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Empirical Evidence from EU-28 Countries on Resilient Transport Infrastructure Systems and Sustainable Economic Growth

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Abstract: This paper examines the nexus between the main forms of transport, related investments, specific air pollutants, and sustainable economic growth. The research is important since transport may act as a facilitator of social, economic, and environmental development. Based on data retrieved from Eurostat, Organisation for Economic Co-operation and Development (OECD), and World Bank, the output of fixed-effects regressions for EU-28 countries over 1990–2016 reveals that road, inland waterways, maritime, and air transport infrastructure positively influence gross domestic product per capita (GDPC), though a negative link occurred in the case of railway transport. As concerning investments in transport infrastructure, the empirical results exhibit a positive impact on economic growth for every type of transport, except inland waterways. Besides, emissions of CO_2 from all kind of transport, alongside other specific air pollutants, negatively influence GDPC. The fully modified and dynamic ordinary least squares panel estimation results reinforce the findings. Further, in the short-run, Granger causality based on panel vector error correction model pointed out a unidirectional causal link running from sustainable economic growth to inland waterways and maritime transport of goods, albeit a one-way causal link running from the volume of goods transported by air to GDPC. As well, the empirical results provide support one-way short-run links running from GDPC to investments in road and inland waterway transport infrastructure. In addition, a bidirectional short-run link occurred between carbon dioxide emissions from railway transport and GDPC, whereas unidirectional relations with economic growth were identified in the case of carbon dioxide emissions from road and domestic aviation. In the long-run, a bidirectional causal relation was noticed between the length of the railways lines, investments in railway transport infrastructure, and GDPC, as well as a two-way causal link between the gross weight of seaborne goods handled in ports and GDPC.

Keywords: transport infrastructure; sustainable economic growth; fixed-effects regression; panel cointegration; panel vector error correction model

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1. Introduction

Infrastructure ensures the provision of basic physical systems and structures that are indispensable for peoples and companies [1]. Amongst the multifarious kinds of infrastructure, the policy makers regard transport infrastructure as one of the most essential, since related cost is critical in setting the location for firms, and hence the economic development of a region [2]. Li and Li [3] reported that one dollar of road investment in China cut input inventory by about 2 cents each year over 1998–2007.

As well, transport is one of the crucial sectors, inasmuch as an economy can benefit from transport services by quickening access to amenities, increasing the market mobility and direct employment [4], encouraging international tourism [5], saving time, and dropping business costs [6,7]. Beyond, through attracting resources from other areas, transport infrastructure can act as a magnet of regional economic growth [8]. According to Chandra and Thompson [9], highways increase the economic activity in the counties that they pass directly through, but draw activity away from nearby counties. Therefore, well-organized transportation networks engender employment and wealth, and lead to economic growth [10]. Bottasso et al. [11] explored the main European ports of Organisation for Economic Co-operation and Development (henceforth "OECD") states and noticed that regional employment is positively associated to port throughput, although the number of passengers was not. Li et al. [12] found that road infrastructure influences the local economy by attracting foreign investments and stimulating real estate development. Contrariwise, a deficiency of infrastructure generates bottlenecks for sustainable growth and poverty reduction [13].

The classical location theory points out the significance of transport costs as a driver of the place of economic undertakings [14,15]. Therewith, the view that the interaction amid transport costs and increasing returns to scale, offers corporations a reason to lay down near large markets, is a central part in the new economic geography literature [16]. In addition, the theory of endogenous growth reinforces that public infrastructure, covering transport infrastructure, is a basis of economic growth via its role in technical change. Barro [17] predicted that only productive government expenditures will positively influence the long-run growth rate. However, well-developed transport infrastructure ensures returns through certain macroeconomic drivers of productivity, such as: "expansion of business activity, innovations, and investments, labor market, competition, domestic and international trade globally mobile activity, regional economic development, wellbeing of population, environment safety and health" [18]. Aschauer [19] revealed that a higher level and enhanced quality of highway size increases transportation services and raises the marginal product of private capital. Thus, investments in transport infrastructure will increase the efficiency and lessen the prices of production inputs [20]. Padeiro [21] examined by the means of logistic regressions whether small municipalities register employment growth based on their position in relation to transport infrastructures, and found that motorways influence very small regions, whilst airports influence bigger ones.

On the other hand, transport externalities such as carbon dioxide emissions (henceforth "CO_2") [22,23] and traffic mortalities [24] cause environmental degradation [25] and a lower quality of life [26]. Likewise, Geist and Lambin [27] emphasized that infrastructure extension is one of the factors that prevail in affecting deforestation. Also, lubricant and substance spills from ships, either from operating activities or catastrophic mishaps, cause health hazards [28]. Unfortunately, dropping emissions in transport is more expensive than in other sectors, inasmuch as transport still heavily relies on fossil fuels [29]. There are environmental sustainability norms for biofuels and bioliquids, with a threshold of 35% savings of greenhouse gas emissions [30,31]. The Paris Agreement [32] aims to restrict global warming to well below 2 °C above pre-industrial levels and confine the temperature increase to 1.5 °C, whilst White Paper [33] pursues a 60% greenhouse gas emission reduction by 2050 in relation to 1990. Hence, in order to accomplish the target of cutting transport emissions, the decarbonization of transport is required [29], alongside improvements in transport energy intensity, the substitution of road transport by rail transport, and the shift from oil products to electricity [34]. As well, smart city solutions can unveil a vital role in alleviating transport emissions and fulfilling reduction targets [35]. However, in 2015, transport (comprising aviation and shipping) contributed 25.8% of total greenhouse gas emissions in the EU-28 [36]. Besides, the European Union (henceforth "EU") member states are required to fulfill the goal of 10% for the share of renewable energy in the transport sector by 2020 [30]. As well, EU set a 30% drop of emissions from both cars and vans in 2030 compared to the 2021 targets [37]. In this regard, investing in up-to-date infrastructure enables the use of more energy-efficient means and alternative technologies that positively affect the economy with minimizing negative externalities [38]. Therefore, Kumari and Sharma [39] noticed a strong association between physical and social infrastructure, and economic development.

The current paper aims at empirically investigating the relationship between transport infrastructure systems and economic growth for EU-28 countries. Therefore, the paper's leading purposes are: (i) to examine the influence of the main forms of transport, namely rail, roads, water, and air on gross domestic product per capita; (ii) to explore the impact of transport infrastructure investments on economic growth; (iii) to analyze the effect of carbon dioxide emissions from transport and other specific air pollutants from transport on economic growth. Transport is a strategic segment of the EU economy that exerts a striking influence on social, economic, and environmental expansion. In the same vein, transport supports economic growth, employment, global competitiveness, and trade, allowing persons and goods to shift across Europe. Withal, transport is the crucial promoter of the four freedoms of displacement outlining the Single Market: citizens, merchandises, services, and funds [40]. Previous papers on European countries studied the impact of port activities on local employment [11], the influence of port activities on local development [41], the relationship between air transportation and regional growth [42], as well as the impact of infrastructure investments on national productivity [43]. To the best of our knowledge, this is the first study that analyzes the influence of transport infrastructure, related investments, and specific air pollutants on sustainable economic growth in EU-28.

The structure of the paper is as follows. Section 2 provides an overview of the previous findings towards the influence of transport infrastructure, associated investments, and related pollutant emissions on sustainable economic growth. Section 3 describes the sample, variables, and econometric methodology, whilst Section 4 discusses the empirical output. The last section summarizes the main conclusions and provides policy implications.

2. Review of Previous Literature

2.1. Transport Infrastructure and Economic Growth

Transport facilities contribute to economic growth by enhancing the whole productivity of production units, by stimulating technological spillovers across economies, as well as by increasing the profitability of transport-connected businesses [44]. Using provincial Chinese panel data from 1993 to 2009, Xuelian [45] indicated that the total output elasticity of transport infrastructure for regional economic growth fluctuates between 0.05 and 0.07. However, there was exhibited that means of transport perform in different ways, respectively modal change of freight transport from road to rail is positive with regard to its impact in total output and the total wages of the economy, whilst freight transport by road has a superior influence in employment [46]. Ikumo [47] noticed that the positive economic effect of high-speed railway service will occur in the regions along the paths, but this will engender a negative influence with other aspects. Nevertheless, large investments in high-speed train infrastructure are not reasonable, as long as its economic development benefits are not assured [48]. Ding [49] revealed that a one percent increase in urban road density will increase the manufacturing gross domestic product share of the city-proper by 0.095 per cent, whereas a one percent growth in major regional roads is related to a 0.144 per cent increase in the manufacturing GDP share in the city-proper. Consequently, road infrastructure can boost economic growth [50].

Air cargo empowers states, regardless of location, to efficiently link to remote markets and global supply chains in a quick, trustworthy mode. Hence, in the current fast-cycle logistics period, nations with suitable air cargo connectivity show competitive commerce and production benefits over those without such capabilities [51]. Fernandes and Pacheco [52] revealed for Brazil, from 1966 to 2006, a unidirectional Granger causal link from economic growth to domestic air transport demand. Yao and Yang [53] depicted for 31 Chinese provinces and municipalities, over 1995–2006, that a positive association ensued between air transport and economic growth, industrial structure, population density, as well as openness. By means of the European-level annual data from eighty-six regions, Mukkala and Tervo [42] noticed a causal relationship from air traffic to regional growth in peripheral regions, although this connection was less evident in central areas. Baltaci et al. [54] examined 26 sub-regions at NUTS 2 level in Turkey, over the period of 2004–2011 and provided support via fixed-effects and two stage least squares methods with instrumental variable approaches that airline transport positively influence economic growth. For Italy, during 1971–2012, Brida et al. [55] found a unidirectional causality running from aircraft movements to real gross domestic product.

Likewise, ports are essential for the support of economic activities in the surrounding areas, as they act as a critical association amid sea and land transport [56]. Besides, according to Golebiowski [57] water carriage is the most energy effective way of transportation. For Iran, during 1978–2012, Taghvaee et al. [58] observed via a dynamic log-linear approach, both in the short-run and long-run, the occurrence of a positive link between maritime transportation and GDP. By exploring a panel of 40 heterogeneous countries, Khan et al. [59] revealed a positive link between container port traffic and per capita income.

Table 1 points out a brief review of previous papers that examined the relationship between transport infrastructure and economic growth.

Table 1. Summary review of prior studies towards transport infrastructure and economic growth.

Study	Sample	Period	Empirical Methods	Conclusions
Munim and Schramm [60]	91 countries	2010, 2012, 2014	Structural equation model	The quality of port infrastructure has a significant positive influence on national economy
Saidi, Shahbaz and Akhtar [38]	MENA countries (the Middle East and North Africa region)	2000–2016	Generalized Method of Moments	Transport infrastructure positively influence economic growth
Li et al. [61]	31 provinces in New Silk Road Economic Belt	2005–2014	Spatial Lag Model with fixed effects	Transport infrastructure shows positive spatial spillover effects on regional economic growth The general effects and spatial spillover effects of highway transport on economic growth are much larger than those of railway transport
Hakim and Merkert [62]	South Asia	1973–2014	Pedroni/Johansen cointegration Granger long-run and Wald short-run causality tests Time Series Cross Section (TSCS) Granger causality	Long-run unidirectional Granger causality running from gross domestic product (GDP) to air passenger traffic and air freight volumes
Park and Seo [63]	Korea	2000–2013	Augmented Solow model	Container port activities positively influence regional economic growth
Arvin, Pradhan and Norman [44]	G-20 countries	1961–2012	Panel vector auto-regressive model	Long-run equilibrium link between transportation intensity, CO_2 emissions, extent of urbanization, and economic growth
Baker et al. [64]	Australia	1985–2011	Granger causality analysis	Airports influence regional economic growth and the economy directly influences regional air transport
Hu et al. [65]	29 Chinese provinces	2006–2012	Panel vector error correction model	1% increase in the air passenger traffic determines an increase of 0.943% of real gross domestic product
Bottasso, Conti, Ferrari and Tei [41]	13 European countries	1998–2009	Spatial panel econometric framework with fixed effects.	Ports increase local GDP
Shan et al. [66]	41 major port Chinese cities	2003–2010	Regression Analysis	Positive effect of port cargo throughput on the economic growth of the host city

Table 1. *Cont.*

Study	Sample	Period	Empirical Methods	Conclusions
Chi and Baek [67]	United States	2001–2011	Autoregressive distributed lag	In the long-run, air passenger and freight services increase with economic growth In the short-run, air passenger service is responsive to economic growth
Hong et al. [68]	31 Chinese provinces	1998–2007	Pooled ordinary least squares (henceforth "OLS"), random-effects and fixed-effects panel data regression models	Land transport (comprising roadway and railway) and water transport infrastructure are related to annual growth rate of real GDP per capita The impact of airway transport infrastructure on economic growth is weak
Marazzo et al. [69]	Brazil	1966–2006	Error correction model	Strong positive response of passenger-kilometer due to a positive change in economic growth

Source: Authors' work based on literature review.

