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Environmental asymmetries in global value chains: The case of the European automotive sector

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A B S T R A C T

The European automotive sector is deeply integrated in the EU regional value chain. Each EU member show differences their economic and environmental performance. While central European countries perform more advanced, higher-value and lower-emission tasks, eastern economies specialize in manufacturing and have a higher share of exports from an environmental perspective. However, the environmental effects resulting from automotive production, as well as the distinctions among European economies based on their development levels, remain unexplored. Similarly, the implications of participation in global value chains (GVCs) in this context have not been examined. Therefore, the aim of this paper is to analyze the Environmental Kuznets Curve and the Pollution Haven/Halo Hypothesis in the case of the EU28 automotive sector under a value-added approach. The multi-regional input-output methodology along with a panel data estimation was used to verify the hypotheses. The results verify an inverted-N shape curve for the Kuznets hypothesis. Nevertheless, the results show no evidence of compliance with the haven or halo hypotheses. Moreover, participation in GVCs implies higher environmental impacts. Based on these findings, some policy recommendations are proposed to enhance the sector's circularity and optimize material use throughout the production chain.

1. Introduction

The past few decades have witnessed a profound transformation in the automotive sector. The impetus towards electric motor, driven by increasing environmental pressures and the looming prospect of fossil fuel depletion, has instigated substantial alterations in the configuration of the automotive Global Value Chain (GVC) (Beuse et al., 2018; Cséfalvay, 2020; Guzik et al., 2020). Recent developments, such as autonomous driving, real-time feedback, and the supply chain disruptions that emerged during the COVID-19 crisis are poised to further amplify this burgeoning "green" trend within the sector (Wu et al., 2021).

The transition towards electric motors finds its primary motivation in the growing concern for environmental conservation, coupled with the escalating institutional apprehension regarding the depletion and subsequent increase in the cost of fossil energy resources. The European Union (EU) has reinforced its commitment to this technology as it formulates its strategy towards a Circular Economy (CE), achieving the distinction of being the second-largest region globally in terms of electric vehicle sales by 2022, surpassed only by China (IEA, 2023). While the widespread adoption of electric vehicles undoubtedly promises a substantial reduction in emissions from vehicular usage, several critical issues necessitate attention, with the most significant ones outlined below.

Firstly, there is a need to address how energy generation will be augmented to support a future fleet of electric vehicles that will replace conventional combustion engines. Secondly, it is imperative to persist in the advancement of technology aimed at producing engines and batteries suitable for road transportation of goods. Lastly, careful consideration must be given to the environmental ramifications stemming from the production processes of various vehicle components and parts.

In reference to the third point, it's worth noting that despite the automotive sector's active involvement in GVCs, its pivotal status and the logistical challenges associated with transporting certain bulky and

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heavy components have necessitated the establishment of domestic factories in most EU countries. Within the context of intra-regional trade, owing to the full commercial integration among member nations, the sector's trade interactions hold significant importance. Consequently, recent integration initiatives have spurred a rise in foreign investments and exports within the automotive sector, particularly benefiting the Eastern European Economies (EEE) (Ambroziak, 2016).

Nonetheless, certain theories within the realm of international trade and its environmental consequences highlight that, under the presumption of unrestricted movement of goods and capital, processes of production relocation can emerge. These relocations might be driven by the pursuit of lower labor costs, less stringent environmental regulations, or other locational advantages, potentially resulting in a net upsurge in emission levels. Among the most noteworthy theories in this context are the Environmental Kuznets Curve (EKC) hypothesis, the Pollution Haven Hypothesis (PHH), and the Pollution Halo Hypothesis (HP) (Balsalobre-Lorente et al., 2019; Destek et al., 2018; Guzel and Okumus, 2020).

In the European context, if these hypotheses were to hold true, it would suggest that the EEE could potentially maintain a relatively higher environmental impact compared to the more developed economies of the EU. This could be attributed to an increase in their economic activity, largely bolstered by integration processes, while simultaneously upholding less stringent environmental regulations and possessing lower technological capacities. Furthermore, it's important to consider the role that each nation plays within the production chain of specific sectors. According to the theories mentioned earlier, these countries might assume responsibility for the relatively more emission-intensive production stages (Martínez-Zarzoso et al., 2017; Rodil-Marzábal and Campos-Romero, 2021; Campos-Romero et al., 2023).

Despite the large number of papers analyzing these hypotheses, various gaps have been identified in the literature. First, in terms of geographical scope, most of the studies are focused on developing countries, maybe under the presumption of better environmental performance in developed economies. However, a detailed examination of trade and investment dynamics reveals that it's not inherently evident that developed countries, including European ones, have successfully decoupled economic growth from emissions. Indeed, in developed regions, very diverse economies of different levels of development coexist, so there is an emerging interest in examining their performance from this perspective. Secondly, regarding the sectoral level, most studies address these hypotheses from a broad, aggregate standpoint, overlooking potential variations across different sectors. This proposal, however, narrows its focus to the automotive sector. This choice is motivated by two main reasons: the sector's unique integration into GVCs, which is predominantly regional, and its critical role in European industry with extensive production networks. Another significant gap in the literature relates to the scarcity of studies analyzing the implications of participation in GVCs through the lenses of the aforementioned hypotheses, particularly from a sectoral perspective. A fourth gap has to do with the limited literature exploring the intersection between regional economic integration, the role of EEE, and their specific environmental impacts under the EKC, PHH, and HP related to the automotive sector.

Hence, the primary aim of this paper is to undertake an analysis of the trade dynamics within the European automotive sector, considering both economic and environmental aspects. This analysis relies on trade statistics that capture value-added components as well as trade data and related carbon dioxide emissions (CO_2). Beyond addressing the EKC, PHH, and HP hypotheses, this paper also aims to explore whether there is a distinct differentiation between the more recently integrated Eastern European countries and other countries within the integrated area. These countries often exhibit characteristics akin to the economic periphery within this sector (Pavlínek, 2022).

This research offers several outstanding contributions. Firstly, it addresses a significant gap in the literature, as mentioned earlier, by enhancing the understanding of emissions perspectives and trends in EU countries, whether due to an increase in economic activity (EKC) or a higher volume of foreign investment (PHH/HP) in automotive production. Secondly, it considers the differences in the territorial distribution of labor and production through a center-periphery framework, particularly examining the distinct role played by EEE in the automotive value chain. Thirdly, it provides a set of economic policy recommendations aimed at strengthening the technological fabric of the European Union and promoting greater environmental responsibility from a meso-institutional perspective. Lastly, it integrates the perspectives of the Kuznets environmental curve and pollution haven hypotheses to provide a holistic understanding of the collective effects of foreign trade in conjunction with foreign investment flows, which is particularly pertinent to the automotive sector.

To address these questions, the research employs a comprehensive approach. It commences with a descriptive analysis of the European Union's automotive sector, encompassing its key characteristics and principal foreign trade patterns, with a focus on the value-added perspective. Additionally, the study provides insights into the emissions produced by the automotive industry within the member countries. Subsequently, an econometric panel data model is proposed to explore whether there is a discernible increase in emissions within the sector, correlated with its expanding involvement in GVCs, particularly in the EEE. For data acquisition to facilitate both analyses, the research leverages the multi-regional input-output methodology (MRIO), enabling the examination of intersectoral flows between different countries. In this context, particular attention is given to the trade flows within the automotive sector among the EU countries. The input-output approach facilitates the tracking of trade flows in GVCs related to automotive production. Additionally, it enables the analysis of its environmental effects through satellite accounts. Combined with the econometric model proposed in Section 3, this approach allows for the effective testing of the Kuznets, pollution, and halo hypotheses.

