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PII: S0967-070X(24)00358-5

DOI: https://doi.org/10.1016/j.tranpol.2024.11.021

Reference: JTRP 3493

To appear in: *Transport Policy*

Received Date: 8 July 2024

Revised Date: 22 October 2024

Accepted Date: 24 November 2024

Please cite this article as: Sai, R., Yuan, H., Kwabena Takyi, E., Abudu, H., Agyeman, S., Evaluation of transport carbon efficiency, reduction potential, and influencing factors in Africa, *Transport Policy*, https://doi.org/10.1016/j.tranpol.2024.11.021.

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Abstract

Africa aims to promote low emission development pathways. As the second-highest CO_2 emitting sector and contributing to an annual average pollution cost of 6.14% of GDP, the transport sector poses a major barrier to sustainable growth. Enhancing transport carbon emission efficiency is essential for achieving both sustainable growth and emission reduction; however, empirical insights regarding Africa remain limited. Therefore, this study employs non-parametric metafrontier technique to asses transport carbon efficiency, reduction potentials, and sources of emission reduction potentials across forty African countries from 2000 to 2020. Panel regression is employed to identify external factors influencing regional carbon efficiency. The findings reveal that transport carbon efficiency (TCE) in Africa averages 0.372**,** indicating low performance. Central Africa leads the continent's optimal green production technology based on the technology gap ratio, closely followed by Southern Africa. Moreover, the potential for CO_2 emission reduction is estimated at 74.479 % of total TCE, averaging 5583.649 kt annually. Over two-thirds of the emission reduction potential is attributed to addressing management inefficiencies. External influencing factors on TCE exhibit regional heterogeneity. Transport alue-added improves TCE in all regions, while energy intensity and renewable energy diminishes it. Sulphur content in diesel, Urbanization, institutional quality, business relations, structural change, and FDI have mixed effects. The findings underscore the need for targeted policies to boost carbon efficiency and align transport planning with regional priorities.

Keywords

Africa transportation; Meta frontier analysis; Carbon efficiency; CO_2 emission potential reduction; Influencing factors

1. Introduction

Africa has long endured the impacts of climate change and remains particularly vulnerable to further global temperature increases. Projections suggest that a 1°C to 4°C rise could result in a significant decline of 2.25% to 12.12% in gross domestic product (GDP) (WMO, 2019). In response, the African Union introduced its comprehensive Climate Change Strategy (2022−2032) in February 2022, aiming to promote low emission and climate resilient development pathways (African Union, 2022, 2009; EPRS, 2022)[1]. Among the key areas for transformation, the transport industry is more crucial in climate change mitigation and sustainable growth. It contributes about 26% of Africa's CO_2 emissions from fossil fuel combustion, second only to the power sector, with average emission growth rate of 3.94%, exceeding all other sectors from 2010 to 2018 (see Fig.1) (EDGAR, 2023). Besides CO_2, the transport industry is a major source of pollution in Africa. Outdoor air pollution causes 383,420 deaths annually, and total air pollution lowers Africa's GDP by an average of 6.14% each year (World Bank, 2022). Moreover, the commencement of trade under the Africa Free Trade Agreement in 2021, combined with rising mineral extraction (for green technology construction), the influx of used imported vehicles, and rapid urban population growth (IEA, 2023; Naré and Kamakaté, 2017), are poised to drive a new wave of transport carbon emissions. In this regard, economies need to pursue growth that fully incorporates the principles of sustainability (the core of carbon

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[1] Other notable initiatives, agents, and forums on transport such as 2004 strategic plan, 2008 environment ministers conferences, 2008 Algeria transport Ministers transport forum, 2015 AfDB sustainable transport conference, African Development Bank and Africa Transport Policy Program, United Nations Environment Program for Africa African Union Agenda 2063 (African Union, 2009, 2008; AMCEN, 2008; DoT, 2018; UN for Africa, 2011), and among others have prioritized efficiency and policies to curtail its related environmental impacts.

efficiency), while also understanding the influence of key driving factors in Africa's low-carbon trajectory.

Prior literature underscores the importance of efficiency improvements and transport technologies like electric vehicles (EV) in reducing the environmental impacts of the transport sector (Wang et al., 2024a). However, as noted by Collett et al. (2021) and Hull et al. (2024), the adoption of electric mobility in Africa remains limited or non-existent due to inadequate electricity infrastructure and capital constraints. Additionally, concerns regarding EV battery charging capacity and recycling and consumers' value orientation remain significant (Wang et al., 2024b, 2023). Hence, enhancing emission efficiency is more economically effective in meeting emission targets amid competing developmental priorities in Africa.

In this study, carbon efficiency illustrates how the transport industry balances inputs (like energy, land, and capital), positive output (such as GDP), and negative output (like CO_2 emissions) in the production process (Wu et al., 2017). This approach allows producers to meet carbon reduction goals while aligning economic and environmental objectives. However, although researchers have contributed to the analysis of carbon efficiency in the transport industry (Bai et al., 2023; Feng and Wang, 2018; Liu et al., 2017), research on Africa has not thoroughly analyzed CO_2 emissions within a multifactorial production framework, and related efficiency studies often overlook undesirable outputs (Barros and Wanke, 2015) or fail to focus extensively on Africa. For example, Adams et al. (2020), and Wang et al. (2020a) treated CO_2 emissions only as partial indicators—such as CO_2 emission intensity or as a specific variable—to reflect sustainable transport. Tamaki et al. (2019) assessed urban transport efficiency in just four African cities, while Wang et al. (2020) focused solely on Egypt out of 51 Belt and Road economies when evaluating carbon intensity. Additionally, the factors influencing transport-related CO_2 emissions remain inconclusive, reflecting the variations across different regions (Adams et al., 2020; Button et al., 2019; Nchofoung and Asongu, 2022). This research **seeks to** close this gap by addressing several critical questions: How has carbon efficiency in Africa's transport industry evolved over the study period (improved or declined?), considering geographical heterogeneity? What is the potential for carbon emission reduction in Africa's transport sector, both in percentage and absolute terms?, what are the primary drivers contributing to potential CO_2 emission reductions? What external factors influence transport carbon efficiency?