2.2. Transport Infrastructure Investments and Economic Growth

Transport infrastructure investments suppose supplementary transport volume, augmented trustworthiness, and an improved quality of transport services. In turn, this determines lower transport costs, as well as shorter transit times. As well, enhanced transport infrastructure is the essential part for business expansion [70]. Pereira and Andraz [71] estimated for Portugal, in the long-term, that one euro in public investment rises output by 9.5 euros, namely a rate of return of 15.9%. Hu and Liu [72] explored 28 provinces in China from 1985 to 2006 via a spatial econometric model and found that each 1% increase of the transportation investment in China leads to 0.28% increase on GDP. Yu et al. [73] unveiled a one-way Granger causal link between transport investment and economic growth at Chinese national level. Based on a sample of 563 estimates obtained from 33 studies, Melo et al. [74] reported that a growth of 10% in public investment in transport infrastructure is related with a rise in output of almost 0.5%. Holmgren and Merkel [75] conducted a meta-analysis of 776 estimates with regards to elasticity of production concerning infrastructure and noticed that the estimated outcome of investing in infrastructure fluctuates from -0.06 to 0.52. However, Deng et al. [76] revealed that transport infrastructure investment can stimulate economic growth, but the extent of outcome variations hinge on the scale of the existing transport network. Hence, there was noticed an insignificant positive association between transport infrastructure accumulation and economic growth when the highway network density is lower than 0.17 km/km^2. Besides, a significant positive effect on economic growth occurred when the highway network density is among 0.17 and 0.38 km/km^2, or higher than 0.38 km/km^2 [76]. As well, it was established that private sector investment in the transport sector and disposal of rail infrastructure lessen transport CO_2 emissions [77]. For Pakistan, Mohmand et al. [78] revealed no causal link in the short run between economic growth and transportation infrastructure, but a unidirectional causality from economic development to infrastructure investment in the long run. Yang et al. [79] established that urban transportation investment increases emissions in the short run because it might determine road jams that would heighten the emissions of the low-speed traffic, but in the long run, the urban transportation investment exhibits a positive influence on decreasing emissions since it could extend the roads and make the traffic system more accessible.

A summary review of papers that explored the link between transport infrastructure investment and economic growth is shown in Table 2.

Table 2. Brief review of previous studies regarding the impact of transport infrastructure investments on economic growth.

Study	Sample	Period	Empirical Methods	Conclusions
German-Soto et al. [80]	71 Mexican urban areas	1985–2008	Panel cointegration	Steady evolution among productivity and water supply, global infrastructure index, road infrastructure index, vehicular density, investment in highways, and the social infrastructure index
Jiang et al. [81]	China	1986–2011	Structural equation model	Investment in transportation influences economic growth
Meersman and Nazemzadeh [82]	Belgium	1980–2012	Error-correction model	Investment in port infrastructure by government drives economic growth Investment in highways drives economic growth
Shi et al. [83]	China	1990–2013	Vector error correction model	Inverse U-shaped link between infrastructure investment and economic growth
Chen et al. [84]	China	2002–2013	Computable general equilibrium model	Strong and positive effect of rail investment on national economic growth and social welfare, although the influence on CO_2 emissions generation has been large
Kodongo and Ojah [85]	45 Sub-Saharan African countries	2000–2011	System generalized method of moments	Expenditure on infrastructure and increases access to infrastructure influence growth
Park and Seo [63]	Korea	2000–2013	Augmented Solow model	Port investment indirectly leads to economic growth
Thoung, Tyler and Beaven [43]	27 Member States of the European Union, Norway and Switzerland	1970–2011	Error-correction model	Investment in road-transport links might be beneficial for productivity growth
Song and van Geenhuizen [86]	China	1999–2010	Panel data analysis	Positive influence of port infrastructure investment on economic growth
Guo et al. [87]	China	1964–2004	Vector Autoregression framework	Long-run positive influence of railway investment to GDP, whilst a negative impact of highway investment on GDP
Hong, Chu and Wang [68]	31 Chinese provinces	1998–2007	Pooled OLS, random-effects and fixed-effects panel data regression models	Water transport infrastructure investment positively influences economic growth only after the investment scale goes above a threshold point

Source: Authors' work based on literature review.

2.3. Pollutant Emissions from Transport and Economic Growth

Roads carry noteworthy economic benefits and are crucial for development, specifically in densely inhabited rural regions that are unrelated to markets and economic activity, but are frequently the forerunners to deforestation and biodiversity harm [88]. However, the transport sector, which comprises the aviation, road, navigation, and railway subsectors, is presently the second highest emitter of greenhouse gases, after power and heat production [89], and it accounts for about a quarter of CO_2 emissions globally [90]. Environmental issues such as air pollution are the consequences of the rise and concentration of greenhouse gases in the atmosphere, which comprises CO_2, methane, and nitrogen oxides [91]. The climate influence of aviation is determined by long-term effects from CO_2 emissions, and shorter-term impacts from non-CO_2 emissions and effects, which comprise the emissions of water vapor, particles, and nitrogen oxides [92]. Ben Abdallah et al. [93] noticed that a reciprocal causal relationship between transport value added, road transport-related energy consumption, road infrastructure, and CO_2 emissions occurs in the Tunisian transport sector, in the long-run. Sousa, Roseta-Palma and Martins [89] found a monotonically increasing relationship between economic growth and CO_2 emissions from transport in Portugal. However, Atte-Oudeyi et al. [94] revealed for a sample of six emerging countries an inverted U-shaped Environmental Kuznets Curve between CO_2

emissions per capita due to road transport and the level of GDP per capita. On the contrary, Alshehry and Belloumi [95] did not confirm the inverse-U association between transport CO_2 emissions and economic growth in Saudi Arabia, but noticed in the long run a unidirectional causality running from economic growth to transport CO_2 emissions. Yang and He [96] revealed a long-term equilibrium link between road transport subsectors and Air Pollution Index in Beijing, whereas both the freight and passenger subsectors are unidirectional Granger causing Air Pollution Index.

Table 3 reveals a brief review of past studies that examined the relationship between pollutant emissions from transport and economic growth.

Table 3. Summary of previous studies on environmental impact of transport infrastructure.

Study	Sample	Period	Empirical Methods	Conclusions
Sun et al. [97]	83 Chinese cities	2000–2012	Regression models: individual specific effects, two-way fixed effects, system generalized method of moments	In the long run, urban traffic infrastructure investment can alleviate air pollution
Ben Jebli and Belloumi [98]	Tunisia	1980–2011	Autoregressive distributed lag and Granger causality	In the short-run, a bidirectional causality occurred between CO_2 emissions and maritime transport, whilst a unidirectional causality occurred running from real GDP, combustible renewables, and waste consumption, rail transport to CO_2 emissions In the long-run, GDP drives a reduction of CO_2 emissions, whereas combustible renewables and waste consumption, and maritime and rail transport exhibit positive effect on emissions
Neves et al. [99]	15 OECD countries	1995–2014	Autoregressive Distributed Lag	Consumption of transports fossil fuels enhances economic growth Investment in rail infrastructure hinders the use of fossil fuels
Saidi and Hammami [100]	75 countries	2000–2014	Generalized Method of Moments	Environmental degradation is influenced by economic growth and freight transport in middle and low-income panels
Talbi [101]	Tunisia	1980–2014	Vector Autoregressive model	Economic development follows an inverted U-shaped form, relative to CO_2 emissions
Xie et al. [102]	283 Chinese cities	2003–2013	STIRPAT model (STochastic Impacts by Regression on Population, Affluence and Technology)	Transportation infrastructure intensifies urban carbon emissions and intensity
Song and Mi [103]	31 ports placed in 13 port provinces	1999–2010	Error Correction Model	In the short-run, a bidirectional causality between port investment and economic growth exists In the long-run, unidirectional causality running from port investment to economic growth
Xie et al. [104]	281 Chinese cities	2003–2013	STIRPAT model	Transport infrastructure, population size, technical progress, and energy intensity negatively influence the environment Transport infrastructure has a negative spatial spillover effect onto the environment
Shahbaz et al. [105]	Tunisia	1980–2012	Vector error correction model	Road infrastructure increases CO_2 emissions Road infrastructure causes CO_2 emissions and the analogous is true from the reverse side in the Granger sense
Liu et al. [106]	China	1980–2012	Logarithmic mean Divisia index (LMDI) method	Road and waterway are the main causes for China's transport CO_2 emissions
Saboori et al. [107]	OECD countries	1960–2008	Fully Modified Ordinary Least Squares	Positive significant long-run bi-directional connection between CO_2 emissions and economic growth
Sobrino and Monzon [108]	Spain	1990–2010	Decomposition analysis based on Modified Laspeyres Index	Economic growth is closely related to the increase in greenhouse gas emissions

Source: Authors' work based on literature review.

3. Data and Econometric Methodology

3.1. Sample and Variables

The research sample comprised panel data for the EU-28 member states, the common period for the complete variables' list being 1990–2016. Depending on availability, the data was gathered from Eurostat, OECD, and the World Bank. Gross domestic product per capita was employed as a proxy for sustainable economic growth [2,34,39,43,44,51,58,68,76,85,89,93,95], whereas several measures towards transport infrastructure [2,8,39,42,50,54,58,61,68,93], investment in transport infrastructure [8,43,73,81,82,97], transport pollution [34,50,58,89,95,106], and country-level controls [2,53,58,61,85,93,95,106] were considered, as exhibited in Table 4.

Table 4. Description of the variables.

Variables	Definitions	Data Source	Time Span
Panel A: Variables towards Sustainable Economic Growth			
(1) GDPC	Gross domestic product reflecting the total value of all goods and services produced, less the value of goods and services used for intermediate consumption in their production (current prices, euro per capita) (logarithmic values)	Eurostat (nama_10_pc)	'75–'16
Panel B: Variables towards transport infrastructure status			
Railway transport infrastructure status			
(2) Length_rail	The length of railways lines, whether electrified or not, on the territory of the reporting country (km) (logarithmic values)	Eurostat (ttr00003)	'70–'15
(3) Passengers_rail	Rail passengers transport in the Member States on its national territory (million passenger-km) (logarithmic values)	Eurostat (ttr00015)	'04–'16
(4) Goods_rail	Rail goods transport in the Member States on its national territory (million tone-km) (logarithmic values)	Eurostat (ttr00006)	'04–'15
Road transport infrastructure status			
(5) Length_motorways	The length of motorways, on the territory of the reporting country (km) (logarithmic values)	Eurostat (ttr00002)	'70–'15
(6) Motorisation_rate	The number of passenger cars per 1000 inhabitants (cars per 1000 inhabitants) (logarithmic values)	Eurostat (tsdpc340)	'90–'15
(7) Goods_road	The carriage of goods by road by means of goods road transport vehicles registered in the reporting countries (million tone-km) (logarithmic values)	Eurostat (ttr00005)	'99–'16
Inland waterways transport infrastructure status			
(8) Goods_water	Inland waterways goods transports (million tone-km) (logarithmic values)	Eurostat (ttr00007)	'82–'16
Maritime transport infrastructure status			
(9) Goods_sea	The gross weight of seaborne goods handled in ports, goods unloaded from vessels plus goods loaded onto vessels (1000 tones) (logarithmic values)	Eurostat (ttr00009)	'97–'16
Air transport infrastructure status			
(10) Passengers_air	The total number of passengers carried in Europe, arrivals plus departures (# of passengers) (logarithmic values)	Eurostat (ttr00012)	'93–'16
(11) Goods_air	The volume of goods transported in Europe by air (tones) (logarithmic values)	Eurostat (ttr00011)	'93–'16
Panel C: Variables towards investments in transport infrastructure			
(12) Inv_rail	Investments in railway transport infrastructure (constant euro) (logarithmic values)	OECD	'95–'15
(13) Inv_roads	Investments in road transport infrastructure (constant euro) (logarithmic values)	OECD	'95-'15
(14) Inv_water	Investments in inland waterways transport (constant euro) (logarithmic values)	OECD	'95–'15
(15) Inv_ports	Investments in maritime port infrastructure (constant euro) (logarithmic values)	OECD	'95–'15
(16) Inv_airports	Investments in airport infrastructure (constant euro) (logarithmic values)	OECD	'95–'15

Table 4. *Cont.*

Variables	Definitions	Data Source	Time Span
Panel D: Variables towards Transport Pollution			
Carbon Dioxide Emissions from Transport			
(17) CO_2_transport	The emissions of carbon dioxide from transport (tonnes per inhabitant) (logarithmic values)	OECD	'94–'14
(18) CO_2_rail	The share of carbon dioxide emissions from railway transport in total carbon dioxide emissions from transport (percentage)	OECD	'94–'14
(19) CO_2_road	The share of carbon dioxide emissions from road transport in total carbon dioxide emissions from transport (percentage)	OECD	'94–'14
(20) CO_2_maritime	The share of carbon dioxide emissions from international maritime bunkers in total carbon dioxide emissions (percentage)	OECD	'94–'14
(21) CO_2_aviation	The share of carbon dioxide emissions from domestic aviation in total carbon dioxide emissions from transport (percentage)	OECD	'94–'14
(22) CO_2_new_cars	The average emissions of carbon dioxide per kilometer by new passenger cars registered in a given year (gram of CO_2 per km) (logarithmic values)	Eurostat (tsdtr450)	'00–'16
Other Specific Air Pollutants from Transport			
(23) SOx_road	Emissions of sulphur oxides (SOx) from road transport (tonnes) (logarithmic values)	Eurostat (tsdpc260)	'90–'15
(24) SOx_non-road	Emissions of sulphur oxides (SOx) from non-road transport (tonnes) (logarithmic values)	Eurostat (tsdpc260)	'90–'15
(25) NOx_road	Emissions of nitrogen oxides (NOx) from road transport (tonnes) (logarithmic values)	Eurostat (tsdpc270)	'90–'15
(26) NOx_non-road	Emissions of nitrogen oxides (NOx) from non-road transport (tonnes) (logarithmic values)	Eurostat (tsdpc270)	'90–'15
(27) NMVOC_road	Emissions of non-methane volatile organic compounds (NMVOC) from road transport (tonnes) (logarithmic values)	Eurostat (tsdpc280)	'90–'15
(28) NMVOC_non-road	Emissions of non-methane volatile organic compounds (NMVOC) from non-road transport (tonnes) (logarithmic values)	Eurostat (tsdpc280)	'90-'15
(29) NH_3_road	Emissions of ammonia (NH_3) from road transport (tonnes) (logarithmic values)	Eurostat (tsdpc290)	'90–'15
(30) NH_3_non-road	Emissions of ammonia (NH_3) from non-road transport (tonnes) (logarithmic values)	Eurostat (tsdpc290)	'90–'15
Panel E: Country-level control variables			
(31) Energy_transport	Energy consumption of transport relative to GDP computed as the ratio between the energy consumption of transport and GDP (chain-linked volumes, at 2010 exchange rates). The energy consumed by all types of transport (road, rail, inland navigation and aviation) is covered, including commercial, individual, and public transport, with the exception of maritime and pipeline transport (Index, 2010 = 100)	Eurostat (tsdtr100)	'90–'15
(32) Trade	Trade openness as the sum of exports and imports of goods and services measured as a share of gross domestic product (% of GDP)	World Bank (NE.TRD.GNFS.ZS)	'60–'16
(33) Fin_dev	Domestic credit to the private sector, namely financial resources provided to the private sector by financial corporations, such as through loans, purchases of nonequity securities, and trade credits and other accounts receivable, that establish a claim for repayment (% of GDP)	World Bank (FS.AST.PRVT.GD.ZS)	'60–'16
(34) Urb	Urban population as people living in urban areas (% of total)	World Bank (SP.URB.TOTL.IN.ZS)	'60–'16

Source: Authors' work. The definitions of the variables are retrieved from Eurostat, OECD, and World Bank.

