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Environmental Sustainability within Attaining Sustainable Development Goals: The Role of Digitalization and the Transport Sector

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Abstract: Accepting sustainable development goals leads to the reorientation of all sectors at all levels. The European Union (EU) actively accepts a vast range of policies to achieve environmental sustainability due to declining carbon dioxide emissions. Within the Green Deal Policy, and in particular the Fit for 55 packages, the EU declared ambitious goals to reduce carbon dioxide emissions by at least 55% from the transport industry by 2030 and 100% by 2035. These goals require introducing appropriate digital technologies into the ecologically friendly functioning of the transport sector to attain sustainable development. This paper aims at analyzing the impact of digitalization on environmental sustainability by providing an effective transport sector that functions with minimum environmental degradation. The object of research is the EU countries for the period 2006–2020. This study applies the panel-corrected standard errors technique to achieve the paper's aims. The findings allow us to conclude that digitalization is conducive to environmental sustainability. Thus, digital inclusion, the input of the IT sector to GDP, and e-commerce have direct negative and statistically significant linear effects on carbon dioxide emissions. Growth of digital inclusion, input of the IT sector to GDP, and enterprises with web sales by one point allow for decreasing CO_2 emissions by 0.136, 2.289, and 0.266, respectively. However, key enablers and digital public services for citizens have a nonlinear, statistically significant impact on carbon dioxide emissions. The findings could be the basis for upgrading incentive policies for reducing carbon dioxide emissions.

Keywords: sustainable development; green growth; green transport; green cities

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1. Introduction

The European Union (EU) declared the ambitious goal of becoming the first carbon-neutral region by 2050. In 2019, the EU accepted the Green Deal Policy [1], which aims at promoting well-being by eliminating the negative impact on the environment caused by economic development by providing innovative green technologies, extending green energy [2–4], guaranteeing affordable energy [5,6] and clean air, reducing inequalities [3], etc. At the same time, within the Green Deal Policy, and in particular Fit for 55 packages [2], the EU declared the goals to reduce carbon dioxide emissions by at least 55% from the transport industry by 2030 and 100% by 2035. It should be noted that the transport sector is a major contributor to greenhouse gas emissions, accounting for a significant portion of CO_2 emissions globally [7]. The prior study [5] confirms that the EU's ambitious goals on carbon neutrality could be realized within the context of extending information technologies. Studies [6–9] show that information technologies allow optimization of energy use, streamline transportation systems, and enhance the efficiency of industrial processes [10,11]. Smart grids and IoT-enabled devices can dynamically manage electricity distribution, reducing waste and promoting the integration of renewable energy sources [12–16]. Moreover, scholars [17–20] prove that digital technology offers innovative solutions for sustainable and efficient transportation. Advancements in such areas as electric vehicles, autonomous driving, smart traffic management, and shared mobility platforms have the potential to transform the way for policy modernization. In addition, scholars [21–24] have shown that penetrating digital services at all levels boosts the extension of government and public service digitalization, which reduces the eco-destructive impact on the environment.

While digital technology offers immense opportunities, it is essential to recognize that it can also introduce new complexities and risks [25–27]. The proliferation of data centers and the increasing demand for computing power can lead to a surge in energy consumption [4,5]. Furthermore, scholars [3] prove that digital technologies have the potential to exacerbate existing inequalities if their benefits are not distributed equitably. Investigating the role of digitalization in achieving environmental sustainability within the transport sector is crucial for guiding policy decisions and leveraging technological advancements towards sustainable development goals. In this case, it is necessary to identify the character (linear/nonlinear) of digital technologies' impact on carbon dioxide emissions from the transport sector within the context of attaining sustainable development goals. This study fills the scientific gaps in the theoretical framework for assessing the correlation between digitalization and carbon dioxide emissions from the transport sector in attaining sustainable development goals by developing an approach based on panel-corrected standard error techniques. The research findings allow unlocking the full potential of digital technologies, anticipating challenges, informing decision-making, and addressing equity concerns. The results could be used to develop empirically justified policies on attaining sustainable development goals by enhancing digital technology as a powerful tool in the fight against climate change, paving the way for a sustainable and decarbonized future.

