



# Investigating the impact of ICT on transport-based CO<sub>2</sub> emissions: empirical evidence from a quantile cointegration regression analysis

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## Abstract

In the global initiative to leverage information and communication technologies (ICT) for reducing emissions, sub-Saharan Africa (SSA), a region of unique significance, has exhibited a delay in adopting ICT. This study aims to investigate the intricate relationship between ICT and carbon dioxide (CO<sub>2</sub>) emissions from transport in SSA. Employing the panel quantile autoregressive distributed lag (PQARDL) technique, the study analyzes panel data from 24 SSA nations spanning from 2000 to 2021. The results indicate that internet usage and fixed telephone subscriptions have a mitigating effect on CO<sub>2</sub> emissions from transport across all quantiles in both the short and long run. However, mobile phone subscriptions contribute to CO<sub>2</sub> emissions from transport across all quantiles. Additionally, the middle-income groups demonstrate negative relationships between ICT variables and emissions from transport, while the low-income group exhibits significant positive associations. These findings imply that ICT plays a pivotal role in mitigating transport-based emissions and reveal pronounced disparities in ICT adoption across various income groups within SSA, highlighting overarching underdevelopment in ICT infrastructure. Robustness checks employing a two-step system generalized method of moment (GMM) model reinforce our findings. The study provides policy recommendations, including the promotion of ICT infrastructure development, implementation of smart transportation solutions, and fostering public-private partnerships to address these challenges, shedding light on the path toward a greener and more sustainable transport ecosystem in SSA.

**Keywords** ICT · CO<sub>2</sub> emission from transport · Panel quantile autoregressive distributed lag · Sub-Saharan Africa

## Introduction

ICT has become an integral component of contemporary society, revolutionizing work, communication, and daily life. Recognized as a vital tool in mitigating global carbon dioxide (CO<sub>2</sub>) emissions, ICT holds significant potential in sub-Saharan Africa (SSA), where the transportation sector is rapidly expanding alongside economic growth (Jahanger and Usman 2022). Transportation is a major contributor to CO<sub>2</sub> emissions worldwide, and SSA is no exception. The African Development Bank (AfDB) reports that the transportation

industry is responsible for approximately 14% of Africa's total CO<sub>2</sub> output, with road transport being the primary culprit (African Development Bank 2012). By leveraging ICT-based solutions, it is possible to reduce CO<sub>2</sub> emissions in SSA's transport sector by promoting sustainable transportation modes, facilitating the adoption of low-emission vehicles, and enhancing traffic management systems.

In recent years, both the private and public sectors have made substantial investments in ICT infrastructure across Africa to enhance connectivity, stimulate economic growth, and improve social services. Consequently, the continent has experienced notable growth in internet accessibility, mobile phone penetration, and e-commerce, among other areas. However, transportation remains a significant bottleneck for economic development as it heavily relies on fossil fuels and contributes significantly to CO<sub>2</sub> emissions. According to the United Nations Environment Programme (UNEP), road transport accounts for about 24% of global carbon dioxide emissions. In SSA, the situation is even worse, with

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transport contributing up to 40% of CO<sub>2</sub> emissions in certain countries (UNEP 2021).

Despite the increasing concern over climate change and the imperative for sustainable development in Africa, there is a dearth of research examining the influence of ICT on CO<sub>2</sub> output from transportation in the region. While many studies have looked into how ICTs affect our carbon footprint and general energy use (Asongu et al. 2018; Atsu et al. 2021; Avom et al. 2020; Danish et al. 2018), limited to no research has focused specifically on transportation in the region (Kwakwa et al. 2023). Because transportation is so important to Africa's economic and social development, this knowledge gap is especially problematic because it undermines efforts to incorporate sustainable practices and reduce CO<sub>2</sub> emissions.

There are several compelling reasons for our research. First off, significant economic growth and CO<sub>2</sub> emissions are both a result of the transportation sector's rapid expansion in SSA (Saboori et al. 2014). Addressing this issue is critical for achieving sustainability and combating climate change. Therefore, the motivation for this study is grounded in the urgent need to understand the relationship between ICT and transportation-based carbon emissions in SSA. The transportation sector's unique challenges in the region, including heavy reliance on fossil fuels, make it imperative to investigate the role of ICT in reducing CO<sub>2</sub> emissions in this context. By focusing on this specific aspect, our research provides insights into an underexplored area and offers a foundation for developing targeted policies. Furthermore, the policy relevance of our research lies in its potential to inform policymakers and decision-makers in SSA about the environmental impact of ICT in the region, particularly in the context of transportation. Understanding this impact is vital for crafting effective strategies to reduce CO<sub>2</sub> emissions, promote sustainable transportation modes, and enhance traffic management systems. In essence, our research aims to bridge the gap between the expansion of ICT infrastructure and its potential to drive sustainable transportation practices, ultimately benefiting both the environment and economic development in SSA.

Transport-related emissions are indeed of paramount importance when it comes to deep decarbonization, and this significance is particularly critical for SSA countries. Transport is a significant contributor to global CO<sub>2</sub> emissions. According to the UNEP, it accounts for approximately 24% of global CO<sub>2</sub> emissions (UNEP 2021). This makes it a crucial sector to target for emission reduction to combat climate change effectively. Given its substantial emission footprint, achieving deep decarbonization is nearly impossible without addressing emissions from the transport sector. The transport sector is central to economic development and social well-being. It enables the movement of goods and people, supports trade, and provides access to essential

services. However, if left unchecked, the emissions associated with transportation can have detrimental effects on both the environment and public health (De Blas et al. 2020).

The unique criticality of transport-related emissions in SSA lies in several key factors. Many SSA countries are experiencing rapid economic growth and urbanization, which often leads to increased demand for transportation. Without sustainable practices, this growth can result in a significant rise in emissions. SSA's transportation sector heavily relies on fossil fuels, which are a major source of CO<sub>2</sub> emissions. Promoting sustainable alternatives is essential for both emission reduction and energy security (Bogdanov et al. 2021). SSA is particularly vulnerable to the impacts of climate change, including extreme weather events and shifts in agricultural patterns. Reducing transport-related emissions is not only a global responsibility but also essential for the region's resilience and adaptation (Frumkin and Haines 2019).

The relationship between ICT and transport-related emissions is multifaceted, with ICT playing a pivotal role in promoting sustainable transportation modes, low-emission vehicles, efficient traffic management, and reducing the need for physical commuting (Julsrud and Standal 2023). Addressing transport-related emissions in SSA is not only environmentally necessary but also essential for sustainable development and climate resilience in the region. The relationship between ICT and transport-related emissions can be understood through several channels: promoting sustainable transportation modes, adopting low-emission vehicles, enhancing traffic management, and remote work and virtual meetings. ICT can facilitate the use of more sustainable transportation modes, such as public transit, cycling, and carpooling. Ride-sharing apps, for instance, can optimize routes and reduce the number of individual car trips, thereby cutting emissions. ICT can encourage the adoption of low-emission and electric vehicles. It provides data and infrastructure for electric vehicle charging stations and supports the development of smart transportation systems that optimize energy use (Golinska-Dawson and Sethanan 2023). Smart city and traffic management systems, powered by ICT, can reduce congestion and idling, which are major contributors to emissions (Guo et al. 2023). Real-time traffic data and intelligent traffic signals can help improve the flow of traffic and reduce emissions. ICT enables remote work and virtual meetings, reducing the need for commuting. This can lead to decreased emissions associated with daily travel to work.

This study holds several significant implications. The first benefit is that it will help policymakers and decision-makers in the SSA region understand the environmental impact of ICT in the region by investigating the connection between ICT and carbon dioxide emissions from transportation. Secondly, it will offer insights into the potential of ICT to enhance transportation sustainability and reduce carbon

footprints in Africa. Lastly, it will address the research gap in this domain, establishing a foundation for future studies.

What sets our study apart from previous research is its specific focus on the relationship between ICT and transport-related CO<sub>2</sub> emissions in SSA. While previous studies have examined the broader impact of ICT on carbon emissions in the region, our research focuses on transportation emissions, which are responsible for approximately 14% of Africa's total CO<sub>2</sub> output, according to the African Development Bank (2012). This targeted approach allows us to investigate how ICT can be harnessed to reduce emissions in a sector critical to SSA's economic and social development. Additionally, our research goes beyond a general analysis of SSA by providing detailed quantile findings for different sub-regions within SSA based on their income group. This is because the income levels of countries impact their ICT and transportation infrastructural development levels, which in turn impact emissions. The novel PQARDL approach allows us to identify the varying effects of ICT on transportation-related CO<sub>2</sub> emissions across different quantiles, enabling governments to formulate scientifically informed and efficient policies tailored to specific regional needs.

The next sections will be organized as follows: The second part provides a comprehensive review of the relevant literature. In the third section, we explain the methods used and provide descriptive statistics for the data we analyzed. The major results and in-depth discussion are presented in “[Results and discussion](#)” section. Finally, the fifth and concluding section summarizes the study and highlights pertinent policy implications derived from the findings.

## Literature review

ICT has emerged as a transformative force across various sectors worldwide. In the context of SSA, a region experiencing rapid urbanization and economic growth, the transportation sector is a significant contributor to CO<sub>2</sub> emissions (African Development Bank 2012). This literature review and analysis looks at how ICT might affect CO<sub>2</sub> emissions from transportation. It does this by drawing on empirical evidence from previous research on the link between ICT and CO<sub>2</sub> emissions from transportation. The discussion is structured around key theoretical frameworks and empirical findings to elucidate the complex dynamics between ICT adoption, transportation, and emission reduction.

## Theoretical framework

This theoretical analysis looks at the theories that explain how this relationship works, as well as the main ways that ICT can affect emissions in this specific situation. The initial part of this literature predominantly revolves

around the well-known Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework, initially introduced by Dietz and Rosa (1997). STIRPAT serves as a fundamental tool for probing critical facets of environmental pollution, offering varying degrees of elasticity among its model variables.

The STIRPAT framework provides a theoretical foundation for understanding the complex relationship between environmental impact, particularly transport-based CO<sub>2</sub> emissions, and various driving forces, especially technology (Dietz and Rosa 1997). In SSA, where rapid urbanization and economic growth are making transportation emissions worse, this analysis uses the STIRPAT framework to look at the role of ICT as a technological driver in reducing or making these emissions worse.

The population component within STIRPAT refers to the number of people who influence environmental impacts. In SSA, population growth is a prominent feature. The link between population and emissions in this context is complex. A larger population may lead to more transportation needs, potentially increasing emissions. However, the role of ICT in influencing population density through enabling telecommuting, e-commerce, and remote work can reduce the need for commuting and, therefore, emissions (Fuchs 2008; Malmudin and Bergmark 2015). The adoption and integration of ICT in transportation infrastructure can reduce CO<sub>2</sub> emissions in SSA by optimizing traffic management, promoting shared mobility solutions, and facilitating the transition to electric vehicles. This, in turn, can promote a shift toward EVs, which emit fewer greenhouse gases, aligning with the concept of sustainable innovation (Rogers 2010).

