The effect of transport services and ICTs on carbon dioxide emissions in South Africa

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Abstract
The rising trend in carbon dioxide emissions has implications on economic livelihoods through global warming and climate change. Attaining lower carbon dioxide emissions is therefore crucial for the realization of the sustainable development goals. South Africa happens to be one of the leading countries in ICT and transport infrastructure in the sub-Saharan African region. Opposing arguments on how ICT and transport services affect carbon dioxide emissions exist. However, their effects on the rising trend in carbon emissions in the country has not received much empirical attention. The study analyses the role ICTs and the transportation sector play in the carbon dioxide emissions of South Africa. Regression analysis of data for the 1989–2018 period shows mobile adoption, internet usage, and telephone usage increases carbon dioxide emissions while transportation services in the country helps reduce carbon dioxide emissions. Income positively affects carbon dioxide emissions while urbanization has negative effects. Implications from the findings include the urgent need to have electricity that power ICT devices and equipment be generated from renewable and sustainable sources rather than from heavy polluting sources.

Keywords ICTs · Transportation · Income · Carbon dioxide emission · Internet, Mobile phone

Introduction
In order to tackle climate change and its associated negative effects, world leaders are determined to have lower levels of carbon dioxide emissions as enshrined in the sustainable development goals (SDGs). This is based on the fact that carbon dioxide emissions form a greater proportion of all greenhouse gases that contribute to climate change menace. This decision requires all countries, developed and developing alike to get on board and manage activities that are associated with carbon dioxide emissions. To this end, arguments or theories have been offered to explain the causes of environmental degradation especially carbon dioxide emissions. Empirical studies have also sought to ascertain the propelling factors driving carbon dioxide emission for countries and regions (Shobande and Asongu 2022; Twerefou et al. 2016; Kwakwa and Adusah-Poku 2020; Kwakwa et al. 2021; Gyamfi et al. 2022; Usman and Balsalobre-Lorente 2022).

Fact is researchers have sought to analyse how economic activities increase or reduce carbon dioxide emissions. As a result, earlier works have looked at the carbon dioxide (CO₂) emission effect of income, industrialization, trade openness, foreign direct investment, energy consumption, and urbanization (Adom et al. 2018; Adusah-Poku 2016; Kwakwa and Adu 2015; Alhassan 2021; Aboagye et al. 2020). To deepen the understanding of the drivers of CO₂ emissions, the effect that other sectors of the economy have on carbon dioxide emissions have also been explored in recent times. These include natural resources, political regime, and financial
development (Kwakwa et al. 2018; 2020; Jahanger et al. 2021; Rafei et al. 2022; Huang et al. 2021; Alhassan et al. 2022; Jahanger et al. 2022). Very recently, the CO2 emission effects of Information and Communication Technologies (ICTs) and transportation are gaining the attention of researchers (Batool et al. 2022; Weiil et al. 2022; Usman et al. 2021; Chatti 2021; Haini 2021; Xie et al. 2017; Zaman et al. 2017).

Transportation has been with mankind since time immemorial. However, the modern transportation system which propels economic activities of production and distribution relies heavily on fossil fuel (Chatti 2021). This has raised concern in an attempt to reduce carbon dioxide emissions. It has been documented that the transport sector accounts for about 21% of global emissions. Out of this, roads transport is responsible for three-quarters which amounts to 15% of total carbon dioxide emissions. Aviation contributes 11.6% of total transport emissions, with shipping, rail and freight, and others contributing 10.6%, 1%, 2.2%, respectively to total transport emissions (Ritchie 2020). There are calls for efficient means of transporting people, goods, and services in order to have a cleaner environment while promoting economic activities. Since its inception over four decades ago, ICTs have contributed to the growth and development process of economies. ICTs have facilitated economic production, led to improved health outcomes, better education, reduced poverty, and better standard of living (Raheem et al. 2020). The pace of ICTs development and its usage has led to divergent opinions regarding its effect of carbon dioxide emissions. Some argue that ICTs lead to higher carbon dioxide emissions as a result of more energy usage and contribution to e-waste (Khanal 2021; Freitag et al. 2021). There are others with the opinion that ICTs facilitate the development of renewable energy and energy efficient gadgets that ultimately lead to lower carbon dioxide emissions (Chatti 2020; Azam et al. 2021).

While developed countries contribute a greater share of carbon dioxide emissions, developing countries are rather the worse affected by the climate change menace (Alhassan et al. 2019). There are some developing countries like China, India, and Malaysia whose contribution to global carbon emissions is significant (see: World Bank 2021). In sub-Saharan Africa where the level of carbon dioxide emission is the lowest among regions, South Africa is the leading carbon dioxide emitting country. Compared with other economic giants in the region like Nigeria, South Africa has seen its carbon emission increased from 247,660 kt in 1990 to 433,250kt in 2018 while Nigeria has jumped from 42,441 to 130,670kt within the same period. It is also among the top 15 countries that emit carbon dioxide in the world (World Population Review 2021). Economically, South Africa is a giant on the continent and among the fastest growing developing countries in the world. The country’s GDP has increased from US$ 159bn to US$ 352bn over the years 1980–2021 (World Bank 2021). This has led some to compare its pace of growth and development to countries like Brazil, China, and Russia (Azahaf and Schraad-Tischler 2021). Industrial activities powered by coal have also expanded greatly in the country (World Bank 2021).