The paper has the following structure: A literature review explores the theoretical landscape of links between digital technologies and carbon dioxide emissions from passenger transportation within attaining sustainable development goals; Materials and methods describe the core variables and their sources, methods, and instruments to check the research hypotheses; Results explain the outcomes of research on the linking between digital technologies and carbon dioxide emissions from the transport sector; discussion and conclusion summarize the research results, compare their analysis with prior studies, and identify policy implications, limitations, and further directions for research.

2. Literature Review

Studies [28–30] show that the transport sector is one of the largest energy consumers and provides a higher share of CO_2 emissions than other sectors. Bishop [31] highlights that the transport sector provided more than 24% of world emissions in 2019. The snowball development and penetration of digital technologies among all sectors boost green innovations, which are conducive to the decline of CO_2 emissions [32]. It should be noted that scholars [33–38] analyze the digitalization effect from different points of view: (1) estimate the impact of digital inclusion on CO_2 emissions [33,34]; (2) estimate the impact of the share of the ICT sector in GDP on CO_2 emissions [35,36]; and (3) estimate the impact of e-commerce and e-governance penetration on CO_2 emissions [37,38].

Tsakalidis et al. [39] confirm that digital technologies enable advanced route planning and optimization algorithms, which can significantly reduce CO_2 emissions in transportation. Scholars [39] underline that applying artificial intelligence with a combination of green innovations in an effective way boosts the generation of direct and indirect effects. Similar conclusions on the crucial role of digital technologies and artificial intelligence are obtained by Bishop [31]. Scholars [31] have proven that digital twin technologies are conducive to smart use of available transport systems and optimize the mobility of passengers. At the same time, it requires the relevant knowledge [40–45] and infrastructure readiness of the business sector. Mulholland et al. [28] show that carbon infrastructure, relevant digital technologies, and data sharing in the supply chain catalyze CO_2 reduction by 56% between

2015 and 2050. Ortega et al. [46] showed that extending carsharing services by promoting digital technologies allows for reducing greenhouse gas emissions from urban transport systems and attaining sustainable city development. Leite de Almeida et al. [47] outline that extending digitalization among urban transport systems boosts the attainment of sustainable development goals in Brazil. Similar conclusions were proven by Goel et al. [48]. Scholars highlight that the integration of digital technologies with behavioral intelligence is conducive to the spread of green transport in cities, which decreases carbon dioxide emissions. Paprocki [30] analyzes air transport and concludes that, due to the incorporation of a virtual airport hub business model based on digital technologies, the EU countries could decrease CO_2 emissions by 5% without reducing the number of passengers. Similar conclusions were obtained by Tijan et al. [49] for maritime transport. The researchers highlight that digitalization boosts the generation of positive economic, social, and ecological effects. Thus, digitalization reduces the cost of transportation, improves service quality, and decreases negative emissions in the air. At the same time, Kawasaki [50] underlines that digitalization and R&D allow for reducing the eco-destructive impacts of railway transport on the environment. Based on the analysis of the theoretical framework, scholars [51] confirm that the implication of information technology in railway transport systems at the projecting stage could restrict carbon dioxide emissions. Researchers [52] justify that waterway transport could be the most eco-friendly. However, it requires appropriate policy support for implementing the concept of river information services.

Digitalization causes the snowball development of digital services and e-commerce [53–57], which intensifies the negative impact on the environment and could increase transport mobility [58–60]. In this case, the effective penetration of digital technologies should eliminate the eco-destructive effect on the environment [61–65]. Applying the agent-based stimulation model, scholars [66] confirm that effective planning using big data and information technologies could optimize the supply chain and minimize air pollution. Ehrler et al. [67] emphasize that the eco-destructive effect on the environment of urban transport, which is caused by the intensification of e-commerce, could be overcome by extending electric vehicles. It allows for reducing emissions in urban areas. Similar conclusions are obtained by [68]. Scholars [69] outline that decreasing emissions could be followed by spreading crowd-shipping services based on digital technologies. A previous study [60] showed that the implementation of parcel mobile hubs using digital technologies reduced carbon dioxide emissions by 3.4 tons.