3.2. *Quantitative Framework*

In order to investigate the impact of transport infrastructure status, related investments, carbon dioxide emissions from transport, and other specific air pollutants on sustainable economic growth, we primary employed a panel data multivariate linear regression model [19,34,49,51,54,66,68,79,86,88,94] with the basic form being as follows:

$$Y_{it} = \alpha_0 + \beta_1 X_{it} + \beta_2 W_{it} + \beta_3 Z_{it} + \beta_4 Controls_{it} + \varepsilon_{it};\ i = 1,\ 2\ \ldots,\ 28,\\ t = 1990,\ 1991,\ \ldots,\ 2016 \quad (1)$$

where Y stands for the dependent variable, respectively gross domestic product per capita, X denotes a vector of explanatory variables capturing the status of the main forms of transport (railway, road, inland waterways, maritime, and air), W signifies a vector of explanatory variables regarding investments in the leading types of transport, Z describes a vector of explanatory variables regarding pollutant emissions from transport (carbon dioxide emissions, sulphur oxides, nitrogen oxides, non-methane volatile organic compounds, and ammonia), and *Controls* is a vector of country-level control variables catching additional features that may impact economic growth. The constant is depicted by α, β_1–β_4 are the coefficients to be estimated, ε is the residual term, i is the subscript of EU-28 countries, and t is the subscript of the time span. The fixed-effects approach was selected since the study was limited to a particular group of states [34].

Onward, the nexus between transport infrastructure, associated investments, emissions of carbon dioxide, and economic growth was explored through a panel vector autoregressive model [2,8,39,44,50,55,59,62,64,65,69,71,82,83,87,93,101,105]. Firstly, the unit root of each variable was examined, then the long-run cointegration link among the variables is investigated, and afterwards the panel vector error correction model (henceforth "PVECM") was estimated to infer the Granger causal associations [44]. A nonstationary panel process occurs if at least one of its moments (mean, variance, or covariance) is time-independent [93], whilst a stationary process occurs whether its statistical features persists constantly [62]. In case of the occurrence of nonstationarity, a cointegration and vector error correction model were put forward to explore the link amid such variables [8]. Provided that a non-stationary series is differenced d times to be converted stationary, then it is assumed to be integrated of order d: $I(d)$ [64]. However, as long as none of the panel unit root tests were free from statistical weaknesses with respect to size and power properties, we applied several unit root tests to find out the order of integration of the variables [44], as follows: Levin, Lin and Chu (henceforth "LLC"), Im, Pesaran, and Shin (henceforth "IPS"), Augmented Dickey-Fuller (henceforth "ADF"), Phillips-Perron (henceforth "PP"), and Breitung. The autoregressive specification for panel data is formulated as below [62]:

$$\Delta Y_{it} = \alpha_i Y_{it-1} + X_{it}\delta_i + \varepsilon_{it};\ i = 1, 2 \ldots, 28,\ t = 1990, 1991, \ldots, 2016 \quad (2)$$

where X denotes the exogenous variables in the model, covering any fixed effect or individual trends, α_i states the autoregressive coefficients, and ε_{it} signifies the error terms which are supposed to be jointly independent. Y_i is weakly stationary if α_i is less than one, whilst Y_i has a unit root when α_i is equal to one [62]. The ADF test considers merely the existence of autocorrelation in the series, but the PP test furthermore takes into account the hypothesis of the occurrence of a heteroskedasticity extent in the series [93]. The LLC test examines the heterogeneity of intercepts across members of the panel, whereas the IPS test investigates the heterogeneity within the intercepts as well as in the slope coefficients [44]. The null hypothesis posits that all series are non-stationary, whilst the alternative one presumes the stationarity of all series [100].

With the purpose of analyzing the long-run connection between the variables, for the robust of the results, several tests of cointegration were employed [5,38,44,50,59,62,64,65,77,93,101,105]: Pedroni [109,110], Kao [111], and Johansen [112]. The series of transport infrastructure, related investments, carbon dioxide emissions from transport, and economic growth were defined as cointegrated when all of the series are established to be integrated with the same order [62]. The PVECM was applied to identify the long- and short-run relations between the variables, and can ascertain sources of causality [50,52,62,64,95,98,103]:

$$\Delta Y_{it} = \varphi_{1j} + \sum_{l=1}^{p} \alpha_{11il}\Delta Y_{it-l} + \sum_{l=1}^{p} \alpha_{12il}\Delta X_{it-l} + \sum_{l=1}^{p} \alpha_{13il}\Delta W_{it-l} + \sum_{l=1}^{p} \alpha_{14il}\Delta Z_{it-l} + \delta_{1i} ECT_{it-1} + \varepsilon_{1it} \quad (3)$$

$$\Delta X_{it} = \varphi_{2j} + \sum_{l=1}^{p} \alpha_{21il}\Delta X_{it-l} + \sum_{l=1}^{p} \alpha_{22il}\Delta Y_{it-l} + \sum_{l=1}^{p} \alpha_{23il}\Delta W_{it-l} + \sum_{l=1}^{p} \alpha_{24il}\Delta Z_{it-l} + \delta_{2i} ECT_{it-1} + \varepsilon_{2it} \quad (4)$$

$$\Delta W_{it} = \varphi_{3j} + \sum_{l=1}^{p} \alpha_{31il}\Delta W_{it-l} + \sum_{l=1}^{p} \alpha_{32il}\Delta Y_{it-l} + \sum_{l=1}^{p} \alpha_{33il}\Delta X_{it-l} + \sum_{l=1}^{p} \alpha_{34il}\Delta Z_{it-l} + \delta_{3i}ECT_{it-1} + \varepsilon_{3it} \quad (5)$$

$$\Delta Z_{it} = \varphi_{4j} + \sum_{l=1}^{p} \alpha_{41il}\Delta Z_{it-l} + \sum_{l=1}^{p} \alpha_{42il}\Delta Y_{it-l} + \sum_{l=1}^{p} \alpha_{43il}\Delta X_{it-l} + \sum_{l=1}^{p} \alpha_{44il}\Delta W_{it-l} + \delta_{4i}ECT_{it-1} + \varepsilon_{4it} \quad (6)$$

where Y denotes the GDPC, X signifies Length_rail (in model 1), Length_motorways (in model 2), Goods_water (in model 3), Goods_sea (in model 4), or Goods_air (in model 5), W symbolizes Inv_rail (model 1), Inv_roads (model 2), Inv_water (model 3), Inv_ports (model 4), or Inv_airports (model 5), and Z indicates CO_2_rail (model 1), CO_2_road (model 2), CO_2_maritime (model 3 and model 4), or CO_2_aviation (model 5). Δ reveals the difference operator, ECT denotes the error correction terms resulting from the long run cointegrating relations, ε are the error terms, and p is the lag length.

4. Empirical Findings

4.1. Descriptive Statistics, Correlation Examination, and Unit Root Testing

Table 5 gives the descriptive statistics of the variables. With reference to goods transportation, road transport showed the utmost mean value (69,372.64 million tone-km), whereas air transport shows the lowest mean value (0.60 million tone). On the contrary, in terms of passenger transportation, air transport showed the highest mean value (41.02 million passengers). Even if the investments in road transport infrastructure highlighted the paramount mean value, in terms of network length, EU-28 railways lines registered the highest mean value. By 2030, the length of the existing European high-speed rail network should be tripled, and by 2050 the majority of medium-distance passenger transport should go by rail [33].

Table 5. Summary statistics (raw data).

Variables	# Obs	Mean	Std. Dev.	Min	Max
Panel A: Variables towards Sustainable Economic Growth					
Gross domestic product per capita (GDPC)	622	21,260.29	14,915.71	1000.00	91,500.00
Panel B: Variables towards Transport Infrastructure Status					
Railway Transport Infrastructure Status					
Length_rail	611	8726.17	9440.00	271.00	41,718.00
Passengers_rail	290	15,666.36	24,605.94	193.00	93,918.00
Goods_rail	303	16,224.06	21,993.66	79.00	116,632.00
Road Transport Infrastructure Status					
Length_motorways	640	2287.83	3542.42	0.00	15,336.00
Motorisation_rate	687	389.76	128.98	54.00	666.00
Goods_road	430	69,372.64	82,451.64	538.00	343,447.00
Inland Waterways Transport Infrastructure Status					
Goods_water	233	14,528.85	20,824.81	25.00	66,465.00
Maritime Transport Infrastructure Status					
Goods_sea	405	169,060.52	170,987.36	3101.00	594,272.00
Air Transport Infrastructure Status					
Passengers_air	497	41,024,996.62	54,168,844.72	270,791.00	248,868,873.00
Goods_air	461	599,889.89	2,071,022.40	0.00	40,687,909.00

Table 5. *Cont.*

Variables	# Obs	Mean	Std. Dev.	Min	Max
Panel C: Variables towards Investments in Transport Infrastructure					
Inv_rail	514	1,412,346,277.64	2,165,355,101.06	0.00	11,191,649,435.00
Inv_roads	538	2,359,720,595.27	3,469,536,585.42	0.00	15,293,172,691.00
Inv_water	319	136,751,434.70	250,670,533.15	0.00	1,205,177,893.00
Inv_ports	373	251,324,122.76	469,905,167.66	0.00	2,763,254,475.00
Inv_airports	476	245,380,661.00	437,602,855.87	0.00	2,782,214,955.00
Panel D: Variables towards Transport Pollution					
Carbon Dioxide Emissions from Transport					
CO_2_transport	567	2.07	2.04	0.40	15.50
CO_2_rail	523	2.05	2.45	0.00	15.80
CO_2_road	567	94.27	4.25	75.70	100.00
CO_2_maritime	457	9.27	23.06	0.00	180.90
CO_2_aviation	406	1.64	1.64	0.00	8.30
CO_2_new_cars	407	147.50	21.26	101.20	200.20
Air Pollutants from Transport					
SOx_road	728	7158.87	20,271.30	0.00	157,200.00
SOx_non-road	728	6276.33	13,757.79	6.00	87,772.00
NOx_road	728	188,709.75	280,202.13	0.00	1,342,661.00
NOx_non-road	728	28,291.43	40,591.11	21.00	218,931.00
NMVOC_road	728	95,985.74	182,276.55	2.00	1,168,550.00
NMVOC_non-road	728	4435.26	9190.89	1.00	56,809.00
NH_3_road	728	2715.18	4516.83	0.00	28,508.00
NH_3_non-road	624	13.82	60.70	0.00	1,117.00
Panel E: Country-Level Control Variables					
Energy_transport	608	102.81	12.04	68.00	140.10
Trade	730	104.24	59.59	33.98	419.53
Fin_dev	686	77.48	44.09	0.19	253.57
Urb	756	71.44	11.97	47.91	97.90

Source: Authors' computations. Notes: For the definition of variables, please see Table 4.

Figure 1 shows the mean volume of transported goods in EU-28, over 1990–2016. Alike Table 4, road transport is the main mode of freight transport, followed by rail freight. Germany registered the highest mean values in relation to all types of transport, except for the gross weight of seaborne goods handled in ports (United Kingdom reveals the highest mean value), whereas the lowest mean values are reported in Ireland (rail transport), Cyprus (road transport), the Czech Republic (inland waterways transport), Malta (gross weight of seaborne goods handled in ports), and Croatia (air transport).

Figure 2 exposes the mean investments in transport infrastructure in EU-28, over 1990–2016. As in Table 4, investments in road transport infrastructure showed the utmost mean value, succeeded by investments in railway transport infrastructure. Again, Germany revealed the highest mean value of investments in roads and inland waterways transport, along with Italy (investments in railway transport), Spain (investments in maritime port infrastructure), and the United Kingdom (investments in airport infrastructure). In contrast, the lowest mean value of investments in roads and maritime port infrastructure was exhibited in Malta, as well as Estonia (investments in railway transport), Luxembourg (investments in inland waterways transport), and Slovenia (investments in airport infrastructure).