Since the booming economic activities of South Africa have been driven mainly by coal which is associated with higher carbon emission, authorities in the country have designed measures towards the attainment of a low carbon economy. Key among such policies is the South Africa’s Low Emission Development Strategy (SA-LEDS) (Republic of South Africa 2020) which spells out the vision that “South Africa follows a low-carbon growth trajectory while making a fair contribution to the global effort to limit the average temperature increase, while ensuring a just transition and building of the country’s resilience to climate change.” In line with the aspirations of policymakers and authorities, researchers have also sought to analyse the driving forces of carbon dioxide emission in South Africa (Kwakwa and Adusah-Poku 2020; Garidzirai 2020; Bekun et al. 2019; Ekwueme et al. 2021; Khobai and Le Roux 2017; Atsu et al. 2021). The growing body of studies on South Africa has placed emphasis on how income, manufacturing, urbanization, foreign direct investment, financial development, trade, and natural resources influence the country’s CO2 emissions rate. However, the evidence has not been conclusive because of mixed results that have been reported. Furthermore, there is dearth of empirical works which unravels the effect of ICTs and the transportation sector on carbon dioxide emission in South Africa.

The country’s ICT sector is one of the most vibrant in the region. It is the leader of smart cities in Africa (van Rensburg et al. 2019). The country’s broadcasting, telecommunications, and information supply services forms about 60.5% of all ICT exports (Government of South Africa 2017). Within the 2010 to 2018 period, the number of people who use internet increased from 24% of total population to 62.5% (World Bank 2021). Total amount spent on South Africa’s ICT infrastructure more than doubled from R 23trillion in 2015 to R 46 trillion in 2018 (Independent Communications Authority of South Africa, 2020). Plans to expand IT infrastructure are very promising. Similarly, the transport sector in South Africa is advancing faster than many countries in the region. It is one of the most visited places on the continent due to its tourist sites. Air Traffic and Navigation Services in South Africa provides air traffic, navigation, training, and associated services within South Africa and a large part of the Southern Indian and Atlantic Ocean, comprising approximately 10% of the world’s airspace. There is an effective Bus Rapid Transport (BRT) in many of its cities (Republic of South Africa 2021). The Oxford Economics (2016) revealed that the air transport sector in the country which offers 490,000 jobs, forms about 3.5% of the
country’s GDP as it facilitates about US$ 9.2 billion of foreign tourist expense, US$ 110 billion of exports, and US$ 140 billion of Foreign Direct Investment (FDI).

While studies have analysed how ICTs (Bacishoga et al. 2016; Johnston et al. 2015) and transportation (Tsikai 2016; Development Bank of Southern Africa 2022; Chakwizira and Mashiri 2009) have helped South Africa’s economy, the lack of empirical studies on how ICTs (Atsu et al. 2021) and transportation affect the country’s level of carbon dioxide emissions gives room for further studies on the subject matter. This is necessary to offer guidelines for policymakers in the country in their quest to have a low carbon economy. This study therefore analyses the effect of ICTs and transport services on carbon dioxide emissions in South Africa.

As a contribution to the literature, this study provides evidence from a country in the sub-Saharan African region where there is dearth of research on the carbon dioxide emission effect of ICTs and transport services. Also, in this paper, the analysis makes use of mobile phone subscription, internet users and fixed telephone subscription to ascertain their respective effects on carbon dioxide emission which is lacking in many of the existing studies (Azam et al. 2021; Khanal 2021; Raheem et al. 2020; Atsu et al. 2021). Without such individual analysis, it leaves one to assume that the effect of one ICT proxy can be generalized for the others. Thinking along such line could mislead policymakers in the formulation of appropriate policies towards dealing with carbon dioxide emission from the ICT sector.

Literature review

This section pays attention to theories or argument regarding the effects of ICTs and transport services on environmental degradation. Also, empirical studies related to these theories or arguments are reviewed. It concludes by highlighting the gaps in the existing literature that this study fills and thus contributes to the literature.