Affluence represents economic factors that affect emissions. In SSA, rising incomes are driving increased vehicle ownership and fuel consumption, leading to higher emissions. However, ICT can affect affluence in two ways: by promoting economic growth through the digital economy and by facilitating more efficient resource allocation in transportation, thereby reducing emissions (Koutroumpis 2009). ICT-enabled economic growth can lead to increased affluence in SSA, potentially driving up emissions due to greater vehicle ownership and fuel consumption. However, this effect may be mitigated if ICT simultaneously promotes sustainable transportation practices and eco-friendly technologies. The theory of planned behavior suggests that attitudes, perceived norms, and perceived behavioral control influence individual intentions and behaviors. In the context of eco-driving applications, ICT can influence driver attitudes and norms by providing real-time feedback on fuel-efficient driving behaviors. This feedback loop can potentially lead to a shift in driver behavior towards eco-friendly practices, reflecting the application of behavioral theories to promoting sustainability (Ajzen 1991).

The technology component encompasses various factors, including ICT. Within the STIRPAT framework, technology can either amplify or mitigate emissions. ICT innovations such as intelligent transportation systems (ITS), ride-sharing platforms, and electric vehicle adoption can substantially reduce emissions by optimizing transportation efficiency (Lv and Shang 2022; Zhao et al. 2022). The adoption of ITS involves the integration of ICT to enhance the efficiency of transportation networks. Drawing from the theory of system integration, it is plausible that ICT-enabled real-time traffic monitoring, smart traffic signals, and vehicle-to-infrastructure communication systems can optimize traffic flow, thus reducing congestion and minimizing fuel wastage. This aligns with the resource-efficiency perspective, where ICT acts as a catalyst for more efficient resource allocation, ultimately leading to emission reduction (Brynjolfsson and McAfee 2014).

While the theoretical foundations support the potential impact of ICT on reducing transport-based CO<sub>2</sub> emissions in SSA, several challenges need addressing. The digital divide, rooted in digital inequality theory, emphasizes disparities in access to and use of ICT. Addressing this divide in SSA is paramount to ensuring equitable access to emission-reducing technologies (DiMaggio and Hargittai 2001). The choice of energy sources for powering ICT infrastructure is crucial. The sociotechnical system theory emphasizes the interconnectedness of technology and societal aspects. In SSA, transitioning to cleaner and more sustainable energy sources is essential to maximizing the emission reduction potential of ICT (Geels 2002).

Numerous research efforts have utilized the STIRPAT framework as a powerful analytical tool to investigate the intricate interplay among environmental, technological, and economic factors. These studies have explored a wide spectrum of variables, including but not limited to CO<sub>2</sub> emissions, energy consumption, economic output, urbanization, GDP, renewable energy usage, and transportation patterns (Dinda 2005; Huang et al. 2020; Jiang et al. 2022; Li et al. 2021; Li and Lin 2015; Ulucak et al. 2021; Usman and Hammar 2021; Wu et al. 2021). These investigations have leveraged the STIRPAT framework to delve into the multifaceted relationships among these critical elements, shedding light on the complex dynamics that underpin environmental, technological, and economic interactions.

### ICT and CO<sub>2</sub> emission relations

Carbon dioxide emissions from transportation account for a sizable portion of the world's total, including sub-Saharan Africa. The region's transport industry accounts for approximately 14% of total energy-related CO<sub>2</sub> emissions (African Development Bank 2012). Challenges related to inefficient vehicles, inadequate infrastructure, and poor management

have raised concerns about the sustainability of transport (Okyerere et al. 2019). The second part of the literature review focuses on exploring the connection between ICT and CO<sub>2</sub> emissions.

Numerous studies have delved into the relationship between ICT and CO<sub>2</sub> emissions (Li and Zhang 2023). The prevailing consensus in much of this research suggests that ICT has a mitigating effect on CO<sub>2</sub> emissions (Islam et al. 2023; Islam and Rahaman 2023; Lu 2018; Shen et al. 2023; Zhang et al. 2022). However, it's worth noting that some studies have reported an opposite trend, indicating that ICT might, in certain cases, lead to increased CO<sub>2</sub> emissions (Batoool et al. 2022; Li et al. 2022b; Shabani and Shahnazi 2019). For instance, Ben Lahouel et al. (2022) analyzed the impact of ICT on CO<sub>2</sub> emissions in 16 MENA countries. According to their findings, advanced information and communication technologies not only mitigate environmental threats but also boost the overall quality of life in the region. In recent investigations conducted by Islam et al. (2023) and Islam and Rahaman (2023), it was revealed that ICT plays a significant role in reducing CO<sub>2</sub> emissions within the Gulf Cooperation Council economies. Asongu (2018) studied the impact of information and communication technologies and globalization on carbon dioxide emissions in 44 nations in sub-Saharan Africa. The study shed light on the potential of ICTs to alleviate the environmental impacts associated with globalization. Batoool et al. (2022) studied ICT adoption, energy consumption, and carbon dioxide emissions in South Africa and discovered a positive association between increased ICT use and higher CO<sub>2</sub> emissions.

Additionally, several research studies have identified that ICT has the potential to decrease CO<sub>2</sub> emissions originating from the transportation sector (Acheampong et al. 2022; Alataş 2022; Erdoğan et al. 2020; Global e-Sustainability Initiative (GeSI) and Accenture Strategy 2015). For example, Acheampong and Asabere (2022) conducted a study on Ghana's transport sector and found that the adoption of ICT solutions such as ride-sharing as well as ITS could potentially reduce CO<sub>2</sub> emissions by up to 60%. The study emphasized the importance of supportive policy frameworks, public-private partnerships, and stakeholder involvement in implementing ICT solutions. Baptista et al. (2012) evaluated the environmental advantages and costs of using ICT technologies in Lisbon's transportation networks. The research found that ICT solutions, in their different application options, may significantly cut down on emissions and energy use in the transportation industry. Shabani and Shahnazi (2019) looked into factors like energy use, CO<sub>2</sub> emissions, ICT, and Iranian GDP. They found that the use of ICT in the transportation and service industries leads to a decrease in CO<sub>2</sub> emissions. In addition, they found that ICT and CO<sub>2</sub> emissions in the transportation sector are interconnected, causal factors with short-term effects. Similar findings by Coroama et al. (2012)



imply that ICT has the potential to reduce carbon dioxide emissions, particularly in the transportation sector. Gelenbe and Caseau (2015) made the argument that ICT could potentially contribute to reduced energy consumption in specific sectors, such as transportation. A study by Salahuddin et al. (2016) on OECD countries found that when car ownership decreased, CO<sub>2</sub> emissions decreased as well. However, Khan et al. (2020) found that the transportation sector increases CO<sub>2</sub> emissions.

Some studies have delved into the relationship between ICT and CO<sub>2</sub> emissions across diverse geographical regions (Oladunni and Olanrewaju 2022; Padayachi and Thambiran 2012; Xu and Lin 2018). For instance, Chen et al. (2019) conducted an investigation into the influence of ICT on CO<sub>2</sub> emission intensity at the provincial level in China. Their study spanned the years 2001 to 2016 and produced some intriguing findings. One noteworthy discovery was that Internet penetration exhibited a substantial negative impact on CO<sub>2</sub> emission intensity across various quantiles. Specifically, this negative effect was observed in all quantiles except the 0.1 quantile for China's eastern provinces. Moreover, the study revealed that Internet penetration had a significant negative effect on CO<sub>2</sub> emission intensity across all quantiles for China's central provinces. In contrast, there was no significant negative impact of Internet penetration on CO<sub>2</sub> emission intensity at any quantile for China's western provinces. This underscores the importance of considering regional variations when assessing the environmental impact of technological advancements like ICT.

Furthermore, limited research has investigated the connection between ICT and transport-based CO<sub>2</sub> emissions, specifically using the CO<sub>2</sub> emissions from transport variable (Xu and Lin 2016). Awan et al. (2022) investigated the nexus between transport sector-based carbon dioxide emissions, economic growth, innovation, and urbanization with balanced panel data from 33 high-income countries from 1996 to 2014 using a robust and novel quantile methodology. The results show that urbanization upsurges while technological innovation mitigates transport-based carbon dioxide emissions. This underscores the urgent necessity to investigate the impact of ICT on CO<sub>2</sub> emissions resulting from transportation. This research aims to precisely determine the extent of this influence and explore how ICT can effectively mitigate these emissions. This inquiry is particularly crucial for developing regions like SSA.

Moreover, multiple research studies have recognized that various economic factors, including GDP, energy consumption, FDI, gross fixed capital formation, and urban population, have an influence on CO<sub>2</sub> emissions (Abbas et al. 2020; Appiah et al. 2023; Islam 2021; Islam et al. 2023; Ngong et al. 2022; Wei et al. 2023). For instance, recent research by Islam and Rahaman (2023) illuminated that an increase in per capita GDP is associated with

heightened pollution, while higher energy consumption exacerbates carbon emissions. Lee and Zhao (2023) have put forward the notion that optimizing human capital potential, managing the transition to urbanization, and strategically harnessing FDI could play pivotal roles in advancing efforts to mitigate CO<sub>2</sub> emissions. Furthermore, the findings by Jalil et al. (2021) have revealed that an increase in gross fixed capital formation leads to a reduction in CO<sub>2</sub> emissions in Malaysia. Meanwhile, Ngong et al. (2022) have demonstrated that urbanization contributes to an increase in carbon emissions in the Central African Economic and Monetary Community.

According to the analyzed literature, ICT has tremendous potential to reduce CO<sub>2</sub> emissions in many different fields. However, the prevalence of contradictory findings regarding the effect of ICT on carbon dioxide emissions highlights the need for further research. There is a dearth of research into the relationship between ICT and the variable CO<sub>2</sub> emissions from transport, especially in SSA. This study aims to fill the gap by investigating the impact of information and communication technologies on carbon dioxide emissions from transport in the region. The panel quantile autoregressive distributed lag (PQARDL) model will be used as the statistical method to examine the relationship and also across different income groups. The development of sustainable and low-carbon mobility strategies in SSA can greatly benefit from a better understanding of the significance of ICT in lowering transport-related carbon dioxide emissions.

## Data and methodology

This research utilizes panel data from 24 different SSA nations, spanning the years 2000 to 2021. The data used in the analysis come from the World Bank's World Development Indicators (WDI) and were transformed using the natural logarithm to make them more manageable and avoid heteroscedasticity issues (World Bank 2023). The chosen time period was determined by the emergence of Africa's ICT advancements in the early 2000s, while the conclusion of the period was influenced by data unavailability. It is essential to acknowledge that the limited availability of more recent data represents a significant constraint in this study. Nevertheless, despite this inherent limitation, the primary aim of the study is to evaluate the impact of ICT on transport-related carbon dioxide emissions. Additionally, the study takes into account the income groups of the countries under examination, recognizing their potential impact. To achieve this, the entire sample is divided into three groups according to income level: upper-middle, lower-middle, and low-income groups (refer to Appendix Table 9).

## The employed variables

### Dependent variable

The CO<sub>2</sub> emission from transport (CO<sub>2</sub>) variable represents the carbon dioxide emissions resulting from transportation activities. It is commonly used as an indicator of environmental impact. This variable directly measures the carbon dioxide emissions resulting from transportation activities (Alshehry and Belloumi 2017; Awan et al. 2022).

### Independent variables

The mobile cellular subscription (MOBILE) variable indicates the number of people who have signed up for mobile phone service in a certain location. It reflects mobile telecommunication infrastructure and connectivity. Mobile technology plays a crucial role in enhancing communication and information sharing, which can influence transportation efficiency and potentially impact CO<sub>2</sub> emissions (Haseeb et al. 2019; Islam et al. 2023).