To address the above questions, we contribute to literature by examining carbon efficiency, CO_2 emissions contraction potential, and sources of emission reduction potentials using non parametric metafrontier technique of forty (40) African countries over 2000-2020, considering regional technology heterogeneity. External factors that influence transport carbon efficiency are also examined. **In particular, first**, the study improves understanding of total factor carbon efficiency framework by considering the production process in measuring transport carbon efficiency. Unlike single-factor indices (e.g., CO_2 intensity), it considers CO_2 emissions, economic development, energy structure, and element replacement, offering a broader view of emission performance. The approach aims to reduce emissions while enhancing economic output, promoting high-quality development. **Second**, the study emphasizes the importance of utilizing a metaproduction function to address performance incomparability across groups. Unlike conventional efficiency studies, this research integrates ex ante information into metafrontier carbon efficiency analysis, acknowledging the challenge of comparing efficiency among Decision-Making Units (DMUs) using different technologies. There exist considerable developmental and transport infrastructure differences among geographical regions Africa. Specifically, the average Transport Composite Index in 2022 for North Africa is 23.189%, West Africa is 6.885%, South Africa is 11.42%, East Africa is 11.08127%, and Central Africa is 5.779% (see Table 1). These variances, often overlooked in traditional non parametric Data Envelopment Analysis (DEA) methods employed in similar studies, are accounted for in our analysis (Demir et al., 2022; Tamaki et al., 2019; Wang and He, 2017). **Third**, the study constructs carbon emission abatement potentials across regions and decomposes the potential for reducing CO_2 emissions under the Meta production frontier into management and technology gap inefficiencies. This analysis offers policymakers fresh insights into CO_2 quotas and potential carbon contraction sources, which are crucial for energy savings policies in the transport sector. **Fourth,** to analyse the impact of external factors on transport carbon emissions efficiency, we utilized a panel fixed effect regression model. Building on existing literature, the authors incorporated factors such as sulphur content in diesel, natural resource rent, structural changes, institutional quality, transport share of renewable consumption, valued added, urbanization, business regulation, FDI, transport energy intensity, and human capital. By accounting for geographic heterogeneity, this analysis enhances the understanding of regional characteristics and supports the development of more effective sustainable energy strategies. **Fifth** and importantly, transport emissions are estimated to improve globally by 60% from 2015 to 2050 to meet the Paris Agreement target[2]. Hence, the study will play a crucial role in achieving African

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[2] Planete Energies(2017) The global transport sector:CO2 emission on the rise. https://www.planete-energies.com/en, retrieved(June 13,2023).

countries' green transport and energy policies (Africa Climate Resilience Strategy and SDG goals 13 and 11) and add to the literature an empirical study of Africa's transport context.

The subsequent sections of this paper are organized as follows: Section 2 provides a review of relevant literature, providing a foundation for the study. Section 3 outlines the methods employed and the data sources. Section 4 delves into the estimated results and provides a detailed discussion of the findings. In Section 5, the paper's key conclusions are summarized, and policy implications based on the study's findings are suggested. Additionally, a comprehensive list of abbreviations and symbols used throughout the paper can be found in **Table K**, located in the supplementary material.

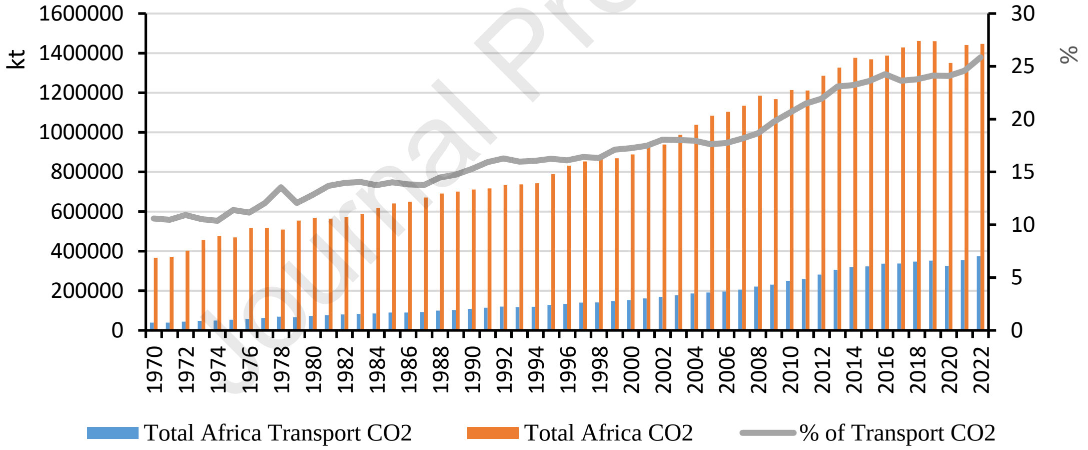

Fig.1. Total Africa fossil CO_2 emissions in Transport ((data and Calculations are sourced from Emissions Database for Global Atmospheric Research, 2023 (EDGAR, 2023)).

2. Literature Review

The literature is categorized into two main areas: one focuses on estimating carbon efficiency performance, and reviews studies on Africa related to transport efficiency in Africa, CO_2 influencing factors, and existing literature gaps.

2.1. Estimating carbon emission efficiency

Estimating transport CO_2 emissions efficiency is key to guiding environmental policies (Du et al., 2021). It can reduce waste in energy consumption, lowers the carbon footprint, and fosters cost savings while promoting sustainability (Du et al., 2019; Sai et al., 2023; Zhang et al., 2023). CO_2 intensity (CO_2 emissions per unit of output) and carbon productivity (economic output per unit of CO_2 emissions) are widely used indicators to assess environmental performance (Ben Abdallah et al., 2015; Lin and Wang, 2023; Lu et al., 2024; Swain and Karimu, 2020). However, these single-factor metrics offer a narrow perspective, often overlooking essential production inputs such as capital and labor, which are critical to a more comprehensive evaluation of emission performance (Zhou et al., 2010).

