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The Environmental Kuznets Curve (EKC) Hypothesis on GHG emissions: analyses for transportation industry of South Africa

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Abstract
A series of energy-econometrics techniques were employed for a 5-year time span between 2016 and 2020. The tests of Environmental Kuznets Curve (EKC) hypothesis were conducted essentially to examine the significance of economic growth (GDP), energy consumption (EC), with energy intensity (EI), and on-road passenger vehicles (PV) as related to economic development on the mitigation of carbon emissions (CO_2-*eq*) in the transportation industry of South Africa. The findings from the prevailing research imply that, with respect to South Africa's transportation industry, CO_2-*eq* emissions increased in the course of early phases of economic growth while it tends to decline at certain levels of economic threshold. Though the nation maintains the edge of turning points in both the industrial and circular economy. The results further indicate a nexus between GDP and EC, which consequently affect the CO_2-*eq* emissions. The findings proffer the needs to monitor the EC from the long-run impacts alongside the short run impacts of the forecast. The per capita GDP from the short-run impacts of t-stat—(4.928) to the long run effects of t-stat—(5.033) rises, indicating its improper influence in the industry. To limit the use of fossil-based fuels, as demonstrated in the negative signal of EI for long-run impacts of a p-value (0.2835), then to the short run effects which possess a significant p-value. It also highlights the directional correlation surfacing between EC, EI and South Africa's on-road PV. In the computation context, the series was determined to be stationary at its first differences, as evident by the R^2 combined with the R^2 (Adjusted) values of 0.9837 and 0.9827, respectively, for both long-run and short-run assessments. The indication of the research among others further reveals that public transportation systems of road and rail options, which have the potentials to incorporate alternative energy sources, can be the required efforts to mitigate climate change and global warming effects in the transportation industry.

Keywords CO_2-*eq* emissions · Economic growth · Energy consumption · Passenger vehicles · Transportation · Climate mitigation

1 Introduction

The World Health Organization links air pollution to airborne particles that are harmful to living beings when they exceed a certain concentration threshold [1]. Greenhouse gases (GHG) are the gaseous compounds present in the atmosphere. They absorb infrared radiation and retain heat in the atmosphere, this is responsible for the greenhouse effect, eventually leading to global warming. On the necessity of economic development, owing to the expansion of economic growth, there has been a significant rise in transportation activities, industrial production, energy use and other human

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activities. These increased activities typically rely on the utilization of polluting energies and natural resources to the extent that economic development is frequently considered as a possible contributor to environmental degradation. In 2018, the International Energy Agency ranked the transportation industry second by virtue of its extensive reliance on fossil fuels (FFs) globally in terms of energy-related GHG and carbon dioxide (CO_2) emissions [2]. In the near future, road transportation, including passenger and freight vehicles, is expected to use more energy, with increase in emissions of over 50% [3–5].

Global concerns include the need for immediate action to mitigate GHG emissions given the increasing impact of the transportation industry on the environment [6]. The emission of GHG particularly carbon compounds, has far-reaching effects that extend beyond the surface consequence of global warming alone. In addition to the increase in respiratory and cardiovascular diseases, the number of all types of such associated diseases are also on the rise for the concerns of public health. These diseases ultimately result in a reduced lifespan for humans [7]. The transportation sector is among the principal sectors that trigger a country's economic growth, in full measure, it impacts daily activities. However, it is strained as one of the main sources of energy consumption, resulting in environmental degradation. The discourse among researchers and experts in twenty-first century has focused on the collateral damage to our world due to the unbearable increase in carbon emissions that led to global warming from the outcome of economic developments that resulted to environmental degradation [8].

Over the course of decades, the transportation industry has relied heavily on nonrenewable energy sources, mostly fossil fuels, this has led to severe environmental effects, significant and increasing contribution to global GHG emissions [9]. The transportation industry continues to play a significant role in all the economic sectors that are main contributors to carbon emissions. It was found that the reason for the increasing energy consumption in the transport sector is the escalating increase in passenger vehicles and the increase in income earned by vehicle users. The sector as indicated in the literature, has its primary direct causes of carbon emissions from multiple dimensions of privately acquired passenger vehicles, accounting for over 700 million on-road passenger vehicles globally [4, 10]. It is now a well-known fact, that achieving emissions' mitigation in transportation industry is more sophisticated than realizing reductions from stationary sources [11].

This ever-increasing debate in the turn of the twenty-first century has to focus on the economic development and environmental degradation associated to carbon emissions, and consequently the global warming [12, 13]. This necessitates global exclamation for several quarters. The global CO_2 atmospheric emissions based on the analysis conducted from NOAA's Global Monitoring Laboratory is 414.72 parts per million [14]. Although China and the United States remain the leading emitters, Africa as accounted by records of formal inspections is found to generate fewer emissions than the rest of the world. However, worldwide carbon emissions in global temperature have now exceeded 1.26^{0}C, evident by Hansen et al. [15]. Moreover, it is not only in the interests of South Africa and Africa, or any nation and, or continent; our world at large are all to take responsibility and be accountable on the bearable reduction of GHG emissions for the required lively air quality with serenity. In OECD nations the effects of transport infrastructure, economic growth, energy consumption, energy sources and carbon emissions were investigated on both short run and long run to determine the level of negative impacts of air quality and the measures to be taken to have an eco-friendly sustainable environment [13, 16, 17]. Countries worldwide, particularly those of developed economies, have acknowledged the importance of proper energy use with by-product emissions for optimal and strategic reductions. It is imperative to address the concerns regarding carbon emissions because emanating emissions negatively impact all forms of mortality via their influence on environmental air quality [18]. Africa carries the upset notoriety of having the highest mortality rate globally, many due to improper air quality as evidenced by available data (World Health Organization, 2018).

The primary source of energy used in the transportation sector is non-renewable energy of fossil fuel types, such as oil and gas, which discharge large amounts of GHG emissions [19]. This negatively impacts the environment and is responsible for a growing proportion of global emissions. The United Nations Conference on Trade and Development, which was established to further advance the role of the organization, stated that the transportation industry globally consumed approximately 67% of petroleum products in 2012. Based on the analysis, it has been forecasted that by the year 2035, if no drastic measures are taken, the energy consumption of fossil fuels will increase to 82%, and due to the persistent increase in passenger vehicles, its demand is deemed to rise to 78% by 2040 [20]. The outcomes surrounding these circumstances are the emissions of pollutants, particularly those of greenhouse gases present in the atmosphere, and of capable CO_2 equivalence. As it is estimated that there will be a 25% increase in CO_2 emissions only due to the combustion of fossil fuels in the transportation industry, it remains imperative to conduct research studies focusing on its mitigation. Furthermore, it is expected that CO_2 emissions will increase to 1.7% annually in industrialized emerging economies by 2030 [21], this is a better fit for concrete and genuine research engagements.

The transportation industry is one of the largest energy consumers, with increasing access of connectivity for point-to-point transfer of peoples, goods and services over the years. This has contributed to the increasing economic development. Although there is a growing demand for transportation services, it will result in increased energy consumption as the case applies, and thus the burning of fossil fuels. Consequently, this degrades air quality and the environment. The mitigation of CO_2 emissions, air pollution control due to road transport activities, energy management, and required freight management have been the prioritized objectives of sustainable ecosystems that are eco-friendly. In Africa, the highest energy consumption is still in the order of fossil fuels > coal > natural gas. Fossil fuels are frequently used in the transportation sector, whereas renewable energy usage is very minute in comparison. Although Africa is rich in clean energy sources that could better enhance air quality, however due to concerns in technological advancements and innovations, drive and will, it still relies heavily on non-renewable sources that degrade the environment [6, 22]. By virtue of the excesses in the utilization of fossils that are consequently factored in sectorial degradation, calls have been made to curb its menace by shifting to clean renewable energy sources, thereby enhancing environmental sustainability. Previous research has demonstrated a nexus between transport energy consumption, economic growth, and carbon emissions in the transportation sector. Transportation is crucial in South Africa and has a significant impact on how daily tasks are carried out. Over the past 20 years, South Africa's population has increased to 60 million, with an economic growth rate of 2.39% from 1994 to 2022. Human population and economic growth are the main influencing factors that enhance the transportation industry, and subsequently, passenger vehicles. Saidi et al. [23] found that an increase in freight transport and per capita income played a significant role in deteriorating the quality of the environment. Nevertheless, the transportation industry is one of the main sectors in which energy consumption is at high ratio.