The study relies primarily on two key databases. Firstly, *TiVA* (Trade in Value Added, OECD) serves as a fundamental reference database for analyzing trade in value-added components. It features an environmental extension that furnishes data on the environmental impact of major trade flows, quantified in terms of CO_2 emissions. Secondly, Eora is a comprehensive multi-regional input-output database encompassing sectoral information for a total of 190 countries over an extended period. Its satellite accounts enable the measurement of emissions associated with trade flows, facilitating a detailed understanding of environmental implications. In addition to these primary databases, the research draws upon supplementary sources such as Eurostat and the World Bank to gather essential information required for the study, including data on FDI flows and stock, population statistics, and others.

In addition to the Introduction, the paper consists of four sections. Section 2 comprehensively examines pertinent literature concerning the characteristics of the European automotive sector, its integration into GVCs, and its ecological footprint. Section 3 delineates the data sources and methodology employed in this study. Section 4 provides an analytical commentary and discussion on the primary research findings, while Section 5 ultimately presents the core conclusions of the research.

2. Literature review

The automotive industry emerges as one of the sectors with the most extensive involvement in international trade (Gorgoni et al., 2018). Dominated by a small number of prominent multinational corporations, it holds a pivotal and strategic role in the economic development of nations. In the context of the EU, it made a substantial contribution, constituting approximately 8% of GDP in 2022. The sector also maintained a favorable trade balance, primarily driven by vehicle exports to countries beyond the Union. Overall, it generated more than 7% of the total European employment and over 11% of manufacturing employment specifically (ACEA, 2023).

Nonetheless, despite its expansive international reach, it can be argued that the automotive industry exhibits a more regional than global orientation, given that major companies predominantly sell their vehicles within the same region where they operate (Rugman and Collinson, 2004). In the case of the EU, the integration process has further deepened this regionalization trend within the sector (Brown et al., 2021; Pavlínek, 2020).

The automotive sector serves as a notable example of the escalating regionalization within international relations. This trend is particularly prominent in the so-called factory regions of Europe, North America, and Asia, which constitute trade blocs characterized by a high degree of integration (Baldwin, 2006; Baldwin and Lopez-Gonzalez, 2014). The heightened regionalization of GVCs does not imply the absence of significant trade interactions between these blocs. However, it's noteworthy that following the COVID-19 pandemic, regionalization processes have intensified, accompanied by a resurgence of certain protectionist measures. Governments and companies are taking such actions to mitigate the vulnerabilities exposed within GVCs during the pandemic (Enderwick and Buckley, 2020; Steinberg and Tan, 2023; Wang and Sun, 2021).

A recent trend that aligns with the regional dynamics of the automotive industry is the growing significance of emerging economies in the production of high-value auto parts. Nations such as China and those situated in Eastern Europe have gained increasing prominence in the manufacturing of complex components for the sector (Gorgoni et al., 2018; Markiewicz, 2020). Furthermore, in addition to providing higher value-added components, suppliers in these regions have also developed capabilities more closely associated with R&D processes than traditional manufacturing processes (Guzik et al., 2020). However, it's crucial to note that the major multinational corporations headquartered in more advanced economies persist in steering the industry's developmental trajectories and trends.

Several characteristics of the automotive sector exert a regional development influence, encompassing both production tasks and post-sales functions. The imperative to foster trust-based relationships and proximity with primary suppliers necessitates an organizational structure in the form of business clusters. These clusters not only economize transportation costs but also facilitate effective communication and the establishment of formal and informal connections among various actors within the production chain. This optimization of organizational and manufacturing processes is well-documented (Albulescu et al., 2021; Lugo-Sánchez and Guzmán-Anaya, 2021; Manzano-Ramos and Guzmán-Anaya, 2020; Mendoza Cota, 2021). Furthermore, geographic distance can adversely impact the quality of inputs sourced from external suppliers, especially when dealing with innovative or highly technologically advanced components (Bray et al., 2018).

The research conducted by Chen et al. (2020) underscores how the cluster-based organizational structure, characteristic of the automotive industry, can play a pivotal role in promoting sustainable development patterns. This becomes particularly evident when the leading companies within these clusters initiate the adoption of environmental policies. Such actions serve as incentives for their primary suppliers, compelling them to adjust to the evolving production standards. Considering this, it is worthwhile to explore policies aimed at fostering the establishment of networks among companies. This approach would enable those with advanced technological capabilities to disseminate their knowledge and expertise to other firms within the cluster, thereby facilitating the adoption of sustainable business practices.

The automotive sector serves as a lens to examine the operations of GVCs and the trends of regionalization in international relations. Consequently, the study of environmental impacts associated with this production structure (Meng et al., 2018; Wang et al., 2019; Wu et al., 2020; Campos Romero and Rodil Marzábal, 2021), characterized by extensive processes of productive fragmentation that inevitably entail a substantial volume of transportation movements –whose numbers escalate with greater supply chain fragmentation– has gained significance in recent decades (Rodrigue, 2006).

Numerous studies highlight a correlation between emission levels and specific stages within the production chain. It's observed that during the initial and final phases of a typical chain, encompassing activities like R&D, design, logistics, marketing, and after-sales, the associated emissions volume tends to be lower than in the central phases, which are more closely linked to manufacturing tasks (Shih, 1992; Campos Romero and Rodil Marzábal, 2024) (self-citation). Sectors with a substantial presence in GVCs tend to locate manufacturing activities in developing regions (Ge et al., 2020; Guzel and Okumus, 2020; Mahmood et al., 2023c; Saqib et al., 2023; Zhao et al., 2020). As companies in these regions develop new capabilities, they initiate upgrading and scaling processes. These processes not only enable them to secure a greater share of the value added within the overall value chain but also contribute to enhanced energy efficiency and reduced environmental emissions (Liu et al., 2018). From this can be derived the first hypothesis of analysis:

H1. A greater insertion of the automotive industry in global value chains implies a higher volume of associated emissions.

Although much of the literature focus on assessing the impact of the automotive sector from the perspective of road traffic, examining the effects stemming from its production process is equally crucial(Andrés and Padilla, 2018; Fan et al., 2018; Mazur et al., 2018; Moro and Lonza, 2018).In terms of the manufacturing impact, emissions within the sector would experience a notable escalation if we were to consider not only the emissions stemming from transportation but also those arising from the manufacturing processes. Consequently, emissions associated with the production of electric vehicles could surpass those of internal combustion vehicles. Additionally, we must account for the environmental repercussions of generating the necessary energy to sustain an expanding electric vehicle fleet. Hence, the utilization of renewable energy in conjunction with electric vehicles emerges as a pivotal strategy for achieving a substantial reduction in emissions within the electric vehicle sector (Kawamoto et al., 2019; Wang et al., 2013; Yan, 2009).

From these considerations regarding the impact of producing transportation components with international trade, questions arise concerning the influence of manufacturing activity locations. In accordance with the EKC hypothesis, regions characterized by lower income levels are anticipated to experience an increase in their emissions as they progress in development (Copeland and Taylor, 2001, 2004; Mahmood et al., 2023a, 2023b; Yasmeen et al., 2019; Zafar et al., 2019).

On the other hand, the PHH posits that within a context of unimpeded mobility of goods and capital, coupled with variations in environmental regulations on a global scale, businesses tend to position emission-intensive activities in regions with less stringent environmental regulations (Copeland and Taylor, 1994; Gill et al., 2018). Consequently, offshoring procedures could lead to an influx of FDI into destination countries and/or an augmentation of GVC participation rates within specific sectors, contingent on the chosen offshoring strategy.

While extensive discourse exists in the literature regarding the validation of these hypotheses (Destek et al., 2018; Shao et al., 2019), numerous studies have put them to the test in specific regions and sectors (Balsalobre-Lorente et al., 2019; López et al., 2018; Mahmood, 2020, 2022, 2023; Pata et al., 2023; Rana and Sharma, 2018), primarily through the application of econometric models. In the case of the PHH, its authenticity has often been contingent on whether the pursuit of regions with less stringent environmental regulations genuinely serves as the primary rationale for offshoring. Nevertheless, these differences in environmental regulations, if present, constitute just one among several factors considered in decision-making processes concerning the location of economic activities. Other factors, such as the search for reduced labor costs or proximity to new markets, among various others, are also significant determinants (Barbieri et al., 2018; Buckley and Ghauri, 2004).