The individuals using the internet (INTERNET) variable indicate the percentage or number of individuals within a population who have internet accessibility and usage. It represents the level of internet penetration and digital connectivity. It is relevant as ICT, including internet usage, can facilitate the optimization of transport systems and the adoption of sustainable practices that may influence CO<sub>2</sub> emissions (Islam et al. 2023; Lee et al. 2022).

The fixed telephone subscription (FXTEL) variable measures the number of fixed telephone lines subscribed to a given area. It reflects the level of telecommunication infrastructure and connectivity. Telecommunication infrastructure can influence communication and coordination in the transport industry, potentially impacting CO<sub>2</sub> emissions (Islam et al. 2023; Shiu and Lam 2008; Wang and Lee 2022). While various ICT indicators like broadband subscriptions, social media engagement, and e-government readiness offer value, our selection of indicators was primarily guided by data accessibility and our intent to conduct a comprehensive yet straightforward analysis. This approach ensures the reliability and clarity of our results. It is worth noting that future research endeavors can consider incorporating additional indicators, contingent on data availability and the specific research objectives at hand. Nevertheless, our choice of these three indicators, justified by their widespread application and their pertinence to our investigation, serves the purpose of exploring the influence of ICT on CO<sub>2</sub> emissions stemming from transport effectively (Ben Lahouel et al. 2022; Islam et al. 2023; Kwakwa et al. 2023).

### Control variables

Energy use (EU). This variable represents energy usage in the transport industry in SSA. It helps to understand the energy requirements of transportation activities and their impact on CO<sub>2</sub> emissions (Adeleye et al. 2023; Armeanu et al. 2021).

Gross domestic product (GDP). This variable indicates the market economic worth of all finished products manufactured inside a country within a certain time frame. GDP is relevant as it reflects the state of economic activity, including the transport sector, which can be associated with CO<sub>2</sub> emissions. Many studies examine the relationship between GDP and various factors, including ICT (Adeleye et al. 2021; Zhang et al. 2022).

Foreign direct investment (FDI). This metric tracks the amount of money invested directly from overseas in a country in SSA. It reflects the extent to which foreign capital is invested in the region and can have implications for technological advancements and economic development, potentially influencing transport-based CO<sub>2</sub> emissions (Appiah et al. 2023; Borensztein et al. 1998).

Urban population (URBP): This statistic measures the share of the population that resides in urban centers across sub-Saharan Africa. It captures the level of urbanization, which has implications for transportation patterns, infrastructure development, and associated CO<sub>2</sub> emissions (Abdo et al. 2022).

Gross fixed capital formation (GFCF): This variable indicates the investment in physical assets, such as infrastructure and machinery, in SSA nations. It is a measure of the industry's commitment to new capital expenditures, which affects the transportation sector's productivity and environmental impact (Adeleye et al. 2021; Kibert 2016). This variable is only used for robustness checks.

The study proposes a hypothesis stating that ICT will negatively affect CO<sub>2</sub> emissions from transportation. As a result, it suggests that an increase in telephone subscriptions, mobile cellular subscriptions, and internet usage would be beneficial in reducing the overall effect of ICT on transport-based CO<sub>2</sub> emissions. Furthermore, ICT's impact on transport-based CO<sub>2</sub> emissions varies among different income groups. The study's variables and their respective sources are summarized in Table 1.

### Model specification

When investigating the key elements of environmental pollution, researchers typically rely on the IPAT model ( $I = P.A.T.$ ), developed by Ehrlich and Holdren (1971). However, there are limitations to this accounting equation due to its assumption of constant elasticity among model variables (Chontanawat 2019). Stochastic Impacts by Regression on

**Table 1** Variable description

Variables	Indicator	Measurement	Source
CO <sub>2</sub>	CO <sub>2</sub> emissions from transport	Percentage of total fuel combustion	WDI 2023
FXTTEL	Fixed telephone subscriptions	Sum of active number of analogue fixed telephone lines	WDI 2023
INTERNET	Internet usage	Percentage of population	WDI 2023
MOBILE	Mobile cellular subscriptions	Subscriptions to a public mobile telephone service	WDI 2023
EU	Energy use	Kg of oil equivalent per \$1000 GDP (constant 2017 PPP)	WDI 2023
GDP	Economic growth	Constant 2015 US\$	WDI 2023
FDI	Foreign direct investment	Net inflows (percentage of GDP)	WDI 2023
GFCF	Gross fixed capital formation	Percentage of GDP	WDI 2023
URBP	Urban population	Percentage of total population	WDI 2023

Population, Affluence, and Technology (STIRPAT) was proposed by Dietz and Rosa (1997) as a solution to these problems. Carbon emissions and other environmental metrics are just some of the many for which this model has become a popular theoretical framework (Hashmi and Alam 2019; Wu et al. 2021; Xiong et al. 2020). The equation below describes the STIRPAT model:

$$I_{it} = \alpha P_{it}^b A_{it}^c T_{it}^d e_{it}, \quad (1)$$

In this equation, the constant term is denoted by  $\alpha$ ,  $I$  represents the environmental pollution intensity,  $P$  represents population size,  $A$  represents, average economic affluence, while  $T$  shows technology index, and  $e$  represents the random error term. The subscripts  $i$  and  $t$  correspond to individual countries and time period, respectively. To address heteroscedasticity, the variables are logarithmically transformed. Consequently, Eq. (1) can be written as follows:

$$\ln I_{it} = \alpha + b \ln(P_{it}) + c \ln(A_{it}) + d \ln(T_{it}) + e_{it}, \quad (2)$$

where  $P$  represents the population (measured in thousands),  $A$  denotes economic development (measured in currency units) and  $T$  signifies technological progress. Therefore, equation (2) can be rewritten as follows:

$$\ln \text{CO}_{2it} = \alpha + b \ln(\text{URBP}_{it}) + c \ln(\text{GDP}_{it}) + d \ln(\text{ICT}_{it}) + e_{it}, \quad (3)$$

where CO<sub>2</sub> is carbon dioxide emissions from transport (in kilotons), GDP is economic growth (measured by GDP constant 2015 US\$), URBP is urban population, measured by percentage of total population), and ICT (as measured by mobile subscription, internet usage and fixed telephone subscription). ICT has been widely used to evaluate the correlation between technological development and CO<sub>2</sub> emissions (Batool et al. 2022; Zhang and Liu 2015). The constant is denoted by  $\alpha$ , and the disturbance term by  $e$ .

To gain a comprehensive understanding of the effect of ICT on transport-based CO<sub>2</sub> emissions, this study extends the STIRPAT model by incorporating several important

factors specific to sub-Saharan Africa's development. Firstly, sub-Saharan Africa is currently undergoing rapid urbanization, a phenomenon well documented in studies such as those by Hove et al. (2013). Rising household earnings are one effect of rapid urbanization and increased population mobility. Residents' increased purchasing power correlates to a rise in the number of cars in circulation. However, the high volume of cars on the road calls for a correspondingly high intake of fossil fuels like gasoline and diesel. So, urbanization is a factor in the model to see how it affects transportation-related carbon dioxide emissions. The STIRPAT also takes into account energy consumption, foreign direct investment, gross fixed capital formation, mobile cellular subscriptions, internet usage for ICT, and fixed telephone subscriptions. In order to examine how ICT affects CO<sub>2</sub> emissions from transportation, we have defined and documented all the variables we used in our investigation. The following econometric model is developed by expanding upon the STIRPAT model and the aforementioned analysis to examine the impact of ICT on CO<sub>2</sub> emissions from transport in SSA:

$$\begin{aligned} \ln \text{CO}_{2it} = & \alpha + \beta_1 \ln(\text{MOBILE}_{it}) + \beta_2 \ln(\text{INTERNET}_{it}) \\ & + \beta_3 \ln(\text{FXTTEL}_{it}) + \beta_4 \ln(\text{EU}_{it}) + \beta_5 \ln(\text{GDP}_{it}) \\ & + \beta_6 \ln(\text{FDI}_{it}) + \beta_7 \ln(\text{URBP}_{it}) + \varepsilon_{it}, \end{aligned} \quad (4)$$

where CO<sub>2</sub> represents carbon dioxide emissions from, MOBILE refers to mobile cellular subscriptions, INTERNET denotes individuals using the internet, FXTTEL represents fixed telephone subscriptions, EU denotes energy use, GDP represents economic growth, FDI denotes foreign direct investment, and URBP represents urban population.

### Panel quantile autoregressive distributed lag

The study employs a PQARDL model to investigate the connections between ICT and CO<sub>2</sub> emissions from transport at different levels of the dependent variable. This modeling

approach offers several advantages, including its robustness against non-normal errors and its ability to account for skewness, heterogeneity, and outliers in variables (Hashmi et al. 2022; Sahin and Sahin 2023). To examine the interaction between ICT and transport-based CO<sub>2</sub> emissions, we initially employ a standard OLS specification as a benchmark. However, we chose the PQARDL technique for its suitability in analyzing panel data, its capacity to address both heterogeneity and time dynamics, its ability to facilitate quantile estimation, and its alignment with the study’s objectives. Notably, this technique is particularly useful when dealing with variables that are integrated of order zero I (0) or one I (1), similar to the ARDL model (Hashmi et al. 2022). We present the PQARDL model in the following structure, following the recommendations of Appiah et al. (2023) and Sahin and Sahin (2023). In this investigation, we have employed the quantile autoregressive distributed lag (QARDL) model as proposed by Cho et al. (2015). The subsequent PQARDL models are built upon the standard OLS model depicted in equation (4).

$$\begin{aligned}
 Q\Delta CO2_{it} = & \alpha_{it}(\tau) + \sum_{i=1}^{q1} \theta_{it}(\tau)\Delta CO2_{it-1} + \sum_{i=1}^{q2} \beta_{it}(\tau)\Delta MOBILE_{it-1} \\
 & + \sum_{i=1}^{q3} \gamma_{it}(\tau)\Delta INTERNET_{it-1} + \sum_{i=1}^{q4} \delta_{it}(\tau)\Delta FXTEL_{it-1} \\
 & + \sum_{i=1}^{q5} \lambda_{it}(\tau)\Delta EU_{it-1} + \sum_{i=1}^{q6} \omega_{it}(\tau)\Delta GDP_{it-1} \\
 & + \sum_{i=1}^{q7} \varphi_{it}(\tau)\Delta FDI_{it-1} + \sum_{j=0}^{q8} \psi_{it}(\tau)\Delta URBP_{it-1} + \mathcal{E}_{it}
 \end{aligned}
 \tag{5}$$

The forthcoming calculations will entail determining the coefficients, which are denoted as ( $\beta$ ,  $\gamma$ ,  $\delta$ ,  $\lambda$ ,  $\omega$ ,  $\varphi$ , and  $\psi$ ). It is noteworthy to mention that the model mentioned earlier incorporates the error correction mechanism (ECM). Within this framework, the parameter  $\phi_{it}$  signifies the rate at which the system adjusts towards its equilibrium level. Furthermore, the dependent variable within the ECM model is denoted as CO<sub>2</sub>, and its specific formulation is as follows:

$$\begin{aligned}
 Q\Delta CO2_{it} = & \alpha_{it}(\tau) + \sum_{i=1}^{q1} \theta_{it}(\tau)\Delta CO2_{it-1} + \sum_{i=1}^{q2} \beta_{it}(\tau)\Delta MOBILE_{it-1} \\
 & + \sum_{i=1}^{q3} \gamma_{it}(\tau)\Delta INTERNET_{it-1} + \sum_{i=1}^{q4} \delta_{it}(\tau)\Delta FXTEL_{it-1} \\
 & + \sum_{i=1}^{q5} \lambda_{it}(\tau)\Delta EU_{it-1} + \sum_{i=1}^{q6} \omega_{it}(\tau)\Delta GDP_{it-1} \\
 & + \sum_{i=1}^{q7} \varphi_{it}(\tau)\Delta FDI_{it-1} + \sum_{j=0}^{q8} \psi_{it}(\tau)\Delta URBP_{it-1} \\
 & + \phi_{it}ECT_{it-1} + \mathcal{E}_{it}
 \end{aligned}
 \tag{6}$$

Next, we proceeded to analyze various quantiles in our empirical investigations, specifically focusing on the quantiles at the following levels: ( $\tau$ ) = 25th, 50th, 75th, and 90th to explore the complicated links between ICT and transport-based CO<sub>2</sub> emissions. Due to economic development and the rising movement of people, transportation in sub-Saharan Africa is undergoing significant expansion. Numerous researchers have used internet usage, mobile subscriptions, and telephone subscriptions to examine the impact of ICT developments on carbon dioxide emissions. (Khanal 2021; Kwakwa et al. 2023; Lee and Brahmastre 2014).

