Potential biases may also arise from the choice of variables, as factors like urban planning and cross-border transport were not included. Future research should use more detailed data, include additional factors, and consider extended timeframes to understand transportation emissions better.

Data availability

The data and materials used to support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

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

Declaration of Generative AI and AI-assisted technologies in the writing process

While preparing this work the authors used ChatGPT-Open AI to improve the language of this research. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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