The application of both theories to the automotive sector in the European context prompts questions about whether the EEE maintain relatively higher and increasing emission levels in comparison to more developed economies. It also raises inquiries into whether they might have evolved into potential pollution havens for emission-intensive sectors. Both of these issues are addressed in the second hypothesis:

H2. The different pattern of participation in the global automotive industry chain explains the different emissions intensity between the EEE and the rest of European economies.

Despite the process of European integration, which entails the harmonization of environmental regulations, initial disparities in technological capabilities could lead to elevated emission rates. Additionally, the lower labor costs in these countries, coupled with the advantages of goods and capital exchange facilitated by economic integration, may have incentivized the localization of manufacturing activities within the EEE (Pavlínek, 2023). This relocation, irrespective of specific environmental regulations, may bring about consequences in line with the predictions of the PHH. The different effects on growth and FDI when differentiating between EEE and other EU countries are included in the third hypothesis:

H3. The increase in the stock of Foreign Direct Investment (FDI) and economic growth leads to an increase in the overall volume of emissions.

Based on the literature reviewed, Table 1 provides a methodological detail of the cited papers, which focus on the EKC, the PHH/HP or both. While the explanatory variables vary according to each paper's specific focus, the overall methodological framework for testing these hypotheses remains uniform. For EKC, the analysis typically involves estimating quadratic or cubic models in relation to GDP per capita and emissions, aiming to identify either an inverted 'U' or an 'N' shaped curve. In the context of PHH and HP, the inclusion of FDI and its squared term is generalized, aimed at analyzing an inverse 'U' shaped relationship between some measure of environmental impact and FDI inflow. In the case of European countries, compliance with the PHH/HP may be uncertain due to the harmonization of environmental regulation linked to the integration process.

The model outlined in Section 3 (see expressions (4) and (5)) is developed based on the literature analyzed, particularly drawing from studies that concurrently analyze the EKC and the PHH/HP. As an innovative element and in addition to per capita CO_2, the emissions intensity in introduced as an explanatory proxy variable related to the environmental impact of the sector.

3. Data and methodology

This research introduces several innovations in the examination of the environmental repercussions of foreign trade. Firstly, it adopts a mesoeconomic approach focused on the automotive sector, renowned for its substantial involvement in regional value chains. Secondly, it combines the analysis of the EKC with the simultaneous exploration of the PHH and HP. This investigation spans an extensive timeframe, encompassing data from the majority of EU28 countries over the period of 1995–2015, employing a value-added trade perspective. Thirdly, the study delves into the environmental consequences of the European automotive sector's engagement in GVCs. Lastly, it places particular emphasis on Eastern European countries, aiming to ascertain whether the developmental disparity between this group and the rest of the EU has given rise to a form of pollution haven within the European Union.

This study relies on an input-output analysis, following the methodology initially developed by Leontief (1951, 1937) adapted to a multiregional scale. Multiregional input-output analysis has gained prominence in recent decades, largely due to the availability of MRIO databases. However, the foundation for this methodology was laid by Leontief and Strout (1963) for analyzing trade among U.S.

Data for this study have been sourced from various databases. Data pertaining to trade flows in terms of value added and environmental impact has been obtained with MRIO methodology from the Eora database (Casella et al., 2019; Lenzen et al., 2012, 2013). This method ins described below. Eora database was chosen for its extensive analytical timeframe and additional data on environmental impacts, energy consumption, and other pertinent variables in its satellite accounts. Additional variables, such as the sectoral stock of FDI,[1] population figures for each country, and average annual exchange rates have been obtained from Eurostat, the World Bank, and the International Monetary Fund, respectively.

Los datos de IED a escala sectorial pueden obtenerse desde Eurostat con un elevado nivel de desglose. Para el caso del sector de la automoción, no se han encontrado problemas de datos en esta variable.

The analysis of trade flows in terms of value added, primarily based on the work by Koopman et al. (2010, 2014) enables the dissection of a country's gross exports into as many as nine value-added components, which represent the various trade flows comprising GVCs. The methodology employed to derive the flows used in this study is elaborated upon below.

For a set of c countries and n sectors, $T_{cn\times cn}$ is defined as the intermediate transactions matrix, $F_{c\times c}$ as the final demand matrix and $X_{cn\times c}$ is the total output vector, obtained as the sum of matrices T and F. Thus, the basic input-output relationships are the following:

$$A = T\widehat{X}^{-1}; \quad L = (I - A)^{-1} \tag{1}$$

Where $A_{cn\times cn}$ is the matrix of technical coefficients of production, $\widehat{X}^{-1}_{cn\times cn}$ is a diagonal matrix containing the elements of the total output matrix on the main diagonal, the other elements being null; $L_{cn\times cn}$ is the Leontief inverse matrix and $I_{cn\times cn}$ is the identity matrix. The value-added coefficients, $v_{1\times cn}$, are needed to subsequently obtain the trade flows relative to the GVCs. The vector of value-added coefficients is obtained by means of the matrix of technical coefficients:

$$v = u - uA \tag{2}$$

Where $u_{1\times cn}$ is a vector made up of "ones" that can also be used to perform sums by columns or by rows, in which case a vector $u_{cn\times 1}$ would be preferred. Following Koopman et al. (2010, 2014), it is possible to decompose each element of the total output matrix according to where each value-added flow is absorbed.

Note that in $\widehat{X}_{cn\times cn}$ the elements lying on the $n \times n$ dimension diagonal represent each country's domestic inter- and intra-industry exchanges, while the non-diagonal elements represent foreign trade flows, thus omitting the diagonal of $\widehat{X}$ yields a gross export matrix.

To define export flows in terms of value added consider any three countries, s, d and z; and any three sectors j, k and r; such that $s \neq d \neq z$ but intra-sector trade is possible, so $j = k = r$. Hence, we define the following three flows of exports in terms of value added considering a total of n columns:

$$EXPF^s = \sum_{\substack{n,\\ s\neq d}} \widehat{v}^s_j L^{ss}_{jk} F^{sd}_{kj}; \quad EXPI^s = \sum_{\substack{n,\\ s\neq d}} \widehat{v}^s_j L^{sd}_{jk} F^{dd}_{kj} + \sum_{\substack{n,\\ s\neq d\neq z}} \widehat{v}^s_j L^{sd}_{jk} F^{dz}_{kr} \tag{3}$$

The element $EXPF^s$ in equation (3) represents the so-called traditional trade, i.e. value added generated in sector j of country s, processed as an intermediate good in the domestic economy and then exported to sector j of country d as a final good. The element $EXPI^s$ represents simple and complex GVC trade. Simple GVC involves value added generated in sector j of country s, exported as an intermediate good to sector k of country d, where it is further processed and consumed as a final good.

[1] Since sectoral FDI data is only available for the period 2008–2012, the sectoral FDI stock for the remaining years has been estimated from the 5-year sectoral average share and the total stock of FDI per country.

Table 1
Literature review summary.