The transportation industry of South Africa has undergone significant growth over the years, however, this expansion has resulted in a number of environmental degradations, particularly those caused by CO_2-*eq* emissions from excessive energy consumption. Estimates based on data provided by Statistics South Africa and South Africa Department of Transportation show that passenger turnover increased from 50.2 billion person-kilometres in 2010 to 152.6 billion person-kilometres in 2020, while it increased from 231.48 billion ton-km to 597 billion ton-km, for freight transportation [4]. According to the research conducted by Oladunni and Olanrewaju [6] of South Africa's transportation industry, the energy (oil) consumption—EC of fossil fuels for the year 2020, which was estimated to be 74,498,076,377 L of kilometers covered, possesses a qualitative nexus to economic growth—in GDP of 101,659 Rand per capita. This, in turn led to the potency for energy intensity—EI of 523.359 tce/ Rand 10,000. Consequently, it produced degrading environmental impacts of around 426.3 million tons in equivalent of CO_2 emissions.

This research is pertinent as it proposes actions to enhance air and environmental quality in reducing GHGs, particularly CO_2 emissions in the transportation industry. The ultimate objective of this study is to analyze the contributions of selected environmental driving forces to carbon emissions in the transportation industry of South Africa and how they impact economic development. Furthermore, it adds to the body of literature, for which few already available on the nexus among energy consumption, its intensity, economic growth, and the required decline in carbon emissions. Consequently, the examined model's study of South Africa presents vital engineering management techniques in addressing the prevailing concerns of GHGs, and more in particular that of the CO_2 emissions for the transportation industry by adopting energy econometrics approaches.

The subsequent sections of the research are as follows: section two presents the literature of relevant studies to the present objective. The section three gives a comprehensive description of the parametric materials and variables, using the procedures that guided the study. The empirical results of the investigation are reported in the fourth section. The discussion of the findings is addressed in the fifth section, and concludes by outlining the practical implications, policy recommendations, study limitations and research gaps for further studies.

2 Literature review

With the application of diverse econometric techniques, a sizable body of literature examines the viability of the EKC hypothesis in respect to GHG emissions of different countries and regions. This resulted in variations in the estimated results [24, 25]. Based on this hypothesis, the links between environmental pollution and economic growth per capita are in many cases (on a few exception) indicated to be inverted U-shape. This implies that working population earnings increase in tandem with economic growth. Therefore, environmental concerns will not require immediate intervention in the early stages, when environmental quality improves while the per capita income reaches the threshold known as the turning point. This hypothesis is as well demonstrated by Kang et al. 2016 [24]. Findings in the year 2016 from the studies of Kais and Sami [26] and Bilgili et al. [27] on EKC for GHG emissions show that the results depend on the type of analysis used (panel or time series) as well as the time period and geographical location that were studied. The pattern of the EKC hypothesis additionally supported by Danesh et al. [28] found that the majority of principal pollutants, including carbon monoxide (CO), nitrogen oxides (NOx), and sulfur oxides (SOx), sensed an inverted U-trajectory and supported the EKC hypothetical concept. According to Galeotti et al. [29], this link indicates multiple and mixed notions. While certain investigators observed a typical inverted U-shaped pattern, others expressed the notion that the turning point could not have been perfectly ideal [30, 31]. Other researchers supported the findings for the existence of N-shaped correlations, as can be seen in the works of [32] and [33]. Nevertheless, the overwhelming nature of this research niche shows that economic growth does not directly translate into a long-term decrease in GHG emissions, as emissions are linked to economic expansion through energy consumption [34, 35]. There is general agreement that rising energy consumption, which depends on the amount of energy the transportation sector uses, is the main cause of rising CO_2 emissions. However, the empirical results have shown that the evidence lacks stability because of variations in methodological approaches and for local, provincial, national, and global considerations, more specifically, the studied time period. Using statistical data from the United States, the empirical tests outcomes of [36] indicate that there is an unavoidable nexus between transportation energy consumption, income and fuels prices, one of which is a long-run relationship. The panel cointegration analysis conducted on OECD member states indicates that there is no connection between the price of gasoline, the amount of gasoline used (energy consumption), income, and car ownership in the short term. However, the results of the parametric variables demonstrate that they are connected. In a case study of the Malaysian economy, [37] analyzed some dynamic relationships between income, transportation energy consumption, and CO_2 emissions. The results demonstrate that income and transportation energy consumption are linked through the Granger causality. In their study of 107 economies, Liddle and Lung [38] evaluated the connection between per capita GDP and transport energy consumption and arrived at empirical findings that indicate that there is a long-term, positive unidirectional nexus between the two driving variables.

The Johansen cointegration results indicate that GDP impacts transportation energy consumption in the work of Achour and Belloumi [39]. However, the converse scenario is not applied in their analyses of the correlation between energy consumption and economic growth with respect to the economy of Tunisia. A generalized method of moments (GMM) was employed in the works [23] for the purpose of having a feedback confirmation on causality between transportation energy consumption and GDP of 75 nations of the world. Hence, determination was concluded. With the same methodology [40] empirically assessed the growth impact of public infrastructure under a panel of 18 OECD countries, revealing that infrastructure growth has a positive influence on labour productivity and total factor productivity. In recent years, a number of empirical studies have been conducted to better comprehend the variables of impacts on environmental quality, particularly energy consumption. Notwithstanding, there have been some attempts to shift from examining the environmental impacts of overall energy consumption to assessing the environmental effects of various energy sources, mostly non-renewable sources.

To further examine the correlation pattern for a country with a large human population, Maparu and Mazumder [41] assess the long-run causal relationship between transportation and economic growth in India. Vector Auto-regression and Vector Error Correction models were used to carry out short- and long-run causality checks, and the outcomes showed no long-run relationship. ARDL testing approach to cointegration and vector error correction model representation have been adopted to evaluate both the long-run and short-run links between economic growth, energy consumption, and carbon emissions to determine their consequential differences in impacts [42, 43]. Rehermann et al. [44] examined the non-linear relationship between GDP per capita and transport energy consumption for countries in Latin America and the Caribbean. The findings support the N-shaped curve, while the elasticity values of transportation energy consumption with respect to GDP per capita do not demonstrate a tendency to decline over time. Sharif et al. [45] of ARDL using quantitative-on-quantitative (QQ) empirical research on the transportation-growth nexus, demonstrates that the United States' transportation services benefit from economic growth. In addition, also with some considerations of ARDL as applied to Iran to include renewable and nonrenewable energies [46]. The fact that they serve as the driving forces for industrial development and economic growth, conversely, they lead to increase in the demand for mobility, increasing energy consumption, and intensity, investments in transportation infrastructure such as roads, highways, and bridges, and rising income levels. All of these play critical roles in the unbearable CO_2 emissions. For the purpose of achieving sustainable economic growth, [47] with [48] examined the EKC hypothesis in relation to substitution effect, growing contribution of transportation energy consumption to the resulting energy intensity and consequently the resulting GHG emissions. Energy intensity, which is a measure of a country's energy efficiency, can be calculated either as total-factor energy efficiency or single-factor energy efficiency, as proposed by Pan et al. [49].

Being aware of how energy functions are essential, as increased energy consumption not only draws economies on track for industrialization, but also has the potential to worsen sustainability concerns [49]. Moreover, researchers continue to find it pertinent to investigate the response pattern of per capita GDP on the economy as it impacts transportation industry. The forecasts increase in GDP per capita in square or cubic functional forms can be measurable with considerable efforts. Taking into account the precepts of per capita GDP, the empirical test of [50] established long-standing assertions that adhering to environmental degradation in the short run would lead to positive environmental effects in the long run. The per capita GDP can be in its short-span increase or squared, and possibly with allowance, and then more. In EU countries, Sterpu et al. [51] investigate the validity of the EKC hypothesis by extending the per capita GDP to its quadratic [27, 48, 52] and cubic functional forms [53–55], examining the correlation between GHG emissions and per capita with the impact of energy consumption on GHGs. This is especially significant in urban areas where demand for automobile is highest [56, 57]. In the modeled works of Gjorgievski et al. [58] as in the case of India argued that promoting nuclear energy production is the remedy to the nation's GHG/CO_2 problems. The findings revealed that in the long term, increased nuclear energy use mitigates India's carbon emissions. These have shown to be far-reaching evidence that one of the most important sectors for reducing carbon emissions is the transportation industry.