Arguments regarding ICTs effect on environmental degradation

Theoretically, different perspectives have emerged as a basis to expect a relationship between ICTs adoption and environmental degradation. One of such is the ecological modernization perspective which suggests that ICTs can drive economic growth and subsequently, structural changes in an economy, improved technology and improved environmental regulatory framework. This will eventually lead to better environmental health since the improved technology and enhanced regulatory framework will promote lower emissions (Simpson et al. 2019; Sadorsky 2014). Another school of thought suggests that ICTs are primarily designed to be heavily dependent on electricity. Thus, increased ICTs adoption implies increased energy consumption which could worsen the state of the environment. This would be especially true if electric energy is not produced from sustainable sources. This school of thought, suggesting that ICTs lead to emissions, also holds that the disposal of ICT equipment and devices also contribute to pollution (Baris-Tuzemen et al. 2020; Shabani and Shahnazi 2019) such as has been seen with e-waste disposal. The third school of thought basically claim that both of the earlier two hold true and therefore ICTs will likely have a neutralizing effect on emissions. They argue that the efficiency of low energy consumption derived from ICT adoption leads people to consume more energy thus cancelling out any positive impacts on carbon emissions (Kouton 2019).

Arguments regarding transport services effect on environmental degradation

With respect to transportation, most vehicles, planes, and trains in both advanced and developing countries use internal combustion engines which are mostly ran on fossil fuels such as gasoline and diesel. The burning of these fuels emits carbon dioxide into the atmosphere. As such, increased demand for transportation is expected to increase environmental degradation. In the USA, for instance, transportation often accounts for the largest share of greenhouse gas (GHG) emissions; contributing 29% of total GHG emissions in 2019 (US EPA 2021). In the UK, domestic transportation accounted for 27% of total GHG emissions in the same year, which was also the highest emitting contributor (UK Department for Transport 2021). According to the United Nations Environment Program (UNEP), an increasing number of old, ill maintained and highly polluting vehicles in developing countries makes the situation no different¹. However, there is expectation of the reversal of this trend if there is a shift towards extensive use of electric vehicles and renewable based fuels such as hydrogen fuels to power vehicles. Also, an efficient transport system that shifts attention from private car usage to public transport will help reduce carbon dioxide emissions from the transport sector (UNEP, 2021). Similarly, Zhao et al. (2022) have argued that smart transportation that applies modern technologies can directly or indirectly reduce carbon dioxide emissions. Transportation can help reduce carbon dioxide emissions when it facilitates the movement of goods produced in environmentally efficient countries to countries that would produce same goods but under environmentally polluting environment.

¹ Transport | UNEP - UN Environment Programme
Empirical studies on ICTs effect on carbon dioxide emissions

Empirical studies in the literature that have examined the linkage between ICTs and carbon dioxide emissions are growing. Haldar and Sethi (2022) found ICT promotes research and development to reduce carbon dioxide emissions among emerging economies. Chatti (2021) conducted a study using data from a panel of 43 countries over the period 2002 to 2014 and found that ICTs increase carbon dioxide emissions potentially due to the reliance on devices and infrastructure that require electric power. The study in reference included some of the world’s most populous countries such as China, India, and Russia which also tend to have higher emission volumes. The study further found out that transport services also has a positive effect on carbon dioxide emissions. Inland freight transport, air freight, and rail freight all increase CO2 emissions. Lastly, Chatti (2021) showed that ICTs could be employed to mitigate the positive influence of freight transport services on carbon emissions. These findings confirm earlier findings by Chatti (2020) on a similar empirical investigation. Raheem et al. (2020) explored the effect of ICTs and financial development on carbon dioxide emissions for the G7 countries over the period 1990 to 2014. They found that in the long run, the effect of ICTs on emissions is positive. Batool et al. (2022) confirmed a positive effect of ICTs on carbon dioxide emissions for East and South Asian countries.

Similarly, Thio et al. (2021) found that both ICT exports and ICT imports contribute to increasing carbon dioxide emissions in a group of ten countries. In contrast, Lu (2018) examined the impact of ICTs and other variables on carbon dioxide emissions of countries in Asia from 1993 to 2013 and found that ICTs have helped in tackling CO2 emissions. Lu (2018) therefore argued that promoting ICT is key to mitigating carbon dioxide emissions. It is important to note that among the countries examined in the study are Japan, Singapore, Korea, and Hong Kong among others with high technological efficiency. These findings are further supported by Shobande and Ogbeifun (2022) who contend that evidence from 24 OECD countries from 1980 to 2019 show that ICT can be useful in promoting environmental sustainability through education, institutional and regulatory quality and transportation. Wei and Ullah (2022) in a study of 37 Asian countries from 1996 to 2019 show that in summary, the growth of digital infrastructure could reduce CO2 emissions. While acknowledging the global nature of variables such as carbon dioxide emissions, cross country studies such as the aforementioned might fail to account for country level heterogeneities that could potentially moderate any effect of ICTs and transport systems on CO2 emissions. In this respect, assessing individual country studies might be equally useful to the ICTs, transport, and carbon emission discussions.