Authorship	Variables	Sample Countries	Period	Method	Hypothesis verified?
Balsalobre-Lorente et al. (2019)	Ecological footprint, FDI, GDP per capita, renewable energy consumption, and share of urban population to total	Mexico, Indonesia, Nigeria, and Turkey (MINT)	1990–2013	FMOLS, DOLS	Pollution halo
Campos Romero and Rodil Marzábal (2024)	Consumption and production-based emissions per capita, GDP per capita, global value chain position and participation, and renewable energy consumption	East and Southeast Asian countries	1995–2018	Fixed effects panel data model	Verifies EKC with differences on the emissions perspective considered
Campos-Romero et al. (2023)	FDI, CO_2 intensity, GDP per capita, exports, energy intensity, and spatial dummy	European Union	1995–2015	Multi-level random effects model	Pollution haven
De Beule et al. (2022)	Locational variable (dummy indicating inside-outside EU), carbon inefficiency (emissions over sales by carbon price), emission-to-cap ratio, size of the investment, market-to-book ratio, return on assets, and a dummy indicating exposure to carbon leakage	358 multinationals under the European Union Emission Trading Scheme	2013–2020	Random-effects LOGIT	Pollution haven
Destek et al. (2018)	Ecological footprint per capita, GDP per capita, renewable energy consumption, and trade openess	European Union	1980–2013	Panel data	Verifies EKC
Ge et al. (2020)	FDI, 11th and 12th Five Year Plan SO2 reduction policy (interactive term between emission targets, actual emissions, and a period dummy), environmental enforcement, industry technology level, and export transactions	China, province level	2001–2015	Difference-in-difference-in-differences analysis (DDD) with panel data	Pollution haven
Guzel et al. (2020)	CO_2 per capita, FDI share of GDP, and energy use per capita	Indonesia, Malaysia, Philippines, Singapore, and Thailand	1981–2014	CCEMG and AMG models	Pollution haven
López et al. (2018)	CO_2, emissions embodied in exports, emissions avoided by imports, balance of avoided emissions	NAFTA, BRIIAT, Eurozone, Rest of EU, East Asia, and China	1995–2009	Multi regional Input Output	Pollution haven
Mahmood (2020)	FDI, CO_2 per capita, GDP per capita, financial market development, trade openess	21 North American countries (North America and the Caribbean)	1990–2014	Pooled OLS, panel data, and spatial model	No effect found on FDI (monotonic), verify Environmental Kuznets Curve
Mahmood (2022)	FDI, CO_2 per capita (territory and consumption based), GDP per capita, exports and imports (% of GDP), financial market development	Gulf Cooperation Council countries	1990–2019	Spatial Durbin model	Pollution halo, also verify EKC
Mahmood (2023)	FDI, CO_2 per capita, GDP per capita, exports and imports (% of GDP), and financial development	18 Latin American countries	1970–2019	Pooled OLS and panel data (fixed effects)	Pollution haven, also verify EKC
Mahmood et al. (2023a)	Literature review analysis	China	–	–	Most studies verify EKC
Mahmood et al. (2023b)	Literature review analysis. Relevance of including renewable energy consumption into the models	No specific country	–	–	Most studies verify EKC, especially when panel data is used compared to country cases
Mahmood et al. (2023c)	FDI, Consumption-based CO_2 per capita, GDP per capita, and exports and imports (% of GDP)	12 MENA countries	1995–2020	Panel data (fixed effects), and Spatial Durbin model	Pollution haven, also verify EKC
Martínez-Zarzoso et al. (2017)	Dirty exports, clean exports, total environmental tax revenues, and GDP	European Union	1999–2013	Panel data analysis	Porter hypothesis
Pablo-Romero et al. (2017)	Gross value-added per capita and per hour, total transport energy use, household transport energy use, and productive transport energy use	European Union	1995–2009	Panel data	Verifies EKC
Pata et al. (2017)	CO_2 emissions for air transport, maritime transport, rail transport, and road transport; GDP per capita, air transport energy consumption per capita, maritime transport energy consumption, rail transport energy consumption, and road transport energy consumption	13 European Union countries	1995–2019	Two-stage panel data	Verifies EKC (depending on transport mode)
Rana and Sharma (2017)	FDI, GDP, CO_2, and trade (exports and imports)	India	1982–2013	Dynamic multivariate Toda-Yamamoto	Pollution haven, also verify EKC
Saqib et al. (2023)	FDI, ecological footprint, GDP per capita, Energy Structure, Renewable energy consumption, human capital	16 European countries	1990–2016	Cross-Sectional AGRL model	Pollution halo, also verify EKC
Shao et al. (2019)	FDI, CO_2 per capita, GDP per capita, energy consumption per capita, trade openness, and urbanization	BRICS, and MINT countries	1982–2014	Panel vector error correction, and panel co-integration	Pollution halo
Zafar et al. (2019)	CO_2 per capita, renewable energy consumption, nonrenewable energy consumption, GDP, and trade openness	18 emerging economies	1990–2015	Panel data	Verifies EKC
Zhao et al. (2020)	CO_2 per capita, CO_2 intensity, industry CO_2 emissions (%), employment in carbon intensive industries (%), regional carbon emissions (%),	China, province level	2000–2014	Mediating effect model	Pollution haven

(*continued on next page*)

Table 1 (*continued*)

Authorship	Variables	Sample Countries	Period	Method	Hypothesis verified?
	intensity of environmental regulation, GDP per capita, FDI, secondary industry output in regional GDP, ration of net fixed assets and number of employees, investment in net fixed assets, and investment on carbon intensive fixed assets to total investment (%)				

Source: Authors

Finally, Complex GVC involves those value-added flows that pass through at least three countries. In this case, it is value added generated in sector *j* of country *s*, exported as an intermediate good to sector *k* of country *d*, where it is processed and subsequently exported to sector *r* of country *z*, where it is consumed as a final good.

To be precise, it's important to note that value-added re-exports, referring to flows that circle back to the country of origin, whether as a final or intermediate good, are also categorized as GVC trade flows. Nonetheless, they constitute only a negligible fraction of an economy's overall value-added exports and have consequently been omitted from the analysis for the sake of simplicity.

In terms of econometric estimation, the study proposes two models derived from the literature, as detailed in Table 1. Expression (4) introduces a novel aspect by utilizing emission intensity as a proxy to measure the environmental pollution resulting from car production in the EU. Meanwhile, Expression (5) presents the conventional model for estimating the Kuznets hypotheses as well as PHH and HP.

$$\text{Model I}: \ln (CO_2GDP)_{ct} = \beta_0 + \beta_1 \ln (GDPpc)_{ct} + \beta_2 \ln (GDPpc)^2_{ct} + \beta_3 \ln (GDPpc)^3_{ct} + \beta_4 \ln (FDIGDP)_{ct} + \beta_5 \ln(FDIGDP)^2_{ct} + \beta_6 \ln (EXPF)_{ct} + \beta_7 \ln (EXPI)_{ct} + \beta_8 \ln (ENERGDP)_{ct} + \beta_9 \ln(URB)_{ct} + \beta_{10} \ln(R\&D)_{ct} + \varepsilon_{ct} \quad (4)$$

$$\text{Model II}: \ln (CO_2pc)_{ct} = \beta_0 + \beta_1 \ln (GDPpc)_{ct} + \beta_2 \ln (GDPpc)^2_{ct} + \beta_3 \ln (GDPpc)^3_{ct} + \beta_4 \ln (FDIGDP)_{ct} + \beta_5 \ln(FDIGDP)^2_{ct} + \beta_6 \ln (EXPF)_{ct} + \beta_7 \ln (EXPI)_{ct} + \beta_8 \ln (ENERGDP)_{ct} + \beta_9 \ln(URB)_{ct} + \beta_{10} \ln(R\&D)_{ct} + \varepsilon_{ct} \quad (5)$$

Both models exhibit similarities, differing primarily in the specification of the dependent variable. The first model employs the natural logarithm of emissions intensity, quantified as the ratio of carbon emissions to GDP. Conversely, the second model utilizes carbon emissions per capita as the dependent variable. Furthermore, $\ln (GDPpc)_{ct}$ represents the natural logarithm of GDP per capita, while $\ln (GDPpc)^2_{ct}$ and $\ln (GDPpc)^3_{ct}$ denote its squared and cubed values, respectively. These additional elements are included to assess the presence of the EKC. Specifically, a positive sign for the first element, coupled with a negative sign for its square, is indicative of an EKC relationship. If the cubic element exhibits a positive sign, it implies the presence of a waveform relationship. Table 2 presents the descriptive statistics for the selected variables.