With respect to transportation, Alimujiang and Jiang [59] argue that energy is an essential component to maintaining economic growth, adding that an excessive reliance on fossil fuels could have two main adverse effects: (1) climate change and (2) air pollution, both of which pose threats to the planetary existence. Thus, the task of controlling air quality and climate change is critical. Nevertheless, new research endeavour are confirming the link between air pollution and global warming Zandalinas et al. [60]. Although relevant research on GHGs and CO_2 emissions from the transportation industry has made real strides, more actions are still required. Lu et al. [61] forecast future development trends for energy (oil) consumption and CO_2 emissions in the road transport industry and made recommendations to reduce intolerable oil usage. To forecast future development trends of energy consumption and GHG emissions for China and India's road transport industry, Mittal et al. [62] created a good-fit model and assessed potential emission reduction programs. It is found that the study of China CO_2 emissions attracted lots of scrutiny. Wang et al. [63] assessed the EKC hypothesis through panel techniques by adopting provincial data of China and found the presence of a U-shaped theorem between economic growth and CO_2 emissions. On some occasions, energy intensity is assessed with convincing results to be a driving force for increasing and (primarily depending on its adaptability) mitigating CO_2 emissions and to ease the transition to low-carbon economy [64]. There is now large-scale evidence that economic development has a positive impact on the environment, while the same economic growth under loose regulatory conditions leads to increased energy consumption. As proposed by researchers, there are causal correlations between the driving forces of GHG emissions Hasan et al. [15]. The correlation between economic growth, energy consumption and intensity, passenger vehicles, and CO_2 reduction having studied by Roinioti and Koroneos, [65] demonstrates that they have both positive and negative impacts on human lives and air quality as further indicated by Khan et al. [66]. Based on these considerations, to efficiently reduce carbon emissions and enhance clean energy use, it is imperative to determine the correlation among energy consumption, its intensity, and economic growth on carbon emissions Zhao et al. [67]. Ensuing the well-known EKC framework Alataş [68], salient literary discussions have been held over the past two decades regarding the nexus between energy consumption, its intensity, and economic growth that led to deteriorating effects on air quality, which account for the increase in GHG emissions. Researchers, especially energy economics experts in the niche, have proffered that, buttressing the significance test of this hypothesis [69–71]. A growing body of research has looked at economic growth and energy consumption, but not simultaneously with their energy intensity to the yielding impacts of carbon emissions on the environment [71, 72]. These studies examined developed, developing, and regional economies.

South Africa is investigated among the five developing countries examined by Sarkodie and Strezov [73] to determine the relationship between energy consumption and CO_2 emissions. Khan et al. [66] used the GMM technique to investigate the effects of energy consumption in transportation and logistics operations on environmental quality in 43 countries. Energy use and its intensities were demonstrated to determine the intensities of energy and how economic expansion affects environmental activities and the ensuing degradation in Malaysia and the OPEC countries, respectively [74, 75]. Paramati et al. [76] applied FMOLS, CCEMG, and DOLS for their analysis to explore how energy can positively impact trade openness and economic growth in OECD countries. Further research activities reliably revealed that the ecological footprint (EF) for carbon emissions in the United States can be mitigated with controlled measures for natural resources, human capital, energy consumption, and economic growth impacts on EF of the United States. This is related to the determination of energy efficiency and its maximization for sectorial use, with respect to the transportation industry.

Consequently, the outcomes of the ARDL further confirm that human capital can reduce EF, as energy consumption affects environmental deterioration [39].

In conclusion, no universally consistent nexus exist among variables, as already supported by the evidence of the EKC presented on the graph of the inverted U-shaped function, which is inconclusive. The findings have been subject to regional and national specifics, namely development path, population size and quality, economic structure, natural endowments, trade policy, and capacity of functioning institutions, as further envisaged in the empirical studies of Onafowora and Owoye [77] and Dijkgraaf and Vollebergh [78]. It can be seen that only few studies consider the presence of energy intensity in their investigative analyses, and far less considered the mixed relationship of transport energy consumption with energy intensity, that has been demonstrated in this research. As the South African transportation sector's rising GHG or CO_2-*eq* emissions becomes the focus of the present study, there exists a correlation between energy consumption, energy intensity, and economic growth. Based on previous research using similar approaches [4, 6, 20] the present research studies make efforts to literature by further widening the analysis of the correlations among the economic variables of impacts (–EC–EI–PV–GDP—CO_2-*eq* emissions) taken from the transportation industry of South Africa as a reference case with the employment of datasets from 2016 to 2020.

3 Data and method

3.1 Data

The 5-year dataset utilized as the parametric variables in this investigation was obtained from [6] for the nine provinces of South Africa between 2016 and 2020. The variables include the following:

- Carbon emissions as per capita greenhouse gas (GHG) emissions, taken in tones of CO_2 equivalent.
- Per capita gross domestic product (GDP), taken in South Africa Rand.
- Per capita gross energy (oil) consumption (EC) taken in tons of oil equivalent.
- Per capita energy intensity (EI), taken in Tce per 10,000 Rand.
- Number of on-road passenger vehicles (PV) contributing to carbon emissions.

Taking into account the fact that the data for each province is different by characteristics in terms of population, energy use, and economic growth, it is observed that using variable per capita values will lead to significant results. To conduct these precepts, as in the case of South Africa, the nominal indices are operated over the population numbers. The employed datasets are presented in panel:

1. The panel dataset provides the values for the driving forces under investigation, namely EC, EI, GDP, and CO_2-*eq* emissions, for the nine provinces of South Africa.
2. Time series data provide parametric values for each of the variables from the time period of 2016 to 2020 for each of the nine provinces of South Africa.

The data series were set up using a panel design. Data for the 2021–2023 timeframe are yet to be drawn to fit the investigation for public purposes.

3.2 Models

In the current research analysis of EKC, three different types of empirical specifications are generally considered: (i) linear specifications, (ii) quadratic (inverted-U) specifications, and (iii) cubic (N-shaped) or sideways-mirrored (S-shaped) specifications [77]. The graph in Fig. 1 as shown illustrates the Environmental Kuznet Curve concepts and perspectives as demonstrated by the authors. This posits a correlation between the indicators of environmental degradation and economic development. It also suggests that during the early stages of industrialization and the absence of knowledge and circular economy, GHG emissions increase as environmental quality decreases. However, beyond a certain level of economic development, which varies based on different indicators, the trend reverses, with high economic growth and the inclusion of circular economy resulting in environmental improvement.

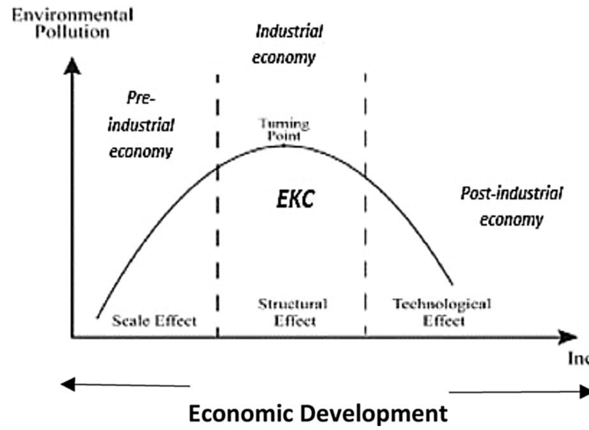

Fig. 1 Enviromental energy-econometrics analysis of EKC hypothesis [Author's design]

There are broad functional forms that possess additional pertinent factors, namely, external variables of time, provincial characteristics, and technical factors. The general form of the equation is as follows:

$$Q_t = a_0 + a_1 \ \ln \ Y_t + X_t + \varepsilon_t \tag{1}$$

$$Q_t = a_0 + a_1 Y_t + a_2 Y_t^2 + X_t + \varepsilon_t \tag{2}$$

$$\ln Q_t = a_0 + a_1 \ \ln Y_t + a_2 (\ln \ Y_t)^2 + X_t + \varepsilon_t$$

$$Q_t = a_0 + a_1 Y_t + a_2 Y_t^2 + a_3 Y^3 + X_t + \varepsilon_t \tag{3}$$

$$lnQ_t = a_0 + a_1 \ lnY_t + a_2 (lnY_t)^2 + a_3 (lnY_t)^3 + X_t + Xn + \varepsilon_t$$

In accordance with the EKC specifications provided above, this study examines CO_2-*eq* emissions (Q) as the dependent variable, per capita yearly GDP (Y) as the independent variable, time period (t) as a factor, and the explanatory variables (X). Furthermore, ε represents the random error component, and a_i denotes the coefficients of the model, which can also be referred to as the marginal propensity for emissions. Upon conducting the EKC analyses for the three specifications, several technical details can be discerned:

(1) IF (→) $\mathbf{a_1 > 0}$**—**linearity of correlation around GDP with CO_2-*eq* emissions. [a_1 must be significant]
(2) IF (↔) $\mathbf{a_1 < 0}$**—**monotonic decrease linkage around GDP and CO_2*eq* emissions. [a_1 must be significant]
(3) IF $\mathbf{a_1 > 0}$, $\mathbf{a_2 < 0}$ & $\mathbf{a_3 = 0}$**—**quadratic linkage around GDP and CO_2-*eq* emissions. [Equilibria to be reached]

This is to evaluate the existence of an EKC-type nexus between CO_2-*eq* emissions, economic growth, and the impact of energy consumption on CO_2-*eq* emissions in the transportation industry, employing two energy-econometrics' models as the basis for further analyses. To measure the environmental impacts, we use CO_2-*eq* emissions as a dependent variable, while GDP, and EC, EI and PV are taken as the independent, controlling independent variables, respectively as the case applies.

