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RESEARCH ARTICLE

Investigating the links between ICTs, passenger transportation, and environmental sustainability

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Abstract
This paper investigates linkages between ICTs, passenger transportation, and environmental sustainability with regard to a panel dataset of 46 countries over the years 1998–2016. Telephone and internet penetration are employed to measure ICTs, while environmental damages are proxied in terms of three different indicators related to carbon emissions coming from different sources. The empirical methodology employs the 2-step system Generalized Method of Moments (GMM) with the consideration of two empirical specifications: without and with conditioning variables (per capita GDP growth, urbanization, and energy consumption). The findings show that the association between ICTs and passenger transportation activity can positively affect environmental sustainability with regard to carbon emission reductions. Second, the adoption of the telephone in the road transport sector is more efficient than the internet in reducing carbon emissions. Third, internet connectivity is better employed in the air and rail passenger sectors. Public policies and their effective implementations are discussed.

Keywords ICTs · Passenger transport · Sustainable transportation · Environmental quality · GMM

Introduction

The transport system is essential in facilitating economic growth and development, but it generally incurs egregious environmental impacts due to reliance on non-renewable energy sources (i.e., fossil fuels) (Santos 2017; Chatti et al. 2019). In 2016, transportation accounted for 30% of greenhouse gas emissions (GHGs) in the European Union, of which road transport contributed 72% (International Energy Agency 2016). Managing transport sector-related emissions has become a global challenge in the contemporary world, requiring innovative solutions on the industrial, national, and global levels. On the most fundamental level, reform entails replacing fossil fuels to the extent possible, and making conventional operations more efficient (with reduced waste and emissions). In this regard, ICTs are of importance in initiating and implementing innovative solutions in the transport sector to manage transport-related emissions.

ICTs directly influence global CO_2 emissions, but there are both positive and negative impacts of new technologies on environmental quality. ICT penetration in the economic system can improve the environment by supporting smart cities, green transport systems, modern logistics systems, and energy usage efficiency (Plepys 2002; Lashkarizadeh and Salatin 2012; Majeed 2018; Zhang and Liu 2015; Lu 2018; Ozcan and Apergis 2018; Chatti 2020; Ahmed and Le 2021; Ahmad and Majeed 2021; Li et al. 2021; Sahoo et al. 2021). Contrary to the positive effects, ICTs can damage the environment by increasing the production of devices, enhancing the use of ICT-related equipment, and producing ICT-related waste (Liu et al. 2006; Houghton 2015; Salahuddin et al. 2016; Avom et al. 2020; Alataş 2021).

To our knowledge, no prior study has linked ICTs and passenger transport with environmental quality. Existing studies mainly focus on green practices and the latest technologies used by the industrial and services sector (Wang et al. 2015), but ignore the role of ICTs in managing environmental quality (Centobelli et al. 2020; Chatti 2020). Besides, the prior studies have mainly focused on road transportation,

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ignoring the role of other transport modes in triggering air pollution such as transportation through air, rail, and sea. The present research aims to address the following research questions: (1) Do ICTs support environmental sustainability? (2) Does the influence of ICTs on CO_2 emissions vary across different measures of ICTs and sources of CO_2 emissions? (3) Do different measures of ICTs mediate the impact of different modes of passenger transportation on CO_2 emissions?

Given the above premises, this study explores the effects of ICTs and passenger transportation on the environment using a panel dataset of 46 national economies from 1998 to 2016. This research extends the existing works in five key areas. First, this study examines the effects of ICTs on CO_2 emissions using alternative measures of ICTs. Second, this study employs different modes of transport systems to explore their effects on diverse sources of emissions. Third, this study explores the mediating role of ICTs in explaining the emissions' effects of different modes of passenger transportation. Fourth, this study considers the issue of potential endogeneity between emissions and the transport sector. Finally, the study offers appropriate policy recommendations to preserve environmental quality in both developed and developing economies.

Literature review

The literature on ICTs and environmental sustainability has been proliferating in recent years owing to its implications for all spheres of human life; this is driven by global and national climate commitments, which are reflected in national policies, and the importance of both ICTs and sustainability for long-term economic performance (Niebel 2018; Majeed and Ayub 2018; Majeed 2020). ICTs have penetrated almost all activities of human life, including environmental concerns, but their relationship with environmental sustainability has not received commensurate attention. Theoretically, there are both positive and negative implications of using technology for the environment. On the one hand, growing new technologies disrupt ecological systems by boosting production activity, spreading ICTs applications, and generating waste. For example, when ICTs are manufactured using fossil fuels and electronic waste is mismanaged, environmental quality tends to deteriorate (OECD 2010; Houghton 2015; Majeed 2018). On the other hand, ICTs also help to alleviate the environmental impacts of traditional activities they replace, as well as intrinsically by increasing information related to environmental preservation and boosting environmentally friendly technologies (Plepys 2002; Lashkarizadeh and Salatin 2012; Lu 2018; Chatti 2020).