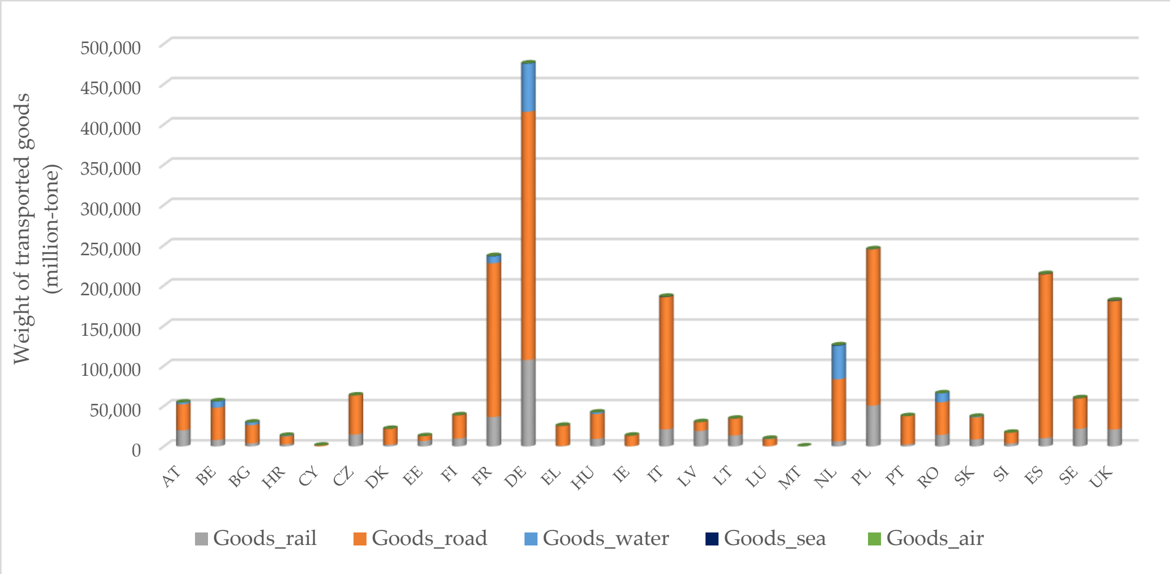

Figure 1. The weight of transported goods (mean values) by type of transport. Source: Authors' work. Notes: For the definition of variables, please see Table 4.

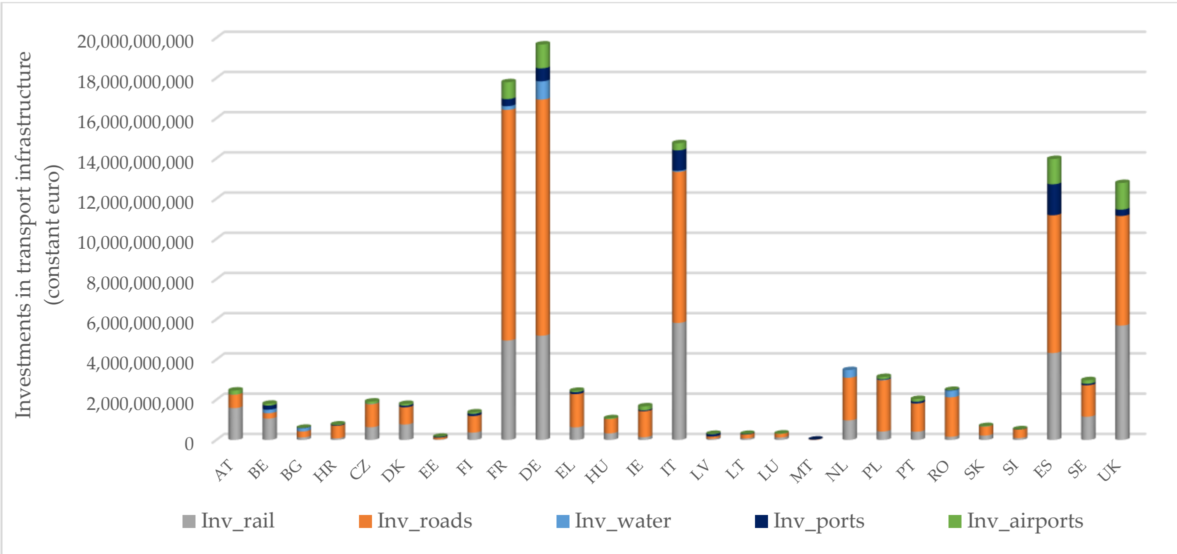

Figure 2. The investments in transport infrastructure (mean values) by type of transport. Source: Authors' work. Notes: Data for Cyprus not available. For the definition of variables, please see Table 4.

With regard to air pollutants, both in terms of the share of CO_2 emissions from road transport in total carbon dioxide emissions from transport and other specific air pollutants, road transport was the most damaging environmental stressor in EU-28 countries. Besides, air transportation revealed the lowest share of CO_2 emissions from domestic aviation in total carbon dioxide emissions from transport, harmonized with the White Paper [33].

The correlations between selected variables are exposed in Table 6. We acknowledged strong linear associations between several variables, with the value associated to the correlation coefficient exceeding 0.7. However, the issue of multicollinearity was removed by considering the aforesaid variables in distinct regression models.

Table 7 summarizes the outcome of the panel unit root tests. When first differences were considered, the null hypothesis of non-stationarity was rejected for all variables. As such, a part of the variables was not stationary in level, but stationary in the first difference. Therefore, the series were integrated at *I(1)* [44].

4.2. Panel Data Regression Models Output

Table 8 shows the econometric outcomes concerning the effect of railway transport infrastructure, related investments, and air pollution on gross domestic product per capita. We noticed a negative impact of the length of railways lines (Equations (4), (7) and (12)) and rail passenger transport (Equation (2)) on economic growth. The negative outcome may have occurred due to regions being short of high-speed rail lines, and respectively, the absence of ripple effects across such areas. Consequently, there may be an influx of companies and dwellings to the extents owing high-speed infrastructure, whereas the rest of zones will exhibit a quite lesser desirability, and scarcer human resources. Accordingly, the progress of a particular area may not be sufficient to develop the entire state [47]. Nevertheless, rail goods transport (Equation (6)) and investments in railway transport infrastructure positively influenced economic growth (all the estimated models).

In line with Chen, Xue, Rose and Haynes [84], investment in rail infrastructure may stimulate economic growth through job creation, enhancement of regional openness, and a drop in transport price. Therewith, along with the expansion of rail infrastructure, several matters such as road traffic congestion or air contamination from cars and air travel will be settled [84]. With regard to air pollution, the share of CO_2 from railway transport in total carbon dioxide emissions from transport negatively influences GDPC (Equations (4)–(6)); this relationship was also proven in case of emissions of sulphur oxides (Equations (7) and (8)), and emissions of ammonia (Equation (12)). Hence, even if railway investment entails more benefits [87], the greater use of rail leads to a rise in electricity demand, causing higher CO_2 emissions [99]. Also, local air pollution, climate change, noise, and land use [48] are the consequences of rail networks, especially high-speed rail systems.

The estimations concerning the impact of road transport infrastructure, associated investments, and air pollution on sustainable economic growth are revealed in Table 9. The results showed that there was a positive influence of the length of motorways (Equations (3), (9) and (13)), the number of passenger cars per 1000 inhabitants (all the estimated models), as well as goods transported by road on GDPC (all the estimated models). Likewise, a strong positive association was noticed between investments in road transport infrastructure and economic growth (Equations (4), (7) and (10)). Investments in roads drives the creation of direct employment [4], attracts many investors, which bring physical and socio-economic development to surrounding areas [24], and improves the productivity of corporations [3].

Table 6. Correlation matrix.

Var	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
(1)	1.00																
(2)	0.12 **	1.00															
(3)	0.28 ***	0.91 ***	1.00														
(4)	−0.22 ***	0.72 ***	0.59 ***	1.00													
(5)	0.46 ***	0.57 ***	0.72 ***	0.22 ***	1.00												
(6)	0.77 ***	0.06	0.10	−0.06	0.49 ***	1.00											
(7)	0.13 **	0.86 ***	0.89 ***	0.63 ***	0.69 ***	0.11 *	1.00										
(8)	0.28 ***	0.25 ***	0.48 ***	0.28 ***	0.69 ***	0.02	0.43 ***	1.00									
(9)	0.51 ***	0.61 ***	0.79 ***	0.36 ***	0.59 ***	0.19 ***	0.82 ***	0.72 ***	1.00								
(10)	0.43 ***	0.68 ***	0.86 ***	0.29 ***	0.72 ***	0.25 ***	0.73 ***	0.63 ***	0.82 ***	1.00							
(11)	0.37 ***	0.26 ***	0.58 ***	0.13 *	0.38 ***	0.32 ***	0.48 ***	0.38 ***	0.50 ***	0.62 ***	1.00						
(12)	0.50 ***	0.62 ***	0.87 ***	0.46 ***	0.65 ***	0.41 ***	0.85 ***	0.54 ***	0.87 ***	0.82 ***	0.47 ***	1.00					
(13)	0.35 ***	0.74 ***	0.83 ***	0.40 ***	0.75 ***	0.15 ***	0.85 ***	0.44 ***	0.74 ***	0.79 ***	0.37 ***	0.71 ***	1.00				
(14)	0.27 ***	0.46 ***	0.54 ***	0.42 ***	0.39 ***	0.04	0.52 ***	0.39 ***	0.51 ***	0.53 ***	0.40 ***	0.52 ***	0.55 ***	1.00			
(15)	−0.16 **	0.60 ***	0.55 ***	0.54 ***	0.45 ***	−0.14 **	0.53 ***	0.67 ***	0.86 ***	0.58 ***	0.01	0.35 ***	0.43 ***	0.31 ***	1.00		
(16)	0.35 ***	0.61 ***	0.73 ***	0.34 ***	0.55 ***	0.30 ***	0.73 ***	0.36 ***	0.69 ***	0.83 ***	0.27 ***	0.74 ***	0.66 ***	0.50 ***	0.44 ***	1.00	
(17)	0.82 ***	−0.18 ***	−0.15 *	−0.43 ***	0.25 ***	0.74 ***	−0.16 **	−0.11	0.50 ***	0.13**	0.22 ***	0.22 ***	0.10*	0.01	−0.58 ***	0.08 †	1.00
(18)	−0.64 ***	−0.26 ***	−0.43 ***	0.16 **	−0.72 ***	−0.62 ***	−0.38 ***	−0.25 ***	−0.37 ***	−0.45 ***	−0.23 ***	−0.52 ***	−0.57 ***	−0.27 ***	0.07	−0.41 ***	−0.52 ***
(19)	0.21 ***	0.06	0.06	0.01	0.18 ***	0.41 ***	−0.03	0.01	−0.19 ***	−0.01	0.15 **	0.09 *	−0.08 †	0.14 *	−0.42 ***	0.02	0.26 ***
(20)	0.06	−0.22 ***	0.01	−0.07	0.04	0.21 ***	−0.00	0.40 ***	−0.41 ***	−0.23 ***	−0.09	0.12 *	−0.32 ***	0.24 ***	−0.18 ***	0.07	−0.10 *
(21)	0.11 *	0.08	0.14 *	−0.05	0.48 ***	0.13 *	0.29 ***	0.20 *	0.30 ***	0.36 ***	−0.08	0.33 ***	0.38 ***	−0.04	0.50 ***	0.39 ***	0.27 ***
(22)	−0.09 †	−0.00	−0.15 *	0.16 **	−0.25 ***	−0.14 **	−0.06	0.02	0.03	−0.16 **	−0.22 ***	−0.14 *	0.03	−0.02	−0.04	0.05	0.16 **
(23)	−0.09 *	0.32 ***	0.64 ***	0.29 ***	0.32 ***	−0.25 ***	0.57 ***	0.39 ***	0.50 ***	0.49 ***	0.21 ***	0.23 ***	0.38 ***	0.29 ***	0.27 ***	0.24 ***	−0.09 *
(24)	0.19 ***	0.52 ***	0.57 ***	0.14 *	0.48 ***	−0.08 *	0.58 ***	0.85 ***	0.76 ***	0.72 ***	0.24 ***	0.49 ***	0.59 ***	0.40 ***	0.59 ***	0.47 ***	−0.03
(25)	0.23 ***	0.80 ***	0.90 ***	0.47 ***	0.73 ***	0.09 *	0.93 ***	0.62 ***	0.82 ***	0.71 ***	0.37 ***	0.73 ***	0.75 ***	0.53 ***	0.43 ***	0.65 ***	0.12 **
(26)	0.18 ***	0.71 ***	0.77 ***	0.34 ***	0.57 ***	−0.05	0.81 ***	0.74 ***	0.91 ***	0.82 ***	0.31 ***	0.63 ***	0.74 ***	0.46 ***	0.72 ***	0.61 ***	−0.09 *
(27)	0.02	0.74 ***	0.82 ***	0.49 ***	0.57 ***	−0.13 ***	0.82 ***	0.49 ***	0.74 ***	0.65 ***	0.21 ***	0.53 ***	0.72 ***	0.43 ***	0.51 ***	0.54 ***	−0.11 **
(28)	0.27 ***	0.78 ***	0.81 ***	0.48 ***	0.58 ***	0.06	0.78 ***	0.60 ***	0.86 ***	0.77 ***	0.21 ***	0.65 ***	0.73 ***	0.40 ***	0.63 ***	0.60 ***	0.00
(29)	0.48 ***	0.66 ***	0.91 ***	0.40 ***	0.72 ***	0.43 ***	0.85 ***	0.53 ***	0.84 ***	0.80 ***	0.37 ***	0.77 ***	0.80 ***	0.56 ***	0.42 ***	0.67 ***	0.31 ***
(30)	0.38 ***	0.64 ***	0.73 ***	0.52 ***	0.60 ***	0.32 ***	0.74 ***	0.72 ***	0.77 ***	0.74 ***	0.36 ***	0.62 ***	0.63 ***	0.40 ***	0.37 ***	0.50 ***	0.18 ***
(31)	0.04	0.21 ***	0.19 **	0.00	0.23 ***	−0.06	0.25 ***	0.36 ***	0.32 ***	0.27 ***	−0.14 **	0.09 *	0.21 ***	0.14 *	0.11 *	0.11 *	0.18 ***
(32)	0.17 ***	−0.63 ***	−0.56 ***	−0.50 ***	−0.35 ***	0.29 ***	−0.46 ***	−0.39 ***	−0.56 ***	−0.54 ***	−0.04	−0.34 ***	−0.54 ***	−0.26 ***	−0.71 ***	−0.39 ***	0.37 ***
(33)	0.59 ***	0.12 **	0.30 ***	−0.22 ***	0.34 ***	0.57 ***	−0.12 *	0.53 ***	0.12 *	0.38 ***	0.26 ***	0.44 ***	0.24 ***	0.21 ***	0.16 **	0.35 ***	0.47 ***
(34)	0.49 ***	0.14 ***	0.26 ***	−0.02	0.28 ***	0.45 ***	0.19 ***	0.20 **	0.34 ***	0.27 ***	0.21 ***	0.33 ***	−0.12 **	0.11 †	−0.06	0.18 ***	0.44 ***

Table 6. Correlation matrix.