## Results and discussion

### Summary statistics, correlation, and multicollinearity analysis

In Table 2, you will find the summary statistics for all countries and income groups. When examining the indicators of interest, it is worth noting that the average CO<sub>2</sub> emissions from transport across the 24 countries amount to 47.354, with a standard deviation (std. dev.) of 20.178. The average values for mobile, internet, and FXTEL are 15 million, 13.272 million, and 399,000, respectively, across the region. Among income groups, low-income countries have the highest average CO<sub>2</sub> emissions from transport (52.342), compared to 51.012 in the lower middle-income group and upper-middle-income (31.592) countries. Upper-middle-income countries have the highest average fixed telephone subscriptions (26.747) and internet users (989,000), while lower-middle-income countries have the highest average mobile phone usage of 20 million. The average energy use for the 24 countries is 187.968, with the upper-middle-income group showing the lowest (116.266) and the low-income group showing the highest (281.949). The average GDP for all countries is US\$53.1 billion, with the low-income group having the lowest average GDP of US\$26.4 billion and the upper-middle-income group having the highest average of US\$70 billion. The mean foreign direct investment value is 3.667. The results reveal that the low-income group has the highest foreign direct investment with 5.386, and the lower-middle-income group recorded the lowest with 2.864. On average, gross fixed capital formation is higher in the low-income group at 24.871, which is higher than the sample average of 22.683. The lower-middle-income group recorded the lowest at 21.882. The full sample’s average urban population is 43,256. The upper-middle-income group recorded the highest urban population at 43,256, and the low-income group recorded the lowest at 30,402.

The pairwise correlation presented in Table 3 measures the relative association between the regressors and dependent variables. With the exception of the EU, the



**Table 2** Summary statistics

Variables	CO2	MOBILE	INTERNET	FXTEL	EU	GDP	FDI	GFCF	URBP
<i>Full sample</i>									
Observations	360	525	508	523	343	518	518	496	528
Mean	47.354	1.52E+07	13.272	399,000	187.968	5.31E+10	3.667	22.683	43.256
Std. dev.	20.178	2.71E+07	16.877	874,000	134.807	9.48E+10	5.705	8.675	15.892
Minimum	10.987	0	0.006	0	51.589	1.90E+09	– 18.918	2	14.74
Maximum	96.781	2.04E+08	73.5	4,960,000	673.844	5.18E+11	39.811	81.021	90.423
<i>Upper middle income (UMI)</i>									
Observations	75	110	110	110	75	110	110	110	110
Mean	31.592	1.28E+07	26.747	989,000	116.266	7.00E+10	3.344	22.178	58.81
Std. dev.	15.707	2.63E+07	23.237	1,710,000	57.839	1.20E+11	2.853	5.062	16.837
Minimum	10.987	82,000	1.216	18,498	56.007	5.61E+09	– 2.003	13.092	32.373
Maximum	61.847	1.00E+08	73.5	4,960,000	225.848	3.60E+11	11.208	35.695	90.423
<i>Lower middle income (LMI)</i>									
Observations	180	264	260	262	179	264	264	264	264
Mean	51.012	2.00E+07	11.495	256,000	171.283	6.06E+10	2.864	21.882	44.273
Std. dev.	21.62	3.24E+07	13.784	273,000	111.838	1.03E+11	5.727	9.755	11.847
Minimum	12.748	15,000	0.006	0	51.589	6.22E+09	– 18.918	2	19.892
Maximum	96.781	2.04E+08	68.2	1,690,000	527.957	5.18E+11	39.811	81.021	68.283
<i>Low income (LI)</i>									
Observations	105	151	138	151	89	144	144	122	154
Mean	52.342	8,610,000	5.878	217,000	281.949	2.64e+10	5.386	24.871	30.402
Std. dev.	14.071	1.19e+07	7.643	290,000	169.213	3.05e+10	6.848	8.457	9.204
Minimum	24.444	0	0.015	19,991	77.423	1.90e+09	– 2.545	39.456	14.74
Maximum	84.649	6.45e+07	34.984	1,250,000	673.844	1.00e+11	3.462	40.671	45.192

For example, 1.52E + 07 = 15,200,000,000.00

**Table 3** Correlation analysis and multicollinearity test results

Variables	CO2	MOBILE	INTERNET	FXTEL	EU	GDP	FDI	GFCF	URBP
CO2	1								
MOBILE	– 0.122*	1							
INTERNET	– 0.356***	0.642***	1						
FXTEL	– 0.559***	0.456***	0.397***	1					
EU	0.00427	0.106	– 0.288***	– 0.0510	1				
GDP	– 0.355***	0.578***	0.183**	0.686***	0.0471	1			
FDI	0.347***	0.0503	0.0410	– 0.294***	– 0.0443	– 0.175**	1		
GFCF	0.286***	0.122*	0.195***	– 0.0978	– 0.404***	0.0119	0.365***	1	
URBP	– 0.302***	0.137*	0.411***	0.0280	– 0.322***	0.133*	0.115	0.147*	1
<i>Variance inflation factor</i>									
VIF		3.996	3.915	2.893	1.655	3.711	1.315	1.488	1.559
1/VIF		0.25	0.255	0.346	0.604	0.269	0.761	0.672	0.641

\*\*\*, \*\*, and \* signifies  $p < 0.01$ ;  $p < 0.05$ ;  $p < 0.1$

regressors exhibit statistically significant relationships with transport-based CO<sub>2</sub> emissions, although the signs vary. Moreover, all the indicators for ICT have negative statistically significant correlations with transport-based CO<sub>2</sub> emissions, indicating that ICT helps reduce

transport-based emissions. When examining Table 3, no evidence of multicollinearity among the covariates is found, as all correlation coefficients are below 0.70. The table also provides the variance inflation factor (VIF) results, allowing us to examine multicollinearity

issues within regression models. Multicollinearity poses a challenge in regression analysis. To diagnose and identify multicollinearity, Dormann et al. (2013) proposed a strategy. Table 3 supports the proposition that there is no multicollinearity between the variables, as the VIF values are all far below 5. Hence, it can be inferred that these indicators are independent of each other and are expected to exert independent influences on transport-based CO<sub>2</sub> emissions.

### Unit root test

It is crucial to address the non-stationarity of economic variables by transforming them into stationary series to ensure appropriate regression analysis. Failure to do so can lead to biased parameter estimation. The first-order difference method is commonly used to achieve stationarity in non-stationary sequences. This study employs two well-known tests, namely, the Im-Pesaran-Shin (IPS) test and the Fisher-Augmented Dickey-Fuller (ADF) test, to accurately determine the variables’ stationarity (Dickey and Fuller 1979; Im et al. 2003).

Table 4 presents the findings of the unit root tests performed on the explanatory and explained variables. The results imply that non-stationarity is present in the level sequences of the majority of variables, which generally exhibit a unit root. Nevertheless, all variables show

stationary behavior when considering their first-order difference sequences.

### Cointegration test

We performed a cointegration test after determining the stationarity of each variable individually to assess whether there was a long-term relationship among the variables as a whole. Cointegration arises when the variables exhibit one or more shared unit roots (Darrat and Al-Sowaidi 2010), signifying a stable and lasting relationship. For this analysis, we employed the cointegration tests by Kao, Pedroni, and Westerlund, known for their effectiveness in identifying cointegration and estimating cointegrating vectors (Kao 1999; Pedroni 1999, 2004; Westerlund 2005). The results of the cointegration test are presented in Table 5. The results overwhelmingly reject the null hypothesis of no cointegration at a significance level of 1%, providing compelling evidence of cointegration relationships between the variables. This suggests that a long-run association exists among these variables.

### Normal distribution test

A normal distribution test was run for each variable used in the regression analysis to determine whether the sample data were normal. The normality of the variables (i.e., CO<sub>2</sub>, MOBILE, INTERNET, FXTEL, EU, GDP, FDI, GFCF, and URBP) was evaluated using both visualization and

**Table 4** Panel unit root test results

	Variables	IPS		Fisher-ADF	
		Level	First difference	Level	First difference
With trend	CO2	− 2.8142***	− 8.0166***	− 0.5082	− 10.6963***
	MOBILE	1.0079	− 9.7195***	− 4.1085***	− 13.9844***
	INTERNET	− 0.0300	− 8.1163***	− 0.1408	− 8.6225***
	FXTEL	0.5717	− 9.3246***	2.3518	− 11.0503***
	EU	− 1.7767**	− 7.7422***	2.0203	− 9.5384***
	GDP	2.2817	− 9.6693***	4.2389	− 10.8485***
	FDI	− 5.7477	− 15.7477***	− 4.1063	− 20.1986***
	GFCF	− 1.0914	− 9.5248***	1.5080	− 12.3845***
	URBP	4.5400	− 1.8745**	− 6.0911***	− 4.9972***
No trend	CO2	− 0.1108	− 7.5084***	0.0278	− 12.9793***
	MOBILE	− 13.2702***	− 6.4723***	− 25.9186***	− 9.5306***
	INTERNET	− 1.9942**	− 6.8566***	− 4.2940***	− 9.3075***
	FXTEL	0.9119	− 8.3838***	0.0601	− 12.9344***
	EU	0.7004	− 7.0597***	1.0091	− 11.5049***
	GDP	2.5828	− 7.5205***	0.4712	− 10.3645***
	FDI	− 4.2823	− 12.0469***	− 5.9613***	− 24.1844***
	GFCF	0.2824	− 8.9187***	0.5138	− 14.2966***
	URBP	2.4352	− 1.7833**	− 12.5366***	− 3.1873***

\*\*\*, \*\*, and \* signifies  $p < 0.01$ ;  $p < 0.05$ ;  $p < 0.1$

**Table 5** Panel cointegration results

Kao test		Pedroni test		Westerlund test	
Test	Statistics	Test	Statistics	Variance ratio	Statistics
Modified Dickey–Fuller $t$	– 1.9813**	Modified Phillips–Perron $t$	4.0346***	Some panels are cointegrated	– 2.6841***
Dickey–Fuller $t$	– 2.7182***	Phillips–Perron $t$	– 8.8538***	All panels are cointegrated	– 1.8609**
Augmented Dickey–Fuller $t$	– 1.5938*	Augmented Dickey–Fuller $t$	– 9.9083***		
Unadjusted modified Dickey–Fuller $t$	– 1.8735**	Modified variance ratio	– 2.7347***		
Unadjusted Dickey–Fuller $t$	– 2.6641***	Modified Phillips–Perron $t$	2.0271**		
		Phillips–Perron test	– 6.3583***		
		Augmented Dickey–Fuller $t$	– 7.8221***		

\*\*\*, \*\*, and \* signifies  $p < 0.01$ ;  $p < 0.05$ ;  $p < 0.1$

computational strategies. The graphical approach utilized various techniques, such as dot plots, histograms, box plots, stem-and-leaf plots, probability-probability (P-P) plots, and quantile-quantile (Q-Q) plots, to analyze and present the data visually. These graphical tools provide visual representations of the variable distributions. To check for normality in the data distribution for this investigation, the frequently used Q-Q plot was employed (see Fig. 1a–i). In the plot, the blue straight line represents the expected values for variables that follow a normal distribution.