3.2.1 Model 1

Taken as the first model, we employ quadratic to perform test on the EKC hypothesis as follow:

$$CO_2 - eq_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP_{it}^2 + \alpha_3 EC_{1it} + \alpha_4 EI_{2it} + \alpha_5 PV_{3it} + \varepsilon_{it} \tag{4}$$

where Q corresponds to CO_2-*eq* emissions, *Y* is the GDP per capita, $X_1 \ldots X_n$ are the covariate explanatory variables. The ε_{it} represents the error term, *i* denotes the provinces of South Africa while *t* is the time period. Other studies have employed similar approach, however, with different explanatory driving factors [78].

3.2.2 Model 2

Using the cubic equation, we applied the second model to conduct tests on the N-Shape hypothesis for the Kuznets curve as demonstrated:

$$CO_2 - eq_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 GDP_{it}^3 + \beta_4 EC_{1it} + \beta_5 EI_{2it} + \beta_6 PV_{3it} + \varepsilon_{it} \tag{5}$$

The order of representations are as specified in Eq. (1). There are other researchers who employed a cubic model similar to the one utilized in this study due to their close proximity [48]. The parametric variables are taken in their logarithmic transform. The sign for coefficients of Y, Y^2, Y^3 applied to economic growth and the specific correlations among them regulate the shape of the approximating surface.

We employed the ARDL bounds testing approach to reconfirm the presence of EKC and cointegration of variables as proposed by [79]. Eq. (5) fully remodeled in Eq. (6) from [48] background as:

$$\begin{aligned}\Delta\left(CO_2 - eq\right)_t = \beta' + \sum_{i-1}^{p} \beta'_{1i}\ \Delta\left(CO_2 - eq\right)_{t-i} + \sum_{i-0}^{p} \beta'_{2i}\ \Delta(GDP)_{t-i} + \sum_{i-0}^{p} \beta'_{3i}\ + \Delta\left(GDP^2\right) \\ + \sum_{i-0}^{p} \beta'_{4i}\ \Delta(GDP^3)_{t-i} + \sum_{i-0}^{p} \beta'_{5i}\ \Delta EC_{t-i} + \sum_{i-0}^{p} \beta'_{6i}\ \Delta EI_{t-i} + \sum_{i-0}^{p} \beta'_{7i}\ \Delta PV_{t-i} \\ + \upsilon_o\left(CO_2 - eq\right)_{t-i} + \upsilon_1 GDP_{t-1} + \upsilon_2\left(GDP^2\right)_{t-1} + \upsilon_3\left(GDP^3\right)_{t-1} + \upsilon_4 EC_{t-1} \\ + \upsilon_5 EI_{t-1} + \upsilon_6 PV_{t-1} + \omega_t\end{aligned} \tag{6}$$

where Δ denotes variable's first difference operator, P stands for lag lengths. To use ARDL we first demonstrate cointegration among the variables. To proceed, the null hypothesis test of no cointegration is conducted against the alternative hypothesis in this other of format:

$$[H_0 \neq \vartheta_0 \neq \vartheta_1 \neq \vartheta_2 \neq \vartheta_3 \neq \vartheta_4 \neq \vartheta_5 \neq \vartheta_6]$$

$$[H_0 = \vartheta_0 = \vartheta_1 = \vartheta_2 = \vartheta_3 = \vartheta_4 = \vartheta_5 = \vartheta_6]$$

F-statistic is inculcated with respect to the series being integrated either at I(0) or I(1). As the case applies, if the F-statistic value is greater than the upper bound value, there exists cointegration among the variables. If the F-statistic value is below the crucial lower bound value, the acceptance of null hypothesis that there is no cointegration is observed, as no precision will be made following that F-statistic lies between upper and the lower bound values [52]. For the study's validation, the critical and F-statistic values are selected by applying cointegration technique as put forward by [52]. The estimates of the short run coefficients are obtained by (***P***) whilst the long run dynamics are estimated with the coefficients $\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4, \vartheta_5, \vartheta_6$ as expressed in Eq. (6). The ARDL bound testing approach is an effective method for simultaneously determining better estimates of both short-run and long-run dynamics. It achieves this through a modest linear transformation, which provides a superior approach for obtaining more accurate estimates. To assess the robustness entirety of the empirical models, diagnostic tests on heteroskedasticity, normality and autocorrelation tests are conducted, thereby running the validity and consistency of the long run dynamics. This is carried using canonical cointegration regression, dynamic ordinary least square (DOLS), and modified least square (FMOLS).

Modeling the data to be analyzed [6], and the time span of 5 years in real terms along with their provincial locations are illustrated in Fig. 2a, and b respectively as shown:

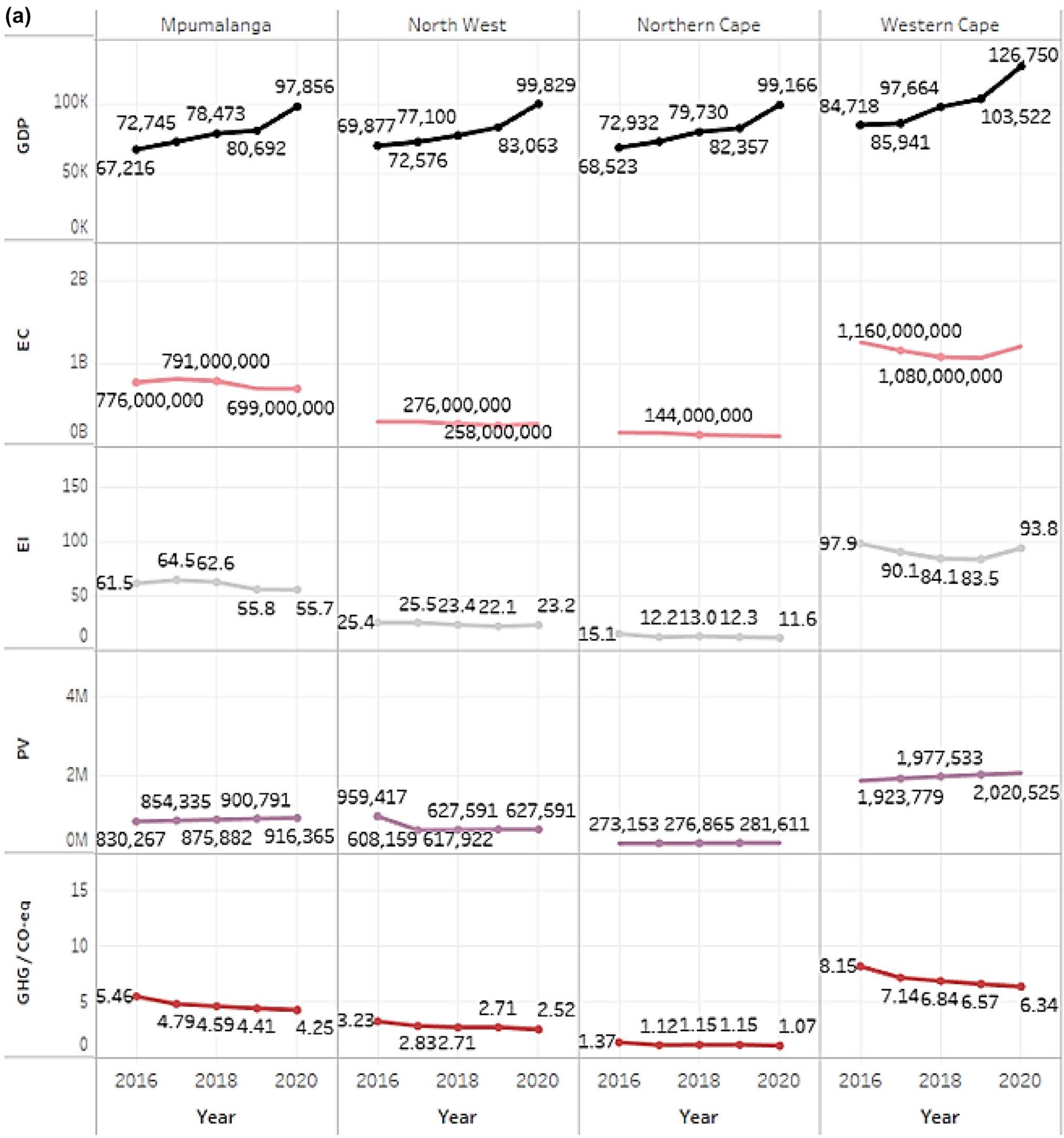

Fig. 2 **a** South Africa's driving forces impacts on GHG/CO_2-*eq* emissions in transportation industry, 2016–2020. **b.** South Africa's driving forces impacts on GHG / CO_2-*eq* emissions in transportation industry, 2016–2020

4 Empirical results and analysis

The study investigates how economic growth in GDP per capita and its extensions, CO_2-*eq* emissions, energy consumption, its yielding energy intensity and the on-road passenger vehicles cointegrate to bring forth the observable environmental impacts in the transportation industry of South Africa. We applied ARDL bound testing method in achieving this and to also prevent spurious regression. It is essential to examine the order of integration prior to