Var	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)
(18)	1.00																
(19)	−0.41 ***	1.00															
(20)	−0.16 **	0.14 **	1.00														
(21)	−0.20 ***	−0.66 ***	0.06	1.00													
(22)	0.22 ***	−0.09	−0.18 **	0.10	1.00												
(23)	−0.04	−0.16 ***	−0.35 ***	0.21 ***	0.30 ***	1.00											
(24)	−0.21 ***	−0.42 ***	−0.27 ***	0.55 ***	0.11 *	0.53 ***	1.00										
(25)	−0.45 ***	−0.08 *	−0.48 ***	0.28 ***	0.12 *	0.58 ***	0.72 ***	1.00									
(26)	−0.20 ***	−0.36 ***	−0.29 ***	0.47 ***	0.01	0.44 ***	0.88 ***	0.83 ***	1.00								
(27)	−0.25 ***	−0.19 ***	−0.46 ***	0.29 ***	0.22 ***	0.70 ***	0.76 ***	0.91 ***	0.84 ***	1.00							
(28)	−0.27 ***	−0.22 ***	−0.29 ***	0.38 ***	0.09 †	0.44 ***	0.82 ***	0.83 ***	0.92 ***	0.85 ***	1.00						
(29)	−0.66 ***	0.05	−0.35 ***	0.18 ***	0.13 *	0.20 ***	0.54 ***	0.77 ***	0.67 ***	0.62 ***	0.70 ***	1.00					
(30)	−0.32 ***	0.04	0.09 †	0.30 ***	0.12 *	0.29 ***	0.60 ***	0.76 ***	0.64 ***	0.60 ***	0.66 ***	0.61 ***	1.00				
(31)	−0.07	−0.21 ***	−0.16 ***	0.23 ***	0.47 ***	0.55 ***	0.37 ***	0.36 ***	0.31 ***	0.45 ***	0.33 ***	0.20 ***	0.28 ***	1.00			
(32)	−0.03	0.37 ***	0.66 ***	−0.49 ***	−0.12 *	−0.54 ***	−0.68 ***	−0.64 ***	−0.69 ***	−0.76 ***	−0.71 ***	−0.46 ***	−0.40 ***	−0.28 ***	1.00		
(33)	−0.41 ***	0.13 **	0.16 **	0.19 ***	−0.09 †	−0.18 ***	0.11 **	−0.01	0.06	−0.15 ***	0.04	0.23 ***	0.32 ***	−0.03	0.06	1.00	
(34)	−0.26 ***	0.07 †	0.47 ***	0.20 ***	−0.02	−0.13 ***	0.09 *	0.02	0.06	−0.13 ***	0.09 *	0.16 ***	0.25 ***	0.13 **	0.28 ***	0.32 ***	1.00

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Bold values depict strong correlations. For the definition of variables, please see Table 4.

Table 7. Panel unit root tests output.

Variables	**Level**								
	Individual Intercept				**Individual Intercept and Trend**				
	LLC	**IPS**	**ADF**	**PP**	**LLC**	**Breitung**	**IPS**	**ADF**	**PP**
GDPC	−10.5126 ***	−4.51304 ***	115.782 ***	142.058 ***	−0.45946	2.95013	3.38895	37.254	35.2628
Length_rail	−78.5717 ***	−37.4461 ***	130.765 ***	119.224 ***	−168.741 ***	−0.85721	−50.2445 ***	126.436 ***	122.544 ***
Passengers_rail	−3.17414 ***	1.69306	44.8616	60.6158	−5.75576 ***	0.43948	0.42287	44.52	42.2018
Goods_rail	−6.10129 ***	−2.9229 **	80.6581 **	92.4904 ***	−6.81734 ***	−2.08469 *	−1.47135 †	68.8706 †	76.8391 *
Length_motorways	−8.43268 ***	−0.24319	82.973 **	101.65 ***	−2.73646 **	4.41991	−0.05524	55.7677	53.7082
Motorisation_rate	−10.8192 ***	−3.71326 ***	135.612 ***	118.617 ***	−2.05387 *	3.97507	1.538	79.9321 *	59.119
Goods_road	−2.62838 **	0.33428	51.3195	84.2883 **	−5.85863 ***	−0.66543	−1.79454 *	80.5227 *	105.787 ***
Goods_water	−3.03575 **	−2.91213 **	56.1648 ***	67.2602 ***	−5.07478 ***	−0.54265	−2.57013 **	53.6246 **	60.3914 ***
Goods_sea	−2.54167 **	−2.28951 *	72.3606 **	52.8047	−2.11154 *	−0.6103	−1.21077	53.84	34.9969
Passengers_air	−8.57872 ***	−2.03805 *	119.485 ***	138.437 ***	−9.73221 ***	1.56763	−4.5359 ***	136.437 ***	111.762 ***
Goods_air	−1.18235	−3.18821 ***	101.394 ***	111.562 ***	−37.5563 ***	0.5215	−39.9046 ***	118.467 ***	128.794 ***

Table 7. *Cont.*

Variables	Level								
	Individual Intercept				Individual Intercept and Trend				
	LLC	IPS	ADF	PP	LLC	Breitung	IPS	ADF	PP
Inv_rail	−3.01111 **	−1.87328 *	72.2692 *	65.8832 †	−18.9202 ***	1.28341	−8.23232 ***	110.462 ***	78.8586 **
Inv_roads	−1.75699 *	−1.41043 †	77.6804 *	68.2755 †	−1.88255 *	1.18976	−0.80404	64.7054	54.6647
Inv_water	−1.62456 †	−3.05038 **	66.7479 ***	86.5577 ***	−2.08519 *	0.86122	−2.26423 *	63.1285 **	76.4116 ***
Inv_ports	−4.34451 ***	−3.53781 ***	81.3796 ***	99.3938 ***	−6.52305 ***	−2.66272 **	−3.11104 ***	91.3304 ***	86.3764 ***
Inv_airports	−2.72743 **	−3.37325 ***	88.2725 ***	81.2506 **	−1.74073 *	−0.57364	−3.17672 ***	93.8352 ***	73.0014 *
CO_2_transport	−3.30662 ***	0.37182	48.4615	50.2247	1.00871	5.06072	4.83962	24.4681	16.6995
CO_2_rail	−7.78923 ***	−4.36651 ***	104.879 ***	134.916 ***	−7.38497 ***	0.64861	−3.75833 ***	155.312 ***	288.533 ***
CO_2_road	−5.87899 ***	−3.81822 ***	119.269 ***	109.554 ***	0.26171	−1.26463	−2.7932 **	84.5564 **	97.266 ***
CO_2_maritime	−2.33453 **	−1.3805 5 †	53.6866	51.8039	−1.55071 †	−0.72108	−0.98171	58.6958 †	56.0563
CO_2_aviation	−4.88223 ***	−1.90751 *	61.9433 **	57.5014 *	−4.30179 ***	0.96426	−2.94289 **	79.4534 ***	67.1231 **
CO_2_new_cars	−14.6491 ***	1.04719	33.8388	19.3704	−8.96017 ***	4.05477	−4.69431 ***	92.3612 ***	85.0231 **
SOx_road	−1.16691	5.11026	20.1234	21.0483	−0.62349	−0.24502	0.47527	44.616	42.2707
SOx_non-road	1.53918	4.80809	36.7416	36.5716	1.46466	3.05547	1.36588	55.8239	50.6843
NOx_road	7.14299	8.21362	37.3241	43.5904	−0.92868	4.83255	−0.7005	94.4198 **	62.865
NOx_non-road	−3.64134 ***	−0.43138	74.6127 *	81.6421 *	−0.13422	2.15593	1.05366	59.6942	55.9195
NMVOC_road	4.18929	11.6526	18.6866	27.3658	−5.19325 ***	3.21161	−1.39226 †	98.2456 ***	82.4922 *
NMVOC_non-road	0.25248	2.04472	61.5774	110.543 ***	-2.30646 *	0.85889	−0.42962	116.574 ***	304.533 ***
NH_3_road	−1.53337 †	−3.35902 ***	115.047 ***	249.808 ***	−13.4457 ***	5.47889	−4.56315 ***	405.945 ***	808.567 ***
NH_3_non-road	−0.07603	1.86835	8.92542	10.1141	−0.47439	0.88019	−0.43055	23.298	18.9172
Energy_transport	−0.44221	1.20856	58.352	54.328	−1.66904 *	−0.06656	−2.10413 *	84.2983 **	74.1384 †
Trade	−0.87442	2.3269	30.7901	30.3969	−2.56082 **	−3.90051 ***	−3.58158 ***	95.4122 ***	94.385 **
Fin_dev	−3.98624 ***	−1.04546	66.1831	38.0466	−1.40323 †	2.14783	1.06792	54.8379	20.3172
Urb	−24.3318 ***	−1.02671	291.005 ***	106.207 ***	−2.23678 *	4.66028	−0.05929	67.9686	61.2622

Variables	First Difference								
	Individual Intercept				Individual Intercept and Trend				
	LLC	IPS	ADF	PP	LLC	Breitung	IPS	ADF	PP
ΔGDPC	−12.4539 ***	−10.542 ***	215.144 ***	218.329 ***	−13.7982 ***	−8.04436 ***	−10.1877 ***	199.639 ***	249.619 ***
ΔLength_rail	−28.4704 ***	−22.2762 ***	620.825 ***	637.51 ***	−738.367 ***	−6.59936 ***	−126.815 ***	589.294 ***	712.423 ***
ΔPassengers_rail	−9.22924 ***	−4.93401 ***	108.256 ***	122.374 ***	−9.8215 ***	−1.42344 †	−1.42531 †	73.1588 *	113.951 ***
ΔGoods_rail	−13.8335 ***	−8.61347 ***	161.876 ***	211.618 ***	−14.2915 ***	−7.32962 ***	−3.97816 ***	111.565 ***	173.548 ***
ΔLength_motorways	−14.791 ***	−14.3743 ***	282.383 ***	289.402 ***	−15.8064 ***	−9.51466 ***	−14.9055 ***	271.239 ***	278.453 ***
ΔMotorisation_rate	−17.6559 ***	−13.6635 ***	252.304 ***	226.733 ***	−12.3484 ***	−1.30805 †	−11.6003 ***	238.524 ***	233.404 ***
ΔGoods_road	−17.2498 ***	−12.8545 ***	252.159 ***	281.256 ***	−15.1753 ***	−4.58306 ***	−8.56772 ***	193.029 ***	240.373 ***
ΔGoods_water	−15.6909 ***	−12.7323 ***	180.921 ***	203.104 ***	−11.495 ***	−6.55647 ***	−7.1527 ***	128.827 ***	725.675 ***
ΔGoods_sea	−14.7165 ***	−11.9494 ***	221.189 ***	245.369 ***	−14.2755 ***	−8.64239 ***	−9.49718 ***	169.469 ***	209.967 ***