Furthermore, ICTs create a dematerialization impact, namely "a shift from delivering physical products to delivering services" (Majeed 2018). For example, paper and physical modes of communication are transited towards online communication using ICTs such as telephone and the internet. Likewise, vehicle mobility can be decreased by ICT-enabled communication, thereby reducing GHG emissions due to decreasing physical travel. In addition, ICTs provide smart and automated solutions, such as energy creation, digitization, and smart municipalities.

The empirical literature can be classified into three strands. The first strand demonstrates positive environmental impacts; the second suggests detrimental environmental impacts; and the third suggests conditional impacts of ICTs on the environment. Lashkarizadeh and Salatin (2012) found a favorable role of ICTs on environmental sustainability for 43 countries, and Zhang and Liu (2015) documented a similar effect for China over the period 2000–2010. However, these studies represented ICTs with electronic goods, which is a rather broad measure.

Ozcan and Apergis (2018) also showed the favorable impact of ICTs on the environment employing data for 20 developing economies over the period 1990–2015. Similarly, Lu (2018) confirmed the environmental caring role of ICTs for Asian economies covering the period from 1993 to 2013. Using annual data over the period 1996–2017 for ASEAN-6, Ahmed and Le (2021) showed the favorable effect of ICT on environmental sustainability. These studies establish an empirical link between ICTs and environmental sustainability; however, they cover a small group of countries, rely on a single measure of the ICTs, and also ignore the indirect effects of ICTs on environmental sustainability. Sahoo et al. (2021) showed that ICT measured by the internet and mobile phone penetration helped mitigate carbon emissions in India between 1990 and 2018.

Contrary to these studies, the second strand of the literature represents the environmentally damaging impacts of new technologies. For instance, Liu et al. (2006) showed environmental damaging effects of electronic waste in China. Considering OECD countries over the period 1991–2012, Salahuddin et al. (2016) also exhibited the environmentally harmful effects of ICTs. Similarly, Avom et al. (2020) have shown some negative consequences of ICT for Sub-Sahara African countries, suggesting that ICTs increase emissions directly and indirectly by increasing energy consumption. Alataş (2021) showed that ICTs negatively affect the environment using a set of 93 countries over the period 1995–2016.

The third strand of the empirical studies presents conditional effects of new technologies on sustainability. For example, Hilty et al. (2006) considered "rebound effects" associated with ICTs that can have diverse effects on the environment. ICTs improve energy efficiency in end-user activities, but on the macro scale they can ultimately increase energy demand, burdening the environment. Thus, the short-run environmental benefits of the ICTs can be counterbalanced in the long run. First-level rebound effects increase e-waste, the second-level effects increase energy efficiency, and the third-level effects suggest the transition from products to services.

Higón et al. (2017) explored the association between ICTs with sustainability employing a global data set of 142 countries over the period 1995–2010. They viewed the ICT-sustainability relationship as an inverted U-shape, whereby the favorable effects of ICTs require a certain threshold level of deployment of ICTs. Initially, ICTs can damage the environment by increasing the production of devices, ICT-related equipment, and ICTs waste management issues. Later on, ICTs can improve the environment by supporting smart municipalities, transport systems, logistic system efficiency, and energy usage efficiency. Their empirical findings show that many developed economies have attained the required level of ICTs whereas many developing economies are operating below this threshold level.

Majeed (2018) demonstrated that the sustainability effects of ICTs vary across developed and developing countries using a sample of 128 economies from 1980 to 2016, whereby environmentally friendly effects of ICTs are limited to the developed world, while the developing world experiences environmentally damaging impacts. Similarly, Danish et al. (2018) also explored the interaction between ICTs and the environment considering the effects of ICTs through GDP for a sample of emerging economies from 1990 to 2015. Their findings suggest that ICTs, GDP, and financial sector growth escalate emissions. However, the interactive effect of ICT with GDP is environmentally supporting.

For the African case, an empirical examination by Asongu et al. (2019) showed that ICTs in the form of mobile phones and internet penetration increase CO_2 emissions, and they exhibited that the interactive effects of ICT with trade and FDI mitigate CO_2 emissions. For G7 countries, Raheem et al. (2020) indicated that ICTs increase emissions, but the interactive effect of ICT and FDI decreases them. Chatti (2020) reported that ICTs can decrease the adverse effects of freight transport on the environment using a panel of 43 economies between 2002 and 2014. Using the data over the period 1995–2018, Chien et al. (2021) showed that ICT lowers emissions only at lower quantiles of emissions. Using a sample of 58 developing countries during the timeframe 1990–2014, N'dri et al. (2021) showed that ICTs have a favorable effect on relatively low-income developing countries, and negligible effects in the case of relatively high-income developing countries.