To overcome the above limitation, a multi-factor (total factor) framework that incorporates various inputs, good (positive) and bad (negative) outputs in environmental efficiency assessments was proposed (Färe et al., 2007; Ray et al., 2022). Data Envelopment Analysis (DEA) is commonly used as a nonparametric technique to calculate the total factor(multi-factor) efficiency index. DEA avoids model misspecification by not requiring an assumed production function or distance function. It offers flexibility with various model types, making it applicable to most efficiency evaluation models (Yen and Li, 2022; Yu et al., 2019). DEA studies applying a multifactor production approach in the transport sector include Rashidi and Cullinane (2019) on OECD logistics, Wang and He

(2017) on 31 Chinese regions, and Cui and Li (2020) on 29 global airlines. Du et al. (2021) studied 52 BRI countries, Gong et al. (2019) examined 26 listed shipping companies, Wei et al. (2021) analyzed 30 provincial Chinese transport sectors, and Heymann et al. (2021) focused on Brazil's transport sector. Similarly, Lin and Sai (2021a) explored Africa's electricity sector.

In relation to environmental concerns, various methods have been used to incorporate factors, like CO_2 emissions, into efficiency models. The directional distance function (DDF), introduced by Chung et al. (1997), is commonly applied but requires balancing increases in desired outputs with reductions in undesired ones, which can lead to underestimating reductions in emissions or increases in desired outputs. It may also overestimate efficiency due to slack. To address these issues, non-radial measures like the Non-Radial Directional Distance Function (NDDF) were developed, allowing for uneven growth between desired and undesired outputs and minimizing slack bias(Zhang et al., 2015). The Shephard CO_2 emission distance function (SCDF), a special case of NDDF, evaluates carbon emission reductions while keeping labor and capital constant (Chen and Xiang, 2019; Fukuyama and Weber, 2009; Zhou et al., 2010). For example, Zhou et al. (2010) used SCDF to assess environmental efficiency in 18 top emitters globally. In the transport sector, Zhang et al. (2015) used NDDF to evaluate CO_2 emission performance in China, while Liu et al. (2017) applied the Shephard function to analyze CO_2 emissions in 12 Chinese airlines. Chen and Xiang (2019) used NDDF to assess the efficiency of 20 coal-fired power plants in Shanghai.

Another key challenge in previous studies is the assumption that all decision-making units (DMUs) operate under the same production technology. This assumption is often unrealistic, as DMUs may vary in technology due to differences in infrastructure, income, institutional environments, and natural resources. To address this, Oh and Lee (2010) introduced meta-frontier analysis for environmental efficiency to compare groups with different technology levels. Lin and Xu (2018a) applied this approach using the Shephard CO_2 emission distance function (SCDF) to measure carbon efficiency in China's metallurgical industry[3]. However, few studies have considered technological differences in the **transport sector**, particularly in Africa. Most research, such as Bai, Chen and Wang (2023), Feng and Wang (2018), and Xia et al. (2022), focused on China's transport sector, utilizing meta-frontier methods to assess CO_2 performance and efficiency. In particular, Bai, Chen and Wang (2023) studied 30 provinces in China, using a parametric meta-frontier technique to evaluate the CO2 performance and contraction potential of the transport sector. Feng and Wang (2018), for instance, employed global metafrontier technique, accounting for regional disparities, to assess energy efficiency and savings in China's transport sector. Xia et al. (2022) utilized meta-frontier DEA to assess the uneven development of low-carbon transport across 30 provinces in China. Li et al. (2020) studied 16 Chinese port firms using a modified NDDF in the meta-frontier setting to assess dynamic CO_2 emissions and their drivers. Li et al. (2020) examined 16 Chinese port firms, using a meta-frontier approach to analyze CO_2 emissions. This highlights a gap in exploring Africa's transport sector using similar methods.

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[3] Further directions of DEA techniques: Li et al. (2023) classified carbon emissions as a 'fixed sum shared undesirable output' (FSSUO) constraint in DEA to support China's carbon peak policy in the transport industry. Chu et al. (2021) explored the effects of carbon emission permit trading on production technology in DEA, proposing revised production axioms for China's thermal power industry. Zhang, Sun and Hu (2024) utilized a three-stage SBM-DEA model to assess land use carbon emission efficiency in China's Yangtze River Economic Belt, factoring in undesirable outputs. Additionally, Chu et al. (2024) developed a dynamic bargaining game approach to allocate carbon emissions reduction among DMUs in 27 EU countries within a DEA framework.

Overall, considering the diverse characteristics of the methodologies discussed, this study utilizes the Shephard carbon distance function (SCDF) within a meta-frontier framework to accurately evaluate carbon efficiency in Africa's transportation industry. In the traditional Shephard distance function, all outputs are scaled up uniformly, so it doesn't reward reductions in undesirable outputs (Zhang and Choi, 2014). Likewise, the directional distance function (DDF) reduces bad outputs (or inputs) and increases good outputs at an equal rate to the frontier, potentially causing the ‘‘bucket effect’’(Lin and Du, 2013). For example, an economy could boost output by 10%, with given inputs and cut CO_2 by 20% through ideal production technology, but a DDF approach would estimate the potential CO_2 reduction at just 10%, missing the full 20% savings potential. Thus, unlike conventional distance functions, we use the SCDF function to overcome these limitations. Its main advantage is that it allows for non-proportional changes between desirable and undesirable outputs (e.g., CO_2 emissions, value added), enabling a more accurate assessment of CO_2 reduction potential (Lin and Sai, 2022a). We further incorporate the meta-frontier model's properties into the SCDF to address regional technological gaps, to as different regions (North, West, South, East, Central —see Table 1) may utilize varied production technologies.