Table 7. *Cont.*

Variables	First Difference								
	Individual Intercept				Individual Intercept and Trend				
	LLC	IPS	ADF	PP	LLC	Breitung	IPS	ADF	PP
ΔPassengers_air	−82.4953 ***	−24.2721 ***	245.729 ***	236.716 ***	−68.3989 ***	−4.01931 ***	−18.0861 ***	204.801 ***	216.832 ***
ΔGoods_air	−203.301 ***	−49.9909 ***	288.855 ***	541.449 ***	−158.313 ***	−6.62491 ***	−37.6977 ***	235.253 ***	339.241 ***
ΔInv_rail	−15.9429 ***	−15.6672 ***	314.109 ***	336.893 ***	−13.551 ***	−5.55603 ***	−13.7934 ***	240.224 ***	270.579 ***
ΔInv_roads	−15.3076 ***	−12.8461 ***	325.402 ***	496.4 ***	−15.1779 ***	−6.96587 ***	−11.1826 ***	207.078 ***	254.716 ***
ΔInv_water	−13.2843 ***	−13.1721 ***	219.922 ***	336.879 ***	−14.5597 ***	−1.30099 †	−9.97675 ***	183.56 ***	210.092 ***
ΔInv_ports	−11.8083 ***	−11.6436 ***	205.166 ***	466.269 ***	−9.99227 ***	−5.57928 ***	−6.03874 ***	148.897 ***	215.934 ***
ΔInv_airports	−15.1929 ***	−14.319 ***	280.717 ***	316.082 ***	−13.3559 ***	−4.43082 ***	−9.9329 ***	224.301 ***	282.076 ***
ΔCO_2_transport	−13.2735 ***	−13.0233 ***	256.22 ***	271.328 ***	−14.1026 ***	−6.68785 ***	−14.3019 ***	259.484 ***	316.669 ***
ΔCO_2_rail	−15.1354 ***	−14.6495 ***	287.471 ***	606.663 ***	−19.5768 ***	−7.51099 ***	−18.1537 ***	300.449 ***	349.457 ***
ΔCO_2_road	−13.6533 ***	−15.7136 ***	306.044 ***	706.521 ***	−18.3639 ***	−9.47032 ***	−17.6178 ***	307.812 ***	344.275 ***
ΔCO_2_maritime	−15.2094 ***	−11.9257 ***	227.58 ***	300.536 ***	−14.3242 ***	−7.27234 ***	−7.9167 ***	187.916 ***	249.853 ***
ΔCO_2_aviation	−17.1407 ***	−15.4537 ***	306.155 ***	535.353 ***	−16.8698 ***	−5.27883 ***	−15.3594 ***	205.831 ***	287.576 ***
ΔCO_2_new_cars	−12.1306 ***	−8.04061 ***	137.912 ***	136.381 ***	−9.84308 ***	−0.75694	−2.72045 **	85.8657 **	101.954 ***
ΔSOx_road	−19.69 ***	−17.1273 ***	364.985 ***	431.039 ***	−18.4774 ***	−15.1203 ***	−16.3473 ***	313.093 ***	409.681 ***
ΔSOx_non-road	−16.8028 ***	−16.077 ***	370.595 ***	411.891 ***	−15.7562 ***	2.12248	−14.596 ***	301.139 ***	390.745 ***
ΔNOx_road	−12.1419 ***	−12.9821 ***	280.87 ***	307.619 ***	−10.3886 ***	−3.54604 ***	−13.0911 ***	260.13 ***	303.514 ***
ΔNOx_non-road	−21.726 ***	−20.4462 ***	430.541 ***	468.619 ***	−19.1662 ***	−8.97074 ***	−18.6921 ***	362.895 ***	651.142 ***
ΔNMVOC_road	−10.758 ***	−12.5538 ***	260.48 ***	288.959 ***	−9.31637 ***	−2.95048 **	−10.0381 ***	207.371 ***	465.472 ***
ΔNMVOC_non-road	−21.2571 ***	−20.6313 ***	430.694 ***	472.788 ***	−15.871 ***	−10.2221 ***	−18.7262 ***	361.517 ***	654.94 ***
ΔNH_3_road	−6.54223 ***	−7.53166 ***	184.296 ***	311.476 ***	−8.03248 ***	−1.9528 *	−14.0702 ***	314.612 ***	701.299 ***
ΔNH_3_non-road	−12.456 ***	−12.2759 ***	131.12 ***	132.088 ***	−10.7893 ***	−5.70291 ***	−11.0624 ***	118.868 ***	137.4 ***
ΔEnergy_transport	−16.2543 ***	−15.7677 ***	319.01 ***	373.69 ***	−14.854 ***	−8.1179 ***	−13.3475 ***	250.5 ***	323.435 ***
ΔTrade	−20.5882 ***	−18.654 ***	387.729 ***	450.459 ***	−17.1797 ***	−14.2973 ***	−15.4695 ***	294.055 ***	406.884 ***
ΔFin_dev	−6.4192 ***	−6.88049 ***	159.926 ***	176.031 ***	−6.04581 ***	0.39639	−5.5254 ***	135.073 ***	143.229 ***
ΔUrb	2.02988	−1.22246	105.985 ***	101.97 ***	−38.8916 ***	0.74043	−12.1585 ***	377.172 ***	187.13 ***

Source: Authors' computations. Notes: lag lengths are determined via Schwarz Info Criterion. Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. LLC: Levin, Lin and Chu t* stat. Breitung: Breitung t-stat. IPS: Im, Pesaran and Shin W-stat. ADF: Augmented Dickey-Fuller Fisher Chi-square. PP: Phillips–Perron Fisher Chi-square. LLC and Breitung assume a common unit root process. IPS, ADF, and PP assume an individual unit root process. Probabilities for ADF and PP are computed using an asymptotic Chi-square distribution. Probabilities for the LLC, Breitung, and IPS tests are computed assuming asymptotic normality. For the definition of variables, please see Table 4.

Table 8. Fixed-effects regressions results on the effect of railway transport infrastructure, related investments, and air pollution on sustainable economic growth.

Variables	Equations												
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**
Length_rail	−0.03 (−0.32)			−0.33 ** (−2.64)			−0.47 ** (−2.71)					−0.44 * (−2.40)	
Passengers_rail		−0.11 * (−2.45)			−0.03 (−0.55)			−0.06 (−0.89)					
Goods_rail			−0.04 (−1.19)			0.09 † (1.87)			0.06 (1.20)	0.06 (1.22)	0.06 (1.26)		−0.01 (−0.13)
Inv_rail	0.01 † (1.96)		0.05 *** (4.00)	0.04 *** (6.53)		0.08 *** (4.83)	0.05 *** (6.03)		0.08 *** (5.12)	0.08 *** (5.20)	0.08 *** (5.18)	0.06 *** (6.01)	0.08 *** (4.72)
CO_2_transport	1.76 *** (36.88)	1.44 *** (16.64)	1.34 *** (16.19)										
CO_2_rail				−0.23 *** (−18.07)	−0.09 *** (−5.21)	−0.09 *** (−5.18)							
SOx_non-road							−0.08 *** (−4.43)	−0.04 † (−1.78)	−0.02 (−1.02)				
NOx_non-road										−0.06 (−1.11)			
NMVOC_non-road											−0.04 (−0.87)		
NH_3_non-road												−0.08 ** (−2.70)	−0.02 (−0.35)
Energy_transport	−0.02 *** (−23.48)	−0.02 *** (−14.00)	−0.02 *** (−14.85)	−0.00 *** (−3.64)	−0.00 * (−2.10)	−0.00 ** (−3.14)	−0.00 ** (−2.87)	−0.01 *** (−4.02)	−0.01 *** (−4.65)	−0.01 *** (−3.52)	−0.01 *** (−4.44)	−0.00 ** (−2.67)	−0.01 *** (−4.46)
Trade	0.00 *** (6.58)	0.00 ** (2.69)	0.00 ** (3.04)	0.01 *** (8.80)	0.00 *** (4.70)	0.00 *** (4.93)	0.01 *** (14.59)	0.00 *** (4.61)	0.00 *** (4.71)	0.00 *** (4.68)	0.00 *** (4.63)	0.01 *** (15.95)	0.00 *** (4.62)
Fin_dev	0.00 * (2.39)	0.00 *** (7.31)	0.00 *** (5.78)	0.00 *** (8.12)	0.00 *** (5.57)	0.00 *** (6.26)	0.01 *** (9.26)	0.00 *** (4.77)	0.00 *** (5.83)	0.00 *** (6.06)	0.00 *** (6.06)	0.01 *** (9.47)	0.00 *** (5.58)
Urb	0.02 *** (5.81)	0.02 * (2.33)	0.02 ** (3.09)	0.01 (1.44)	−0.02 † (−1.68)	−0.01 (−0.55)	−0.01 (−1.57)	−0.03 ** (−2.99)	−0.01 (−0.98)	−0.01 (−0.60)	−0.01 (−0.85)	−0.01 (−1.02)	−0.01 (−0.67)
_cons	8.47 *** (10.49)	9.96 *** (12.36)	8.35 *** (12.19)	11.00 *** (8.99)	11.43 *** (9.59)	7.84 *** (7.90)	12.97 *** (7.67)	12.95 *** (11.46)	8.43 *** (8.18)	8.48 *** (8.17)	8.40 *** (8.02)	11.67 *** (6.62)	8.67 *** (8.52)
F statistic	687.45 ***	90.78 ***	94.08 ***	233.05 ***	21.97 ***	28.56 ***	115.43 ***	20.77 ***	27.11 ***	27.15 ***	27.03 ***	103.54 ***	26.05 ***
R-sq within	0.93	0.70	0.74	0.82	0.37	0.48	0.68	0.33	0.43	0.43	0.43	0.67	0.44
# Obs	402	265	262	381	254	251	417	287	281	281	281	386	259
# Countries	26	26	26	25	25	25	26	26	26	26	26	24	24

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Figures in brackets depict t-statistic. For the definition of variables, please see Table 4.

Table 9. Fixed-effects regressions results on the effect of road transport infrastructure, related investments, and air pollution on sustainable economic growth.

Variables	Equations														
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**
Length_motorways	0.02 (1.17)		0.25 *** (5.54)			0.02 (0.73)			0.21 *** (5.18)				0.22 *** (5.46)		
Motorisation_rate				1.28 *** (17.13)			0.59 *** (7.84)			1.11 *** (17.21)		1.46 *** (23.91)		1.39 *** (23.54)	1.20 *** (18.61)
Goods_road		0.07 * (2.17)			0.30 *** (9.14)			0.35 *** (12.35)			0.36 *** (12.35)				
Inv_roads				0.08 *** (5.24)			0.04 ** (3.04)			0.10 *** (7.87)					
CO_2_transport	1.81 *** (40.04)	1.22 *** (14.25)													
CO_2_road			−0.01 (−1.19)	−0.01 ** (−3.09)	0.02 *** (3.64)										
CO_2_new_cars						−0.57 *** (−6.29)	−0.44 *** (−5.46)	−0.59 *** (−8.76)							
SOx_road									−0.08 *** (−8.36)	−0.07 *** (−11.99)	−0.05 *** (−7.08)				
NOx_road												−0.03 † (−1.69)			
NMVOC_road													−0.23 *** (−7.98)	−0.11 *** (−7.26)	
NH_3_road															0.13 *** (8.34)
Energy_transport	−0.02 *** (−26.38)	−0.02 *** (−13.91)	−0.01 *** (−3.70)	−0.00 *** (−4.09)	−0.00 ** (−3.23)	0.00 (0.00)	−0.00 (−1.24)	−0.00 ** (−2.76)	−0.00 † (−1.72)	−0.00 (−1.45)	−0.01 *** (−5.70)	−0.00 * (−2.55)	−0.00 (−0.26)	−0.00 (−0.29)	−0.00 *** (−3.89)
Trade	0.00 *** (5.44)	0.00 *** (7.18)	0.01 *** (12.88)	0.00 *** (9.58)	0.01 *** (10.31)	0.00 *** (6.35)	0.00 *** (6.25)	0.00 *** (5.54)	0.01 *** (10.69)	0.00 *** (6.41)	0.00 *** (7.11)	0.00 *** (9.80)	0.01 *** (9.26)	0.00 *** (7.90)	0.01 *** (11.86)
Fin_dev	0.00 * (2.05)	0.00 *** (6.55)	0.00 *** (8.55)	0.00 ** (3.26)	0.00 *** (7.19)	0.00 *** (4.28)	0.00 * (2.03)	0.00 *** (4.26)	0.00 *** (5.31)	-0.00 (−0.65)	0.00 *** (3.33)	0.00 (1.33)	0.00 *** (5.65)	0.00 (0.10)	0.00 (1.28)
Urb	0.02 *** (4.53)	0.01 * (2.25)	−0.03 *** (−4.14)	−0.01 (−1.13)	−0.00 (−0.59)	−0.02 *** (−3.48)	−0.01 † (−1.86)	−0.02 *** (−3.62)	−0.04 *** (−5.39)	−0.02 *** (−3.91)	−0.01 * (−2.29)	−0.00 (−0.95)	−0.05 *** (−6.48)	−0.01 ** (−2.82)	−0.00 (−0.96)
_cons	8.76 *** (32.84)	8.66 *** (18.40)	10.12 *** (12.03)	1.64 * (2.29)	4.79 *** (5.95)	13.75 *** (17.19)	8.35 *** (8.79)	10.44 *** (16.67)	10.74 *** (19.81)	2.77 *** (4.76)	7.32 *** (15.02)	1.23 * (2.10)	13.18 *** (18.44)	3.08 *** (5.15)	1.50 ** (2.95)
F statistic	834.31 ***	184.81 ***	114.79 ***	289.42 ***	97.01 ***	48.22 ***	70.46 ***	94.88 ***	161.29 ***	419.33 ***	119.01 ***	335.14 ***	158.46 ***	377.56 ***	391.93 ***
R-sq within	0.93	0.78	0.63	0.83	0.65	0.51	0.64	0.64	0.68	0.87	0.67	0.81	0.67	0.82	0.83
# Obs	435	339	435	436	339	311	316	351	491	455	379	520	491	520	520
# Countries	25	26	25	27	26	26	27	27	26	27	27	28	26	28	28

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Figures in brackets depict t-statistic. For the definition of variables, please see Table 4.

Therewith, all the estimated equations point out that both the share of CO_2 emissions from road transport in total carbon dioxide emissions from transport and other specific air pollutants, except NH_3, negatively influence GDPC, due to their adverse effects on the atmosphere, on health, and on climate change [25].

Table 10 shows the empirical outcomes regarding the effect of inland waterways transport infrastructure, related investments, and air pollution on sustainable economic growth. The econometric results provide support for a positive influence of inland waterways goods transports on economic growth (Equations (1), (3) and (8)), except Equation (4), due to its features such as reduced energy consumption, reduced external costs, and a reduced number of accidents [57].

Table 10. Fixed-effects regressions results on the effect of inland waterways transport infrastructure, related investments, and air pollution on sustainable economic growth.

Variables	Equations								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Goods_water	0.09 ** (3.06)		0.08 * (2.55)	−0.03 † (−1.71)	0.04 (1.32)			0.09 ** (3.14)	
Inv_water		0.00 (0.09)	−0.00 (−0.47)	−0.00 (−0.29)	−0.01 * (−2.10)	0.00 (0.51)	0.00 (1.28)	−0.00 (−0.71)	0.00 (0.01)
CO2_transport				1.77 *** (18.06)					
CO2_maritime					0.01 * (2.17)				
SOx_non-road						−0.14 *** (−7.27)			
NOx_non-road							−0.49 *** (−8.62)		
NMVOC_non-road								−0.30 *** (−6.17)	
NH3_non-road									−0.10 † (−1.90)
Energy_transport	−0.00 † (−1.87)	−0.00 ** (−2.82)	−0.00 (−1.08)	−0.02 *** (−15.01)	−0.01 *** (−3.79)	−0.00 ** (−3.04)	−0.00 * (−2.06)	0.00 (0.25)	−0.00 * (−2.52)
Trade	0.01 *** (11.43)	0.01 *** (16.38)	0.01 *** (10.63)	0.00 * (2.58)	0.01 *** (9.11)	0.01 *** (15.90)	0.01 *** (14.39)	0.00 *** (8.44)	0.01 *** (15.93)
Fin_dev	0.00 ** (2.97)	0.01 *** (8.98)	0.00 † (1.84)	0.00 † (1.74)	0.00 *** (5.29)	0.01 *** (9.96)	0.01 *** (10.43)	0.00 *** (3.49)	0.01 *** (8.43)
Urb	0.00 (0.37)	−0.04 *** (−3.79)	0.00 (0.21)	0.01 * (2.10)	0.01 * (2.39)	−0.05 *** (−5.22)	−0.04 *** (−4.23)	−0.01 (−0.93)	−0.04 *** (−3.79)
_cons	8.20 *** (14.97)	10.93 *** (16.39)	8.29 *** (11.42)	10.06 *** (24.01)	8.13 *** (16.22)	12.62 *** (19.33)	15.44 *** (19.56)	10.86 *** (14.03)	11.05 *** (16.07)
F statistic	55.94 ***	99.98 ***	36.76 ***	151.56 ***	98.57 ***	108.28 ***	118.56 ***	44.42 ***	79.32 ***
R-sq within	0.62	0.65	0.59	0.88	0.88	0.71	0.73	0.67	0.66
# Obs	191	289	175	166	106	289	289	175	271
# Countries	13	17	13	13	9	17	17	13	16

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Figures in brackets depict t-statistic. For the definition of variables, please see Table 4.