Following the above-discussed literature, it can be inferred that existing works show conflicting confirmation on the association between ICTs and sustainability. Besides, the literature suggests that linear effects of ICTs can be misleading, as their effects change depending upon ICT penetration levels, samples, methodologies, and time periods analyzed. To our knowledge, the role of ICTs through different modes of transportation systems is overlooked in the existing literature. Against this backdrop, this study explores the direct as well as indirect effects of ICTs on CO_2 emissions over the period 1998–2016.

Empirical methods

The main objective of this study is to explore whether new technologies interact with passenger transportation in order to improve environmental conditions with regard to pollution reduction. To this end, we utilize balanced panel data during the time period between 1998 and 2016. The chosen set of economies and time frame are motivated by the availability of data. Environmental degradation is measured using three variables: CO_2 emissions from transport, CO_2 emissions from energy use, and CO_2 emissions per capita. ICTs are indexed in terms of telephone and internet penetration. Tables 1 and 2 report the study variables and descriptive statistics, and Table 3 shows the correlation matrix. The multicollinearity problem seems to be less relevant when employing interactive estimators (Brambor et al. 2006).

To investigate the relationships between ICTs, passenger transportation, and environmental quality, the dynamic 2-step system GMM technique was used for four reasons. First, the number of groups is larger than the covered period used in the estimate. More precisely, the number of countries (N) across all models exceeds the number of years (T) (1998–2016, or 19 years). Second, the dependent variables (CO_2liq, CO_2trans, and CO_2pc) appear to be persistent in all empirical specifications, with a coefficient of the first lag variable greater than 0.8. Third, the use of panel dataset in the estimates enables consideration of cross-sectional

Table 1 Variable definitions

Variables	Definitions	Sources
CO_2trans	CO_2 emissions from transport activity	WDI
CO_2pc	Per capita CO_2 emissions	WDI
CO_2liq	Carbon emissions from liquid fuel	WDI
INT	Internet penetration	WDI
TEL	Telephone penetration	WDI
GDPg	Per capita GDP growth rate	WDI
EC	Energy consumption	WDI
URB	Urban population	WDI
RdPT	Road passenger transport	OECD
RPT	Rail passenger transport	OECD
APT	Air passenger transport	OECD

Table 2 Summary statistics (1998–2016)

	Obs.	Mean	S.D.	Min.	Max.
CO_2trans	627	107.048	304.346	0.067	1807.712
CO_2pc	627	6.909	4.085	0.851	20.178
CO_2liq	627	166545.4	412385	407.037	2446414
INT	627	45.616	30.485	0.037	98.240
TEL	627	34.048	16.896	1.842	74.987
GDPg	627	3.191	4.503	−14.559	33.030
EC	627	9.423	23.025	0.075	138.935
URB	627	70.028	15.094	27.24	97.919
RdPT	627	528672.3	1681083	1013	1.75e+07
RPT	874	55604.98	174060.8	3.2	1257930
APT	741	4.44e+07	1.17e+08	11098	8.24e+08

differences. Fourth, the existence of eventual endogeneity, heterogeneity, and simultaneity issues can be solved through the GMM methodology (Asongu et al. 2019; Chatti and Khoj 2020).

The 2-step system GMM methodology of Roodman (2009) used in this study is considered to be an extended version of the earlier methodology of Arellano and Bover (1995). The advantage of adopting this empirical strategy is its ability to reduce the number of instruments and control for dependence across sections (Boateng et al. 2018). The 2-step GMM is presented through in the following two equations in level (1) and first difference (2).

$$\mathrm{LnCO2}_{i,t} = \alpha_0 + \alpha_1 \mathrm{LnCO2}_{i,t-r} + \alpha_2 \mathrm{LnPT}_{i,t} + \alpha_3 \mathrm{ICT}_{i,t} + \alpha_4 \mathrm{Ln(ICT.PT)}_{i,t} + \sum_{n=1}^{3} \delta_n W_{n,i,t-r} + \gamma_i + \mu_t + \varepsilon_{i,t} \quad (1)$$

$$LnCO2_{i,t} - LnCO2_{i,t-r} = \alpha_1 \left(\mathrm{LnCO2}_{i,t-r} - \mathrm{LnCO2}_{i,t-2r}\right) + \alpha_2 \left(\mathrm{LnPT}_{i,t} - \mathrm{LnPT}_{i,t-r}\right) + \alpha_3 \left(\mathrm{ICT}_{i,t} - \mathrm{ICT}_{i,t-r}\right) + \alpha_4 \left(\mathrm{LnICT.PT}_{i,t} - \mathrm{LnICT.PT}_{i,t-r}\right) + \sum_{n=1}^{3} \delta_n (W_{n,i,t-r} - W_{n,i,t-2r}) + (\mu_t - \mu_{t-r}) + \varepsilon_{i,t-r} \quad (2)$$

here $\ln CO2_{i,t}$ is the quantity of carbon emissions for country i at year t, α_0 is the constant, lnPT is the transport mode in million passenger-km, ICT indicates the technology adopted in each passenger transport sector,ln(ICT.PT) shows the interaction between communication technology and passenger transport dependent on transportation mode (i.e., road, rail, and air), W includes three control variables, r equals unity, μ_t is the time-specific constant, γ_i is the country effect, and $\varepsilon_{i,t}$ is the error term.