2.2 The case of Africa: Related transport efficiency studies, CO_2 influencing factors, and literature gaps

While numerous studies using various methods have explored transport carbon efficiency internationally (see Section 2.1), research focused specifically on Africa is still limited. The few focus on single or small samples, utilize partial indicators, omit undesirable outputs in production settings, and lack comprehensive analysis. Studies like

Tamaki et al. (2019) only included four cities out of 86 in their sample and used the 1995 World Cities Database to estimate urban transport efficiency, finding lower efficiencies in several cities across Europe, Western Australia, and South Africa. Two studies by Wang et al. (2020) and Wang et al. (2020b) concentrated solely on Egypt, among 51 Belt and Road economies, to evaluate transport CO2 emission intensity using the Tapio decoupling index, semi-variogram analysis, and Theil index. They identified three decoupling states: expansive negative decoupling, recessive coupling, and weak decoupling. Additionally, they found that transportation-related CO_2 emission intensity in Western Asia, Central, and North Africa is significantly higher than in other regions along the Belt and Road Initiative. Barros and Wanke (2015) did not consider undesirable outputs and used the TOPSIS model (Technique for Order Preference by Similarity to the Ideal Solution) to analyze the efficiency of African Airlines, using 29 airlines over four years (2010-2013). They observed generally low average efficiency and identified economies of scope as the primary factor for enhancing efficiency. Engo (2019) focused on Cameroon and used both Tapio and LMDI techniques to study the decoupling of CO_2 emissions and economic growth in the transport sector from 1990 to 2016. They identified weak negative decoupling, strong negative decoupling, weak decoupling, and strong decoupling, noting that energy structure, scale, and energy intensity effects hindered decoupling, while economic structure effects facilitated it.

More so, the next strand of studies focuses on the drivers and computation of CO_2 emissions. Studies demonstrate varied findings in Africa's transport sector, reflecting differences across regions. For instance, Nchofoung and Asongu (2022) identified both negative and positive impacts of infrastructure on CO_2 emissions through trade and governance interactions in 36 African countries. Oladunni et al. (2022) highlighted that economic growth and population are the most significant factors influencing greenhouse gas emissions in South Africa's transport sector. Additionally, it showed that passenger vehicles, energy intensity, and freight transport are key contributors to increased GHG emissions. Adams et al. (2020) revealed that CO_2 emissions increase and decrease with transport energy consumption and urbanization but vary significantly, demonstrating that in 19 Sub-Saharan African economies. Tongwane et al.(2015) calculated and compared greenhouse gas emissions from road transport in South Africa and Lesotho from 2000 to 2009 and concluded that in 2009, road transport emitted an estimated 43.5 million tonnes of carbon dioxide equivalent in South Africa and 0.28 million tonnes in Lesotho. Bubeck et al. (2014) examined how public transport can help mitigate GHG in South Africa. They discovered that Gautrain rapid rail link and the Rea Vaya BRT cannot effectively reduce the total transport's greenhouse gas emissions from well to wheel.

The last strand of literature focuses on exploring transport polices and insights on EV adoption. The findings highlight the link between competing priorities and low-carbon transport measures, emphasizing the need for cost-effective carbon efficiency strategies. Button et al. (2019) examined air transport regulation and the development of Sub-Saharan Africa's common markets for goods and services, noting that the expected benefits of deregulation have not materialized due to competing priorities, a lack of trained personnel, and inadequate infrastructure. Jennings (2020) conducted expert interviews to examine policy knowledge on high-volume, low-carbon transport in selected South Asian and African countries. They emphasized that mobility and basic needs take priority over low-carbon mobility. Godard (2013) analyzed urban transport sustainability by drawing lessons from West and North Africa, noting that income levels, institutional issues, urban sprawl, rising energy costs, public transport expenses and impede transport sustainability. Walters (2013) studied transport policy development in South Africa and found that sustainable funding, skill shortages, complex political relationships, and urban migration impede effective policy implementation. Cinderby et al. (2024) explored the state of inclusive mobility and climate-resilient transport in Africa. The priority for both government and non-governmental groups was active travel infrastructure, driven by road safety and health, not climate resilience and a lack of knowledge hindered agencies' efforts to tackle the growing climate challenge. Insights into electric vehicle studies: Hull et al. (2024) found that environmental concerns, risk perceptions, and cost perceptions are the most significant factors driving the adoption of electric vehicles in South Africa. Sadiq and Chidi (2024) assessed the barriers to achieving energy efficiency through electric vehicles in five African economies, identifying income levels, the scale of EV adoption, technological shortcomings, and political and institutional inertia as key impediments to realizing carbon neutrality benefits. Collett et al. (2021) found that insufficient capital and unreliable electricity systems are key obstacles to electric vehicle adoption in sub-Saharan Africa. Ayetor et al. (2020) assessed the competitiveness of electric and hybrid-electric vehicles against fossil fuel vehicles in Ghana. The findings indicate that although the Toyota Prius offers a 30% cost savings per mile, owning an electric vehicle is at least 13.5% more expensive than owning a Toyota Corolla.

In summary, prior studies have discussed a diverse array of research on transportation both within Africa and globally. However, existing studies on Africa fail to consider CO_2 emissions within the context of production framework. They focus on single-factor indicators like CO_2 and carbon intensity. Related studies either ignore undesirable outputs or do not focus on Africa as a study area. Besides, while some countries may demonstrate the benefits of new transport technologies, competing priorities highlight the need to prioritize carbon efficiency measures. More so, the influencing factors of CO_2 remain inconclusive, highlighting the importance of geographic heterogeneity. This study aimed to address the gaps. Hence, taking into account group heterogeneity, we use Shephard carbon distance function within a Meta frontier analysis framework to compute transport total factor CO_2 emission efficiency of forty African economies over the 2000-2020 period. Then the potential for reducing transport CO_2 emissions for countries or regions under Meta frontier technology is examined. Subsequently, we examine and decomposed contributors to these potential reductions into addressing inefficiencies relative to technology gaps and management inefficiencies. Lastly, we employ OLS to explore external influencing factors. The findings will contribute to the advancement of green carbon resilience in transport sector of developing economies.

3. Model and Methodology

3.1. Shephard CO_2 distance function in Africa's Transport Industry

To model transport carbon efficiency across African countries, we draw from the approaches used by Wang et al. (2012) **and** Lin and Xu (2018a) to employ the Shephard CO_2 distance function. Unlike, the traditional distance functions, this method assesses the optimal reduction in CO_2 emissions (transport), keeping current inputs and outputs constant. Thus, SCDF enhances discriminating power by accurately distinguishing between DMUs' performance levels, identifying those that significantly reduce CO_2 emissions relative to their outputs, thus facilitating better decision-making and environmental management.