With respect to single country studies, Atsu et al. (2021) examined the connection between ICTs, energy consumption, financial development, and carbon dioxide emissions in South Africa spanning the period 1970 to 2019. The study observed that ICTs and the consumption of fossil fuel increase carbon emissions with a 1% increase in ICT adoption yielding a 0.57% increase in emissions in the long-term. Khanal (2021), however, found contrasting results in the case of Australia. Khanal (2021) observed that while ICTs increase carbon dioxide emissions in the short run, it reduces emissions in the long run. Godil et al. (2021) examined the role of technology innovation and renewable energy in transport sector carbon emissions in China with data from 1990 to 2018 and found that technology innovation has a negative impact on transport sector CO2 emissions.

Shabani and Shahnazni (2019) examined the relationship between ICT, energy consumption, carbon emissions, and GDP in the economic sectors in Iran between 2002 and 2013. They found that ICT increase emissions in the industrial sector but reduced emissions in the transportation and services sectors. Shabani and Shahnazni (2019) showed that within a single country, the effects of ICT could be dependent on their use and application across different sectors of the economy. Buris-Tuzemen et al. (2020) found a non-linear relationship between ICT and pollution in Turkey over the period 1980 to 2017. Meanwhile, in a rather forward-looking study, Mersky and Langer (2021) show that operational improvements based on ICT in the freight transport in the USA can contribute to major reductions in GHG emissions. They model that by year 2035, annual GHG emissions from truck transported freight could reduce by 41% with ICT-induced reductions contributing 55% of the total reductions whereas ICT-induced reductions in GHG emissions could amount to 43% of total reductions by 2050.

Empirical studies on transport service effect on carbon dioxide emissions

Still with respect to transportation, studies such as Jiang et al. (2019) examined the impact of public transportation on CO2 emissions in China and observed a heterogenous effect across the different provinces. On the whole, a non-linear relationship was found to exist when after some threshold of public transportation, the carbon emission effect changes from positive to negative. These findings are corroborated in part by Xu and Xu (2021) who studied the factors driving carbon dioxide emissions in China’s transportation sector. Xu and Xu (2021) confirmed positive effects of transportation intensity on carbon dioxide emissions among China’s provinces emphasizing the existence of spatial correlations. In other words, increased
transformation intensity positively influenced carbon dioxide emissions both in the local region and neighboring regions as well. Xu and Xu (2021) further agree with Chatti (2021) that an increase in the technology within the transportation sector will have a dampening effect on CO₂ emissions. Sun et al. (2020) examined carbon emission in the Yangtze River Delta Area in China resulting from the transportation sector and their results emphasize the contributing role of the sector to carbon dioxide emissions. They observed that factors such as population size, GDP, energy intensity, and freight turnover among others are key to increasing emissions from transport. However, energy structure could reduce transport sector emissions if the proportion of clean energy in the total energy mix increases. Gyamfi et al. (2022) established for E7 countries that rail transport improves environmental quality by reducing carbon dioxide emissions while air transportation exerts the opposite effect.

**Gaps in the literature and contribution of this study**

The review of the literature has identified apparent contrasts in findings of the ICT-carbon carbon emission nexus both in cross-country studies and in single country studies and justifies further examination of the relationship between these variables to provide further evidence. Also, scanty empirical analysis for transportation effect on carbon dioxide emissions exists and none for an African country. Moreover, there is limited studies that examine how various ICT variables affect carbon dioxide emissions. Consequently, the current study seeks to examine the nexus between ICTs and transportation on one hand and carbon dioxide emissions on the other in South Africa. The study contributes to the literature by providing further empirical evidence on the existing relationship between these variables. Specifically, the analysis includes the effect of mobile phone subscription, internet users, and fixed telephone subscription on carbon dioxide emissions. Furthermore, the focus on an African country fills the gaps in the literature particularly with respect to the nexus between transportation and carbon emissions.

**Data and methods**

The “Data and methods” section is divided into three subsections. The “Theoretical and empirical modelling” section introduces and specifies the theoretical and empirical model for this study. Our main source of data is disclosed in the “Sources of data” section while the methods used to estimate our empirical model are specified in the “Estimation technique” section.

**Theoretical and empirical modelling**

Sustainability theories argue for the need to judiciously use environmental resources to benefit both current and future generations equally (Meadowcroft 2022). Current activities by mankind which deteriorate the quality of the environment has serious implications for future generations. Sustainability theory thus calls for measures to put breaks on environmentally degrading activities but promote those that preserves the environment. It is based on this that the study assesses the effect of transport services and Information Communication Technologies on carbon dioxide emissions in South Africa.