Figure 1 unambiguously demonstrates that the recorded values for all variables stray from the linear trend represented by the blue line. This indicates that these variables do not follow a normal distribution, and the magnitude of the deviation has grown steadily over the past few years. It is important to note that economic variables often exhibit important information in their tail distributions, which cannot be fully captured by ordinary least squares (OLS) regression. This finding supports the appropriateness and validity of employing a quantile regression model for the empirical analysis, as suggested by (Angrist et al. 2006).

The robustness of any quantile regression results in the presence of non-normality in the sample data has been demonstrated in prior studies (Fusco et al. 2023; Lin and Xu 2018; Xu et al. 2017; Xu and Lin 2018). Therefore, it is imperative to conduct the normality test before performing the regression analysis to ensure the reliability of the subsequent estimations.

### Panel quantile autoregressive distributed lag results

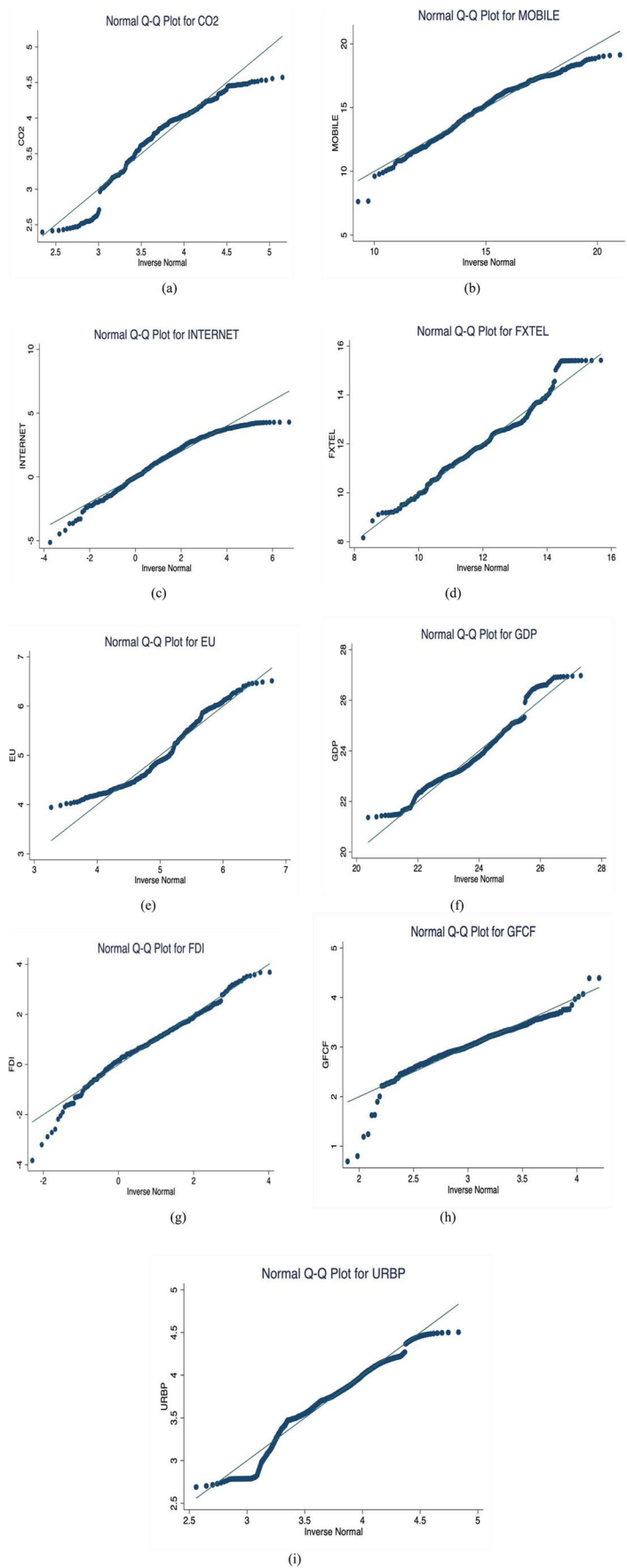
The novel PQARDL estimation serves as a potent model for comprehending the distribution of transport-related CO<sub>2</sub> emissions. Within this study, our emphasis lies on analyzing a PQARDL model for four distinct quantiles, namely, the 25th, 50th, 75th, and 90th percentiles. This section focuses specifically on the variables of interest, namely CO<sub>2</sub>

emissions from transport and ICT indicators. The following interpretations and discussions will mostly revolve around these two variables and their long-run estimates.

### Full sample results

In Table 6, you will find the results of the PQARDL analysis for the full sample, which examines the nexus between ICT (MOBILE, INTERNET, and FXTEL), and CO<sub>2</sub> emissions from transport in selected sub-Saharan African countries. In the selected sub-Saharan African countries, the impact of ICT is evident at all four quantiles (25th, 50th, 75th, and 90th) with a statistically significant negative effect for INTERNET (– 0.0570, – 0.295, – 0.327, and – 0.226) and FXTEL (– 0.279, – 0.138, – 0.0722, and – 0.0739) and a statistically significant positive effect for MOBILE (0.0735, 0.201, 0.211, and 0.169). This implies that a 1% increase in individuals using the internet and fixed telephone subscriptions reduces transport-based CO<sub>2</sub> emissions. Contrarily, a 1% decline in internet usage and telephone subscriptions results in an increase in CO<sub>2</sub> emissions from transport. The adoption of the internet and fixed telephone subscriptions can facilitate telecommuting, where individuals work from home or other remote locations. This reduces the need for daily commuting to work, which in turn reduces transportation-related CO<sub>2</sub> emissions. The findings support the results of Zhang and Liu (2015) who discovered that a 1% increase in the ICT industry decreases CO<sub>2</sub> emissions by 0.238%. Additionally, the findings are consistent with a recent study by Wang et al. (2023) that examined the effect of the internet economy on CO<sub>2</sub> emissions in China. The study revealed that a 1% increase in the internet economy index led to a 0.135% decrease in CO<sub>2</sub> emissions. The internet enables individuals to access various online services, such as online shopping, telemedicine, and virtual meetings. These services can reduce the need for physical travel, thereby lowering emissions associated with transportation. ICT can influence individual behavior and choices. For instance, the availability of ride-sharing apps and public transportation

**Fig. 1** The normal Q-Q plot of CO<sub>2</sub>, MOBILE, INTERNET, FXTEL, EU, GDP, FDI, GFCF, and URBP





**Table 6** PQARDL results for full sample

Variables	25th quantile	50th quantile	75th quantile	90th quantile	OLS
<i>Short run</i>					
MOBILE	0.0735*** (0.000994)	0.201*** (0.00215)	0.211*** (0.000106)	0.169*** (0.00116)	0.157*** (0.0221)
INTERNET	− 0.0570*** (0.000624)	− 0.295*** (0.00323)	− 0.327*** (0.000335)	− 0.226*** (0.00189)	− 0.180*** (0.0262)
FXTEL	− 0.279*** (0.000478)	− 0.138*** (0.00317)	− 0.0722*** (0.000561)	− 0.0739*** (0.00304)	− 0.150*** (0.0225)
EU	− 0.343*** (0.000867)	− 0.390*** (0.00290)	− 0.428*** (0.000803)	− 0.119*** (0.00255)	− 0.242*** (0.0440)
GDP	0.0395*** (0.00106)	− 0.209*** (0.00385)	− 0.237*** (0.00103)	− 0.137*** (0.00280)	− 0.110*** (0.0370)
FDI	0.0725*** (0.000221)	0.0943*** (0.00144)	0.0769*** (0.000333)	0.0378*** (0.00272)	0.0916*** (0.0188)
URBP	− 0.487*** (0.000549)	− 0.323*** (0.00446)	− 0.286*** (0.00129)	0.0268** (0.0113)	− 0.359*** (0.0669)
<i>Long run</i>					
CO2	− 1.081*** (0.00112)	− 1.282*** (0.00500)	− 1.236*** (0.000589)	− 1.113*** (0.00467)	
MOBILE	0.0841*** (0.000637)	0.299*** (0.00470)	0.274*** (0.000496)	0.176*** (0.00334)	
INTERNET	− 0.0755*** (0.00106)	− 0.350*** (0.00490)	− 0.357*** (0.000538)	− 0.232*** (0.00375)	
FXTEL	− 0.281*** (0.00113)	− 0.150*** (0.00304)	− 0.101*** (0.000990)	− 0.0665*** (0.00256)	
EU	− 0.306*** (0.00125)	− 0.525*** (0.00424)	− 0.536*** (0.000411)	− 0.0990*** (0.00394)	
GDP	0.0690*** (0.00115)	− 0.327*** (0.00560)	− 0.378*** (0.00136)	− 0.175*** (0.00394)	
FDI	− 0.0147*** (0.000406)	0.0825*** (0.00211)	0.0928*** (0.000356)	0.0767*** (0.00215)	
URBP	− 0.0917*** (0.000634)	− 0.510*** (0.00948)	− 0.548*** (0.00206)	− 0.0682*** (0.0225)	
Observations	262	262	262	262	313
R-squared					0.557
F statistics					59.71