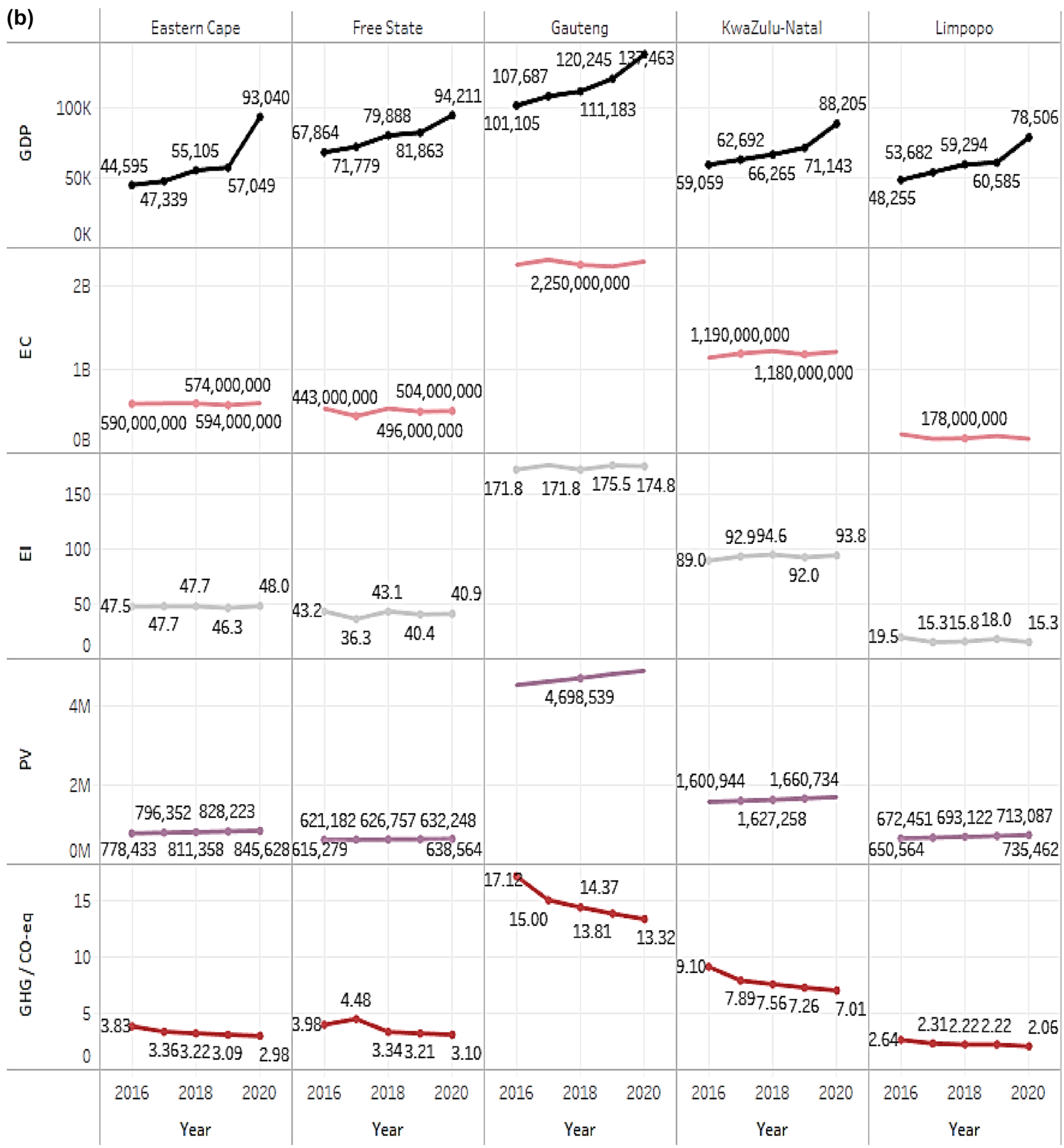

Fig. 2 (continued)

ARDL bound testing method. Augmented Dickey-Fuller (ADF) and Philips Pearson (PP) tests are employed in attaining the consequential values in order to proceed. The findings of both ADF and PP indicate that none of the series is stationary at Level, as illustrated in Table 1. Hence, the hypothesis of no stationary is rejected, as it implies that all the variables are integrated at first difference. The results further show that none of the variables is integrated at I(2). By the revealing response, the ARDL bounding technique is found appropriate.

When it has been demonstrated that none of the variables are integrated in the order I(2), the cointegration between them is further evaluated. The decision is prerequisite prior assessments of parametric variables for cointegration. To begin with, unrestricted VAR models are utilized and to subsequently identify the optimal lag length of 2 using SIC

Table 1 Unit root tests results from log transforms of variables

Variables	Augmented Dickey Fuller (ADF)		Phillips Pearson (PP)		Integration Order
	At level	First difference	At level	First difference	I (1)
CO_2-*eq*	− 4.406 [0.037]	− 23.294* [0.000]	− 4.980* [0.025]	− 40.831 [0.000]	I (1)
GDP	− 0.677 [0.737]	− 1.900* [0.296]	− 0.519 [0.776]	− 2.468 [0.186]	I (1)
GDP^2	− 0.577 [0.761]	− 1.605* [0.379]	− 0.577 [0.761]	− 1.872 [0.303]	I (1)
GDP^3	− 0.686 [0.734]	− 1.515* [0.408]	− 0.686 [0.735]	− 1.694 [0.354]	I (1)
EC	− 1.294 [0.518]	− 2.861* [0.141]	− 1.295 [0.518]	− 3.086 [0.123]	I (1)
EI	− 1.939 [0.292]	− 1.678* [0.358]	− 3.198* [0.093]	− 1.678 [0.359]	I (1)
PV	0.407 [0.942]	− 12.464* [0.00]	0.655 [0.960]	22.013 [0.000]	I (1)

criterion. The optimal lag length of 2 adjustments is imperative at the selection of the optimal length. Thereafter, proceeding to find adjustments from the parametric variables. In confirming the cointegration, Wald test is applied to determine the value of F-statistic. The findings of Table 2 reveal the rejection of null hypothesis on the condition that no cointegration on the modeled equations.

Johansen cointegration test is employed to verify the validity of the F-statistic as generated by Wald test performance. In conducting Johansen cointegration, Trace statistics with Eigen-values were obtained. The relevance of Trace statistics and that of Eigen-values demonstrates the cointegration correlation among the investigated parametric variables. These are as presented in Table 3 in which the analyses made it evident that at the very least, cointegration correlations exist. Hence, Johansen cointegration results validate Wald statistics. Both long run and short run estimates for Eq. (6) were conducted to determine the level of significance of the exogenous variable of CO_2-*eq* emissions and the underlying independent variables. In Table 4, it can be observed that all the coefficients possess the responsive signs. More so, all the series are made significant at 0.05% level. In other words, the indication of GDP positive-path coefficient buttress

Table 2 ARDL and ARDL with Bounds test of variables

Variables	Pure ARDL			Variables	ARDL for Long Run and Bounds Test		
	Coefficient	t-stat	Prob*		Coefficient	t-stat	Prob*
CO_2-*eq*	0.269	4.038	0.000	CO_2-*eq*	0.249	6.494	0.000
GDP	49.854	2.201	0.029	GDP	49.856	2.201	0.029
GDP^2	1.439	1.252	0.212	GDP^2	9.825	2.128	0.035
GDP^3	0.637	0.591	0.555	GDP^3	0.596	2.969	0.003
EC	0.011	0.572	0.568	EC	0.011	0.572	0.577
EI	0.043	0.681	0.024	EI	0.043	0.670	0.565
PV	721.233	3.955	0.000	PV	721.267	3.954	0.000
R^2	–	0.985		R^2		–	
F-stat	–	2.086		F-stat		8.264	

Table 3 Results of Johansen test for cointegration of variables

Rank	Trace values			Eigen values statistics		
	Trace statistics	Critical value	Prob.**	Eigen values	Critical value	Prob.**
None	3630.172	125.615	1.000	2508.077	46.231	1.0000
At most 1	1122.096	95.754	0.000*	574.506	40.078	0.0000*
At most 2	547.589	69.819	0.000	276.764	33.877	0.0001**
At most 3	270.826	47.856	0.000	180.389	27.584	0.0000
At most 4	90.437	29.797	0.000	70.718	21.132	0.0000
At most 5	19.719	15.495	0.010	12.990	14.265	0.0781
At most 6	6.728	3.841	0.010	6.728	3.841	0.0100

* denotes hypothesis rejection at 0.05 levels. Mackinnon-Haug-Michelis (1999) p-values

Table 4 Long run and short run for parametric variables

Endogenous (dependent) variable: CO_2-*eq* emissions					
Long run estimations			Short run estimations		
Series	*t*-stat	p-values	Series	*t*-stat	p-values
GDP	5.033*	0.000	GDP	4.928*	0.0000
GDP^2	− 4.945*	0.000	GDP^2	− 5.219*	0.0000
GDP^3	− 0.947*	0.3448	GDP^3	− 2.237*	0.0265
EC	0.393*	0.6947	EC	0.383*	0.7019
EI	− 1.076*	0.2835	EI	− 1.100*	0.0000
PV	4.758*	0.0004	PV	− 4.283*	0.0000
Constant	− 5.87	0.0000	Coint.Eq. (6)		
Diagnostic tests					
R-squared					0.9837
R-squared (adjusted)					0.9827
DW Stat					1.5999

* connote the level of rejection 5% level of significance

that CO_2-*eq* emissions in the transportation industry surfaces with increasing economic growth in both forecasts for long run and the short run.