Results and discussion

Two specifications are introduced for each transport mode: without and with conditioning variables. Three empirical specifications are considered in relation to three dependent variables, and for each sub-specification, regressions were run using ICTs (i.e., telephone and internet penetration). Similar to other works, we employ the AR(2) test of Arellano and Bond (1991) and Hansen-*J* test. These tests are very important to ensure that the empirical strategy is appropriate.

Table 4 shows the links between ICT, road passenger transport, and environmental sustainability without control variables. Overall, the results indicate the negative effect of new technologies on the environment, especially when using

Table 3 Correlation matrix

	CO_2trans	CO_2pc	CO_2liq	INT	TEL	GDPg	EC	URB	RdPT
CO_2trans	1								
CO_2pc	0.490*** (0.000)	1							
CO_2liq	0.988*** (0.000)	0.447*** (0.000)	1						
INT	0.070* (0.077)	0.371*** (0.000)	0.024 (0.536)	1					
TEL	0.159*** (0.000)	0.493*** (0.000)	0.116*** (0.000)	0.440*** (0.000)	1				
GDPg	−0.032 (0.411)	−0.178*** (0.000)	−0.007 (0.856)	−0.385*** (0.000)	−0.246*** (0.000)	1			
EC	0.877*** (0.000)	0.361*** (0.000)	0.919*** (0.000)	−0.010*** (0.000)	0.033 (0.407)	0.072* (0.068)	1		
URB	0.053 (0.179)	0.521*** (0.000)	−0.007 (0.855)	0.506*** (0.000)	0.603*** (0.000)	−0.332*** (0.000)	−0.093** (0.018)	1	
RdPT	0.570*** (0.000)	0.112*** (0.000)	0.604*** (0.000)	−0.063 (0.110)	−0.100** (0.012)	0.022 (0.567)	0.504*** (0.000)	−0.249*** (0.000)	1

Standard errors in brackets. *$p<10\%$, **$p<5\%$, ***$p<1\%$

fixed telephone networks. This result is in perfect accordance with the existing literature (Fuchs 2008; Majeed 2018; Chatti 2020), and can be attributed to the increased electricity consumption necessary for running machines and equipment, in addition to the use of different networks and infrastructures (Wang et al. 2015). Moreover, the same negative effect can be shown when studying the relationship between road passenger activity and carbon emissions coming from both transport and liquid fuel consumption. A 10% increase in road passenger activity would amplify carbon emissions by 1–3.63%, thereby negatively affecting the environment. This is mainly due to traveling from homes to workplaces and other daily necessities for life (Chatti et al. 2019).

Only the interaction between ICT and road passenger transport seems to positively affect environmental quality with regard to CO_2 emission reductions. This effect is clearly shown with the use of fixed telephone networks rather than internet technology. More precisely, a 10% improvement in the association *TEL*RdPT* can mitigate environmental damages by between 1 and 2.87%, dependent on the origin of CO_2 emissions. The use of the telephone in road passenger transport appears to be the most efficient combination to reduce CO_2 emissions coming from liquid fuel consumption. This result is due to the fact that the use of the telephone enables users to reduce face-to-face contacts, thereby reducing demand for energy consumption (Fuchs 2008; Mckinnon 2010; Wang et al. 2015). From another point of view, it appears that internet technology is not really efficient when used in road passenger activity. The only significant and positive impact on the environment appears when considering the dependent variable CO_2liq.

Table 5 reports the association of ICTs and road transport with the environment by considering three control variables (i.e., *URB*, per capita *GDPg*, and *EC*). The results indicate the importance of the interaction between telephone technology and road passenger transport positively affecting environmental quality. Indeed, for the magnitudes of −0.046 and −0.228, a 10% rise in the association *TEL*RdPT* can reduce pollution by 0.46% and 2.28%, respectively. In the same context, internet technology seems to positively impact the environment when associated with road passenger transport. Empirically, a 10% rise in the combination *INT*RdPT* leads to a decrease in CO_2 emissions by between 0.41 and 1.29%. Moreover, the variables *GDPg* and *URB* positively affect CO_2 emissions while considering some empirical specifications. The finding on *GDPg* is in accordance with Ullah et al. (2021a), while the positive and significant effect of *URB* suggests a negative impact on the environment (Ullah et al. 2021a, b).