From the above and other empirical studies such as Kwakwa and Adu (2015) and Atsu et al. (2021), CO₂ emissions are modelled as a function of the usual contributors such as urbanization and income which is specified in Equation (1) as:

\[
CPC = f(UBS, YPC)
\]  

(1)

where CPC, UBS, and YPC represent CO₂ emissions, urbanization, and income, respectively. To incorporate our two main variables which are ICTs and transport, Eqn. (1) is modified to Eqn. (2) as shown below:

\[
CPC = f(UBS, YPC, MOB, TELE, INTERNET, TRANSPORT)
\]  

(2)

where MOB, TELE, and INTERNET are the ICT variables denoting mobile phone adoption, fixed telephone adoption, and internet usage, respectively. Our transport variable is TRANSPORT denoting transport services. CPC is proxied by CO₂ emissions per capita while UBS is proxied by the share of urban population in total population. The ICT variables namely MOB, TELE, and INTERNET are proxied by mobile cellular telephone subscriptions, fixed telephone subscriptions, and the share of individuals using the internet, respectively. Our transport variable, TRANSPORT, is proxied by the sum of the share of transport services in commercial service exports and the share of transport services in commercial service imports.

By introducing parameters and time subscripts, Eqn. (2) can be modified to:

\[
CPC_t = f\left(UBS_t, YPC_t, MOB_t, TELE_t, INTERNET_t, TRANSPORT_t, \epsilon_t\right)
\]  

(3)

By introducing natural logarithms, Eqn. (3) can be rewritten as:

\[
\ln CPC_t = \alpha_1 \ln UBS_t + \alpha_2 \ln YPC_t + \alpha_3 \ln MOB_t + \alpha_4 \ln TELE_t + \alpha_5 \ln INTERNET_t + \alpha_6 \ln TRANSPORT_t + \epsilon_t
\]  

(4)

Where \( \epsilon \) is the error term which is assumed to be independent and identically distributed and \( \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6 \) are parameters to be estimated.
Sources of data

This study sourced yearly time series data from the World Development indicators of the World Bank (2021). That is mobile phone adoption, fixed telephone adoption, and internet usage were taken from World Bank (2021). Also, transport services, urban population, and income were all sourced from World Bank (2021). The data on all these variables span from 1989 to 2018. This study period is selected because of data availability for all these variables.

Estimation technique

We follow a three-step approach to estimate our final model in Eqn. (4). First, we conduct a stationary test. The reason is that non-stationary variables used in regression estimations lead to spurious results which could bias the findings. The Zivot-Andrew unit root test is employed in this study. This test is preferred because it does not suffer from any short fall when the time series data suddenly changes at a particular point in time. The processes that generate the various time series occasionally experience sudden changes which are permanent leading to structural breaks. The points at which these sudden changes occur are called structural breakpoints. If these structural changes are not accounted for, inferences and projections made on the basis of the relationship between the variables will be inaccurate and invalid (Hansen 2001). Second, we test the existence or otherwise of a long-run association between our variables using Pesaran et al.’s (2001) autoregressive distributed lag (ARDL) bounds cointegration test. The main advantage of this test is the ability to apply to variables with different order of integrations, specifically, zero and one. The bounds cointegration test uses the Ordinary Least Squares (OLS) approach to estimate the unrestricted error correction model (UECM) which is known to incorporate both the long- and short-run dynamics. Third, we obtain the long- and short-run coefficients from the error correction model (ECM). Generally, the standard ARDL \((m, n)\) model is given as:

\[
\Delta \ln CPC_t = \alpha_0 + \delta_1 \ln CPC_{t-1} + \delta_2 \ln UBS_{t-1} + \delta_3 \ln YPC_{t-1} + \delta_4 \ln MOB_{t-1} + \delta_5 \ln TELE_{t-1} + \delta_6 \Delta \ln \text{INTERNET}_{t-1} + \delta_7 \Delta \ln \text{TRANSPORT}_{t-1} + \sum_{j=1}^{m} \gamma_j \Delta \ln CPC_{t-j} + \sum_{j=1}^{n} \gamma_j \Delta \ln UBS_{t-j} + \sum_{j=1}^{n} \gamma_j \Delta \ln YPC_{t-j} + \sum_{j=1}^{n} \gamma_j \Delta \ln MOB_{t-j} + \sum_{j=1}^{n} \gamma_j \Delta \ln TELE_{t-j} + \sum_{j=1}^{n} \gamma_j \Delta \ln \text{INTERNET}_{t-j} + \sum_{j=1}^{n} \gamma_j \Delta \ln \text{TRANSPORT}_{t-j} + \mu_t
\]

where \(m\) and \(n\) denote the optimal lag length of the dependent variable and regressors, respectively. The parameters \(\gamma_1, \ldots, \gamma_7\) are the short-run dynamics and \(\delta_1, \ldots, \delta_7\) are the long-run coefficients. \(\mu_t\) is the error term assumed to be normally distributed. To ensure that our results, particularly the long-run results are robust, we employ the Dynamic Ordinary Least Squares (DOLS) method to run another regression.