In contrast as revealed in Table 4, there are strong indications of long run and short run correlations among economic growth in square and cubic forecast with CO_2-*eq* emissions found possessing negative sign coefficients. The implication as derived, implies that CO_2-*eq* emissions in South Africa's transportation industry increases at the early industrial phase of economic growth and fall after reaching certain level of economic expansion. The investigation validates the U-shaped EKC hypothesis in South Africa relating to transportation sector. The findings are related to [42] who conducted such line of analyses to confirm the existence of EKC in Italy, and in Turkey by [80], more so, in OECD countries [13, 16, 17].

With the peculiar case of South Africa transportation industry in the staggering amount of energy (oil) consumed, the on-road passenger vehicles, energy in oil consumption with its intensity are integrated in the model. This offers new directions to mitigate carbon emissions on the level at which South Africa's economic development has reached from the general interpretation for the U-shaped EKC hypothesis, a level being depicted in Fig. 3. It is observed that from the level at which energy are used in the transportation sector of South Africa, Energy consumption as inspected with its intensity contributes to the emissions of GHGs/CO_2-*eq* in South Africa. On the other hand, although in the long run passenger vehicles do not reveal a negative impact, however, in the scale of short run it possesses a sensitive negative impact. The demonstrated energy-econometrics analysis implies that increasing passenger vehicles (IC Engines) concurrently lead to increase in energy (oil) consumption vis-à-vis energy intensity.

The findings of the study relate to that of Zhao et al. [67] with a similar outcomes for China. Based on the research conducted, it was discovered that in numerous instances, public transportation alternatives are more eco-friendly for South Africa's transportation systems than the high volume of passenger vehicle traffic, which was found to be one of the primary contributors to CO_2-*eq* emissions in the transportation industry.

This is proved viable as South Africa heavily relies on conventional (fossil) energy sources such as oil and coal, particularly oil (in fossil) for its transportation activities. Already, well over 90% of the energy use in the transportation industry is fossil-based fuels.

To check the capacity of the analyses, the resulting model of Eq. (6) is assessed by employing three different techniques, namely, fully modified least squares (FMOLS), dynamic least squares (DOLS), and canonical cointegration regression (CCR), purposed to examine the validity and reliability of the obtained outcomes through the ARDL bound test approaches [80]. The findings of Table 5 indicate that whilst economic growth possess a positive and significant impact on CO_2-*eq* emissions, the square and cubic of economic growth (GDP^2 and GDP^3) have negative significant impacts. This is the implied case applied to the transportation industry of South Africa. In addition, from the analytical interpretations being sensitive of the GDP flow-line, it can be rewarding to improve eco-friendly environment. Ultimately, the results of the ARDL bound test approach applied under three distinct techniques support the findings of the research which are further presented in Table 5.

The CUSUM and CUSUMsq are performed with high sensitivity to verify the lack of structural invariance, endogeneity tests, and the reliability and stability of the models for both long and short run estimations. The results are graphically

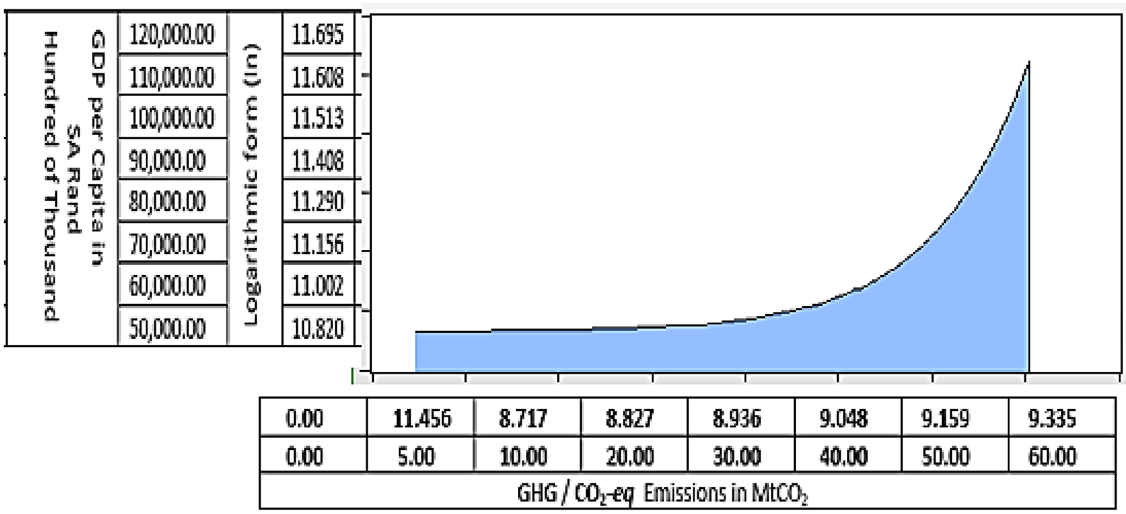

Fig.3 Plot-trends correlations between economic growth and CO_2-*eq* emissions in SA transport

presented in Fig. 4a and Fig. 4b. The assessed stability diagnostics for both tests largely reside between the critical (red) lines; this implies that the model can be put forward for policy recommendations with respect to the availability of the data employed. They are found fit. It is noteworthy that, based on the most current literature, this research is considered to be forthcoming in South Africa and the continent of Africa. In Fig. 4b, it can be observed that the data as they were not readily available from a single source of a database.

The readings may not be efficient and robust enough, however optimum determination has been exercised. Figure 4b can only further implies that at the readings of 5% level of significance CUSUMsq for high sensitivity can be determined (as it also travels between red-lines indicator) with respect the prevailing empirical analysis.

As presented in Fig. 5a, both the short-run and long-run impacts are identified. The parametric variables taken into consideration are contingent on the interpretations of EKC hypothesis in the derived models of energy econometrics technique for the South Africa's transportation sector. This serves as the underlying approach of the research studies. The interpretation of the readings depicts that for both long and short runs, indications exist for the correlation between economic growth in GDP per capita (**A** region) and GHG emissions (**E**) of the transportation industry. As Energy Intensity (in the **C"** region) has to bridge the gap, there also exists a causal relationship between Energy Consumption—EC in the **B'** region and Passenger Vehicles—PV in the **D** region. Along the axis of **A-D-E** in the composition of GDP, PV and GHGs there exist an indication of causal interconnection between the variables as evidently provided in empirical analyses of the 5-year employed dataset of transportation industry of South Africa.

Figure 5b, as indicated, conveys the relational linkages of variables' controls that exist among the selected driving forces impacting on GHG emissions in the transportation sector of South Africa. In line with the analyses performed on

Table 5 Validity and reliability inspections with FMOLS, DOLS and CCR

Variables	Endogenous variable of CO_2-*eq* emissions					
	FMOLS		DOLS		CCR	
Series	*t*-stat	*p*-value	*t*-stat	*p*-value	*t*-stat	*p*-value
GDP	0.584*	0.5601	– 2.335*	0.0208	6876.906*	0.0000
GDP^2	– 1.806*	0.0725	– 1.7802*	0.0660	72,245.04*	0.0000
GDP^3	1.162*	0.2465	1.158*	0.2387	– 95,056.49*	0.0000
EC	– 3.786*	0.0002	– 3.296*	0.0012	– 13,311.43*	0.0000
EI	– 1.870*	0.0630	0.343*	0.7323	– 5256.16*	0.0000
PV	3.784*	0.0002	– 1.837*	0.0682	8110.55*	0.0000
Constant	– 3.581*	0.0004	– 3.568*	0.0003	27,372.28*	0.0000