Similarly, in line with the approach for the emissions-to-GDP per capita ratio, this analysis also integrates the natural logarithm of the ratio of FDI to GDP along with its squared term. This inclusion aims to capture the possible existence of an inverted U-shaped curve in the relationship between these variables. Depending on the positioning of each country on this curve, it could potentially verify the presence of the PHH or the HP.

Furthermore, the analysis encompasses a set of variables designed to capture the influence of different trade flows in terms of value added. Specifically, $\ln (EXPF)_{ct}$ denotes the natural logarithm of the first expression as defined in equation (3), which pertains to the traditional trade Flow. $\ln (EXPI)_{ct}$ represents the sum of the other two flows in

Table 2
Data sources and descriptive statistics, 504 observations per variable.

	Average	Standard deviation	Min	Max	Definition	Source
GDPpc	578.1559	1636.801	11.9395	29960.87	GDP per capita (deflated)	Eora
$GDPpc^2$	3008067	4.28e+07	142.5519	8.98e+8	Square of GDPpc	Eora
$GDPpc^3$	6.73e+10	1.23e+12	1702	2.69e+13	Cubic of GDPpc	Eora
FDIGDP	0.7998	1.1027	0.005	7.834	Stock of foreign direct investment to GDP	Eurostat (FDI) and Eora (GDP)
$FDIGDP^2$	1.8534	6.2278	0.0000301	61.3729	Square of FDIGDP	Eurostat (FDI) and Eora (GDP)
EXPF	16.4109	7.9343	3.208	58.9648	Direct exports of final goods	Eora
EXPI	14.666	7.4003	3.5895	59.2594	Direct and indirect exports of intermediate goods	Eora
ENERGDP	0.003	0.005	0.0002	0.0438	Energy intensity (ratio of energy consumption to GDP)	Eora
URB	70.706	11.649	50.622	97.876	% or urban population	The World Bank
R&D	1.463	0.878	0.352	3.874	% of R&D expenditure over GDP	The World Bank

Note 1: The statistics have been obtained from the original data before logarithmic conversion.
Note 2: The conversion from euros (Eurostat data) to dollars (Eora data) has been made using the annual average exchange rate of the International Monetary Fund (IMF).
Note 3: Cyprus, Luxembourg, Malta, and Portugal have been excluded from the econometric analysis due to large data gaps in some of the variables.
Source: Authors from Eora and Eurostat

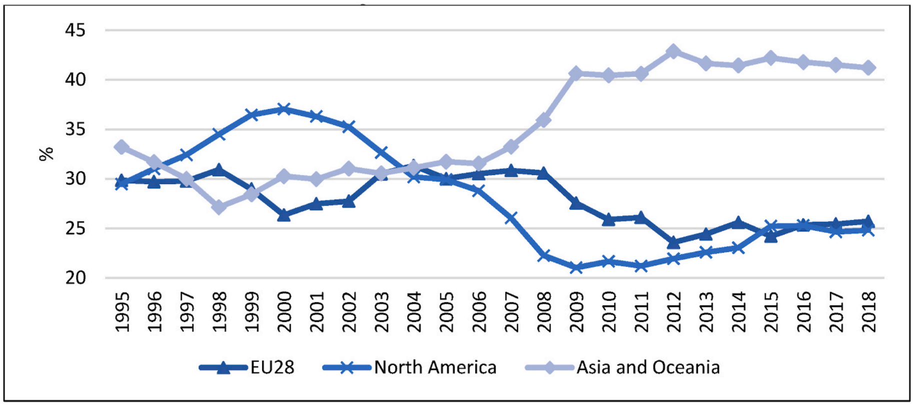

Fig. 1. Share of automotive value added contributed by EU28, North America and Asia and Oceania in world production, 1995–2018.
Source: Authors from TiVA (Trade in Value Added, OECD, 2021 edition)

Expression (3), which correspond to trade flows within both simple and complex GVC. Additionally, the natural logarithm of the ratio of energy consumption to GDP is introduced as a control variable. This variable is anticipated to exert a significant and positive influence on carbon emissions, whether measured as emissions intensity or emissions per capita.

4. Results and discussion

The EU28 holds a significant position in automotive production, commanding a 16.2% share of global production in 2022, as reported by the International Organization of Motor Vehicle Manufacturers (OICA). Nevertheless, its influence in the global market has gradually waned over time, mirroring a similar trend observed in the union formed by the United States, Mexico, and Canada through the T-MEC treaty, previously NAFTA. In the early 2000s, both regions contributed slightly over 30% each to global automotive production. However, they subsequently ceded ground to the Asian market and Oceania, which accounted for more than 58.8% of total automotive production (in terms of manufactured units) by 2022. It's worth noting that China accounts for nearly 29% of total global automotive production by itself.

When examining the value-added generated (see Fig. 1), it becomes evident that there was a decline in the contribution of both the EU and North America to global automotive production during the 2004–2008

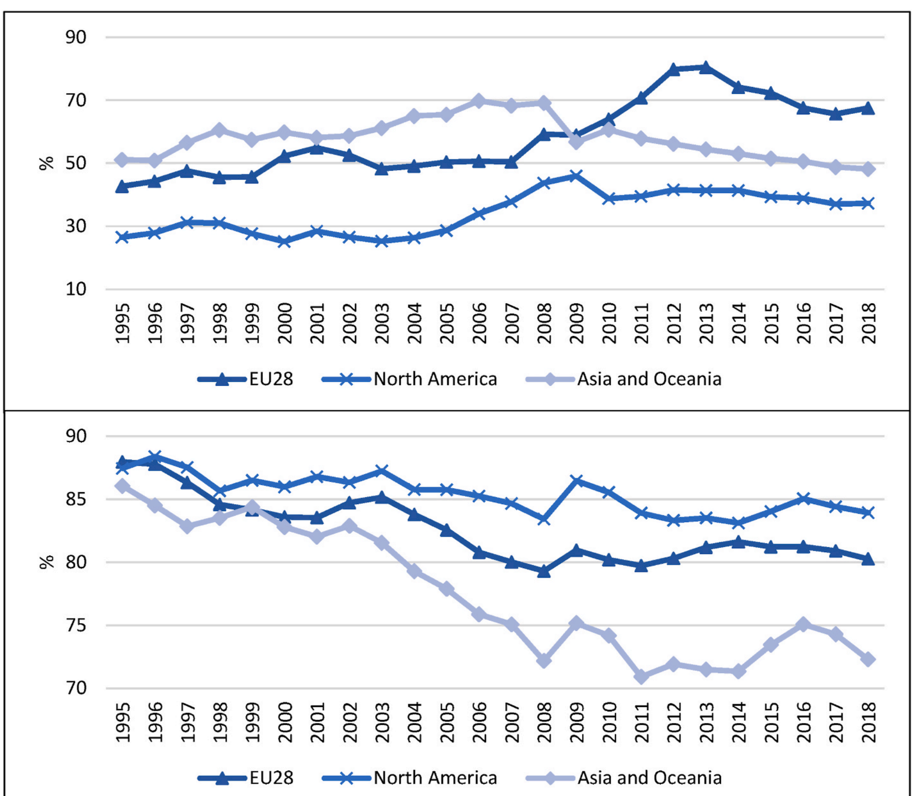

Fig. 2. Percentage of exported domestic content over value added generated in the automotive sector (top) and percentage of exported domestic content over gross exports of the automotive sector (bottom), EU28, North America and Asia and Oceania, 1995-2018
Note: When calculating the exported domestic content, the domestic value added that returns to the country of origin for final consumption has been discounted. Intraregional trade is not included.
Source: Authors from TiVA (Trade in Value Added, OECD, 2021 edition)

period. Furthermore, since the years preceding the 2008 financial crisis, the major Asian economies have significantly increased their contribution to the sector, accounting for approximately 41% of global production by 2018. It's important to note that the disparity in contribution in terms of value-added is somewhat smaller than the disparity in units produced. This discrepancy may arise from variations in the technological sophistication of vehicles manufactured in each region. Vehicles produced in the European and North American markets tend to possess a higher intrinsic value compared to those produced in the Asian market. This difference in technological sophistication may explain the somewhat narrower gap observed in terms of value-added contribution.