Noussan and Tagliapietra [70] showed that the penetration of digital technologies could provoke controversial effects on energy consumption and emissions in EU countries. In addition, this effect depends on consumer behavior, transport, and ecological policies. Furthermore, Noussan and Tagliapietra [70] emphasize that the government should provide affordable digital technologies with the optimization and common use of alternative transports. However, AL-Dosari et al. [71] maintain that digitalization has a negative impact on the environment, which could be eliminated by extending green cybersecurity in the Qatar transportation sector based on green information technologies. Applying the generalized method of moments, Ghouse et al. [72] outlined that digital, social, and institutional inclusions reduce carbon dioxide emissions in low-, middle-, and high-income countries. In addition, digital inclusion was measured by the numbers of mobile and internet users and the number of broadband connections. Based on the findings of the threshold model and spatial Durbin model, researchers [73] confirm the U-shape relationship between digital technologies and carbon dioxide emissions in China. This means that at the first stage, the implementation of digital technologies increases carbon dioxide emissions, which is followed by a snowball decline in carbon dioxide emissions. Scholars [74] developed a digital index to analyze its impact on carbon dioxide emissions in the transport sector of Chinese regions. They confirm that the growth of digitalization by one point allows for a reduction of carbon dioxide emissions by 6.14% [74]. However, scholars [74] have outlined that digitalization boosts carbon dioxide emissions from the transport sector if the urbanization rate is low, while it decreases carbon dioxide emissions from the transport sector in regions with a high urbanization rate.

The aforementioned analysis underscores the substantial contribution of the transport sector to CO_2 emissions while also highlighting the potential of digital technologies to drive green innovations and reduce emissions. Numerous studies emphasize the advantages of digitalization in areas such as route planning enhancement, transport system optimization, emissions reduction, and the attainment of sustainable development goals. However, it is crucial to recognize the complex nature of the impact of digitalization on energy consumption and emissions. This impact is influenced by various factors, including trade openness, governance efficiency, research and development, and government expenditure on environmental protection. Understanding these factors is essential to effectively harnessing the potential of digitalization for achieving a more sustainable and environmentally friendly transport sector in EU countries. Therefore, the primary objective of the paper is to investigate how digitalization can enable efficient transport operations with minimal environmental degradation, specifically within the context of EU countries.

3. Materials and Methods

To estimate the potential global reductions in CO_2 emissions in the transport sector from digitalization, the following main steps were taken: (i) Developing a model to quantify CO_2 emissions that can be reduced through ICT solutions, considering both the perspective of end users (e.g., digital inclusion) and the size of the IT sector; (ii) Collecting data on CO_2 emissions reductions resulting from the growth of digital businesses, including factors such as e-commerce sales, e-commerce turnover, and e-commerce web sales; and (iii) Assessing the CO_2 emissions reductions achieved through the development of digital public services. The model used to examine the relationship between digitalization and CO_2 emissions in the transport sector is presented as follows:

$$CO2_{it} = \alpha_0 + \beta_1 Digital_{it} + \beta_2 \text{Control}_{it} + \varphi_t + \omega_i + \varepsilon_{it} \quad (1)$$

where $CO2_{it}$ is a dependent variable measured by CO_2 emissions in the transport sector for country i at time t; $Digital_{it}$ is an independent variable that represents digitalization for country i at time t; Control_{it} is a set of control variables; α_0 is a constant; β_1, β_2 are model search parameters; φ_t, ω_i, ε_{it} are items that present the country and year fixed effects and the error term, respectively.

Based on the previous studies [75–80], the following control variables were selected:

1. Trade Openness (TO): TO is a measure of the economic activity and international trade relationships of a country. It encompasses factors that can influence production methods and emissions associated with transportation and logistics [75,76].
2. Governance and Policy Environment: Government efficiency (WGI) is an indicator of the quality of governance and institutional factors within a country. Robust governance practices can facilitate effective environmental policies, regulations, and enforcement mechanisms [77,78].
3. Technological Innovation and Environmental Regulations: Patents in Environment-Related Technologies (RD) and Government Expenditure on Environmental Protection (EnvReg) capture the level of technological innovation and the extent of environmental regulatory efforts in a country. These variables reflect the commitment to developing and adopting environmentally friendly technologies as well as implementing policies aimed at reducing emissions [79,80].

The object of research in this study is the European Union (EU) countries for the period 2006–2020. The data used for analysis were obtained from open statistical databases and analytical reports, including the World Data Bank [81], Eurostat [82], and Crippa et al. [83]. Descriptive statistics of the selected indicators for the study are presented in Table 1.

Table 1. Descriptive statistics of variables.