Results and discussion

The main results of the study are presented and discussed in this section. It follows this order: results of the Zivot-Andrews unit root tests; results of ARDL bounds cointegration tests; ARDL long- and short-run results; causality results and diagnostic results.

Zivot-Andrews unit root tests results

Before proceeding to test for cointegration and using the variables in regression estimations, it is very important to check for stationarity. Non-stationary variables used in regression estimations lead to spurious results which could bias the results. The results are presented in Table 1. At levels, two of the ICT variables namely, mobile phone adoption and internet usage, as well as \(\text{CO}_2\) emissions, are all stationary at levels at a significant level of 1%. The remaining variables, namely urbanization, income, fixed telephone adoption, and transport services, were differenced making them stationary. This implies that whereas mobile phone adoption, internet usage, and \(\text{CO}_2\) emissions are integrated of order zero, \(I(0)\), the remaining variables such as urbanization, income, fixed telephone adoption, and transport services are integrated of order one, \(I(1)\).

| Variable  | At levels | At first difference |
|-----------|-----------|---------------------|
|           | \(t\)-statistic | Break year | \(t\)-statistic | Break year |
| InUBS     | -0.2601   | 2014               | -21.8153*** | 2002      |
| InYPC     | -4.3631   | 2004               | -4.7983*    | 2008      |
| InMOB     | -16.6798*** | 2005            | -5.5696*** | 2002      |
| InTELE    | -2.1372   | 1997               | -5.2367**   | 2010      |
| InTRANS-  | -4.8338   | 2000               | -5.5696**   | 2002      |
| PORT      | -21.8153*** | 2002            | -5.2367**   | 2010      |
| InCPC     | -9.2792*** | 2001               | -         |          |
| INTERNET  | -9.2526*** | 2010               | -         |          |

* **, and *** represent significant levels at 10%, 5%, and 1%, respectively Authors’ estimation using data from World Bank (2021)
ARDL cointegration test results

Following from the unit root tests, we conduct a cointegration test to ascertain whether a linear combination among the series is stationary or otherwise. We use the ARDL bounds cointegration test since our time series variables have integrated of different orders. The null hypothesis and alternative hypothesis are specified as follows: $H_0$: no cointegration and $H_1$: cointegration exists. The ARDL cointegration results are shown in Table 2. With an $F$-statistic of 11.2510 which exceeds the upper critical bound, $I(1)$ at 1%, 5%, and 10%, the null hypothesis of no cointegration is rejected. This result implies that a long-run association among the variables exists and that the linear combination among the variables is stationary.

Long-run and short-run estimation results

Our main goal is to examine the effect of ICTs and transport services on CO₂ emissions in South Africa. After establishing that there exist a cointegrating association among the variables, we proceed to ascertain the long- and short-run relationship between the variables. Table 3 reports both the long-run and short-run estimation results using ARDL and DOLS. From the results in Table 3, we observe that the ICT effect on CO₂ emissions in South Africa depends on the measure of ICT. In the long run and using the ARDL results, whereas two of the ICT variables, namely mobile phone adoption and internet usage, have a direct relationship with CO₂ emissions, fixed telephone adoption has an inverse relationship with CO₂ emissions, although it is statistically insignificant. Specifically, a 1% increase in mobile phone adoption and internet usage increases per capita CO₂ emissions by 0.05% and 0.002%, respectively, with these two coefficients being statistically significant at 1% level of significance. From the result, it can be concluded that ICT adoption in South Africa increases CO₂ emissions. This finding lends support to prior studies done in other countries such as those of Weili et al. (2022); Shabani and Shahnazi (2019); Lee and Brahmasrene (2014); and Salahuddin et al. (2016). Ulucak and Khan (2020) argue that the overall effect ICT has on CO₂ emissions depends on the magnitudes of the use effect, substitution, and cost effects. Per the use effect, ICT increases CO₂ emissions via the increase in energy consumption resulting from the production and consumption of ICT equipment. With regard to the substitution effect, ICT reduces CO₂ emissions via improvement in energy efficiency resulting from technological advancement in different economic sectors. The cost effect accelerates CO₂ emissions as ICT adoption increases due to the increasing demand for goods and services from the cost of production reduction potential of ICT adoption. In the case of South Africa, our results suggest that the positive use effect and cost effect outweigh the negative substitution effect of ICT adoption. South Africa is a hub to several hardware international production companies whose production processes accelerate energy consumption and subsequently CO₂ emissions. South Africa also consumes a lot of ICT equipment judging from their widening trade deficit that began in the year 2011. In fact, trade deficit for ICT increased from R42 billion to R97 billion from 2011 to 2014.² The increasing consumption and production of ICT equipment in South Africa could explain the significant positive effect of ICT on CO₂ emissions. The positive effect of ICT on CO₂ emissions is also consistent in the short run. In the short run, a 1% increase in mobile phone adoption increases per capita CO₂ emissions by 0.08%; however, per capita CO₂ emissions reduce by 0.34% if fixed telephone adoption is increased by 1%. The DOLS long-run results confirm our ARDL long-run results as ICT adoption largely increases CO₂ emissions in South Africa.