In accordance with neoclassical production theory, it is presumed that each country's transport industry employs inputs such as capital (k), labor (l), and energy (e) to generate transportation gross value added (p) as desired output and CO_2 emissions (c) as undesired output, respectively. Let m denote the number of inputs, r denotes number of output, b denote number of bad output. Let $X_i \in \mathbf{R}^+_\mathbf{m}$, $Y_i^\mathbf{p} \in \mathbf{R}^+_\mathbf{r}, Y_i^\mathbf{c} \in \mathbf{R}^+_\mathbf{b}$ represent I observed decision making units (transport industries), each of which uses m inputs to produce r good output and s bad output. The $X_i \in \mathbf{R}^+_\mathbf{m}$, represents the set of non negative inputs for DMU_i , where every DMU uses m inputs (k, l, e) to produce outputs. The $Y_i^\mathbf{p} \in \mathbf{R}^+_\mathbf{r}$ denotes the set of non negative good output for DMU_i, where r good output (p) is produced. Lastly, $Y_i^\mathbf{c} \in \mathbf{R}^+_\mathbf{b}$ represents the set of non negative bad output, where b bad output (c) is generated. The PPs can be denoted as:

$$PPS = \{(k, l, e, p, c) : (k, l, e)\ can\ produce (p, c)\} \qquad \text{(eq1)}$$

In production theory, the boundary of the Production Possibility Set (PPS) is known as the production frontier or production technology, which is typically considered a closed and bounded set (Lin and Du, 2015; Lin and Xu, 2018b; Zhou et al., 2010), suggesting that limited finite amount of outputs (p, e)can be produce by limited inputs(k, l, e). Likewise, the inputs and the desired output are considered to be either strongly or freely expendable. This suggests that transport gross value added (p) Can be easily reduced using the same inputs(k, l, e) , or the inputs can be readily increased to produce the same level of output.

In the spirit of Färe et al. (1989) and Sai et al. (2023), we incorporate additional assumptions like weak disposability and null-jointness to analyze the simultaneous production of desired and undesired outputs. **Weak disposability** is illustrated as:

$$If (k, l, e, p, c) \in S \; and \; 0 \leq \theta \leq 1, then \; (k, l, e, \theta p, \theta c) \in S$$

Null-Jointness is expressed as $If (k, l, e, p, c) \in S \; and \; c = 0, then \; p = 0$

The **weak disposability** signifies that minimizing unwanted output, such as CO_2 emissions, typically involves decreasing the desired output (e.g., gross value added), indicating that reducing undesirable outputs comes at a cost. It captures the opportunity cost associated with reducing unaccepted (bad) outputs by acknowledging the trade-offs involved with unaccepted outputs (see Ray et al. (2022) **and** Wang et al. (2012) **for details)**. Similarly, the **Null-Jointness** posits that the positive production of desirable output (transport gross value added) must be coupled with the production of some amount of undesirable output ($C0_2$ emissions), as they are assumed to be inseparable (Sai et al., 2023; Zhang et al., 2015).

3.2 Technology gap and carbon emission efficiency

Table 1 shows considerable differences in transport infrastructure among the regions in Africa; therefore, the heterogeneity between regions must be considered. The n DMUs are categorized into North, West, South, East, and Central (see Table 2). In equation two (eq2), the g superscript denotes the group frontier, while the m superscript signifies the meta frontier.

$$S^g = \{(k^g, l^g, e^g, p^g, c^g) : (k^g, l^g, e^g)\ can\ produce(p^g, c^g)\} \quad ….. \qquad \text{(eq2)}$$

The meta frontier production technology, denoted as S^m, encompasses all the group technology production frontiers, represented as S^g.

Table1 Transport Composite Index in selected years (Average)

Region	2005	2010	2015	2020	2022
North	24.86447	24.942	23.59792	23.02773	23.18999
West	7.131478	7.320026	7.223089	6.918039	6.85785
South	11.45761	11.04401	10.71437	11.54874	11.42018
East	11.09083	12.09169	11.31382	11.01662	11.08127
Central	7.151338	6.605122	6.325987	5.817486	5.779413
Africa	12.33915	12.40057	11.83504	11.66572	11.66574

Source; The Africa Infrastructure Development Index (2016 and 2022)
North=North Africa, West= West Africa, South = Southern Africa, East= Eastern Africa, Central =Central Africa.

Based on Lin and Xu (2018a), the SCDF can be used to estimate the static $CO2$ emission performance in relation to the production technology; this is defined below as:

$$d(k, l, e, p, c) = sup\,\{\zeta : (k, l, e, p, c/\zeta)\epsilon S\} \quad ……..(\text{eq3})$$

Therefore, the group frontier and meta frontier in the context of distance function is shown as:

$$d^g(k, l, e, p, c) = sup\,\{\rho : (k, l, e, p, c/\zeta)\epsilon S^g\ \} …….. (\text{eq4})$$

$$d^m(k, l, e, p, c) = sup\,\{\zeta : (k, l, e, p, c/\zeta)\epsilon S^M\ \} ……. . (\text{eq5})$$

The distance functions evaluate the optimal proportion (best ratio) for reducing CO_2 emissions while maintaining the current levels of input and output. Based on this, the calculation of CO_2 emission performance can be done using linear programming in the following manner:

$$d\left[\left(k_{jt}, l_{jt}, e_{jt}, p_{jt}, c_{jt}\right)\right]^{-1} = min\colon \zeta$$

$$s.t. \sum_{i=1}^{I} \psi_{it} k_{it} \leq k_j; \sum_{i=1}^{I} \psi_{it} l_{it} \leq l_j; \sum_{i=1}^{I} \psi_{it} e_{it} \leq e_j; \sum_{i=1}^{I} \psi_{it} p_{it} \geq p_j;$$

$$\sum_{i=1}^{I} \psi_{it} c_{it} = \zeta c_j;$$

$$\psi_{it} \geq 0, i = 1,2,3, \ldots . . I \qquad \text{(eq6)}$$

The j denotes the $j-th$ DMU to be evaluated. Therefore, formulas 7 and 8 can be constructed; thus, CO_2 emissions efficiency measured based on the specific group frontier (GECF) and meta frontier (MECF) is evaluated. Scores for both GCEF and MCEF range from 0 to 1. Scores nearer 1 in both the GCEF and MCEF imply higher CO_2 efficiency.