Table 6 reports the links between ICT, rail passenger transport, and environmental sustainability without control variables. Rail passenger transport and new technologies exert a negative effect on environmental quality. It should

Table 4 Links between ICTs, road passenger transport, and environmental sustainability

	Road passenger transport (RdPT)					
	Without control variables					
Dependent variable	CO_2 per capita		CO_2 from transport		CO_2 from liquid fuel	
	INT	TEL	INT	TEL	INT	TEL
Constant	0.713 (0.101)	0.740* (0.090)	−1.570*** (0.002)	0.306 (0.101)	0.057 (0.886)	0.639* (0.084)
Ln CO_2 (−1)	0.731*** (0.000)	0.645*** (0.000)	0.758*** (0.000)	0.998*** (0.000)	0.846*** (0.000)	0.918*** (0.000)
INT	0.001 (0.559)		0.0006 (0.652)		0.002 (0.243)	
TEL		0.009** (0.015)		0.001** (0.030)		0.009** (0.028)
Ln RdPT	0.109 (0.350)	0.136 (0.101)	0.247*** (0.002)	0.100*** (0.003)	0.299*** (0.002)	0.363*** (0.008)
Ln INT*RdPT	−0.105 (0.256)		−0.031 (0.502)		−0.129* (0.076)	
Ln TEL*RdPT		−0.136* (0.083)		−0.100*** (0.001)		−0.287*** (0.008)
AR (2)	(0.619)	(0.417)	(0.978)	(0.845)	(0.154)	(0.333)
Hansen test	(0.151)	(0.146)	(0.421)	(0.661)	(0.645)	(0.180)
Instruments	27	27	27	27	27	27
Countries	33	33	33	33	33	33
Obs.	594	594	594	594	594	594

Standard errors in brackets. *p<10%, **p<5%, ***p<1%

Table 5 Links between ICTs, road passenger transport, and environmental sustainability

	Road passenger transport (RdPT)					
	With control variables					
Dependent variable	CO_2 per capita		CO_2 from transport		CO_2 from liquid fuel	
	INT	TEL	INT	TEL	INT	TEL
Constant	0.113 (0.670)	−1.910 (0.183)	−0.063 (0.695)	−0.215 (0.451)	0.759* (0.099)	0.431 (0.302)
Ln CO_2 (−1)	0.967*** (0.000)	0.508*** (0.005)	0.970*** (0.000)	0.964*** (0.000)	0.896*** (0.000)	0.912*** (0.000)
INT	0.002 (0.157)		0.001* (0.082)		0.004 (0.1411)	
TEL		0.012* (0.085)		0.0009 (0.254)		0.007* (0.084)
Ln RdPT	0.070 (0.108)	0.101 (0.513)	0.044 (0.127)	0.076** (0.021)	0.193* (0.079)	0.301** (0.042)
Ln INT*RdPT	−0.067 (0.111)		−0.041** (0.037)		−0.144* (0.075)	
Ln TEL*RdPT		−0.019 (0.884)		−0.046** (0.011)		−0.228* (0.055)
GDPg	0.006** (0.015)	0.007*** (0.000)	0.006*** (0.000)	0.009*** (0.000)	0.002 (0.200)	0.002 (0.103)
URB	0.0001 (0.952)	0.020*** (0.003)	0.002 (0.141)	0.001* (0.083)	0.0005 (0.931)	0.002 (0.465)
EC	0.0001 (0.961)	0.0003 (0.919)	0.001 (0.521)	0.0004 (0.577)	0.001 (0.753)	0.001 (0.504)
AR(2)	(0.539)	(0.396)	(0.937)	(0.951)	(0.117)	(0.398)
Hansen test	(0.356)	(0.192)	(0.382)	(0.196)	(0.409)	(0.270)
Instruments	29	29	31	25	27	29
Countries	33	33	33	33	33	33
Obs.	594	594	594	594	594	594

Standard errors in brackets. *p<10%, **p<5%, ***p<1%

be noted that rail passenger activity seems to have a harmful effect on the environment compared to road passenger activity. The coefficients of 0.259, 0.620, and 0.637 indicate that a 10% rise in *RPT* can increase pollution by 2.59%, 6.20%, and 6.37%, respectively. This can be explained by the fact that users typically utilize more than one transport mode to reach their final destination by rail; consequently, while the adoption of ICTs in the rail transport sector itself may positively affect environmental quality, this is offset by the negative environmental impacts of ancillary modes of transportation used in conjunction with rail journeys (e.g., traveling by a fossil-fuel burning car to and from a railway station). Empirically speaking, a 10% development in the combination *TEL*RPT* can mitigate CO_2 emissions by 2.68–6%, thus enhancing environmental quality. The same positive effect on the environment can be shown using the internet technology in rail transport activity. The coefficients of −0.074, −0.112, and −0.154 show that a 10% rise in the association *INT*RPT* can reduce atmospheric pollution by 0.74%, 1.12%, and 1.54%, respectively. It is notable that telephone technology is more efficient than internet technology when interacting with rail passenger transport to improve environmental quality. This result is in accordance with literature regarding the positive environmental impact of telephone adoption in road freight transport (Chatti 2020) and rail freight transport (Chatti 2021) when associated with ICTs.