In terms of trade insertion patterns, Fig. 2 illustrates the percentage of domestically produced content exported relative to the value added generated by the automotive sector and gross exports. This initial metric exhibits variations depending on the region under consideration (see Fig. 2 top). Following the 2008 financial crisis, North America's contribution remained relatively stable, while Asia and Oceania experienced a decline in their share of the region's economy. Conversely, the percentage of domestic content exported in relation to the EU28's value added saw an increase following the crisis.

Turning to the second metric, as shown in Fig. 2 bottom, it underscores a distinguishing characteristic of the automotive sector in comparison to other industries. The proportion of domestically generated value added that is exported within gross exports exceeded 70% in Asia and Oceania and exceeded 80% in both the EU28 and North America. This lower reliance on foreign value added reflects the inherently regional nature of the sector's GVCs, as previously discussed.

Nonetheless, a prevailing long-term trend becomes apparent, whereby the exported domestic value added constitutes a diminishing proportion of the overall gross exports. This signifies an expanding reliance on foreign value added within the automotive exports of each region, with Asia and Oceania contributing to 28% of this foreign value added. The mounting significance of this share in Asia can be attributed to the necessity to import high-tech components due to a shortage in internal technical capabilities for their development (Kobayashi et al., 2015; Nag, 2009).

Within the EU28 countries (Table 3), a notable disparity becomes evident in the sector's significance within each member country. Countries such as Germany, Hungary, the Czech Republic, and the Slovak Republic make substantial contributions, exceeding 5% of the total value added in each respective country. In contrast, the remaining nations contribute less than 1%, with a particularly pronounced difference observed in countries like Ireland and the smaller regions (Luxembourg, Malta, and Cyprus), which exhibit a stronger presence in specific service activities.

These discrepancies extend to trade indicators, especially in those countries where the automotive sector constitutes a larger portion of national value added and plays a significant role in their exports. Nonetheless, even in countries with a relatively modest contribution to GDP (considering only direct activities in this context), the automotive sector represents a substantial fraction of exports. This holds true whether analyzed in gross terms or when variables are selected based on value added, addressing the issue of double counting often found in traditional statistics (Koopman et al., 2010, 2014).

Among exports measured in terms of value-added, those categorized as DVA exported as final goods stand out in comparison to those exported as intermediate goods. However, when evaluating the foreign trade activities of the entire EU28 region in terms of value-added, extra-regional exchanges take precedence over intra-regional ones –a significant shift compared to raw trade statistics.

Drawing from data sourced in the TiVA database, intra-regional trade, when assessed within the context of traditional export statistics, constitutes 37% of the total (which exceeds extra-regional trade). However, when using value-added statistics, the situation is reversed, especially in the case of exports of final goods, where extra-regional trade surpasses intra-regional trade by 65%. In contrast, the difference between extra-regional and intra-regional exports of intermediate goods is only 10%, with extra-regional exports holding a slight advantage.

These data highlight a distinctive aspect of the European automotive sector's international market engagement. Given its inherent nature, the

Table 3
The automotive sector in the EU28. Value added, gross exports and domestic value added (DVA) exported, 2018

	VA automotive share of total VA (%)	Gross automotive exports as a share of total gross exports (%)	Automotive DVA exported over total DVA exported (%)	Automotive DVA exported as intermediate goods over total intermediate DVA exported (%)
Austria	1.72	8.61	6.08	4.68
Belgium	0.92	5	3.34	2.01
Bulgaria	0.82	2.38	2.11	1.81
Croatia	0.46	1.95	1.45	1.56
Cyprus	0.03	0.09	0.09	0.03
Czech Republic	5.8	26.73	19.9	15.47
Denmark	0.27	0.96	0.96	0.64
Estonia	0.74	2.8	2.12	0.99
Finland	0.65	3	2.68	1.52
France	1.49	14.87	11.07	7.96
Germany	5.21	18.64	17.4	12.31
Greece	0.22	0.35	0.4	0.27
Holland	0.87	3.74	2.92	1.82
Hungary	5.25	23.11	15.16	13.24
Ireland	0.15	0.52	0.19	0.13
Italy	1.62	9.01	8.09	6.53
Latvia	0.44	1.9	1.49	0.89
Lithuania	0.66	1.53	1.3	0.91
Luxembourg	0.08	0.02	0.03	0.01
Malta	0.56	0.44	0.48	0.33
Poland	2.32	11.75	8.89	7.13
Portugal	1.6	10.57	6.86	5.73
Romania	3.57	15.93	13.73	10.77
Slovak Republic	5.42	30.83	19.72	14.61
Slovenia	2.3	10.51	6.69	5.11
Spain	1.79	13.01	10.02	8.1
Sweden	3.4	14.44	12.4	8.14
United Kingdom	1.69	10.19	8.49	5.44
EU28	2.43	–	–	–
EU28 (extra)	–	11.40	11.12	7.58
EU28 (intra)	–	11.78	8.52	6.63

Note: Foreign trade data for each member country include intra- and extra-regional trade.
Source: Authors from TiVA (Trade in Value Added, OECD, 2021 edition)

Table 4
Emissions intensity of the automotive sector (tons of CO_2 per thousand dollars of GDP), 1995–2015.

	1995	2015		1995	2015
Slovak Republic	7.45	1.46	Portugal	1.72	0.45
Poland	10.20	1.25	Belgium	1.57	0.43
Hungary	10.50	1.24	Slovenia	2.29	0.42
Luxembourg	2.15	1.10	Finland	1.27	0.38
Bulgaria	4.24	1.06	Ireland	1.39	0.34
Lithuania	6.58	0.88	United Kingdom	1.53	0.30
Romania	12.97	0.86	Spain	1.14	0.29
Croatia	1.61	0.67	France	1.03	0.27
Latvia	7.88	0.57	Italy	1.21	0.25
Czech Republic	4.02	0.56	Sweden	0.89	0.23
Greece	1.50	0.55	Holland	0.66	0.22
Estonia	9.05	0.51	Germany	0.39	0.17
Cyprus	1.72	0.49	Denmark	0.27	0.09
Austria	1.20	0.46	Malta	0.01	0.05

Source: Authors from Eora

Table 5
Share of each member country on intra- and extra-regional exports of automotive intermediate goods in terms of ADV and CO_2 exported, 2015

Domestic DVA exported as intermediate goods		CO_2 exported as intermediate goods	
Germany	28.30	Germany	15.31
France	14.90	France	13.10
Poland	2.01	Poland	8.18*
Italy	9.27	Italy	7.60
Spain	7.95	Spain	7.59
United Kingdom	6.53	United Kingdom	6.42
Czech Republic	3.30	Czech Republic	5.98*
Belgium	4.18	Belgium	5.83*
Holland	8.07	Holland	5.67
Austria	3.39	Austria	5.09*
Slovak Republic	0.84	Slovak Republic	4.01*
Sweden	4.88	Sweden	3.59
Hungary	0.81	Hungary	3.26*
Romania	0.87	Romania	2.44*
Portugal	1.09	Portugal	1.58*
Finland	1.21	Finland	1.50*
Slovenia	0.40	Slovenia	0.55*
Ireland	0.39	Ireland	0.44*
Lithuania	0.13	Lithuania	0.38*
Bulgaria	0.10	Bulgaria	0.33*
Denmark	0.94	Denmark	0.27
Estonia	0.14	Estonia	0.23*
Luxembourg	0.06	Luxembourg	0.22*
Greece	0.09	Greece	0.16*
Croatia	0.06	Croatia	0.14*
Latvia	0.03	Latvia	0.06*
Cyprus	0.03	Cyprus	0.05*
Malta	0.04	Malta	0.01

Note: The symbol "*" identifies those countries whose share in intra- and extra-European intermediate goods exports is higher in terms of emissions than in DVA.
Source: Authors from Eora

automotive industry exhibits a more regional orientation rather than a global one, as depicted in Fig. 2. Interestingly, despite this regional focus, most of the value-added exports generated in the EU find their way to other countries.