$$\text{GCEF} = 1/d^g(k, l, e, p, c) \qquad \text{(eq7)}$$

$$\text{MCEF} = 1/d^m(k, l, e, p, c) \quad \text{(eq8)}$$

The link between the Group Production Frontier (GCEF) and the Meta Production Frontier (MCEF) is denoted by GCEF ≥ MCEF, illustrating that the meta production frontier encompasses the GCEF. To compute how nearer the group production technology frontier is to the meta production frontier is called the technology gap ratio (TG). This is expressed as :

$$TG = \frac{MCEF}{GCEF} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(eq9)}$$

The estimation of potential CO_2 emission reduction is conducted using the group production frontier (GCEFP) and Meta production frontier (MCEFP) frameworks. The scores generated by these frontiers represent the difference (gap) between the evaluated decision making unit and either the group production or Meta production frontier.

$$\text{GCEFP} = 1 - 1/d^g(k, l, e, p, c) \ \ldots\ldots\ldots\ldots\ldots\ldots\text{(eq10)}$$

$$\mathrm{MCEFP} = 1 - 1/d^m(k, l, e, p, c) \text{ ....(eq11)}$$

3.3. Potential sources of CO_2 emission contraction

The study adopts the approach outlined by Du et al. (2014) to decompose CO_2 emissions inefficiency within the meta frontier framework (EIFFM) into two components: technology gap inefficiency (TGIFF) and managerial inefficiency (MIFF) inefficiency. This is illustrated as:

$$EIFFM = MIFF + TGIFF \text{ ....(eq 12)}$$

$$MIFF = 1 - MCEF \text{..........................(eq 13)}$$

$$TGIFF = MCEF * (1 - TGR) \text{ ....(eq14)}$$

$MIFF$ illustrates the inefficiencies related to group production technology, stemming from either a shortage of (or deficiency in) desirable outputs or an excess of undesirable outputs. Managerial inefficiency is defined as the deviation of a DMU from the optimal frontier, based on its group's current technology. The inefficiency (eq14) from the Meta-group production technology gap, denoted $TGIFF$, is attributed to technology differences between the group and the meta frontier. In this context, the total CO_2 emission potential reduction (TCP) can be determined, taking into account both technology gaps and managerial deficiencies. Mathematically;

Total CO_2 emission potential contraction (TCP) is estimated as $= EIFFM * c$... (eq15)

Where c = the Transport CO_2 emission.

The CO_2 emission potential contraction due to management failure ($TCPMIFF$) calculated as $= MIFF * c$..(eq16)

And CO_2 emission potential contraction due to technology gap (TCPTGIFF) is estimated as $\mathrm{TGIFF} * \mathrm{c}$..................................(eq17)

Table 2 Selected countries classified under their regions

Regions	Countries
North Africa (NA)	Morocco, Egypt, Tunisia, Algeria, Mauritania
West Africa (WA)	Ghana, Cabo Verde, Benin, Nigeria, Guinea, Senegal, Cote d’Ivoire, Burkina Faso, Mali, Niger, Togo
Southern Africa (SA)	Botswana, Zambia, Angola, Lesotho, Zimbabwe, Mozambique, South Africa, Namibia, Malawi
East Africa (EA)	Tanzania, Seychelles, Ethiopia, Mauritius, Uganda, Rwanda, Sudan, Kenya, Madagascar
Central Africa (CA)	Cameroon, Equatorial Guinea, Burundi, Congo DR, Gabon, Chad

3.4. Data and variables

The model outlined in Sections 3.1 to 3.3 is employed to assess carbon efficiency performance in the transport sector across 40 African countries. This study, spanning from 2000 to 2020, also calculates the potential for CO_2 emission reduction on a regional basis and further explores the contributory factors to their emission reduction potentials. A total of 840 observations are used, encompassing approximately 94%[4] of the overall CO_2 emissions from the transport industry in Africa as of 2022 (EDGAR, 2023). This sample effectively represents the narrative of Africa's transport CO_2 emissions. The selection of the sample and the period of study (2000 to 2020) was guided by data availability from the UN-Energy Statistics database and emission data from the 2023 Emissions Database for Global Atmospheric Research (EDGAR, 2023) and the regression variables. The study employed five variables, and Table 3 presents detailed descriptive statistics for both the outputs and inputs.

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[4] Calculations are sourced from Emissions Database for Global Atmospheric Research (EDGAR, 2023)

Table 3. Descriptive statistics of the inputs and outputs

Region	Var	Unit	Obs	Mean	Std.Dev	Min	Max
North	K	10^6 USD	105	68026.677	61613.174	551.527	258869
West			231	30142.148	83510.272	589.786	502880
Southern			189	30468.134	61605.157	391.936	256228
Eastern			189	12198.885	14634.867	241.575	74989.8
Central			126	8800.81	9384.667	137.413	32771.6
North	L	10^3 persons	105	577.858	692.866	26.747	2556.76
West			231	387.522	802.818	8.14	3875.99
Southern			189	235.34	385.075	7.026	1618.03
Eastern			189	333.397	326.162	4.366	1382.77
Central			126	176.105	230.795	4.008	862.886
North	E	ktoe	105	5737.068	4936.151	128.455	17454.8
West			231	1655.494	3579.808	49.42	19790.9
Southern			189	2281.716	4849.854	88.305	19149.3
Eastern			189	920.913	925.362	22.643	3655.18
Central			126	357.021	320.069	38.362	1462.3
North	C	kt	105	18517.45	16752.71	441.733	54814.7
West			231	4833.764	10545.231	122.591	58245.2
Southern			189	6419.348	13537.329	152.163	52068.3
Eastern			189	2767.293	2900.783	290.117	12177.6
Central			126	946.412	968.244	72.515	3780.9
North	P	10^6 USD	105	8549.609	8637.1	39.204	38216.4
West			231	4712.419	13868.318	109.134	84195.5
Southern			189	3673.127	7447.743	31.291	29763.9
Eastern			189	2441.542	2842.106	83.959	11808.8
Central			126	1310.494	1388.109	28.989	4667.11

K=capital, L=labour, E=energy C=CO_2, P= transport value added

The input and output variables were chosen based on relevant literature and expert views (Feng and Wang, 2018; Lin and Sai, 2021b, 2022a; Sai et al., 2023; Zhang et al., 2015; Zhang and Wei, 2015) to comprehensively assess the transport sector's carbon efficiency and CO_2 emissions in Africa.