* indicate the level of rejection at 5 percent level of significance

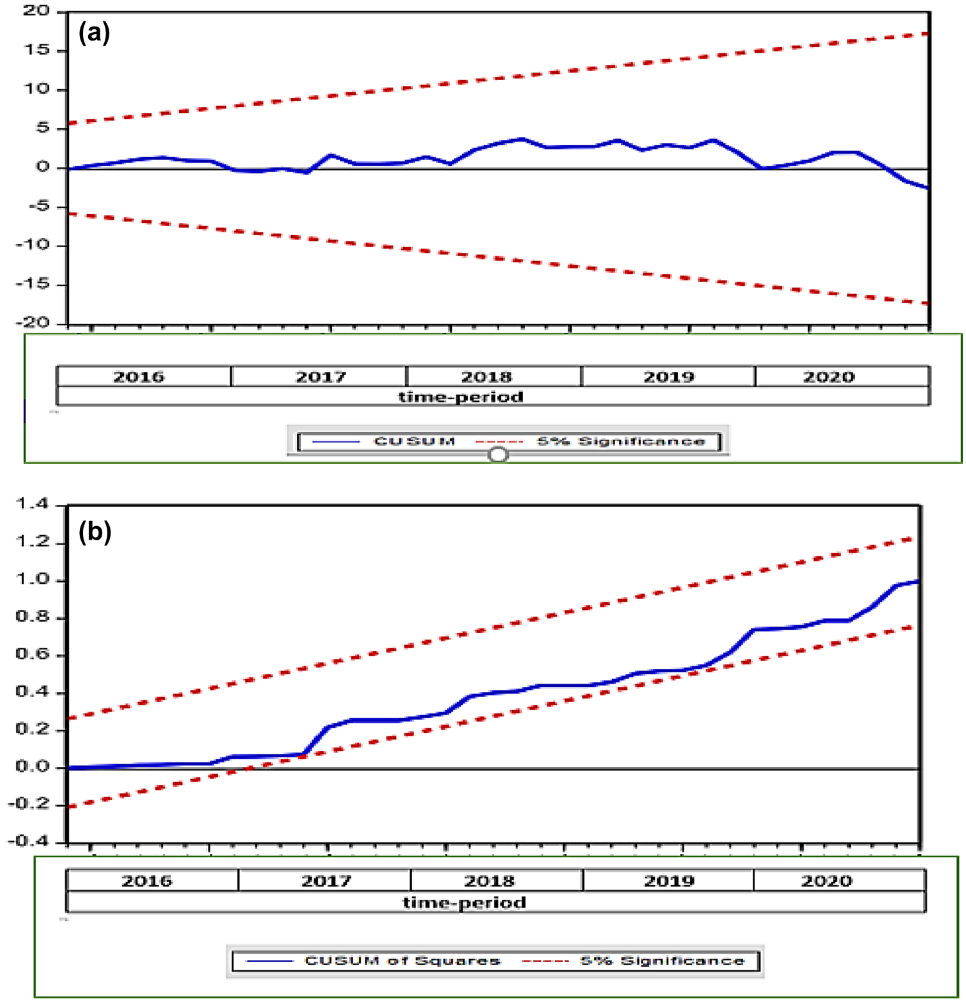

Fig. 4 **a** Trend-plot for cummulative sum of recursive residual at critical bound of 5% significance. **b** Trend-plot for cummulative square of recursive residual at critical bound of 5% significance

the hypothetical EKC, it can be deduced that the outcomes of GHG emissions are well dependent on variable's computational inputs both quantitatively and qualitatively. As investigated for all the nine provinces of South Africa with time period of five years spanning from 2016 to 2020. The alterations and the adjustments of one or two or more of the endogenous variables can significantly lead to the required environmental outcomes.

5 Conclusion and policy implication

5.1 Policy implications for reducing GHG emissions in transportation

The study delves into the concept of energy econometrics complexity and applies the Environmental Kuznets Curve hypothesis, commonly utilized to analyze the nexus between economic development and environmental quality. South Africa is still a developing nation, despite being more developed of Africa's member states. In line with its Paris Agreement obligations, South Africa has been determined to further reduce its transportation sector GHG emissions from the 10-year of 60MtCO_2-*eq*. This value serves as the share of the tranportation industry from the South Africa's overall contribution of 1.2% of the world's GHG emissions, totaling 8.08 billion metric tons in CO_2 equivalent, globally. Identifying the pattern of the Environmental Kuznets Curve (EKC) hypothesis as it pertains to economic development and environmental degradation for the requisite air quality is essential for assessing the impacts of the driving forces in the industry that contribute to carbon emissions.

Provinces in South Africa should be cognizant of their respective stages of economic development, energy use, and GHG emissions, particularly that of transportation sector. They should make targeted advances in economic development

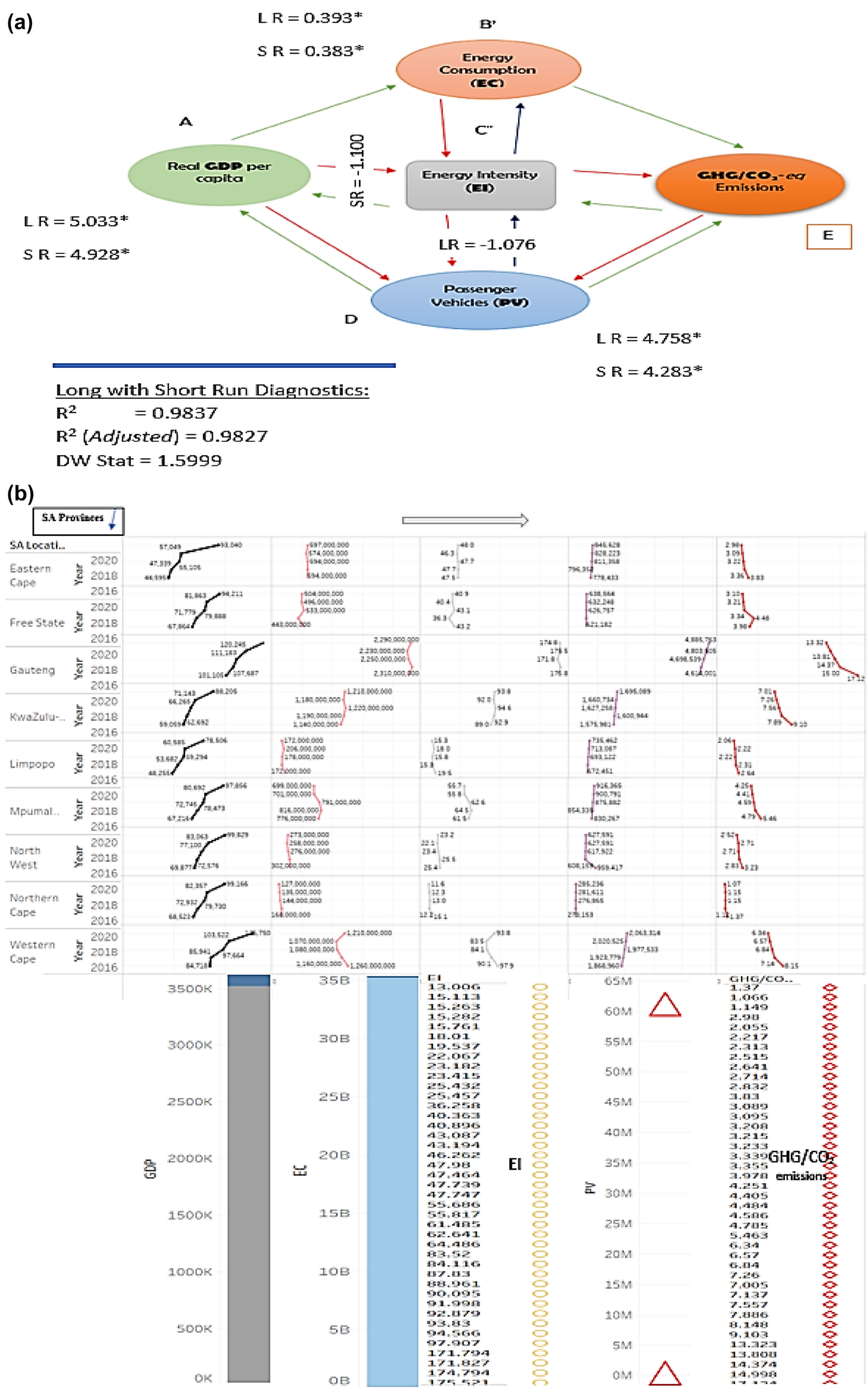

Fig. 5 **a** Acyclic model indicator of parametric variables-flow on EKC hypothetical analysis. **b** Directional linkages of resource-controls among selected driving forces over GHG/CO-*eq* emissions

while effectively mitigating GHG emissions. At present, all the provinces are in the rising stage and have not yielded to the turning point of the interpreted EKC. The rising economic development due to carbon intensive energy is the primary reason for the accounted carbon emissions in the industry. Although, significant environmental degradation has been recorded, the nation still requires a lot of transportation systems to move people, goods, and services, nevertheless, those with sustainable air quality. According to the analysis of the development trend of transportation in various cities and provinces of South Africa at this stage, there are still problems of energy sources for both renewable and nonrenewable, and that of transportation means and modes. This, obviously lack transportation's economic development objevtives. By updating the economic structure and controlling the development of transportation systems reasonably, a high developed economy with low carbon emissions can be achieved.