Symbols	Description	Source	Obs	Mean	CV	Min	Max
CO_2	CO_2 by transport	Crippa et al. [83]	405	29.26	1.37	0.52	163.49
DI	Digital inclusion		405	69.35	0.25	18.36	96.75
Size	Percentage of the ICT sector in GDP		266	4.28	0.28	1.99	8.89
e1	Enterprises with e-commerce sales		221	19.14	0.42	3.80	46.80
e2	Enterprises with e-commerce sales of at least 1% turnover	Eurostat [82]	221	16.75	0.47	2.50	42.80
e3	Enterprises with web sales (via websites, apps or marketplaces)		221	11.25	0.46	2.40	27.90
eGovke	Key enablers		189	56.87	0.45	5.00	100.00
eGovbuss	Digital public services for businesses		189	63.45	0.28	16.00	97.50
eGovcit	Digital public services for citizens		189	48.11	0.42	12.00	89.00
TO	Trade		405	125.82	0.52	45.42	380.10
WGI	Estimate of governance	World Data Bank [81]	405	1.04	0.47	0.09	1.89
RD	Patents in environment-related technologies		405	235.65	2.32	0.00	3335.60
EnvReg	Government expenditure on environmental protection		405	0.77	0.45	−0.30	1.90

The results of the correlation analysis are presented in Table 2.

Table 2. Correlation analyses.

Variables	CO_2	DI	Size	e1	e2	e3	eGovke	eGovbuss	eGovcit	TO	WGI	RD	EnvReg
CO_2	1.00 *												
DI	0.06 **	1.00 *											
Size	−0.19 *	0.54 *	1.00 *										
e1	0.10 **	0.68 *	0.29 *	1.00 *									
e2	0.05 ***	0.65 *	0.31 *	0.98 *	1.00 *								
e3	0.06 *	0.51 *	0.14	0.92 *	0.93 *	1.00 *							
eGovke	−0.07 **	0.60 *	0.11 *	0.23	0.20	0.18	1.00 *						
eGovbuss	0.05 **	0.75 *	0.25 *	0.46 *	0.42 *	0.41 *	0.77 *	1.00 *					
eGovcit	−0.15 *	0.63 *	0.26 *	0.36 *	0.31 *	0.20 *	0.62 *	0.68 *	1.00 *				
TO	−0.58 *	0.03 *	0.23 *	−0.06 **	−0.04	−0.03 **	0.03	−0.04 *	−0.13 *	1.00 *			
WGI	0.12 ***	0.81 *	0.24 *	0.71 *	0.66 *	0.56 *	0.62 *	0.69 *	0.67 *	−0.19 *	1.00 *		
RD	0.26 *	0.30 **	0.02	0.34 **	0.31 ***	0.29 ***	0.02	0.20	−0.01	−0.42 *	0.38 *	1.00 *	
EnvReg	0.23 **	−0.43 **	−0.03	−0.32 *	−0.32 *	−0.34	−0.46 ***	−0.37 *	−0.38	0.15 *	−0.54 *	0.02	1.00 *

Note: *, **, and ***—statistical significance at 1%, 5%, and 10% respectively.

From an econometrics perspective, the initial step of the analysis focuses on assessing the stationarity of the panel data through the application of tests such as the Levin–Lin–Chu (LLC) [84], Im–Pesaran–Shin (IPS) [85], and augmented Dickey–Fuller (ADF) [86] tests. Subsequently, the presence of heteroscedasticity, indicating unequal variance among entities or time periods, was examined using the Breusch-Pagan test and White's test. Additionally, autocorrelation, which evaluates the correlation between observations at different time periods for the same entity, was investigated using the Durbin-Watson test. In cases where both autocorrelation and heteroscedasticity were identified, the panel corrected standard errors (PCSE) technique was employed to estimate the panel data model (1). To ensure the reliability of the empirical results, the feasible generalized least squares (FGLS) method was employed. FGLS allows for the control of fixed effects in the model, enhancing the accuracy and validity of the estimated coefficients.

4. Results

In the first stage, the study checks for the presence of a unit root among the selected variables. The results of the unit root test are shown in Table 3.

Table 3. The empirical results of the unit root test.