Turning to the environmental dimension of the automotive sector, Table 4 illustrates the emissions intensity of the sector in EU28 countries for the years 1995 and 2015. The trend in the emissions intensity of the automotive sector mirrors the broader pattern observed in the European economy, declining over time due to ongoing technological advancements in energy efficiency and continual reductions in emissions.

In terms of each country's impact, both in 1995 and 2015, the EEE emerged as the nations with the highest levels of emissions per dollar of production, partially verifying *H3*. Of particular significance are the results for Slovak Republic, Poland, and Hungary, which also show a substantial participation of the automotive sector in their economies. It has been previously pointed out that *H3* has been partially verified. In one hand, Eastern European countries continue to maintain higher emission intensity levels. On the other hand, over the 20 years analyzed, the average emission intensity of the EEE in the automotive sector has been drastically reduced, narrowing its differential with the average emission intensity for the remaining EU28 countries (see Appendix A).

Table 5 highlights the disparities between the sector's economic and environmental impacts, unveiling significant variations in the member countries' contribution to intra- and extra-regional exports of automotive intermediate goods when viewed from the perspectives of value-added or emissions. Significant disparities in the sector's export share become evident when examining it from both economic and environmental perspectives. These discrepancies, particularly pronounced in the instances of Poland, the Czech Republic, the Slovak Republic, and Hungary, could be attributed to their roles in the European regional value chain. As per the EKC and PHH, the lower level of economic development and the initial disparities (prior to economic integration) may have led these countries, including those in EEE, to undertake the more emission-intensive tasks within the automotive sector.

The adoption of such tasks, coupled with slower technical progress, could account for the variations in emissions intensity and the proportion of intermediate goods exports within the automotive sector, depending on whether these aspects are analyzed from an economic or environmental standpoint. To examine the presence of EKC, PHH, and HP within the automotive sector, we present the following econometric models. Table 6 outlines the results of Model I in Expression (4) for all 24 countries included in the estimation, as well as two additional estimations for EEE and non-EEE countries. Table 7 outlines the results of Model II in Expression (5), also differentiated the previous 3 cases.

Table 6 shows the estimation outcomes of Model I across three scenarios: all countries, EEE, and non-EEE. Table 7 shows the results for the same models with CO_2 per capita as the dependent variable. In neither model across any scenario is evidence found to support the PHH or HP. However, an inverse linear relationship is observed between the ratio of sectoral FDI stock inflows to GDP and both dependent variables. These findings imply that increased investments in the European automotive

Table 6
Model I estimation results. Dependent variable: emissions intensity (CO_2 to GDP ratio).

	All countries (24)		EEE countries (11)		Non-EEE countries (13)	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
ln(GDPpc)	0.316	1.54	0.907	2.09**	−1.256	−2**
ln(GDPpc)^2	−0.197	−5.73***	−0.345	−3.94***	0.064	0.72
ln(GDPpc)^3	0.010	5.52***	0.020	3.56***	−0.003	−0.61
ln(FDIGDP)	−0.163	−9.21***	−0.160	−7.25***	−0.081	−2.34**
ln(FDIGDP)^2	−0.036	−8.05***	−0.043	−6.38***	−0.015	−2.03**
ln(EXPF)	−0.275	−3.98***	−0.340	−4.03***	−0.013	−0.1
ln(EXPI)	0.193	2.83***	0.264	3.16***	−0.061	−0.47
ln(ENERGDP)	0.100	3.91***	0.020	0.57	0.189	5.21***
ln(URB)	−1.952	−6.75***	−1.006	−1.62	−2.650	−7.75***
ln(R&D)	−0.137	−3.66***	−0.093	−2.09**	−0.320	−4.54***
constant	11.589	8.72	6.257	2.32	18.274	9.53
R^2 within	0.94		0.96		0.91	
R^2 between	0.58		0.00		0.29	
R^2 overall	0.61		0.28		0.36	
rho	0.98		0.98		0.98	
N. observations	504		231		273	
Period	1995–2015		1995–2015		1995–2015	

Note: "***", "**" and "*" indicates significance at 1%, 5% and 10% respectively.
Source: Authors from Eora, the World Bank, Eurostat, and IMF

Table 7
Model II estimation results. Dependent variable: CO_2 per capita.

	All countries (24)		EEE countries (11)		Non-EEE countries (13)	
	Coefficient	t-value	Coefficient	Coefficient	t-value	t-value
ln(GDPpc)	1.316	6.41***	1.907	4.4***	−0.256	−0.41
ln(GDPpc)^2	−0.197	−5.73***	−0.345	−3.94***	0.064	0.72
ln(GDPpc)^3	0.010	5.52***	0.020	3.56***	−0.003	−0.61
ln(FDIGDP)	−0.163	−9.21***	−0.160	−7.25***	−0.081	−2.34**
ln(FDIGDP)^2	−0.036	−8.05***	−0.043	−6.38***	−0.015	−2.03**
ln(EXPF)	−0.275	−3.98***	−0.340	−4.03***	−0.013	−0.1
ln(EXPI)	0.193	2.83***	0.264	3.16***	−0.061	−0.47
ln(ENERGDP)	0.100	3.91***	0.020	0.57	0.189	5.21***
ln(URB)	−1.952	−6.75***	−1.006	−1.62	−2.650	−7.75***
ln(R&D)	−0.137	−3.66***	−0.093	−2.09**	−0.320	−4.54***
constant	4.681	3.52	−0.651	−0.24	11.367	5.93
R^2 within	0.42		0.39		0.56	
R^2 between	0.0003		0.01		0.02	
R^2 overall	0.003		0.001		0.03	
rho	0.98		0.98		0.98	
N. observations	504		231		273	
Period	1995–2015		1995–2015		1995–2015	

Note: "***", "**" and "*" indicates significance at 1%, 5% and 10% respectively.
Source: Authors from Eora, the World Bank, Eurostat, and IMF

sector could lead to reduced environmental impacts from the manufacturing of vehicles and auto parts. This effect appears to be more pronounced within the EEE compared to other EU28 countries. As mentioned above, in the case of European countries, non-compliance with the PHH/HP may be due to the harmonization of environmental regulations linked to the integration process.

In terms of the EKC, an inverse N-shaped relationship is identified within the EEE. Examination of the tipping points reveals that none have reached the local minimum for either emissions intensity or CO_2 per capita. Consequently, these results position the EEE within the initial declining segment of the inverse N-shaped curve. Nonetheless, the future trajectory of emissions intensity and per capita emissions could change based on various factors, including sectoral developments, forthcoming industrial policies, or changes in production and consumption patterns that may modify the current production framework of the automotive sector. Therefore, these results provide partial support for *H3*, with full verification of EKC and rejection of PHH/HP. Moreover, these results are in line with the contributions made by other authors, verifying the presence of the EKC and pointing to a favorable effect of FDI on environmental impacts (Destek et al., 2018; Martínez-Zarzoso et al., 2017; Pablo-Romero et al., 2017; Pata et al., 2023; Saqib et al., 2023).

Regarding the foreign trade variables associated with the automotive sector, they show distinct behaviors across the models. Final exports (EXPF), which are not related to GVCs, show an inverse relationship with both emissions intensity and CO_2 per capita. In contrast, exports of intermediate goods (EXPI), serving as a proxy for GVC participation in the automotive sector, demonstrate a positive impact on emissions. This relationship remains significant across the entire set of countries and within the EEE, but not among non-EEE countries.