With a measure of controlling unbearable population and decreasing mortality rates while improving technological innovations, the effect of passenger vehicles on traffic emissions can be restrained. More to this effect, passengers can be guided on individual and personal benefits of choosing clean and green travel options. The transportation pricing index has the potential to be a significant factor in reducing carbon emissions. Altering consumption approach can be a viable strategy for achieving balance between the economy and the environment that will lead to sustainable development.Furthermore, the government should promote and incentivize the use of environmentally-friendly modes of transportation and the use of clean products among local residents. Modifying the cost of transportation services is an essential measure that can influence people's travel choices and subsequently impact the energy demand and carbon emissions in the transportation industry. Efforts should be made to enhance the affordability and convenience of public transportation in order to change people's preconceived notions about travel. Highway transportation is among the passenger travel that should be considered, particularly intercity and city buses, which mostly relies on fossil fuels for passenger transit. By so doing, the use of energy for automobile will predominantly shift towards natural gas and electricity. The government has the ability to diminish individuals' reliance on gasoline-powered vehicles by implementing tax policies, fuel surtaxes, and vehicle purchase taxes that are tailored to particular vehicle types. Furthermore, providing policy assistance for environmentally friendly automobile manufacturers to foster the growth of automobile industry that is clean. Offering of incentives and benefits to consumers who purchase such automobiles, can encourage individuals who use private cars to transition to a more environmentally friendly mode of transportation with reduced carbon emissions. To encourage long-distance of on-road travel that is environmentally friendly, it is important to build gas stations and charging infrastructures along the highway. This will gradually shift people's transportation practices and promote the development of low-carbon traffic in South Africa transportation sector and elsewhere.

It is important to note that there are limitations and gaps in the research. This study investigates the nexus between economic development and environmental degradation, specifically focusing on the income-emissions aspect of the EKC hypothesis in the transportation industry of South Africa. Due to limitations in data and geographic scope, our analysis is restricted to the nine provinces of South Africa over a five-year period from 2016 to 2020. Additional research investigations have the potential to broaden the temporal scope and increase the number of countries examined. Moreover, it has the capability to examine many sectors or industries both independently, and as integrated concerns, resulting in changes to the methods, and scale of the tests and diagnostics, which will ultimately lead to more outcomes.

5.2 Conclusion

Using energy econometrics techniques, this study investigates the effects of economic growth (GDP per capita), with it being squared and cubic, followed by energy consumption (EC), energy intensity (EI), and on-road passenger vehicles (PV) on the mitigation of GHG emissions in CO_2 equivalence for the transportation industry of South Africa. A five-year dataset spanning from 2016 to 2020, as it appears in Fig. 2a, and b are adopted. The year can further be extended, only to portray an extension for subsequent forecasts. The study examined South Africa's nine provinces, considering their varying rates of economic development and dependence on fossil fuels for energy in the sector across all the provinces.

From the study period of 2016 to 2020 as 2021 only being the model's extension forecast, South Africa's per capita GDP ranges from R71, 920.00 to 101,659.00. The country's energy (in oil) consumption (EC) from 2016 to 2020 is estimated ranging from 6,925,070,093 to 7,799,172,128 L and in conversion it tallies between 39.850 to 41.039 metric tons of oil consumption in energy content. The energy intensity (EI) for the study periods is within the range of 513 Tce per R10, 000.00 to 537 Tce per R10, 000.00 from 2016 to 2020 as estimated. South Africa's on-road passenger vehicles for the research period of 2016 to 2020 are taken in units of vehicle population within the range of 11,964,234 and 12,701,630 of vehicle units. Considering the energy-econometrics debates around the EKC hypothesis sectioned into four main categories, namely; cointegration of the parametric variables, endogeneity concerns, simultaneity and omission bias for variables, the prevailing econometrics instruments are employed in the peculiar case of South Africa's transportation industry.

In the context of South Africa, economic growth in GDP (inculcating GDP^2 and GDP^3), energy consumption with its intensity, and on-road passenger vehicles are modeled on CO_2-*eq* emissions. In the investigation, the EKC test is employed to South Africa's industry using the aforementioned variables as explanatory while taking CO_2-*eq* emissions as the dependent variables. With the outcome of the prevailing research, CO_2-*eq* emissions in South Africa's transportation industry grew through the early phases of its economic expansion at specific level of economic threshold. To clarify the research main contribution, the study further demonstrates the directional nexus among South Africa's on-road PV, EC, EI and per capita GDP with its excesses which is negatively probable, especially the economic expansion by a cubic scenario. The ARDL bound test approach was employed to analyze the cointegration correlation among the parametric variables. For the high performance of the model, three high-powered techniques were employed to examine the accuracy and reliability of the results from the ARDL bound test approach: FMOLS, DOLS and CCR, respectively.

Quantitatively, the series were determined to be stationary at their first differences, as indicated by $\boldsymbol{R^2}$ and $\boldsymbol{R^2}$ (***Adjusted***) values of **0.9837** and **0.9827**, respectively, for both long-run and short-run estimations. From the deductions of the findings, it is imperative to monitor the reactions of EC on the long effects of the *t-stat*—(**0.393**) and *p-value*—(**0.6947**) alongside the short run forecast impact of the *t-stat*—(**0.383**) and *p-value*—(**0.7019**). From the short run effects shown in the t-stat—(**4.928**) with p-value (**0.0000**) to the long run effects demonstrated with p-value (**0.0000**), the per capita GDP increases, indicating its improper influence in the sector. Limiting the burning of fossil fuels is essential as shown by the negative signal of EI for the short run impacts of t-stat (**-1.100**) with p-value (**0.0000**) and the long- run impacts shown of *t-stat* (**-1.076**) with p-value (**0.2835**).

From these analyses, the following conclusions have been drawn:

1. There are implications of Environmental Kuznets curve (EKC) hypothesis in the significance of economic growth, energy consumption with its intensity, and on-road passenger vehicles in the transportation industry of South Africa.
2. Economic growth has a significant positive impact over GHG/CO_2-*eq* emissions provided that it is checked without spanning out of control.
3. In both the long and short run paths, energy intensity can have significant positive impacts in South Africa.
4. Under proper investigation, the neutrality hypothesis is confirmed, as a correlation exist between CO_2-*eq* emissions and economic growth which at large contribute to economic development.
5. There is also evidence of proportional nexus between the energy consumption and passenger vehicles with CO_2-*eq* emissions in the transportation industry of South Africa.

In line with the outcomes of the research studies, it can be put forward for decision making, that there are convincing revelations between per capita economic growth and energy (oil) consumption that led to CO_2-*eq* emissions. Automobiles that are IC-Engines running on fossil fuels should be minimized in order to contribute to the efforts of mitigating the impacts of climate change. By doing so, the mass transit can be cushioned. In addition, South Africa's GHGs intensity can be mitigated by further enhancing renewables in the energy mix. To further support an eco-friendly environment, decision and policy makers should support alternative energy transport vehicles to limit the consumption of fossils.

Based on the accounts of this study, the following implied knowledge among others are derived:

First, South Africa can further restructure the transportation industry to develop in a more sustainable ways, as its impacts on the environment are significantly dominant. Similarly, developing countries as a case with South Africa can focus on how their transportation systems and economic development affect environmental degradation to fully achieve intergovernmental sustainability goals, such as the ones outlined by the United Nations. For instance, that of the sustainable development goals. Consequently, this can further align South Africa's policies framing with those that are highly developed.

Furthermore, in the era of information age, the structure of the economy can be enhanced to move from carbon intensive energy to knowledge and circular economies. Notwithstanding their complexities, they are reliable path to post-industrial economy. Passenger vehicles contribute significantly to South Africa's total vehicle fleet GHG emissions. However, with rigorous fuel economy standards and increasing use of hybrid and electric vehicles, this share can be expected to decline over time as indicated by the EKC. To achieve sustainable development, it is imperative that governmental bodies prioritize policies targeting commercial vehicles, with particular emphasis on passenger on-road vehicles, in domains such as fuel economy regulations and electric vehicle (EV) deployment. Incentive-based regulations for hybrid and EV passenger vehicles can facilitate the production of cleaner energy and promote sustainable development.

Author contributions OJO: Conceptualization, methodology, software application, validation, formal analysis, investigation, data resources, data curation, writing—original draft preparation, writing—review and editing, OJO, OAO and CKM Lee: visualization, project administration. OAO and CKM Lee: supervision. OAO and CKM Lee: internal funding acquisition.

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Data availability The data used to support this research is included within the manuscript. However, upon request, additional sources that involve analyses can be provided.

Declarations

Ethics approval and consent to participate We declare that we have no human participants, physical contacts and human data.

Consent for publication We do not have any individual person's data in any form.

Competing interests The authors declare no competing interests.

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