With regard to the effect of transport services on CO₂ emissions, our ARDL results indicate a negative relationship between the two, both in the long run and short run. This is also confirmed by the DOLS results. A 1% increase in transport services in South Africa reduces CO₂ emissions by 0.285% and 0.302% in the long run and short run, respectively. This result supports other earlier studies such as Gyamfi et al. (2022); Xu and Xu (2021); and Mustapa and Bekhet (2016). The negative relationship between transport services and CO₂ emissions in South Africa could partly be explained by the less reliance of transport services on crude oil. For instance, oil consumption in South Africa reduced from 502.04 to 489.98 barrel/day in 2020.³ Also, the increasing use of public transport services as opposed to the use of private vehicles in South Africa could explain this negative relationship. In South Africa, road transport accounts for 90% of all transport emissions, and as such, steps taken

Table 2 ARDL cointegration results

|                  | I(0) Bound | I(1) Bound |
|------------------|------------|------------|
| 10%              | 2.12       | 3.23       |
| 5%               | 2.45       | 3.61       |
| 1%               | 3.15       | 4.43       |

Authors’ estimation using data from World Bank (2021)

² http://www.statssa.gov.za/?p=9852
³ https://www.ceicdata.com/en/indicator/south-africa/oil-consumption
to limit emissions from road transport could significantly reduce CO₂ emissions. We also observe that the short-run transport services effect exceeds the long-run transport services effect suggesting a possible adjustment towards efficient transport services overtime. The smaller long-run effect of transport services could also be partly explained by the initiatives taken by the South African government to reduce national CO₂ emissions by 42% in 2030 and to also reduce transport sector emissions by 5% by the end of the year 2050. These initiatives are on the back of South Africa’s Green Transport strategy which is a long-term strategy from 2018 to 2050 (Department of Transport, South Africa 2018). The DOLS results for transport services lend support to the ARDL results indicating that transport services significantly reduce CO₂ emissions in South Africa.

We also found variables such as urbanization and income to significantly influence CO₂ emissions in South Africa. Urbanization significantly reduces CO₂ emissions only in the long run and not in the short run but income significantly increases CO₂ emissions in South Africa, both in the long run and short run. Positive effect of urbanization on carbon dioxide emissions is commonly reported in many studies (Kwakwa et al. 2021; Kwakwa et al. 2020a, 2020b; Adom et al. 2018). However, the negative effect of urbanization reported in this study confirms earlier work by Kwakwa and Adusah-Poku (2020) for South Africa. This outcome supports Elliot

| Table 3 | Estimation results (long and short run) |
|---------|----------------------------------------|
| Variable | ARDL | DOLS |
|         | Coefficient | Std. error | Coefficient | Std. error |
| Long-run results | | | | |
| InUBS | -3.6169*** | 0.6903 | -3.968** | 1.3397 |
| InYPC | 1.5538*** | 0.1738 | 1.885*** | 0.3755 |
| InMOB | 0.0517*** | 0.0096 | 0.0097 | 0.0129 |
| InTELE | -0.0360 | 0.0538 | 0.3376** | 0.1112 |
| InTRANSPORT | -0.2853**** | 0.0433 | -0.3011** | 0.0926 |
| INTERNET | 0.0017*** | 0.0006 | 0.0039** | 0.0014 |
| C | 4.620436 | 1.9299 | -1.5181 | 3.0878 |
| Short-run results | | | | |
| D(InUBS) | 138.433129 | 38.7733 |
| D(InYPC) | 0.7815*** | 0.551 |
| D(InMOB) | 0.0807** | 0.0305 |
| D(InTELE(-1)) | -0.3816*** | 0.1047 |
| D(InTRANSPORT) | -0.3016** | 0.0977 |
| D(INTERNET) | -0.0001 | 0.0020 |
| ECT(-1) | -2.4078*** | 0.3707 |

*, **, and *** represent significant levels at 10%, 5%, and 1%, respectively
Authors’ estimation using data from World Bank (2021)

| Table 4 | Toda-Yamamoto causality approach results |
|---------|----------------------------------------|
| Explanatory variables | Dependent variables |
| | InCOPC | InUBS | InYPC | InTELE | InTRANSPORT | InMOB | INTERNET |
| InCOPC | 0.7653* | 0.1813 | 2.3306 | 0.0390 | 6.6554*** | 2.3087 |
| InUBS | 4.1206** | 0.0408 | 5.5692 | 3.0208* | 8.8260*** | 0.0455 |
| InYPC | 0.7659 | 0.6843 | 3.3044 | 3.9456** | 2.8810* | 4.0323** |
| InTELE | 3.1856* | 3.2698 | 1.2682 | 0.5815 | 0.2204 | 1.503 |
| InTRANSPORT | 0.5828 | 0.9590* | 0.0631 | 4.0343 | 0.7767 | 2.1598 |
| InMOB | 0.4809 | 0.4491 | 0.2165 | 1.8618 | 0.1785 | 0.8615 |
| INTERNET | 0.1942 | 0.7651 | 0.0080 | 1.3375 | 0.4277 |