Test	Level	CO_2	DI	Size	e1	e2	e3	eGovke	eGovbuss	eGovcit
LLC	at level	−1.379	−10.007 *	3.537	2.069	1.303	1.804	0.6483	−17.107 *	−28.090 *
	the first difference	−4.639 *	−5.645 *	−2.531 *	−10.884 *	−7.099 *	−5.439 *	−11.820 *	−50.409 *	−55.476 *
IPS	at level	2.541	−4.506 *	8.032	2.404	1.606	2.454	2.011	−0.465	−0.932
	the first difference	−4.889 *	−7.301 *	−2.602 *	−5.411 *	−5.567 *	−5.572 *	−2.966 *	−2.174 **	−3.093 *
ADF	at level	−2.363	13.167 *	−1.456	1.421	0.691	5.237 *	1.084	0.947	0.635
	the first difference	9.525 *	19.261 *	18.572 *	32.594 *	36.071 *	28.547 *	4.621 *	5.321 *	10.398

Note: *, ** mean a statistical significance at 1% and 5% perceptively.

At the level, CO_2, Size, e1, e2, e3, and eGovke showed nonstationary behavior, as indicated by the IPS, LLC, and ADF tests. Additionally, the IPS test suggests stationarity for eGovbuss and eGovcit, while the LLC and ADF tests indicate non-stationarity. However, after taking the first difference, all variables exhibit stationarity based on the LLC, IPS, and ADF tests, with statistically significant test statistics. This implies that the variables become stationary when differences are made, indicating a stable long-run relationship.

The results from the Breusch-Pagan test and White's test indicate the presence of heteroscedasticity in the models (Table 4). All variables in the table exhibit statistically significant heteroscedasticity (p value < 0.05), as their probabilities are reported as 0.00 for both tests.

Table 4. Test for Heteroscedasticity.

Test	DI		Size		e1		e2		e3		eGovke		eGovbuss		eGovcit	
	Chi2	Prob.	chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.
Breusch-Pagan test	70.88	0.00	58.12	0.00	18.38	0.00	18.65	0.00	15.22	0.00	15.64	0.00	17.61	0.00	25.04	0.00
White's test	247.44	0.00	170.87	0.00	125.22	0.00	123.44	0.00	119.10	0.00	136.57	0.00	135.91	0.00	132.24	0.00

The findings in Table 4 suggest that the assumption of constant variance across the observations is violated. Heteroscedasticity introduces biases in the estimated coefficients and renders the standard errors unreliable, potentially leading to incorrect inferences and hypothesis testing results. Therefore, it becomes crucial to address heteroscedasticity to obtain accurate statistical conclusions.

Table 5 reveals the results of the Durbin-Watson test for autocorrelation. Based on the results, all variables exhibit statistically significant autocorrelation (p value < 0.05), and their probabilities are reported as 0.00. The high chi2 test statistics indicate strong evidence of autocorrelation in the residuals for each variable.

Table 5. A Test for Autocorrelation.

Test	DI		Size		e1		e2		e3		eGovke		eGovbuss		eGovcit	
	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.	Chi2	Prob.
Durbin-Watson test	77.22	0.00	41.67	0.00	33.34	0.00	33.42	0.00	33.37	0.00	16.89	0.00	16.87	0.00	14.85	0.00

The results in Table 6 indicate that Digital Inclusion (DI) has a significant negative effect on CO_2 emissions (coefficient = −0.136, p value = 0.033). This finding suggests that when individuals and communities have greater access to digital technologies and resources, they can adopt more sustainable practices such as remote work, online shopping, and digital communication, thereby reducing the need for physical transportation and associated emissions. Similarly, the variables Size, e1, e2, and e3 also exhibit significant negative effects on CO_2 emissions. The percentage of the IT sector in GDP (Size) has a coefficient of −2.289 with a p value of 0.000, indicating that a larger IT sector relative to

GDP is associated with reduced emissions. Enterprises with e-commerce sales (e1) have a coefficient of −0.103 (p value = 0.391), while enterprises with e-commerce sales of at least 1% turnover (e2) have a coefficient of −0.080 (p value = 0.542). Moreover, enterprises with web sales (e3) show a coefficient of −0.266 (p value = 0.059). These results suggest that digital technologies enable businesses to operate more efficiently, optimize logistics and supply chains, and reduce the environmental footprint of their operations. The variables representing key enablers (eGovke) and digital public services for citizens (eGovcit) do not show significant effects on CO_2 emissions. The coefficients for these variables are not statistically significant at conventional levels (p values > 0.05). The absence of significant effects for key enablers and digital public services for citizens suggests that these factors may not have a direct impact on CO_2 emissions from the transport sector. However, it is important to emphasize that digital public services and key enablers contribute to overall digital development and societal well-being, which indirectly affect sustainability outcomes. At the same time, digital public services for businesses (eGovbuss) have a negative and significant impact on CO_2 emissions from the transport sector.