\*\*\*, \*\*, and \* signifies  $p < 0.01$ ;  $p < 0.05$ ;  $p < 0.1$ . Standard errors in parentheses

information via the internet can encourage people to use more sustainable modes of transportation, such as carpooling or public transit (Ali Aden et al. 2022). It is possible that the adoption of ICT leads to changes in economic activities. For example, e-commerce enabled by the internet can change the way goods are distributed, potentially reducing the need for long-distance transportation and decreasing emissions (Circella and Mokhtarian 2017). Additionally, a 1% increase in mobile subscriptions increases CO<sub>2</sub> emissions from transportation. The use of mobile apps for ride-hailing services like Uber and Lyft may encourage more individual car trips. People might choose to use these services instead of public transportation or carpooling, leading to more carbon-intensive transportation options since ride-hailing vehicles are not always as fuel-efficient as public transit or shared rides. The convenience of mobile phones might encourage

behavior that is less environmentally friendly. For example, individuals might be more inclined to take last-minute trips or use transportation modes that are less energy-efficient because they can easily access transportation services and information via their mobile devices. The widespread availability of mobile phones can increase individual mobility (Aguilera et al. 2012; Nobis and Lenz 2009). People may be more likely to travel and commute when they have constant access to mobile communication and information services. This increased mobility can result in more trips and, consequently, higher emissions. This result is consistent with the findings of the Kwakwa et al. (2023) study on the relationship between ICT, transportation services, and CO<sub>2</sub> emissions. Their study revealed that mobile subscriptions have a positive effect on CO<sub>2</sub> emissions from transport. The results may be due to the fact that people tend to use their mobile

phones for travel-related activities like ride-hailing services and navigation, leading to more carbon-intensive transportation options. Also, higher mobile phone penetration tends to result in higher CO<sub>2</sub> emissions from transport, possibly due to increased mobile-dependent commuting and transportation behavior (Brazier 2021). There is also a significant negative connection between the EU and CO<sub>2</sub> emissions from transport on all quantiles, a positive significance between URBP and a mixed significant impact of FDI and GDP on transport-based CO<sub>2</sub> emissions at all quantile levels. In more urbanized areas, there is often better access to public transportation systems, which can reduce individual car usage and lower emissions. Urban areas may have more energy-efficient infrastructure and buildings, leading to reduced energy consumption and emissions per capita. Urban areas might have policies and incentives in place to encourage sustainable practices, such as clean energy adoption and waste reduction. The GDP result aligns with the environmental Kuznets curve hypothesis, which suggests that as economies grow and reach higher income levels, they tend to invest in cleaner technologies and shift away from highly polluting industries (Dinda 2005; Islam 2021; Islam and Rahaman 2023). This decline may result from the adoption of cleaner technologies, increased energy efficiency, and a shift toward less carbon-intensive industries. Foreign investors often bring in advanced technologies and best practices that can lead to more efficient and environmentally friendly production processes. Additionally, foreign investment can stimulate economic growth, as reflected in GDP, which, as mentioned earlier, can be associated with emission reduction at higher income levels. Lee and Zhao (2023) proposed that maximizing the potential of human capital, navigating the transition to urbanization, and strategically leveraging FDI could be instrumental in advancing efforts to reduce CO<sub>2</sub> emissions.

Interesting patterns emerge when looking at the connection between ICT factors and CO<sub>2</sub> emissions from transport in SSA. While internet and telephone subscriptions demonstrate an inverse relationship with CO<sub>2</sub> emissions, indicating that higher adoption of these technologies is associated with lower emissions, mobile subscriptions exhibit a direct relationship with CO<sub>2</sub> emissions. These findings highlight the significance of technological progress in ICT for reducing transport-related CO<sub>2</sub> emissions in SSA. Several research studies on ICT's ability to reduce CO<sub>2</sub> emissions support the findings (Lu 2018). These results highlight the complex and context-dependent nature of factors influencing CO<sub>2</sub> emissions. Different factors may have varying effects on emissions across different levels of quantiles, suggesting that the relationship between these factors and emissions is not uniform but depends on specific circumstances and stages of development. Overall, these findings underscore the importance of considering a range of socioeconomic and

environmental factors when analyzing CO<sub>2</sub> emissions and designing policies to mitigate them.

The last column of Table 6 includes the OLS estimates to facilitate comparison analysis. In Table 6, we observe that the impact coefficient of each variable on CO<sub>2</sub> emissions from transport differs across quantiles, but only the average is reported using the OLS approach. Quantile-wise, the impact of INTERNET size on CO<sub>2</sub> emissions from transportation is the largest (− 0.327) at the 75th percentile. The OLS-estimated coefficient is − 0.180, which exceeds the estimated values for FXTEL size on CO<sub>2</sub> emissions from transport in three quantiles. Similarly, FXTEL follows a similar pattern, where the OLS estimate (− 0.150) of FXTEL surpasses the PQARDL estimations for the 50th (− 0.138), 75th quantile (− 0.0722), and 90th (− 0.0739) quantiles but falls below the 25th quantile (− 0.279). Also, above the 50th, 75th, and 90th quantiles and below the 50th quantile among MOBILE estimated coefficients. By comparing these findings, it becomes evident that PQARDL offers a comprehensive understanding of the influences on transport-based CO<sub>2</sub> emissions across distinctive quantiles, while the OLS estimate merely represents the average impact. The PQARDL model proves to be a valuable tool for examining the impact of independent variables on transport-based CO<sub>2</sub> emissions due to the variations in their effects throughout the quantiles.

### Sub-sample results

The sub-sample findings are presented in Table 7, with transportation-related CO<sub>2</sub> emissions broken down by income level. The focus of the analysis revolves around examining the specific impacts of MOBILE, INTERNET, and FXTEL on emissions related to transportation. The results show that the INTERNET has a 1% positive influence at the 25th quantile (0.0125), and 50th quantile (0.0523) on transport-based CO<sub>2</sub> emissions in the upper middle-income group. However, INTERNET reduces transport-based CO<sub>2</sub> emissions in the upper middle-income group at the 75th (− 0.0189) and 90th (− 0.0113) quantiles. Moreover, with the exception of the 75th quantile, INTERNET has an inverse effect on emissions from transport in the lower middle-income group at 1% significant level. According to the results, a 1% upsurge in INTERNET will reduce transport-based CO<sub>2</sub> emissions by 25th (− 0.0522), 50th (− 0.0584), and 90th (− 0.0776). Higher internet adoption may enable more people to work from home and access online services, reducing the need for daily commuting and physical travel. Improved access to information about transportation options and real-time traffic updates through the internet can lead to more efficient transportation choices (Dal Fiore et al. 2014). There is a positive significant effect in the low-income group in the 25th (0.0809), 50th (0.0860), and 75th (0.0566) quantiles. In low-income countries, the energy generation often

Table 7 PQARDL results for sub-samples

Variables	Upper middle income			Lower middle income			Low income			
	25th quantile	50th quantile	90th quantile	25th quantile	50th quantile	90th quantile	25th quantile	50th quantile	90th quantile	
<i>Short run</i>										
MOBILE	0.135*** (0.00000977)	0.146*** (0.000772)	0.211*** (0.0000447)	0.192*** (1.16e-15)	0.104*** (0.000911)	0.116*** (0.000975)	0.0850*** (0.0100)	-0.0459*** (0.00430)	-0.0445*** (0.00106)	-0.0309*** (5.49e-17)
INTER-NET	0.00814*** (0.0000400)	0.0264*** (0.000574)	0.0200*** (0.0000260)	0.0401*** (2.80e-16)	-0.107*** (0.000968)	0.00886*** (0.000869)	-0.0991*** (0.0126)	0.0215*** (0.00374)	0.0242*** (0.000730)	-0.0000204*** (6.70e-17)
FXTEL	0.0498*** (0.00000553)	0.00705*** (0.0000929)	-0.0120*** (0.0000782)	-0.0390*** (6.81e-16)	-0.295*** (0.00114)	-0.288*** (0.000701)	-0.255*** (0.00930)	0.0226 (0.0145)	0.0492*** (0.00237)	0.0588*** (1.78e-16)
EU	-0.681*** (0.0000248)	-0.569*** (0.00180)	-0.250*** (0.000145)	-0.410*** (1.04e-15)	-0.262*** (0.00181)	-0.184*** (0.00263)	-0.193*** (0.0115)	0.321*** (0.0330)	0.482*** (0.0182)	0.348*** (9.16e-16)
GDP	-0.190*** (0.0000219)	-0.259*** (0.00181)	-0.458*** (0.0000614)	-0.369*** (1.20e-15)	0.0162*** (0.00219)	-0.144*** (0.00318)	-0.197*** (0.0150)	-0.0380 (0.0312)	0.153*** (0.0141)	0.0166*** (6.15e-16)
FDI	-0.0253*** (0.0000207)	-0.0106*** (0.000217)	-0.0409*** (0.000153)	0.00390*** (7.01e-17)	0.00135 (0.000755)	0.0538*** (0.000821)	0.0395*** (0.00810)	-0.0321*** (0.00242)	-0.0227*** (0.0000835)	-0.0105*** (3.32e-17)
URBP	0.214*** (0.0000234)	0.237*** (0.000256)	0.0603*** (0.000320)	0.294*** (3.59e-15)	0.0186*** (0.00297)	0.0717*** (0.000576)	0.0959*** (0.0249)	-0.695*** (0.0638)	-0.677*** (0.0312)	-0.367*** (1.37e-15)
GFCF	0.343*** (0.00000891)	0.254*** (0.000927)	0.230*** (0.000259)	0.208*** (9.35e-16)	0.525*** (0.000734)	0.146*** (0.00318)	0.238*** (0.0100)	0.00504 (0.0158)	0.0233*** (0.00107)	-0.0371*** (2.44e-16)
<i>Long run</i>										
ICO2log	-0.848*** (0.0000270)	-1.035*** (0.00182)	-0.924*** (0.000463)	-1.046*** (2.54e-15)	-1.434*** (0.000743)	-1.286*** (0.00228)	-1.416*** (0.0195)	-1.456*** (0.115)	-0.972*** (0.00351)	-0.876*** (1.26e-15)
MOBILE	0.0390*** (0.00000546)	0.0564*** (0.000327)	0.117*** (0.0000454)	0.157*** (1.07e-15)	0.0646*** (0.000877)	0.0391*** (0.000909)	0.113*** (0.0129)	0.157*** (0.0184)	0.0702*** (0.00101)	0.0948*** (1.25e-16)
INTER-NET	0.0125*** (0.00000293)	0.0523*** (0.000360)	-0.0189*** (0.0000410)	-0.0113*** (4.13e-16)	-0.0522*** (0.000991)	0.0136*** (0.00167)	-0.0776*** (0.0157)	0.0809*** (0.0132)	0.0860*** (0.00144)	0.0566*** (2.61e-16)
FXTEL	0.00437*** (0.00000822)	-0.0800*** (0.000664)	-0.0954*** (0.0000505)	-0.212*** (1.18e-15)	-0.197*** (0.000836)	-0.188*** (0.00186)	-0.144*** (0.0107)	-0.0708 (0.0466)	0.00493 (0.00750)	0.0379*** (4.80e-16)
EU	-0.179*** (0.0000288)	-0.155*** (0.00231)	0.0908*** (0.0000742)	-0.283*** (1.51e-15)	-0.361*** (0.00294)	-0.474*** (0.00422)	-0.458*** (0.0279)	0.226*** (0.0498)	0.305*** (0.0195)	0.118*** (1.38e-15)
GDP	-0.215*** (0.0000111)	-0.383*** (0.00105)	-0.361*** (0.0000653)	-0.691*** (1.24e-15)	-0.0798*** (0.00249)	-0.296*** (0.00347)	-0.457*** (0.0175)	-0.0836 (0.0644)	0.266*** (0.0207)	0.116*** (1.09e-15)
FDI	-0.0170*** (0.00000188)	-0.0122*** (0.000241)	-0.0441*** (0.0000422)	-0.0265*** (1.72e-16)	-0.0568*** (0.000472)	0.0366*** (0.000982)	0.0380*** (0.00861)	-0.0133*** (0.00143)	-0.0133*** (0.00118)	0.0239*** (3.98e-17)
URBP	0.243*** (0.0000430)	0.260*** (0.000533)	0.800*** (0.000936)	0.152*** (3.76e-15)	-0.323*** (0.00568)	0.0812*** (0.0116)	-0.534*** (0.0471)	-1.510*** (0.101)	-1.682*** (0.0596)	-0.960*** (2.61e-15)
GFCF	0.283*** (0.00000844)	0.230*** (0.00112)	0.154*** (0.000359)	0.173*** (8.20e-16)	0.449*** (0.00161)	-0.0608*** (0.00610)	0.195*** (0.0170)	-0.145*** (0.0523)	-0.0305*** (0.00518)	-0.283*** (6.64e-16)

\*\*\*, \*\*, and \* signifies  $p < 0.01$ ;  $p < 0.05$ ;  $p < 0.1$ . Standard errors in parentheses

relies heavily on fossil fuels, which are major sources of CO<sub>2</sub> emissions. The growth in internet usage can thus lead to an increase in energy consumption from fossil fuels. As per findings reported by Wang and Xu (2021) study, it has been observed that there is a potential for increased CO<sub>2</sub> emissions associated with higher internet usage, especially when human capital falls below a certain critical threshold.