Desirable Output: We utilize the gross value added (p) from transportation, measured in millions of US dollars, due to the unavailability of passenger numbers data. This data is sourced from the United Nations National Official Accounts (United Nations, 2023).

Undesirable Output: We focus on the transport sector's CO_2 emissions, which amounted to 373,844.7515 kt in 2022, making it the second-highest emitter after the electricity sector according to the Emissions Database for Global Atmospheric Research (EDGAR, 2023). This study combines fossil fuel CO_2 emissions data from road transportation and other transportations, as recorded by EDGAR, to proxy for the undesirable output, measured in kilotonnes (kt).

The inputs considered labor, fuel consumption, and capital stock:

Labor data (l) for the transport industry is gathered from the International Labour Organization (ILO, 2023). It is defined as the sum of all employed persons in each country's transport sector, measured in thousands of persons.

Capital stock of transportation data is often employed as a proxy for capital (Du and Lin, 2017; Feng and Wang, 2018). However, due to the unavailability of transport capital stock data in the African context, this study, drawing from the findings of (Zhang and Yan, 2022), uses the share of transport sector GDP to compute transport capital stock from each country's total economy capital stock, based on data from Penn World Table version 10.01 (Feenstra et al., 2015), measured in millions of dollars. The linear interpolation method was employed to fill in the missing data.

Finally, transportation fossil fuel usage (e) data was compiled from the United Nations Energy Statistics database (United Nations, 2023). This figure, measured in thousands of tonnes of oil equivalent (ktoe), represents the aggregate consumption of various oil products (Gas Oil/Diesel Oil, Kerosene, Motor Gasoline, Fuel Oil), gas, and electricity in each country's transport system.

3.5 Regression variables

To further examine the external influence on transport carbon efficiency, the authors employ a two-stage analysis using OLS regression, which (Hoff, 2007) found to perform similarly to Tobit regression for analyzing DEA efficiency scores. Studies such as Jaraitė and Di Maria (2012), Haider et al. (2019), Wang et al. (2021), Song et al. (2024), and (Zhou et al., 2010) have used OLS regression in their second-stage analyses. Based on previous research (Adams et al., 2020; Gao and Zhang, 2019; Haouraji et al., 2021; Nchofoung and Asongu, 2022; Oladunni et al., 2022; Sai et al., 2023), factors such as transport value-added per capita (VP), human capital (HC), Sulphur content (SfC), urbanization (UB), and institutional capacity (IC) are selected. FDI as a share of GDP, transport energy intensity (TEI), business regulation (BR), structural change (SC), natural resource rent (NRT), and renewable energy (TRE) share of transport are also considered. Carbon efficiency (CE), the dependent variable, is measured by equation 8. Detailed descriptions, sources, and statistics of the variables are in **Tables H** and section 3.5 in the supplementary material.

4. Results and discussion

4.1. Transport CO_2 emission efficiency - Meta Cabon frontier (MCEF) and group carbon frontier (GCEF)

This section presents and analyzes the carbon efficiency performance and the potential for CO_2 emissions contraction (TCP) in Africa's transport sector from 2000 to 2020. The analysis includes both regional and country-level insights for a comprehensive understanding.

The study employs equations 10 and 11 to calculate the Metafrontier Carbon Efficiency (MCEF) and Group Carbon Efficiency (GECF) annually from 2000 to 2020. Table 4 showcases the yearly average carbon efficiency performance in the context of meta and group production technologies across different regions (refer to Tables A and B in the supplementary material for annual score specifics). The ArcGIS 10.8 software is used to visually represent MCEF outcomes in Fig. 2, providing a clear depiction of each sample economy's performance. Additionally, average technology gap ratios for each country are detailed in Table 4. The data (Table 4) reveals that most African countries fall short of achieving carbon efficiency when benchmarked against the metafrontier (MCEF). The average total score for Africa is 0.372, suggesting that, on average, there is a potential 62.8% improvement in CO_2 emission performance under the meta production technology frontier. Regionally (as shown in Table 4), annual average efficiency scores range from 0.233 to 0.641. Central Africa leads in efficiency (0.641), followed by East (0.382), Southern (0.323), West (0.283), and North Africa (0.233). This indicates that Central Africa is relatively more efficient in low-carbon investments compared to other regions.

At a country level, five economies -- Congo Dr, Equatorial Guinea, Gabon, Kenya, and Zimbabwe -- show efficiency scores above 0.7 (Fig.2). Notably, three of these countries (Congo DR, Equatorial Guinea, Gabon) are in Central Africa, characterized by a high reliance on renewable energy sources and friendly business regulations. Kenya, an East African country, is recognized for its clean investment activities and power generation and, with over 73% of its generation capacity derived from green energy (Sai and Lin, 2022). Conversely, Mauritania (0.082), Namibia (0.101), Lesotho (0.121), and Burkina Faso (0.41) exhibit the lowest MCEF scores. These countries predominantly rely on fossil fuels (Mauritania=76%, Namibia=70%, Lesotho=61%) (World Bank Group, 2023), except for Burkina Faso, which face challenges due to unclear vehicle import regulations (UNEP, 2020) and high energy intensity(UNECA, 2024). The poor performance of North African economies aligns with their high diesel and gasoline consumption and their ranking as the world's most dust-prone region (Engelstaedter et al., 2006).