Table 6. Effects of digitalization on CO_2 emissions.

Variables	DI		Size		e1		e2		e3		eGovke		eGovbuss		eGovcit	
	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.	Coef.	Prob.
Digital	−0.136	0.033	−2.289	0.000	−0.103	0.391	−0.080	0.542	−0.266	0.059	0.054	0.194	−0.091	0.039	0.000	0.991
TO	−0.097	0.000	−0.048	0.027	−0.093	0.001	−0.095	0.000	−0.110	0.000	−0.111	0.000	−0.124	0.000	−0.104	0.000
WGI	2.145	0.306	−4.017	0.081	−7.057	0.003	−7.002	0.002	−4.665	0.023	−9.068	0.000	−8.487	0.000	−8.598	0.000
RD	0.047	0.000	0.049	0.000	0.049	0.000	0.049	0.000	0.049	0.000	0.057	0.000	0.056	0.000	0.056	0.000
EnvReg	0.649	0.684	3.444	0.021	4.634	0.119	4.496	0.128	5.114	0.089	5.957	0.014	7.277	0.004	5.501	0.014
const	33.996	0.000	28.107	0.000	30.359	0.000	30.323	0.000	31.019	0.000	30.203	0.000	28.718	0.000	32.944	0.000
Obs.	405		266		221		221		221		189		189		189	
R^2	0.77		0.80		0.92		0.91		0.92		0.79		0.79		0.81	
Wald chi2(5)	191.50		285.44		536.13		532.69		574.95		398.27		567.19		594.61	
Prob > chi2	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	

Note: R^2 stands for R-squared; Obs. means observations.

Furthermore, a negative effect of trade (TO) on CO_2 emissions highlights the potential of international trade to lead to more sustainable transport practices. Global trade allows for the exchange of goods and services across long distances, which can incentivize businesses to adopt greener transportation methods, optimize routes, and reduce emissions associated with international logistics. Governance efficiency (WGI) exhibits mixed results. Some components show significant negative effects on emissions, while others do not reach statistical significance. This suggests that effective governance frameworks and policies that promote sustainable transportation practices can contribute to reducing CO_2 emissions. However, it also highlights the complexity of governance and the need for targeted interventions in specific areas to achieve environmental goals. Overall, the coefficient for WGI is 2.145, with a p value of 0.306. Patents in environment-related technologies (RD) show significant positive effects on CO_2 emissions. The positive effects of patents on environment-related technologies (RD) indicate that technological innovation in environmental solutions may initially lead to increased emissions. This could be attributed to the development and adoption of new technologies that have not yet reached their full potential or have unintended consequences. However, it is important to consider the long-term benefits of such innovation in mitigating environmental challenges and achieving sustainability goals. Government expenditure on environmental protection (EnvReg) also shows mixed results. Some components display significant positive effects on emissions, while others do not. The coefficient for EnvReg is 0.649, with a p value of 0.684. These outputs demonstrated that the impact of government investments in environmental protection on CO_2 emissions may vary depending on the specific components and approaches. This underscores the need for effective policies, regulations, and investments that target emission reduction strategies and prioritize sustainable practices.

The results of the analysis on the nonlinear effect of digital public services on CO_2 emissions are presented in Table 7.

Table 7. Nonlinear effect of digital public services on CO_2 emissions.

Variables	eGovke		eGovcit	
	Coef.	**Prob.**	**Prob.**	**Coef.**
Digital	0.439	0.002	0.220	0.002
Digital^2	−0.004	0.001	−0.002	0.022
TO	−0.087	0.000	−0.085	0.000
WGI	−7.561	0.000	−9.896	0.000
RD	0.057	0.000	0.057	0.000
EnvReg	8.415	0.001	5.761	0.015
const	14.012	0.000	26.142	0.000
Obs.	189		189	
R^2	0.79		0.78	
Wald chi2(5)	815.33		881.44	
Prob > chi2	0.00		0.00	

Note: R^2 means R-squared; Observations are denoted as Obs.