Similarly, with the exception of the 25th quantile, FXTEL significantly impacts CO<sub>2</sub> emissions from transport negatively at 1% level on the 50th quantile (− 0.0800), 75th quantile (− 0.0954), and 90th quantile (− 0.212) in the upper middle-income group. The lower middle-income group also exhibits negative statistically significant FXTEL at 1% (− 0.197, − 0.178, − 0.188, and − 0.144) in the 25th, 50th, 75th, and the 90th quantiles, respectively. However, FXTEL is positive and significant at the 75th quantile (0.0379) within the low-income group. In low-income countries, people may rely on fixed telephone subscriptions because they have limited access to alternatives such as mobile phones or internet-based communication. The level of internet adoption is lower compared to the upper middle-income group, and the infrastructure and behavioral changes associated with the internet may be less developed. Low-income countries may have limited ICT infrastructure and different priorities that affect the impact of the internet on emissions. There may be lower adoption rates and different communication priorities in these countries.

Contrarily, the results of Table 7 reveal that MOBILE increases CO<sub>2</sub> emissions from transport in the upper middle-income group by 1% (0.0390, 0.0564, 0.117, and 0.157) in the 25th, 50th, 75th, and 90th quantiles, respectively. Mobile phones are used for travel-related activities like ride-hailing services and navigation, which can lead to more carbon-intensive transportation options. Also, MOBILE is positively significant in the lower middle-income group at 5% (0.0646, 0.0558, 0.0391, and 0.113) in the 25th, 50th, 75th, and 90th quantiles, respectively. Furthermore, MOBILE is significant and positive in the low-income group, at 1% (0.157, 0.0702, and 0.0948) in the 25th, 50th, and 75th quantiles, respectively. These PQARDL estimations yield mixed results for sub-Saharan African countries based on their income groups. Mobile phone usage patterns in low-income countries are different from those in higher-income countries, leading to varying effects on emissions. The relationship between ICT factors like the INTERNET, FXTEL, MOBILE and CO<sub>2</sub> emissions from transport is complex and depends on income levels. Factors such as the level of adoption, infrastructure, and usage patterns of these ICT technologies, as well as the socioeconomic context, play a role in determining their impact on emissions. These results highlight the importance of considering income-specific policies and strategies to harness the potential of ICT for emission reduction effectively. The findings and contributions

presented in this study carry substantial significance within the existing body of literature.

To back up this assertion, we employ a graphical approach to illustrate the varying significance of ICT in relation to CO<sub>2</sub> emissions from transportation across different income categories. Figures 2, 3, and 4 show how the PQARDL and OLS tests found that ICT has an effect on CO<sub>2</sub> emissions from transportation. The coefficients obtained from long run quantile estimates (represented by the green line or the gray region of the confidence interval) exhibit significant variations across diverse quantiles, indicating diverse effects on transport-based CO<sub>2</sub> emissions. On the contrary, the OLS model, denoted by the dashed line, holds true for all quantiles of interest. This further highlights the fact that the impact of ICT (in particular, the INTERNET and FXTEL) on CO<sub>2</sub> emissions from transport varies among upper and lower middle-income and low-income groups.

### Robustness analysis

To ensure the validity of our results, we conducted additional analyses by introducing the variable GFCF into the model. Incorporating GFCF into the analysis alongside ICT variables and transport-based CO<sub>2</sub> emissions allows for a more comprehensive examination of the factors influencing emissions. Investments captured by GFCF can directly impact the quality and capacity of transportation and ICT infrastructures, such as roads, railways, and ports, as well as broadband networks and smart transportation systems, which can influence transportation efficiency and emissions (Li et al. 2022a; Lv and Shang 2022). Moreover, GFCF can vary significantly between regions within a country or across countries. Considering GFCF as a variable in the analysis allows for the exploration of regional variations in the impact of ICT on transport-based CO<sub>2</sub> emissions. Furthermore, to ensure the robustness and reliability of our findings, this study employed a robust analytical approach. Specifically, we utilized the two-step system generalized method of moment (GMM) model to assess the relationship between ICT and CO<sub>2</sub> emissions from transport. The two-step system GMM model was also used to incorporate time variants, individual and multiple fixed effects, and address concerns about endogeneity (Naseem and Guang Ji 2021). By employing this robust analytical technique, we aimed to strengthen the reliability of our results, ensuring a comprehensive examination of the ICT and transport-based CO<sub>2</sub> emission nexus. The robustness results, presented in Table 8, demonstrate that the outcomes are consistent with our main results in Tables 6 and 7. These findings highlight that the advancement of ICT has a significant impact on reducing CO<sub>2</sub> emissions from transport, thereby promoting environmental sustainability.



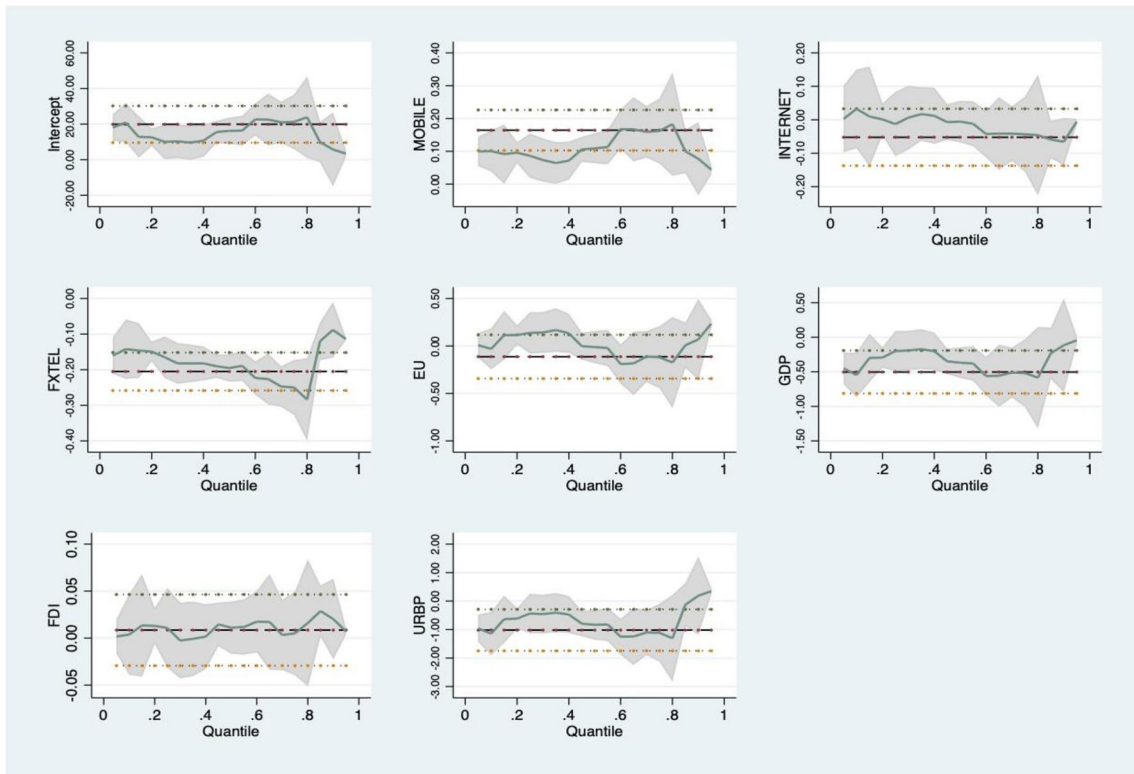


Fig. 2 Long-run quantile estimation for upper middle-income group

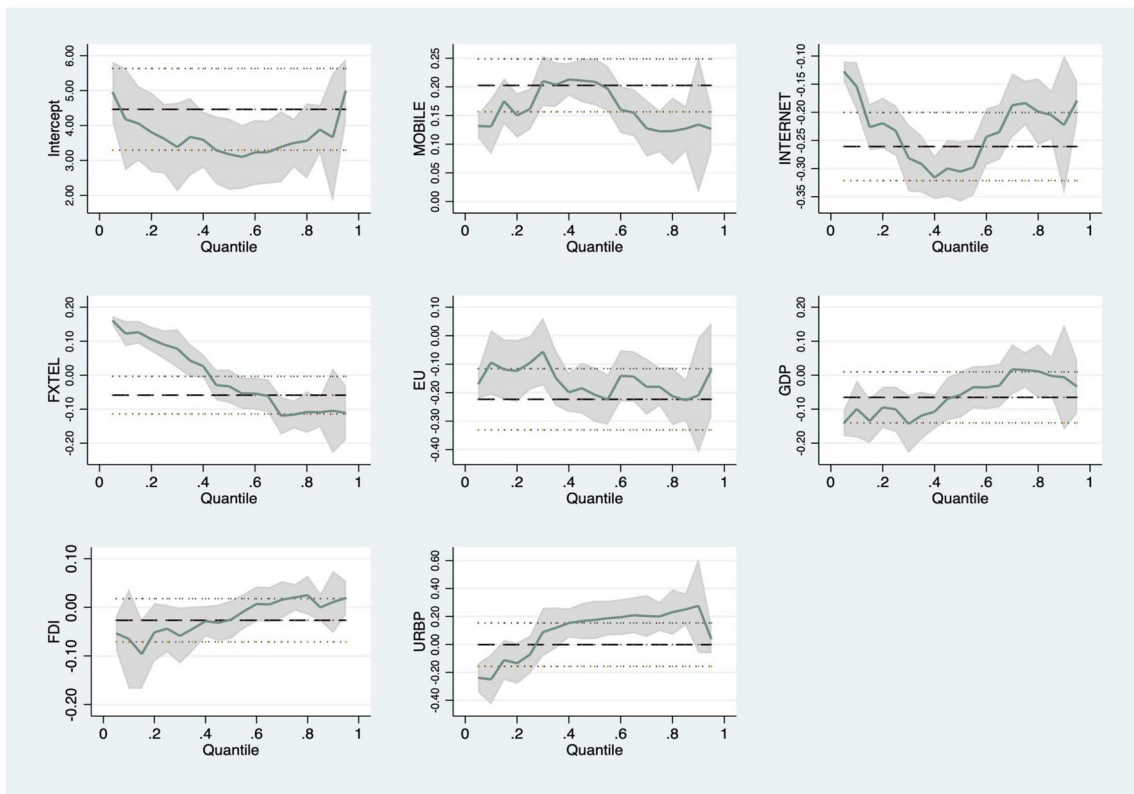
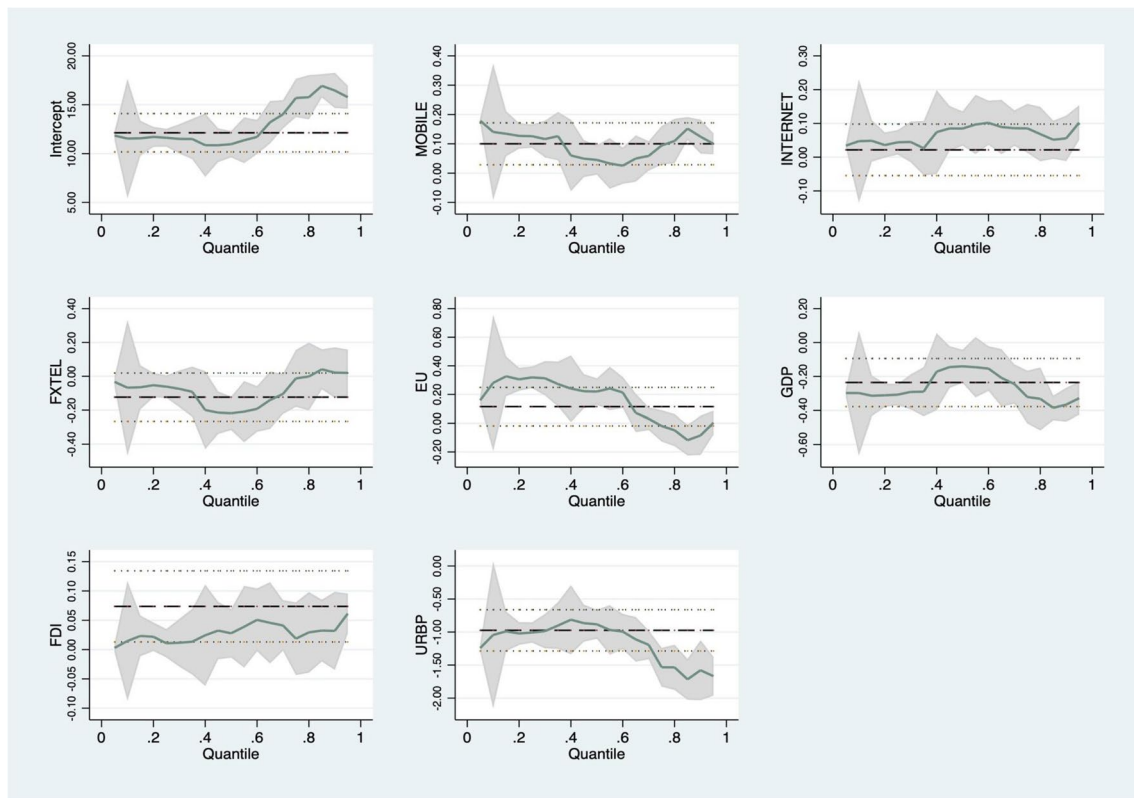