The disparity between EEE and non-EEE countries is notable, highlighting the significant role of GVC trade in the so-called Factory Europe, particularly in supplying inputs for the automotive sector. In non-EEE countries, both final and GVC-related export variables lack significance, indicating their distinct roles within the production chain. Generally, tasks more directly related to manufacturing tend to have higher environmental impacts compared to those involved in design, sales, and after-sales services. The outcomes of both models provide partial support for *H1* and fully verify *H2*.The results of the additional variables vary depending on the country group for each model. Energy intensity has a significant and positive effect for all countries and non-EEEs, whereas the urban population share exhibits an inverse relationship. These variables are not significant for the EEE group; however, an inverse linear relationship is observed between a higher R&D expenditure as a percentage of GDP and the dependent variables. This underscores the importance of promoting R&D activities to mitigate the environmental impacts of the automotive industry. Achieving further environmental benefits and moving towards a decoupling of sector growth from its emissions necessitates progress in designing production processes. These processes should aim for increased material and energy efficiency and endorse the reintegration of resources at the end of their lifecycle back into production, aligning with circular economy principles.

The rho statistic quantifies the share of variance in the dependent variable explained by individual effects within the panel data model. A higher rho value indicates significant disparities among the countries studied, which aligns with the results. The R^2 within, that indicates how the model fits for each country; and the R^2 between, that assesses the model's capacity to explain variations across countries; aligns with the results of the model regarding the differences between EEE and other EU countries. The analysis introduces novel insights into the environmental impacts within the EU, distinguishing itself from previous contributions. Firstly, it employs a mesoeconomic approach by concentrating on a specific sector. Secondly, it challenges the assumption of better environmental performance (decoupling) within the EU. And thirdly, it explores the differences among member countries based on their development levels. To conclude, the following section presents the main conclusions of the paper and the policy recommendations that can be derived from the results.

5. Conclusions

The aim of this paper was to examine the trade dynamics of the automotive sector within the EU28 from both economic and environmental standpoints, with a particular focus on the sector's involvement in global and regional value chains. To achieve this goal, we have conducted an analysis of the regional automotive chain using a value-added approach based on MRIO analysis. This method enables a comparative assessment between the economic and environmental perspectives, while also allowing for the differentiation of trade flows within the analytical framework of global or regional value chains from other trade flows, commonly known as traditional trade.

The European automotive sector exhibits a distinct feature of active participation in its regional value chain, with most of the value added exported from the region being of domestic origin (resulting in a lower percentage of foreign value added). Within the EU, various countries assume different roles in this sector. Central European countries are notable for their substantial contributions to value added, often involved in tasks related to the initial and final stages of the production chain. In contrast, Eastern European countries tend to specialize more heavily in manufacturing activities. Given these variations in specialization within the sector, it is worth exploring whether differences in trade patterns among these countries emerge when considering exports from either an economic or environmental perspective.

The findings presented in this study align with this perspective: the EEE tend to have a larger share of exports when measured in terms of carbon emissions compared to their economic share. This contrast is especially noticeable in the cases of Poland, the Slovak Republic, and the Czech Republic, which play significant roles as suppliers to the Central European automotive industry. It should also be noted that the reduction in the sector's emissions intensity has been notable, approaching the average levels of the non-EEE. Additionally, we have conducted two econometric models utilizing panel data and fixed effects to examine the presence of the EKC and the PHH/HP.

In the first case, we have confirmed the presence of an inverted-shape curve correlating per capita income, emissions intensity, and per capita emissions This hypothesis is fulfilled when considering the EU as a whole and the EEE individually, but not in the other cases, revealing a differential behavior of the Eastern economies. Regarding the PHH and HP, the results do not confirm these hypotheses. However, they indicate that an increase in FDI inflows may lead to a reduction in environmental impacts. The results have also shown that increased involvement in global or regional value chains within the automotive sector corresponds to a deterioration in environmental conditions.

These findings raise intriguing questions about the existence of a center-periphery pattern in the European automotive sector. It appears that Eastern European countries focus on manufacturing tasks, which contribute less value but have a more significant environmental impact. Meanwhile, central European economies specialize in more advanced tasks, capturing a greater share of value-added while avoiding a substantial portion of the environmental damage associated with these activities. This complexity adds nuance to the assignment of environmental responsibilities, depending on whether we consider a producer perspective or a consumer perspective. From a producer standpoint, economies that gain relatively less benefit from their foreign trade participation would bear a higher economic cost due to environmental externalities. Conversely, a consumer or demand-side approach would attribute higher emissions volumes to more developed economies (C40 Cities, 2018; Guerzoni and Raiteri, 2015).

Our results point to the need to consider the entire automotive supply chain when planning the sustainability of the automotive industry at European level. There is still a long way for implementing actions that advance the green transition in this sector. In this regard, a greater "greening" plan and transparency of the automotive supply chain "End-to-end" should be adopted. In this point, some authors suggest that this action would contribute to rigorous upstream CO_2 and emissions testing to warn European buyers to desist from sourcing strategies that generate considerable carbon footprints in other countries (Brown et al., 2021).

Among the overall sustainability strategies, CE has a long-term projection and transformative potential beneficial to the environment and well-being (Capgemini, 2020; He et al., 2023). For this reason, awareness of the CE, its principles and incentives for circular practices should be promoted. This is linked to what is suggested by other works (Hernandez and Bakthavatchaalam, 2022), which indicate that companies could increase the upstream demand of CE over the downstream demand to the customer, increasing the demand for CE through competition and collaboration.

As shown by previous works, many companies, particularly SMEs in EEE, find it difficult to move outside their industry and establish contact and partnerships with key players (Brown et al., 2021). This gap needs to be addressed by encouraging diversification and greening through the existing cluster network to enable SMEs to better integrate into GVC. In addition, regulations must go beyond the percentage of recyclability and reuse, promoting technological innovations and collaboration among stakeholders, the academia, and related industries.

A specificity of this research is that it is limited to the European case (Factory Europe), which is justified by the strong regional character of the automotive value chain; in fact, more than 45% of its production depends on cross-border value chains within the EU (Brown et al., 2021). However, the results could serve as a basis for analysis in other areas, such as the Factories North America or Asia.

Finally, this research outlines, as future work, the need to further study the environmental implications of the transformation of the sector towards electric vehicles. In this sense, it is important to analyze whether the changes in production processes and in the use of new parts and components due to the change of engine are taking place with the objectives of sustainability and circularity encouraged by the EU. A second future line of research has to do with the extension of this study to the relation of the sector between the different global regions (Asia and America), thus analyzing the possible implications not only from the producer side, but also from a demand perspective (consumption).

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Data statement

Authors will provide access to the data in reasonable request considering that part of the original information is not in open access and, therefore, cannot be offered freely (Eora database). Only some elaborated indicators, from which the original data cannot be obtained, can be shared.

CRediT authorship contribution statement

Hugo Campos-Romero: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **Óscar Rodil-Marzábal:** Conceptualization, Data curation, Validation, Writing – original draft, Writing – review & editing. **Ana Laura Gómez Pérez:** Conceptualization, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hugo Campos-Romero and Óscar Rodil-Marzábal reports financial support was provided by Agencia estatal de investigación (Spain). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A

Table A1
Average emissions intensity, automotive sector, for non-EEE and EEE countries[1]

	Non-EEE countries	EEE countries
1995	1.16	6.98
1996	1.16	6.40
1997	1.18	5.70
1998	1.12	4.56
1999	1.06	4.04
2000	1.08	3.50
2001	1.08	3.60
2002	0.99	3.21
2003	0.85	2.73
2004	0.73	2.21
2005	0.66	1.95
2006	0.62	1.70
2007	0.54	1.41
2008	0.49	1.14
2009	0.50	1.19
2010	0.51	1.19
2011	0.45	1.13
2012	0.43	1.03
2013	0.42	1.00
2014	0.36	0.91
2015	0.36	0.86

Source: Authors from Eora
[1] EEE includes Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia.

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