*, **, and *** represent significant levels at 10%, 5%, and 1%, respectively
Authors’ estimation using data from World Bank (2021)
et al.’s (2014) assertion that urban pressure can reduce carbon dioxide emission through the need to tackle the pressure. The long-run positive effect of income confirms the general assertion that an expansion in economic activities usually leads to a deterioration of the environment (Aboagye 2017; Kwakwa 2020). Previous studies including those on South Africa (Adebayo and Odugbesan 2021) recorded a long-run direct effect of income on CO2 emission.

### Causality results and diagnostic test results

We also conduct a causality test to determine the direction of the relationship between our variables. To do so, we employ the Toda-Yamamoto causality approach with the results presented in Table 4. The results show a bidirectional relationship between urbanization and CO2 emissions and also between transport services and urbanization. On the other hand, a unidirectional relationship runs from fixed telephone adoption to CO2 emissions, income to transport services, CO2 emissions to mobile phone adoption, urbanization to mobile phone adoption, income to mobile phone adoption, and income to internet usage. The results generally show that ICT positively contributes to CO2 emissions in South Africa. Also, the development and improvement of transport services in South Africa could be influenced by the level of income and urbanization in the country.

Table 5 presents the results of some diagnostic checks deemed necessary to ensure the stability of our regression results. We subjected our results to some series of diagnostic tests namely, heteroskedasticity, serial correlation, normality, and stability. On the basis of the probability values of 0.5314, 0.2321, 0.4847, and 0.3642 for heteroskedasticity, serial correlation, normality, and stability respectively, we conclude that our model results are free from the problems of heteroskedasticity, serial correlation, non-normality, and non-stability. This diagnostic test results imply that our results are robust, consistent, and reliable.

### Conclusion and policy recommendations

The quest to mitigate climate change and its effects has led to studies on factors that influence carbon dioxide emission and policies to achieve a low carbon economy globally. Among these, however, there is a dearth of empirical analysis on the CO2 emission effect of ICTs and transportation. Given the heightened role that ICTs are beginning to assume in the development and modernization of economies in sub-Saharan Africa, not least in South Africa where the ICTs sector is vibrant, this study sought to examine the role of ICTs on carbon dioxide discharges in South Africa. Furthermore, the effect of transportation on carbon emissions was also investigated. After controlling for urbanization and income, the study noted that ICTs adoption has a direct effect on carbon dioxide emissions in South Africa. Mobile phone subscriptions increased carbon emissions in both the short and long run while internet usage increased emissions in the long run. Transport services, on the other hand, reduced carbon emissions in both periods. Since the reported outcome appear to affirm the school of thought that in South Africa, ICTs lead emissions, it is recommended that the government of South Africa pays particular attention to ICT devices and equipment used in the country as well as the sources of energy used to power these devices and equipment. In the manufacture and/or importation of ICT devices into the country, energy efficient devices should be prioritized over non-energy efficient ones. Moreover, the devices should be designed such that they can be disposed off after their useful years in an environmentally friendly manner without leading to further pollution from e-waste. Furthermore, it is recommended that electricity to power the ICT devices and equipment be generated from renewable and sustainable sources rather than from heavy polluting sources. That way, emissions from the ICTs sector could be reduced despite continued adoption of ICTs. With respect to transportation, the negative effect on carbon dioxide emissions suggests that the government of South Africa ought to maintain and aim at further improvements in the energy efficiency of the transport system to increase the dampening effect of the sector on CO2 emissions. Given that the available dataset for this study terminates pre-COVID-19, the inability of this study to factor the pandemic period and its effects on the variables under consideration might be a limitation of the study. Thus, a future study that incorporates data that captures the COVID-19 period of 2020 and beyond will be a useful addition to the literature in view of the considerable reduction in global travels and the surge in the use of ICT and related services due to lock downs and virtual work environment.
Data Availability  The datasets analysed during the current study are available in the World Bank’s World Development Indicators repository, [https://databank.worldbank.org/source/world-development-indicators#].

Author contribution  PAK conceived research idea and analyzed the data. FAP did methodology and discussed results; KAM did literature review and conclusion/recommendations; all authors read and approved the final manuscript.

Declarations

Ethics approval and consent to participate  Not applicable.

Consent for publication  Not applicable.

Research involving human participants and/or animals  Not applicable.

Informed consent  The study did not rely on data or participants that consent was needed.

Competing interests  The authors declare no competing interests.

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