Fig. 3 Long-run quantile estimation for lower middle-income group



**Fig. 4** Long-run quantile estimation for low-income group

## Conclusion and policy recommendation

### Conclusion

This study uses panel data from 2000 to 2021 to examine how ICT affects CO<sub>2</sub> emissions from transportation in 24 SSA countries. It employs the PQARDL model. Based on the amount of transport-based CO<sub>2</sub> emissions, the study divides the 24 SSA countries into three main income groups: upper and lower-middle income, and low-income groups. In an effort to emphasize the PQARDL model's benefits, this research compares its results to those of OLS regression. The PQARDL takes into account the short- and long-term effects of the distribution and provides a more complete picture of ICT and CO<sub>2</sub> emissions from the transportation nexus at different quantiles. This technique allows us to identify the varying impacts of ICT across different income groups and quantiles, providing valuable insights for policy interventions.

Findings for all SSA nations in the sample show that ICT indicators have a significant impact on CO<sub>2</sub> emissions across the 25th, 50th, 75th, and 90th quantiles. Notably, internet usage and fixed telephone usage exhibit significant negative impacts on CO<sub>2</sub> emissions, indicating that higher adoption of these technologies is associated with lower emissions from

transport. Conversely, mobile subscriptions show a positive impact on transport emissions. Additionally, variables such as energy use, urban population, GDP, and FDI also demonstrate mixed significant effects on CO<sub>2</sub> emissions across different quantiles.

Analyzing the sub-sample based on income groups further substantiates the diverse impact of ICT on CO<sub>2</sub> emissions from transport. These findings reveal that the connection between ICT and transport-based CO<sub>2</sub> emissions varies among income groups. Within the upper-middle-income group, internet usage has both positive and negative significant connections with transport emissions, and fixed telephone subscriptions exhibit a negative relationship. In the lower-middle-income group, internet usage and fixed telephones exhibit a negative influence on emissions, while mobile subscriptions exhibit a positive effect in the upper and lower-middle-income groups. Interestingly, the low-income group exhibits a positive and significant relationship between ICT variables and CO<sub>2</sub> emissions from transport. These findings highlight the heterogeneity of ICT's influence on emissions across different income groups in SSA.

The results emphasize the potential of ICT, particularly internet usage and fixed telephones, in reducing emissions and promoting environmental sustainability. However, the positive effect of mobile subscriptions on emissions requires

**Table 8** Two-step system GMM results—robustness checks

Variables	Full sample	Upper middle income	Lower middle income	Low income
L1. CO2	− 0.525* (0.285)	0.520* (0.281)	− 0.457** (0.136)	− 0.238** (0.0756)
MOBILE	0.163*** (0.0276)	0.188** (0.0776)	0.114** (0.0508)	0.105* (0.0440)
INTERNET	− 0.205*** (0.0286)	− 0.214** (0.0905)	− 0.169** (0.0591)	0.208** (0.0582)
FXTEL	− 0.217*** (0.0625)	− 0.162*** (0.0960)	− 0.288*** (0.0502)	0.0954* (0.0349)
EU	− 0.221** (0.0753)	− 0.276 (0.281)	− 0.261** (0.115)	− 0.0504 (0.0569)
GDP	− 0.0793 (0.0652)	− 0.257* (0.136)	0.0990 (0.0872)	− 0.237*** (0.0541)
FDI	0.0371 (0.0333)	0.0175 (0.0378)	0.0426 (0.0583)	0.0341 (0.0495)
URBP	− 0.165 (0.132)	− 0.567** (0.200)	− 0.136 (0.113)	0.412* (0.175)
GFCF	0.376** (0.160)	0.0249 (0.290)	0.248 (0.345)	0.613*** (0.102)
Constant	8.610*** (0.936)	10.20*** (3.050)	6.139*** (1.258)	7.030*** (0.827)
Income group		Yes	Yes	Yes
Observations	284	73	151	60
Instruments	26	26	26	26
F Statistics	160.6	218.0	34.59	29.85
AR (1)	− 2.52**	− 3.33***	− 1.95*	− 2.06**
AR (2)	0.89	− 1.34	− 0.90	− 1.57
Sargan test	198.59***	90.76***	126.74***	68.13***
Hansen test	13.14	12.52	12.74	12.10

\*\*\*, \*\*, and \* signifies  $p < 0.01$ ;  $p < 0.05$ ;  $p < 0.1$ . Corrected standard errors in parentheses

attention and calls for targeted policies to mitigate their environmental impact. These findings underscore the significance of harnessing the power of ICT to achieve sustainable development goals and tackle climate change challenges in the transport sector. The robustness results from the two-step system GMM estimation show that ICT has the potential to play a key role in reducing emissions from transport and improving environmental sustainability in SSA.

Additional research is essential to gain a comprehensive understanding of how various ICT-driven solutions influence CO<sub>2</sub> emissions. Moreover, it is crucial to delve into the intricate dynamics of transportation modes, such as road, air, marine, and trains, and how they intersect with the adoption of ICT, subsequently influencing the environment. To advance knowledge regarding the intricate relationship between ICT and CO<sub>2</sub> emissions, forthcoming investigations should consider broadening the scope of their analysis to encompass the entirety of the African continent. This expansion should also involve the incorporation of more extensive and up-to-date datasets, enabling a more thorough and nuanced examination of these complex interactions. Such research endeavors will be instrumental in developing

effective strategies to mitigate the environmental impacts of ICT while harnessing its potential for positive change. Moreover, in future research endeavors, an innovative approach could be adopted, such as the quantile cointegrating regression method introduced by Xiao (2009) and successfully employed by Lee and Zeng (2011) in their research study. This approach allows for a comprehensive investigation of the long-term cointegrated relationship between ICT and CO<sub>2</sub> emissions across all transport sectors, including road, air, train, and marine. By employing such advanced methodologies, researchers can gain a more nuanced understanding of the intricate dynamics between ICT and carbon emissions within the various transportation sectors, shedding light on potential avenues for environmental improvements.

### Policy implications

Based on the findings, several policy recommendations are proposed to harness the potential of ICT in reducing CO<sub>2</sub> emissions from transport in sub-Saharan Africa. First, promote ICT infrastructure development: governments should prioritize investments in ICT infrastructure,

including internet connectivity and fixed telephone networks, to enhance accessibility and affordability for all income groups. This would facilitate the adoption of smart transportation systems and reduce transport-related emissions. Second, encourage sustainable mobile usage: policies should be implemented to promote sustainable mobile phone usage, encouraging the adoption of eco-friendly transportation options and discouraging carbon-intensive travel behaviors. This can be achieved through incentives for public transportation usage, carpooling, and telecommuting. Third, implement smart transportation solutions: governments and relevant stakeholders should invest in smart transportation solutions, such as intelligent traffic management systems and real-time data analysis, to optimize transport operations and reduce congestion, leading to lower CO<sub>2</sub> emissions. Fourth, foster public-private partnerships: collaborations between governments, private sectors, and international organizations can facilitate the adoption

of ICT solutions in the transport sector. This could include initiatives to provide affordable and energy-efficient transportation options, leveraging the power of ICT for sustainable development. Fifth, enhance digital literacy and awareness: efforts should be made to improve digital literacy and awareness among the population, especially in low-income areas, to foster the adoption of ICT solutions for sustainable transportation practices. Finally, incorporate ICT in climate policies: governments should integrate ICT-related measures and incentives into their climate policies and nationally determined contributions (NDCs) to achieve emission reduction targets and address climate change challenges in the transport sector. By implementing these policy recommendations, sub-Saharan African countries can harness the potential of ICT to achieve sustainable and low-carbon transportation systems, contributing to environmental protection and long-term economic development (Liu et al. 2021; Owusu-Manu et al. 2021).

## Appendix

**Table 9** List of countries

S no.	Country	Income group	S no.	Country	Income group
1	Angola	LMI	13	Mauritius	UMI
2	Benin	LMI	14	Mozambique	LI
3	Botswana	UMI	15	Namibia	UMI
4	Cameroon	LMI	16	Niger	LI
5	Congo, Dem Rep.	LMI	17	Nigeria	LMI
6	Congo, Rep.	LMI	18	Senegal	LMI
7	Cote d'Ivoire	LMI	19	South Africa	UMI
8	Eritrea	LI	20	Sudan	LI
9	Ethiopia	LI	21	Tanzania	LMI
10	Gabon	LMI	22	Togo	LI
11	Ghana	UMI	23	Zambia	LI
12	Kenya	LMI	24	Zimbabwe	LMI

Source: authors' compilation

**Author contribution** Baffour Gyau Emmanuel: conceptualization, methodology, data collecting and analysis, and writing—original draft. Yaya Li: leadership, review and editing, and revised draft preparation. Adu Daniel: review and editing.

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**Data availability** Data is available upon request from the authors.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable as no human participants were involved.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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