Table 7 reports the relationships between ICT, rail passenger transportation, and environmental quality with control variables. Overall, the findings report the same positive impact on CO_2 emissions when considering ICTs (i.e., telephone and internet), rail passenger activity, and *GDPg* in the estimations. These results are in accordance with those proposed by Chatti (2020), who found a similar positive effect on environmental damage. However, the results show a positive impact on environmental quality when using both telephone and internet in rail passenger transportation. Contrary to the last specification without control variables, the interaction *INT*RPT* seems to be more efficient in damping environmental damage than using telephone technology. This result confirms those proposed by Fuchs (2008), who highlighted the importance of avoiding some unnecessary traveling when using internet technology.

Table 6 Links between ICTs, rail passenger transport, and environmental sustainability

Dependent variable	Rail passenger transport (RPT)					
	Without control variables					
	CO_2 per capita		CO_2 from transport		CO_2 from liquid fuel	
	INT	TEL	INT	TEL	INT	TEL
Constant	0.142** (0.018)	0.739*** (0.000)	0.193*** (0.180)	1.301*** (0.008)	0.824*** (0.009)	1.554*** (0.003)
Ln CO_2 (−1)	0.974*** (0.000)	0.919*** (0.000)	0.921*** (0.000)	0.958*** (0.000)	0.952*** (0.000)	0.970*** (0.000)
INT	0.001 (0.244)		0.002 (0.153)		0.004*** (0.004)	
TEL		0.011*** (0.001)		0.017*** (0.009)		0.016** (0.015)
Ln RPT	0.085* (0.057)	0.259*** (0.006)	0.148* (0.098)	0.620*** (0.003)	0.150*** (0.009)	0.637*** (0.003)
Ln INT*RPT	−0.074* (0.071)		−0.112* (0.067)		−0.154*** (0.006)	
Ln TEL*RPT		−0.268*** (0.002)		−0.591*** (0.004)		−0.607*** (0.003)
AR(2)	(0.486)	(0.291)	(0.781)	(0.379)	(0.424)	(0.283)
Hansen test	(0.129)	(0.259)	(0.256)	(0.1116)	(0.371)	(0.206)
Instruments	27	29	27	29	27	29
Countries	46	46	46	46	46	46
Obs.	828	828	828	828	828	828

Standard errors in brackets. *p<10%, **p<5%, ***p<1%

Table 8 reports the empirical relationships between ICTs, air passenger transport, and environmental quality without control variables. The results show similar evidence to that found with respect to the other transportation modes (i.e., road and rail); it is very clear that telephone technology and air passenger transport negatively influence the environment. The coefficients of 0.151, 0.171, 0.159, and 0.220 show that a 10% rise in air transport activity extends atmospheric pollution by 1.51%, 1.71%, 1.59%, and 2.20%, respectively. On the other side, it appears that the use of both telephone and internet technologies in air passenger transport may positively improve environmental quality. For example, a 10% increase in the association *TEL*APT* is able to reduce CO_2 emissions by 0.6–1.68%. Also, it should be noted that the impact on environmental quality is larger when using cellphones rather than the internet. The positive effect of telephone and internet technologies on the environment was underlined in the context of the air transport sector in a recent study by Chatti (2021), which demonstrated that the implementation of new technologies in air transport can positively affect the environment. Nowadays, using the internet in the air transport sector is becoming crucial to generate innovative interaction and facilitate transactions at lower costs, without the need for physical face-to-face contacts. In the same context, the telephone plays an important role in decreasing pollution, since it reduces unnecessary household journeys.

When considering control variables in the estimates, Table 9 shows similar results about the undesirable effects of ICTs, per capita GDP growth, urbanization, and air passenger activity on the environment. The finding concerning per capita GDPg is in perfect harmony with the existing literature (Zhang and Lin 2012; Ahmad et al. 2021). In addition, urbanization negatively affects environmental quality. In fact, the urban concentration of activities for both firms and households in some medium and large cities increases urban costs, thus, negatively influencing the environment (Chatti et al. 2019; Ullah et al. 2021b). For instance, rapid urbanization boosts demand for a variety of goods and services, which can accelerate the demand for transport and industrialization (Danish et al. 2018).