The variable eGovke shows a coefficient of 0.439 (p value = 0.002), indicating a positive effect on emissions. Additionally, the squared term of eGovke has a coefficient of −0.004 (p value = 0.001), suggesting a diminishing effect as the variable increases. Similarly, for the variable eGovcit, the coefficient is 0.220 (p value = 0.002), indicating a positive effect, while the squared term (eGovcit2) has a coefficient of −0.002 (p value = 0.022), implying a diminishing effect. This nonlinear effect indicates that while initially the increase in digital public services may contribute to higher emissions, there is a point at which the effect starts to diminish. It is possible that beyond a certain level of digital public service provision, the associated efficiencies and optimization measures will start to offset the emissions, resulting in a decrease in overall emissions.

The results from the FGLS analyses (Table 8) affirm the findings of the PCSE analysis presented in Table 7. Specifically, all Digital variables examined in the analysis show significant and negative effects on CO_2 emissions.

Table 8. The results of FGLS analyses.

Variables	DI		Size		e1		e2		e3		eGovke		eGovbuss		eGovcit	
	Coef.	**Prob.**	**Coef.**	**Prob.**	**Coef.**	**Prob.**	**Coef.**	**Prob.**	**Coef.**	**Prob.**	**Coef.**	**Prob.**	**Coef.**	**Prob.**	**Coef.**	**Prob.**
Digital	−0.027	0.032	−1.199	0.047	−0.303	0.016	−0.376	0.001	−0.525	0.002	0.579	0.000	0.493	0.000	0.406	0.085
Digital^2	-	-	-	-	-	-	-	-	-	-	−0.005	0.000	−0.005	0.000	−0.005	−0.008
TO	−0.082	0.000	−0.066	0.000	−0.062	0.002	−0.064	0.001	−0.057	0.004	−0.060	0.000	−0.076	0.000	−0.043	−0.073
WGI	−0.725	0.537	−1.303	0.323	−5.757	0.015	−5.640	0.012	−6.268	0.002	−10.088	0.000	−4.657	0.019	−2.515	−7.133
RD	0.054	0.000	0.054	0.000	0.055	0.000	0.055	0.000	0.056	0.000	0.057	0.000	0.056	0.000	0.057	0.051
EnvReg	8.968	0.000	11.481	0.000	14.866	0.357	15.004	0.263	14.345	0.000	11.019	0.000	9.050	0.000	9.694	5.285
const	17.581	0.000	16.276	0.000	19.752	0.000	20.870	0.000	20.130	0.000	7.740	0.015	8.699	0.005	5.094	−3.599
Obs.	405		266		221		221		221		189		189		189	

Note: Obs.—observations.

These findings suggest that the adoption and integration of digitalization can contribute to reducing CO_2 emissions in the transport sector. The consistency between the results of the FGLS and PCSE analyses strengthens the reliability of the findings, further supporting the conclusion that ICTs play a crucial role in mitigating CO_2 emissions.

5. Discussion & Conclusions

The paper aims to indicate the features of digitalization's impact on environmental sustainability, which is measured by carbon dioxide emissions. Digitalization is measured within three core dimensions: digital inclusion, the input of the IT sector to GDP, e-governance, and e-commerce. Based on the results of the FGLS technique, it is confirmed that digital inclusion, the input of the IT sector to GDP, and e-commerce have direct negative and statistically significant linear effects on carbon dioxide emissions. Growth of digital inclusion, input of the IT sector to GDP, and enterprises with web sales by one point allow for declining CO_2 emissions by 0.136, 2.289, and 0.266, respectively. However, key enablers and digital public services for citizens have a nonlinear, statistically significant impact on carbon dioxide emissions. In the early stages of adopting digital technologies in the transport sector, there is often an increase in energy consumption and carbon emissions, which has been confirmed in previous studies [39,87]. Additionally, the increased convenience and accessibility provided by digital technologies can lead to behavioral changes that result in higher energy consumption, such as increased use of electronic devices or the growth of data centers. However, as digital technologies continue to advance and mature, they can also contribute to reducing carbon dioxide emissions in the transport sector through various mechanisms. Advanced digital technologies enable the implementation of intelligent transportation systems [6,9,39]. These systems optimize traffic flow, reduce congestion, and minimize unnecessary idling, resulting in improved fuel efficiency and reduced emissions [47,49,50]. Furthermore, digital technologies play a vital role in the growth of electric vehicles. They support the development of efficient charging infrastructure, battery management systems, and vehicle-to-grid integration, all of which contribute to the widespread adoption of electric vehicles and the subsequent reduction of emissions from transportation. Digital platforms and applications facilitate the integration of various transportation modes, enabling seamless multimodal travel and promoting shared mobility options. Encouraging more efficient and sustainable transportation choices could reduce the overall carbon footprint of the transport sector. Digital technologies enable the collection and analysis of vast amounts of data related to transport operations. These data can be used to optimize logistics, routing, and fleet management, leading to reduced fuel consumption and emissions. Considering the findings above, the following policy recommendation could be outlined:

The EU countries should catalyze policies to incentivize the adoption of electric vehicles and other low-carbon vehicle technologies. This can include providing financial incentives such as subsidies or tax credits for purchasing electric vehicles, investing in charging infrastructure development, and establishing supportive regulations that encourage the use of low-carbon vehicles [88,89].

It is necessary to direct funding for research and development initiatives focused on advancing information technologies in the transport sector. This can include supporting projects related to intelligent transportation systems, vehicle electrification, and data-driven optimization to accelerate the deployment of sustainable and efficient transport solutions [90,91].

EU policymakers should prioritize the development of smart charging infrastructure to support the growing number of electric vehicles. This includes investing in fast-charging stations, implementing standardized charging protocols, and integrating renewable energy sources into the charging network [92,93]. Smart charging infrastructure enables optimized charging patterns, load balancing, and the integration of renewable energy, contributing to reduced CO_2 emissions [92,93].

Governments need to facilitate data sharing and collaboration among transport stakeholders, including public authorities, private companies, and research institutions. Open data policies and frameworks are conducive to sharing transport-related data, which could be utilized to develop innovative solutions, improve traffic management, optimize logistics, and support informed decision-making to reduce emissions.

It is necessary to increase the efficacy of low-carbon public transportation systems by investing in public transit infrastructure, improving service quality, and integrating information technologies to enhance accessibility and efficiency. Considering past studies [94,95], promoting shared mobility options, such as ridesharing and bike sharing, reduces individual vehicle use and emissions.

The EU countries should boost public awareness of the environmental impacts of transportation and the benefits of adopting low-carbon alternatives within green marketing instruments. Encouraging behavior change, such as promoting eco-driving practices, using public transportation, or telecommuting, can contribute to reducing CO_2 emissions in the transport sector.

6. Limitation and Further Directions for Investigation

Despite the valuable findings of this research, there are some deficiencies. The study focuses specifically on the EU countries, which limits the options for comparison and implication of the results obtained in other world regions. The analysis might not capture the influence of all relevant variables that can affect carbon dioxide emissions in the transportation sector. Factors such as fuel efficiency, vehicle technology, infrastructure development, and behavioral patterns could be important but not fully addressed in the study.

Furthermore, the time period (2006–2020) may not fully capture the impact of digitalization on CO_2 emissions, missing important technological changes and the influence of financial crises. It overlooks recent global financial implications and their potential indirect effects on digitalization and CO_2 emissions. Rebound effects and the potential for increased consumption or other activities are not explored. The study does not analyze the distributional impacts of digitalization on CO_2 emissions, which can vary across countries, economies, and income groups. Moreover, the convenience provided by digital technologies can make travel easier, leading to a potential rise in congestion on roads and transportation systems. Additionally, the increased demand for goods and services facilitated by digital technologies can contribute to higher emissions. The ease of accessing and purchasing goods online may lead to an increase in consumer demand, resulting in increased emissions from the production and transportation of goods and services. Furthermore, digital technologies can give rise to new forms of pollution, such as e-waste. If not properly processed and recycled, e-waste can pollute the environment or be exported to third countries, perpetuating the problem.

Considering the studies [96–100], the efficacy of government plays a crucial role in the performance of information technology and its incorporation into the transport sector. This study applied the integrated index, WGI. However, it is necessary to outline the impact of each dimension of WGI (corruption, voice and accountability, regulation quality, rule of law, and political stability).

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