However, investments in inland waterways transport negatively influenced GDPC, but the relationship was statistically weakly significant merely in Equation (5). In line with Hong, Chu and Wang [68], investment in water transport infrastructure will positively influence economic growth only after the investment scale surpasses a threshold level. Besides, we noticed a negative association between all other specific air pollutants and GDPC (all the estimated models), but the share of CO_2 emissions from international maritime bunkers in total carbon dioxide emissions positively influenced economic growth (Equation (5)). However, inland water networks are usually overfilled in CO_2, being documented as a prominent side in the global carbon cycle [22].

The results, with reference to the influence of maritime transport infrastructure, associated investments, and air pollution on sustainable economic growth, are shown in Table 11. Like inland waterway goods transport (see Table 10), the gross weight of seaborne goods handled in ports exerted a strong positive effect on the GDPC (Equations (1), (3), (5)), in line with previous studies [58,59]. Similar to Song and van Geenhuizen [86], we reinforced that investments in maritime port infrastructure positively influence economic growth (Equations (6) and (8)), apart from Equation (4). In case of air pollutants, it was revealed that emissions of sulphur oxides (Equation (7)) and emissions of ammonia (Equation (9)) negatively influenced the GDPC.

Table 11. Fixed-effects regressions results on the effect of maritime transport infrastructure, related investments, and air pollution on sustainable economic growth.

Variables	Equations								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Goods_sea	0.51 *** (7.14)		0.18 *** (3.45)		0.64 *** (8.95)				
Inv_ports		0.01 (1.64)		−0.01 † (−1.85)		0.11 *** (6.41)	0.01 (1.45)	0.01 † (1.72)	0.01 (1.34)
CO2_transport			1.34 *** (21.06)	1.57 *** (35.20)					
CO2_maritime					−0.00 (−0.67)	0.00 (1.11)			
SOx_non-road							−0.05 ** (−2.87)		
NMVOC_non-road								−0.06 (−1.19)	
NH3_non-road									−0.10 *** (−3.76)
Energy_transport	−0.00 *** (−4.31)	−0.01 *** (−7.65)	−0.02 *** (−17.54)	−0.02 *** (−30.56)	−0.00 ** (−2.92)	−0.01 *** (−8.04)	−0.01 *** (−7.23)	−0.01 *** (−7.05)	−0.01 *** (−7.01)
Trade	0.00 *** (7.63)	0.01 *** (9.57)	0.00 * (1.99)	0.00 (1.41)	0.00 *** (7.41)	0.01 *** (7.23)	0.01 *** (9.44)	0.01 *** (9.34)	0.01 *** (8.87)
Fin_dev	0.00 *** (8.78)	0.01 *** (11.51)	0.00 *** (6.29)	0.00 *** (7.79)	0.00 *** (10.71)	0.01 *** (10.71)	0.01 *** (10.50)	0.01 *** (11.52)	0.01 *** (11.15)
Urb	0.00 (0.26)	−0.02 * (−2.31)	0.02 *** (4.06)	0.03 *** (5.81)	−0.01 (−1.48)	−0.02 † (−1.79)	−0.02 * (−2.44)	−0.03 ** (−2.60)	−0.02 * (−2.22)
_cons	3.59 *** (4.04)	11.20 *** (14.75)	7.20 *** (11.41)	8.68 *** (25.25)	2.68 ** (3.10)	9.08 *** (10.34)	11.65 *** (15.19)	12.00 *** (11.81)	11.32 *** (14.42)
F statistic	97.33 ***	103.44 ***	277.27 ***	644.75 ***	101.29 ***	92.81 ***	89.55 ***	86.55 ***	85.18 ***
R-sq within	0.59	0.62	0.84	0.93	0.67	0.67	0.63	0.62	0.65
# Obs	371	342	335	333	323	303	342	342	302
# Countries	23	21	22	21	22	20	21	21	18

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Figures in brackets depict t-statistic. For the definition of variables, please see Table 4.

The estimation results with respect to the impact of air transport infrastructure, associated investments, and air pollution on sustainable economic growth, are presented in Table 12. As in previous studies [53,54,65,67], the total number of passengers (Equations (1), (3)), alongside the volume of goods transported in Europe (Equation (4)) positively influenced GDPC. Likewise, investments in airport infrastructure positively influenced economic growth (Equations (4)–(8)). With regard to transport pollution, we noticed a positive connection between the share of CO_2 emissions from domestic aviation in total carbon dioxide emissions from transport and GDPC (Equation (4)), but other specific air pollutants, except NH_3, negatively influence GDPC (all the estimated models).

Table 12. Fixed-effects regressions results on the effect of air transport infrastructure, related investments, and air pollution on sustainable economic growth.

Variables	Equations							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Passengers_air	0.13 *** (8.93)		0.19 *** (8.09)					
Goods_air		−0.00 (−0.65)		0.01 * (2.09)	0.00 (0.81)	0.00 (0.91)	0.01 (1.37)	0.00 (0.64)
Inv_airports		−0.00 (−0.16)		0.03 * (2.27)	0.02 *** (3.46)	0.02 *** (3.45)	0.01 ** (3.30)	0.01 ** (3.23)
CO_2_transport	1.20 *** (20.71)	1.35 *** (19.49)						
CO_2_aviation			0.02 (1.41)	0.04 * (2.40)				
SOx_non-road					−0.05 ** (−2.85)			
NOx_non-road						−0.12 * (−2.04)		
NMVOC_non-road							−0.13 ** (−2.97)	
NH_3_non-road								−0.00 (−0.09)
Energy_transport	−0.02 *** (−19.88)	−0.02 *** (−19.14)	−0.00 *** (−3.60)	−0.00 * (−1.97)	−0.01 *** (−5.09)	−0.01 *** (−3.88)	−0.01 *** (−4.38)	−0.01 *** (−6.14)
Trade	0.00 * (2.17)	0.00 *** (4.41)	0.00 * (2.21)	0.01 *** (6.71)	0.00 *** (9.83)	0.01 *** (9.95)	0.00 *** (9.61)	0.01 *** (9.51)
Fin_dev	0.00 *** (4.41)	0.00 *** (5.83)	0.00 *** (4.41)	0.00 *** (6.35)	0.00 *** (7.32)	0.00 *** (8.00)	0.00 *** (7.97)	0.00 *** (7.85)
Urb	0.01 *** (3.63)	0.02 *** (3.91)	0.02 ** (3.15)	0.02 † (1.83)	−0.02 * (−2.09)	−0.01 † (−1.89)	−0.02 ** (−2.77)	−0.01 (−1.36)
_cons	7.62 *** (23.12)	8.82 *** (22.74)	5.62 *** (10.54)	7.63 *** (10.71)	10.85 *** (19.27)	11.41 *** (15.24)	11.88 *** (16.01)	10.22 *** (17.83)
F statistic	356.32 ***	203.25 ***	87.29 ***	35.96 ***	67.65 ***	66.23 ***	67.91 ***	62.83 ***
R-sq within	0.86	0.83	0.67	0.55	0.61	0.61	0.61	0.61
# Obs	379	316	291	234	333	333	333	308
# Countries	27	25	22	21	25	25	25	23

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Figures in brackets depict *t*-statistic. For the definition of variables, please see Table 4.

In relation to country-level control variables, trade openness and domestic credit to private sector positively influence economic growth since the high volume of freight boosts economic prosperity [12]. In the case of urbanization, there are noticed mixed relationships, whereas energy consumption of transport relative to GDP negatively influences the gross domestic product per capita.

4.3. Cointegration and Causality Examination

Considering that all of the selected variables have a unique order of integration (see Table 7), the cointegration examination was further employed. Table 13 shows the results of the Pedroni test [109,110]. There are two sets covering tests for homogeneous and heterogeneous panels: the tests of the first set average the results of single state test statistics, whereas tests of the second set pool the statistics along the within-dimension [38]. Thereby, several statistics provide support for the cointegration connection among the variables from the five models.

Table 13. The output of the Pedroni (Engle Granger-based) panel cointegration test.

Models		Cointegration Test Null Hypothesis: No cointegration	Individual Intercept		Individual Intercept and Individual Trend		No Intercept or Trend	
			Statistic	Weighted Statistic	Statistic	Weighted Statistic	Statistic	Weighted Statistic
(1)	GDPC Length_rail Inv_rail CO_2_rail	Panel v-Statistic	0.9955	−6.0568	6.486962 ***	6.067955 ***	−14.5877	−4.2945
		Panel rho-Statistic	0.2408	1.9983	2.6909	2.6603	−0.1668	3.9127
		Panel PP-Statistic	−5.197391 ***	−0.3368	−0.4058	−1.2702	−3.544359 ***	7.0341
		Panel ADF-Statistic	−3.54039 ***	−0.3368	−0.8048	−1.84431 *	−0.4787	7.0341
		Group rho-Statistic	2.9436		4.6577		2.1558	
		Group PP-Statistic	−3.479931 ***		−1.605767 †		−2.683107 **	
		Group ADF-Statistic	−2.12394 *		−1.458767 †		−1.41845 †	
(2)	GDPC Length_motorways Inv_roads CO_2_road	Panel v-Statistic	−0.3917	0.7199	5.447141 ***	4.315155 ***	−0.1045	−0.3268
		Panel rho-Statistic	1.8695	1.1208	3.0033	2.4397	0.7564	0.8406
		Panel PP-Statistic	−0.0693	−1.646831 *	−0.8076	−1.838436 *	−1.0061	−1.0607
		Panel ADF-Statistic	−0.8446	−2.339715 **	−2.85224 **	−3.370604 ***	−2.178221 *	−2.021556 *
		Group rho-Statistic	3.2642		4.7287		2.7699	
		Group PP-Statistic	−2.124862 *		−1.779161 *		−1.422233 †	
		Group ADF-Statistic	−2.555264 **		−4.069135 ***		−3.098295 **	
(3)	GDPC Goods_water Inv_water CO_2_maritime	Panel v-Statistic	−0.7262	−1.3386	1.684538 *	4.102849 ***	−15.8361	−1.5757
		Panel rho-Statistic	1.6557	1.6467	2.9981	2.4029	0.5720	1.0333
		Panel PP-Statistic	0.4373	1.2822	1.1928	−0.5004	−0.6848	0.5721
		Panel ADF-Statistic	0.2133	1.0621	-0.2257	−1.794222 *	−0.9617	0.4528
		Group rho-Statistic	2.8704		2.5592		2.3241	
		Group PP-Statistic	0.0549		−3.410143 ***		1.2302	
		Group ADF-Statistic	0.1864		−5.015604 ***		1.3615	
(4)	GDPC Goods_sea Inv_ports CO_2_maritime	Panel v-Statistic	−2.3135	−2.1287	3.72849 ***	6.707587 ***	−1.7624	−1.4283
		Panel rho-Statistic	3.4328	3.5290	4.7109	4.4862	2.2421	2.1355
		Panel PP-Statistic	2.2600	2.7517	4.1318	3.4173	1.2842	1.2253
		Panel ADF-Statistic	1.6834	2.3079	3.5073	2.7828	0.9138	0.7323
		Group rho-Statistic	4.9362		6.0786		4.1977	
		Group PP-Statistic	1.7794		2.9878		0.7744	
		Group ADF-Statistic	2.1735		2.0991		1.0567	
(5)	GDPC Goods_air Inv_airports CO_2_aviation	Panel v-Statistic	−1.4497	−1.4319	1.624962 †	1.908246 *	−2.9800	−3.2409
		Panel rho-Statistic	2.1187	1.8316	3.1578	3.1447	−0.6803	−1.0155
		Panel PP-Statistic	−0.8387	−0.5263	−1.307292 †	−0.4934	−4.279738 ***	−5.037545 ***
		Panel ADF-Statistic	−1.0704	−1.719588 *	−4.086478 ***	−1.908308 *	−4.091758 ***	−4.876058 ***
		Group rho-Statistic	3.4694		4.5895		2.0465	
		Group PP-Statistic	−4.113342 ***		−1.317666 †		−3.908474 ***	
		Group ADF-Statistic	−3.729115 ***		−3.682943 ***		−3.030543 **	

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. The Schwarz Info Criterion was selected for lag length. For the definition of variables, please see Table 4.

Onward, as in [62,65,103], the long-run equilibrium between variables was checked via the Kao [111] test presented in Table 14, as well as the Johansen [112] test shown in Table 15. Hence, the null hypothesis of no cointegration between variables was rejected, thus reinforcing the existence of cointegration. Therefore, transport infrastructure, related investments, emissions of carbon dioxide, and economic growth has a long-run relationship in the EU-28 countries.