However, the interaction between the internet and air passenger transport can positively affect environmental quality. This is due to the fact that rapid access and information exchange through the internet can enable customers to reduce search costs and increase their trading power. Indeed, internet technology can make firms more efficient, especially in the air transport sector (Agheli and Hashemi 2018; Molero et al. 2019; Chatti 2021). In other words, the use of the internet can enhance transaction efficiency due to the amelioration of decision-making. Moreover, it can provide a larger variety of services at lower costs, as a result of lowering distribution and inventory costs. Contrary to the previous specification without control variables, telephone

Table 7 Links between ICTs, rail passenger transport, and environmental sustainability

Dependent variable	Rail passenger transport (RPT)					
	With control variables					
	CO_2 per capita		CO_2 from transport		CO_2 from liquid fuel	
	INT	TEL	INT	TEL	INT	TEL
Constant	0.009 (0.933)	0.567*** (0.002)	−0.745 (0.525)	0.323 (0.269)	0.888 (0.167)	0.305 (0.343)
Ln CO_2 (−1)	0.950*** (0.000)	0.961*** (0.000)	0.908*** (0.000)	0.970*** (0.000)	0.890*** (0.000)	0.995*** (0.000)
INT	0.001 (0.241)		0.003 (0.134)		0.004** (0.017)	
TEL		0.008** (0.045)		0.004 (0.235)		0.004 (0.263)
Ln RPT	0.057* (0.087)	0.192** (0.035)	0.165 (0.134)	0.115 (0.290)	0.237 (0.117)	0.156* (0.099)
Ln INT*RPT	−0.051* (0.099)		−0.204*** (0.001)		−0.215** (0.026)	
Ln TEL*RPT		−0.210*** (0.011)		−0.117 (0.324)		−0.167* (0.053)
GDPg	0.007*** (0.000)	0.007* (0.096)	0.004*** (0.009)	0.006*** (0.000)	0.001 (0.358)	0.003*** (0.000)
URB	0.001 (0.489)	0.0005 (0.753)	0.026 (0.257)	0.0001 (0.972)	0.007 (0.126)	0.003 (0.482)
EC	0.0002 (0.468)	0.001 (0.628)	0.009 (0.297)	0.002 0.591)	0.005 (0.130)	0.0002 (0.836)
AR(2)	(0.404)	(0.319)	(0.581)	(0.766)	(0.351)	(0.961)
Hansen test	(0.261)	(0.428)	(0.292)	(0.122)	(0.221)	(0.197)
Instruments	41	29	21	33	25	35
Countries	46	46	46	46	46	46
Obs.	828	828	828	828	828	828

Standard errors in brackets. *p<10%, **p<5%, ***p<1%

Table 8 Links between ICTs, air passenger transport, and environmental sustainability

Dependent variable	Air passenger transport (APT)					
	Without control variables					
	CO_2 per capita		CO_2 from transport		CO_2 from liquid fuel	
	INT	TEL	INT	TEL	INT	TEL
Constant	−0.170 (0.593)	0.030 (0.847)	−0.865 (0.291)	0.565 (0.339)	−0.472 (0.119)	0.332* (0.060)
Ln CO_2 (−1)	0.901*** (0.000)	0.829*** (0.000)	0.910*** (0.000)	1.008*** (0.000)	0.881*** (0.000)	1.003*** (0.000)
INT	0.001 (0.100)		0.0006 (0.730)		0.0003 (0.887)	
TEL		0.005*** (0.010)		0.004** (0.020)		0.003 (0.102)
Ln APT	0.151*** (0.000)	0.086 (0.162)	0.171*** (0.001)	0.159* (0.070)	0.220*** (0.000)	0.148 (0.124)
Ln INT*APT	−0.111*** (0.000)		−0.082** (0.020)		−0.094** (0.042)	
Ln TEL*APT		−0.066 (0.253)		−0.168** (0.012)		−0.148* (0.074)
AR(2)	(0.519)	(0.331)	(0.674)	(0.608)	(0.486)	(0.719)
Hansen test	(0.146)	(0.281)	(0.315)	(0.296)	(0.483)	(0.308)
Instruments	27	27	29	27	29	27
Countries	39	39	39	39	39	39
Obs.	702	702	702	702	702	702

Standard errors in brackets. *p<10%, **p<5%, ***p<1%

Table 9 Links between ICTs, air passenger transport, and environmental sustainability

	Air passenger transport (APT)					
	With control variables					
Dependent variable	CO_2 per capita		CO_2 from transport		CO_2 from liquid fuel	
	INT	TEL	INT	TEL	INT	TEL
Constant	0.090 (0.604)	0.002 (0.992)	−0.361 (0.186)	0.220 (0.280)	0.234 (0.163)	0.171 (0.439)
Ln CO_2 (−1)	1.000*** (0.000)	0.872*** (0.000)	0.943*** (0.000)	0.994*** (0.000)	0.939*** (0.000)	0.991*** (0.000)
INT	0.0003 (0.774)		0.0001 (0.837)		0.0008 (0.493)	
TEL		0.003** (0.044)		0.002 (0.393)		0.0001 (0.954)
Ln APT	0.010 (0.794)	0.015 (0.698)	0.050** (0.041)	0.078 (0.337)	0.061* (0.083)	0.022 (0.653)
Ln INT*APT	−0.018 (0.609)		−0.024* (0.086)		−0.046* (0.053)	
Ln TEL*APT		−0.033 (0.471)		−0.084 (0.296)		−0.030 (0.495)
GDPg	0.005*** (0.060)	0.006*** (0.000)	0.006*** (0.000)	0.005*** (0.005)	0.003*** (0.007)	0.003*** (0.009)
URB	0.0006 (0.578)	0.006** (0.040)	0.002 (0.208)	0.001 (0.545)	0.003 (0.185)	0.001 (0.270)
EC	0.001 (0.318)	0.003 (0.267)	0.001 (0.411)	0.0003 (0.855)	0.003 (0.151)	0.001 (0.411)
AR(2)	(0.715)	(0.635)	(0.562)	(0.788)	(0.470)	(0.327)
Hansen test	(0.441)	(0.417)	(0.344)	(0.148)	(0.193)	(0.125)
Instruments	30	35	29	30	30	30
Countries	39	39	39	39	39	39
Obs.	702	702	702	702	702	702

Standard errors in brackets. *p<10%, **p<5%, ***p<1%

technology seems to have a positive but insignificant effect on environmental sustainability. This is due to the fact that travelers use the internet more than telephone technology for planning and booking their travels, thereby reducing commuting costs and energy consumption (Fuchs 2008; Gutierrez et al. 2009; Chatti 2021).

Concluding remarks

This study, based on a panel dataset of 46 countries during a time span from 1996 to 2016, explores the effects of growing ICTs on the association between passenger transportation and environmental degradation. It addresses the dearth of studies on the role of ICTs in explaining passenger transportation and environmental degradation nexus. Particularly, this study explores the influence of telephone and internet penetration as measures of ICTs on three different sources of environmental degradation. This study employs the 2-step system GMM considering two empirical models: without and with control variables (per capita GDP growth, urbanization, and energy consumption).

The empirical analysis reveals interesting outcomes. The deployment of new technologies mitigates carbon emissions. Comparatively, telephone technology has a stronger impact on environmental sustainability. In addition, its interactive effect with road passenger transport mitigates all types of emissions. This result is due to the fact that the use of the telephone enables users to reduce face-to-face contact, lowering the demand for energy consumption and transportation associated with traditional forms of communication. Rail passenger transport and new technologies exert a negative influence on the environment, but the interactive effect of rail passenger transport and new technologies turns out to be favorable for the environment. This finding suggests that ICT usage in rail transportation can alleviate environmental burdens of rail travel. Telephone technology seems to be relatively more efficient than internet technology when interacting with rail passenger transport for environmental preservation, and the results for air passenger transport show similar evidence. Overall, we can conclude that ICTs can help to conserve environmental quality by influencing different modes of transportation systems. ICTs alleviate pressure on energy consumption and transport-related activities by minimizing the need for physical visits. Besides ICTs help to acquire travel information, use planning tools, share transport modes, work from home, evaluate transport mode costs, and pay online.

This study offers the following policy implications: ICT infrastructure needs to be enhanced in passenger transport activity, as its interactive role is conducive for environmental sustainability. Following the empirical outcomes, the study suggests that fixed telephone networks need to be enhanced for road passenger transport, while internet technology needs to be implemented more comprehensively in the air and passenger sectors. To enhance internet penetration, the affordability and deployment of ICT infrastructure needs to be prioritized in related policies. Moreover, internet policy needs to be tailored in such a way that its adoption, access, interactions, and reach effects are escalated. ICTs integration into the transport sector in the form of transport-sharing applications, smart traffic controls, intelligent vehicle monitoring, eco-driving, and navigation software can help to manage green and sustainable transportation. Thus, the empirical findings suggest that facilitating and supporting investment in ICTs, particularly in the transport sector, can alleviate environmental impacts. This research is limited to the analysis of ICTs and environmental sustainability with regard to the transport sector. Future studies can explore the role of ICTs through other contexts such as smart urbanization. Moreover, future research can also provide a comparative analysis for developed and developing economies.

Author contribution Walid Chatti proposed the main idea, elaborated the empirical methodology, and wrote the paper. Muhammad Tariq Majeed analyzed the data and wrote the paper.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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