Table 14. The output of the Kao (Engle Granger-based) panel cointegration test.

	Models				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Null Hypothesis: No cointegration	GDPC Length_rail Inv_rail CO_2_rail	GDPC Length_motorways Inv_roads CO_2_road	GDPC Goods_water Inv_water CO_2_maritime	GDPC Goods_sea Inv_ports CO_2_maritime	GDPC Goods_air Inv_airports CO_2_aviation
ADF (*t*-Statistic)	−7.033588 ***	−2.002150 *	2.209614 *	−2.546363 **	−3.409450 ***
Residual variance	0.007358	0.006635	0.004099	0.005512	0.003988
HAC Variance	0.013221	0.009894	0.004197	0.011835	0.007143

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. HAC: Heteroskedasticity and autocorrelation consistent. Schwarz Info Criterion was selected for lag length. For the definition of variables, please see Table 4.

Table 15. The output of the Fisher (combined Johansen) panel cointegration test.

Models		**Hypothesized No. of CE (s)**	**Fisher Stat. (from Trace Test)**	**Fisher Stat. (from Max-Eigen Test)**
(1)	GDPC	None	371.4 ***	315.5 ***
	Length_rail	At most 1	197.1 ***	159.2 ***
	Inv_rail	At most 2	85.75 ***	62.6 *
	CO_2_rail	At most 3	88.18 ***	88.18 ***
(2)	GDPC	None	261 ***	198.9 ***
	Length_motorways	At most 1	147.6 ***	120.4 ***
	Inv_roads	At most 2	88.46 ***	71.08**
	CO_2_road	At most 3	76.65 ***	76.65 ***
(3)	GDPC	None	89.43 ***	82.76 ***
	Goods_water	At most 1	48.25 ***	41.97 ***
	Inv_water	At most 2	16.12 †	15.71
	CO_2_maritime	At most 3	12.98	12.98
(4)	GDPC	None	169.3 ***	109.1 ***
	Goods_sea	At most 1	166.4 ***	123.7 ***
	Inv_ports	At most 2	93.15 ***	68.21 ***
	CO_2_maritime	At most 3	76.42 ***	76.42 ***
(5)	GDPC	None	203.9 ***	162.9 ***
	Goods_air	At most 1	199.9 ***	169.4 ***
	Inv_airports	At most 2	89.34 ***	75.6 ***
	CO_2_aviation	At most 3	51.16 ***	51.16 ***

Source: Authors' computations. Notes: Superscripts ***, **, * and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Probabilities are computed using asymptotic Chi-square distribution. For the definition of variables, please see Table 4.

For robust statistical estimates, we employed a non-parametric approach, namely a panel with a fully modified ordinary least squares (henceforth "FMOLS") estimator as in [5,59,65,77,82,107], but also an alternative parametric method, respectively a dynamic ordinary least squares estimator (henceforth "DOLS"), as in [5]. The FMOLS is the desirable econometric way to assess the long-run parameter estimates that handle both the endogeneity and serial correlation concerns [59], whilst DOLS covers the lagged first difference [77]. Table 16 displays the parameter estimates by FMOLS and DOLS. As in Table 8, we noticed a negative impact of the length of railways lines on GDPC

(Equation (1)). Contrariwise, consistent with [82] and analogous to Table 9, the length of motorways positively influenced economic growth (Equation (2)). With regard to the carriage of goods by the main forms of transport, a positive and statistically significant impact was observed (Equations (3)–(5)), similarly [59]. Likewise, investments in transport infrastructure positively influenced economic growth (Equations (1)–(3)), apart from investments in airport infrastructure that negatively influenced GDPC (Equation (5)). In the case of investments in maritime port infrastructure, a statistically non-significant impact was observed (Equation (4)), contrary to [82]. In relation to air pollutants, the share of CO_2 emissions from railway transport in total carbon dioxide emissions from transport negatively influenced GDPC (Equation (1)), as in Table 8. Nevertheless, the share of CO_2 emissions from international maritime bunkers in total carbon dioxide emissions had a positive influence on GDPC (Equation (3)), consistent with [107].

Table 16. The results of panel fully modified OLS (FMOLS) and dynamic OLS (DOLS) regressions.

Variables	Equations									
	(1)		(2)		(3)		(4)		(5)	
	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS
Length_rail	−0.49 † (−1.80)	−1.13 ** (−3.25)								
Length_motorways			0.47 *** (12.69)	0.49 *** (8.00)						
Goods_water					0.25 *** (3.95)	0.61 *** (4.37)				
Goods_sea							1.22 *** (11.77)	1.17 *** (7.68)		
Goods_air									0.03 *** (5.07)	0.04 *** (5.99)
Inv_rail	0.05 *** (6.99)	0.05 *** (4.06)								
Inv_roads			0.33 *** (10.52)	0.29 *** (5.95)						
Inv_water					−0.01 (−1.08)	0.03 * (2.25)				
Inv_ports							0.00 (0.14)	−0.01 (−0.19)		
Inv_airports									−0.03 † (−1.65)	−0.03 (−0.81)
CO_2_rail	−0.38 *** (−19.45)	−0.37 *** (−16.60)								
CO_2_road			−0.01 (−0.63)	0.01 (1.02)						
CO_2_maritime					0.02 *** (7.32)	0.02 ** (3.01)	0.00 (0.45)	−0.01 (−1.06)		
CO_2_aviation									−0.03 (−1.41)	−0.01 (−0.22)
R-squared	0.95	0.98	0.92	0.97	0.98	0.99	0.94	0.96	0.96	0.96

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. Panel method: Pooled estimation. Heterogeneous variances. The Schwarz lag and lead method are used in the case of DOLS estimation. Figures in brackets depict t-statistic. For the definition of variables, please see Table 4.

Since the variables were cointegrated, we could estimate the panel vector error correction model to assess the direction of the causality [62]. Therefore, Table 17 reveals the PVECM Granger causalities where the *ECT* denotes the long-run dynamics, whilst the differenced variables shows the short-run dynamics between the variables [44]. As such, when ΔGDPC served as the dependent variable, the error correction term was statistically significant, except for model 5. This denotes that economic growth tends to converge to its long-run equilibrium path in response to changes in its regressors [44].

Table 17. Panel vector error correction model (PVECM) Granger causalities.

Models	Excluded	Short-Run (or Weak) Granger Causality Dependent Variables				Long-Run Granger Causality
		ΔGDPC	ΔLength_Rail	ΔInv_Rail	ΔCO_2_Rail	ECT
(1)	ΔGDPC	-	3.0069	1.1277	35.76643 ***	0.005381 †
	ΔLength_rail	2.4596	-	2.0786	2.5571	−0.002476 *
	ΔInv_rail	3.5032	1.7593	-	9.288777**	0.451737 ***
	ΔCO_2_rail	15.93513 ***	2.1459	2.0171	-	0.031600
(2)		ΔGDPC	ΔLength_motorways	ΔInv_roads	ΔCO_2_road	ECT
	ΔGDPC	-	0.3434	7.220526 *	5.538128 †	−0.025857 ***
	ΔLength_motorways	0.4483	-	5.977704 †	1.4136	0.001168
	ΔInv_roads	4.2116	9.813639 **	-	0.5114	−0.056647 ***
	ΔCO_2_road	2.8318	0.6579	6.47522 *	-	0.030072
(3)		ΔGDPC	ΔGoods_water	ΔInv_water	ΔCO_2_maritime	ECT
	ΔGDPC	-	6.854446 *	5.964414 †	0.3307	−0.033704 ***
	ΔGoods_water	0.7641	-	4.3229	0.8496	−0.014254
	ΔInv_water	1.3538	5.659045 †	-	0.1609	0.416428
	ΔCO_2_maritime	0.2766	2.1582	0.8588	-	−0.001582
(4)		ΔGDPC	ΔGoods_sea	ΔInv_ports	ΔCO_2_maritime	ECT
	ΔGDPC	-	13.10969 **	2.2379	1.3903	−0.032450 ***
	ΔGoods_sea	2.8715	-	5.544528 †	0.5619	−0.030166 ***
	ΔInv_ports	3.2968	2.6954	-	4.1582	0.084286
	ΔCO_2_maritime	0.8349	3.2689	0.4721	-	−0.343821
(5)		ΔGDPC	ΔGoods_air	ΔInv_airports	ΔCO_2_aviation	ECT
	ΔGDPC	-	1.7382	3.6635	4.0359	0.000133
	ΔGoods_air	5.532539 †	-	0.0310	3.8523	0.139901 ***
	ΔInv_airports	4.3800	0.3167	-	4.3489	0.005357
	ΔCO_2_aviation	17.29063 ***	0.3364	0.6622	-	−0.010573 †

Source: Authors' computations. Notes: Superscripts ***, **, *, and † indicate statistical significance at 0.1%, 1%, 5%, and 10% respectively. ECT reveals the coefficient of the error correction term. The number of appropriate lag is two according to Schwarz information criterion. For the definition of variables, please see Table 4.

With respect to the first model, regarding railway transport, in short-run, we noticed a bidirectional causal link between the share of CO_2 emissions from railway transport in total carbon dioxide emissions from transport and GDPC, similar to [107]. Besides, the empirical results provided support for a one-way causality link running from investments in railway transport infrastructure to CO_2_rail. Thereby, investments in rail infrastructure entail higher amounts of energy, mostly in the steel industry, and per se, greater CO_2 emissions [99]. Besides, we noticed long-run causality running from Length_rail, Inv_rail, and CO_2_rail to GDPC, from GDPC, Inv_rail, and CO_2_rail to Length_rail, as well as from GDPC, Length_rail, and CO_2_rail to Inv_rail.

In the case of the second model, concerning road transport, in short-run, we acknowledged a bidirectional causal association between investments in road transport infrastructure and the length of motorways. Further, we noticed a unidirectional causal relation running from GDPC to investments in road transport infrastructure, as well as a unidirectional causal relation running from GDPC to CO_2_road, consistent with [95]. In the long-run, causal links ran from Length_motorways, Inv_roads, and CO_2_road to GDPC, from GDPC to Inv_roads, similar to [78], and from Length_motorways, CO_2_road to Inv_roads.

The third model towards waterways transport revealed in the short-run a couple of one-way causal links running from GDPC to inland waterways goods transports, and from GDPC to investments in inland waterways transport, similar to [103]. As well, further short-run causal relationships ran from investments in this transportation type to Goods_water. In the long-run, we noticed a causal link running from Goods_water, Inv_water, and CO_2_maritime to GDPC.

The model regarding maritime transport revealed a unidirectional causal link running from economic growth to the gross weight of seaborne goods handled in ports, consistent with [2,59], alongside a unidirectional causal relation running from Goods_sea to investments in maritime port infrastructure. The following causal links were observed in the long-run: Goods_sea, Inv_ports, and CO_2_maritime to GDPC, along with GDPC, Inv_ports, and CO_2_maritime to Goods_sea.

The fifth model with regard to air transport revealed in the short-run a unidirectional causal association running from the volume of goods transported by air to GDPC, like [42,64], and from the share of CO_2 emissions from domestic aviation in total carbon dioxide emissions from transport to GDPC. Moreover, we remarked on long-run causalities running from GDPC to Goods_air alike [62], also from Inv_airports and CO_2_aviation to Goods_air, and from GDPC, Goods_air, Inv_airports to CO_2_aviation.

5. Concluding Remarks and Policy Implications

The transport sector reveals itself as a fundamental factor towards economic growth, ensuring the efficient distribution of resources and mobility for people [107]. This paper examined the relationship between the main types of transport, related investments, specific air pollutants, and sustainable economic growth for EU-28 countries over 1990–2016. By the means of fixed-effects regressions, the empirical results provide support for a positive impact of road, inland waterways, maritime, and air transport infrastructure on economic growth. Likewise, investments in transport infrastructure positively influence gross domestic product per capita for every form of transport, apart from inland waterways, whilst CO_2 emissions from transport and other specific air pollutants exhibit a negative impact on economic growth. Overall, the output of panel fully modified OLS and dynamic OLS regressions confirm the findings.

According to Granger causality based on a panel vector error correction model, we noticed a short-run one-way link running from the volume of goods transported by air to GDPC, as well as from inland waterways goods transports and the gross weight of seaborne goods handled in ports to GDPC. In the case of the length of railways lines and the length of motorways, no short-run causal relationship with economic growth was noticed. With reference to transport investments, we found a short-run causal connection running from investments in road transport infrastructure and investments in inland waterways transport to GDP. Concerning air pollutants, a bidirectional link occurred between CO_2 emissions from railway transport and GDPC, while unidirectional relations appeared from economic growth to CO_2 from road, and from CO_2 related to domestic aviation to economic growth. In the long-run, we notice a two-way causal link between the length of railways lines, investments in railway transport infrastructure, and economic growth, as well as a bidirectional causal connection between the gross weight of seaborne goods handled in ports and gross domestic product per capita.

With reference to policy decision-making processes, the EU-28 nations should continue the enlargement of the railway system in order to follow the targets established in the White Paper [33]. As well, in order to achieve the EU goals concerning emissions of air pollutants from transport [30,37], manufacturers should aim to decrease the usage of fossil fuels [99], whilst designing more fuel efficient-vehicles. With respect to maritime transport, even if CO_2 discharges per 1 tonne/kilometer are up to five times less in inland waterway carriage than road transport [57], replacing current fleet with bigger vessels may be considered in terms of the decrease in greenhouse gases [23]. Therewith, investments within airport and maritime port infrastructure should be speeded up. Likewise, second generation biofuels should be promoted with regard to the challenge of transportation sector decarbonization.

A limitation of the current study ensues from the fact that high-speed rail network was not considered distinctly from traditional rail, whilst the density of transport networks in relation to the total area and the number of citizens was not taken into account. For future research, this study can be extended by segregating the investments in transport infrastructure into public, private, and public-private partnerships, along with urbanized kilometers of road.

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