The analysis of carbon efficiency under the group production frontier (**GCEF**), as shown in Tables 4 and B, indicates higher annual averages compared to the metafrontier (MCEF) values, highlighting the presence of technology gaps among different countries and regions. The average efficiency scores across all regions under GCEF range from 0.508 to 0.769, with a relatively smaller gap between regions compared to MCEF. The total average value for Africa under GCEF is 0.641, suggesting a potential for a 35.9% reduction in CO_2 emissions over the study period. Regionally, Central Africa shows a minimal efficiency score difference under both frontiers (0.641 for MCEF and 0.644 for GCEF), unlike North, West, Southern, and East Africa (refer to Table 4). For instance, Central Africa can improve its carbon efficiency by 35.6% by adopting the best technology within the region. Gabon simultaneously ranks at the top in both group and metafrontiers. Conversely, North Africa leads in group frontier efficiency (0.769), followed by East Africa, (0.716), Central Africa (0.644), South (0.569) and West Africa exhibits the lowest score (0.508). These variations are attributable to each region's efficiency being measured against its own technological frontier, reflecting the carbon efficiency level of its unique technology vis-à-vis the metafrontier standard. Specific countries like Mauritius and Egypt achieved a perfect score of 1, whereas Equatorial Guinea, Zimbabwe, Malawi, Côte d'Ivoire, and Tunisia scored above 0.9. On the other end, Burundi (0.179), Namibia (0.160), Lesotho (0.217) and Burkina Faso (0.269) recorded the lowest GCEF scores.

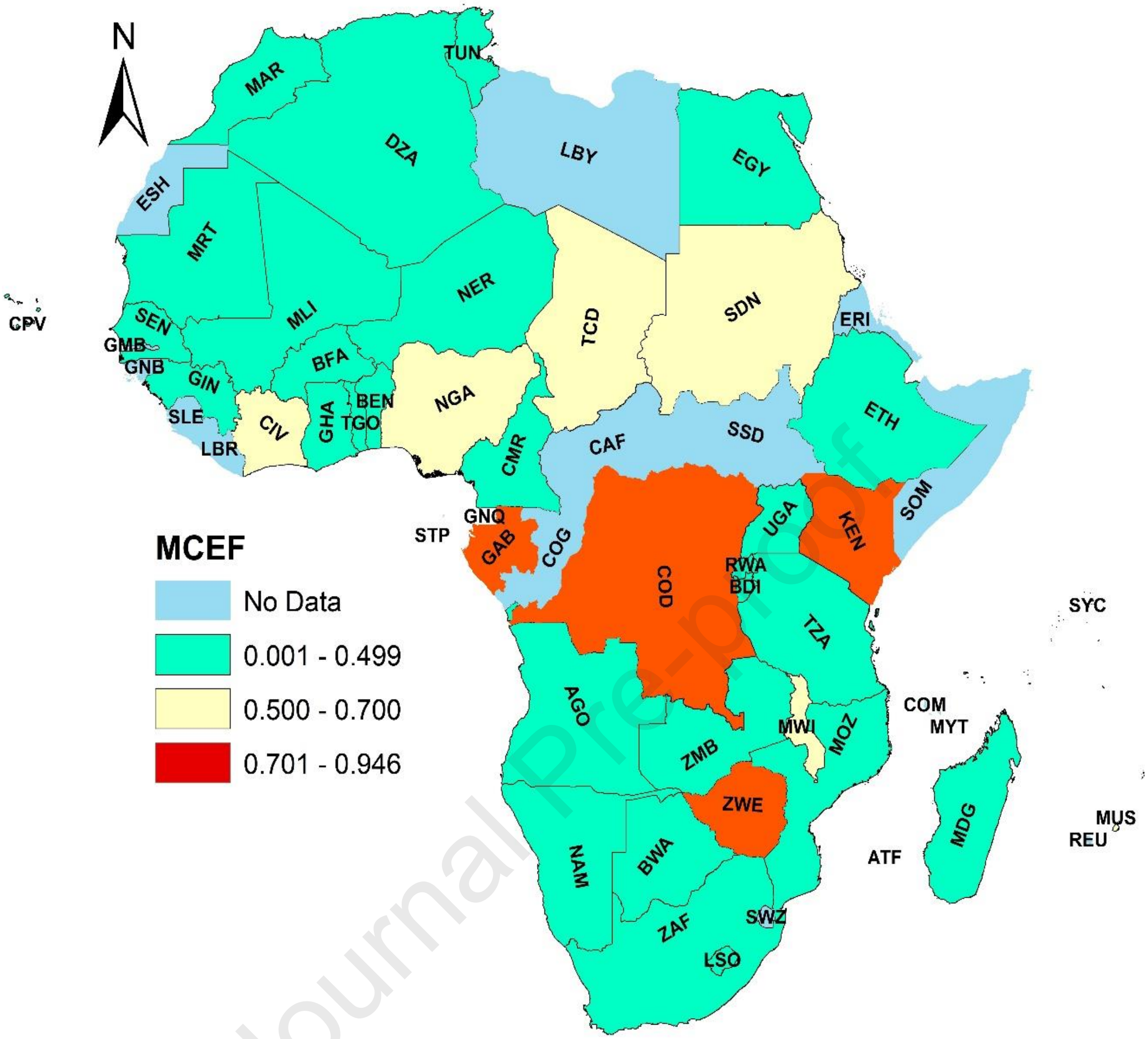

Fig.2 Average MECF, by country from 2000 to 2020[5]

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[5] **Note:** Tunisia (TUN), Mali (MLI), Central African Republic (CAF), Egypt (EGY), Angola (AGO), Seychelles (SYC), Gabon (GAB), Sudan (SDN), Libya (LBY), Somalia (SOM), Mauritania (MRT), Rwanda (RWA), Republic of Congo (COG), Comoros (COM), Lesotho (LSO), Equatorial Guinea (GNQ), Burkina Faso (BFA), Benin (BEN), South Africa (ZAF), Botswana (BWA), Nigeria (NGA), Mayotte (MYT), Madagascar (MDG), Sao Tome and Principe (STP), Democratic Republic of the Congo (COD), Niger (NER), Mauritius (MUS), Guinea (GIN), Zambia (ZMB), Morocco (MAR), South Sudan (SSD), Gambia (GMB), Ivory Coast (CIV), Cape Verde (CPV), Guinea-Bissau (GNB), Ethiopia (ETH), Western Sahara (ESH), Algeria (DZA), Liberia (LBR), Chad (TCD), Kenya (KEN), Ghana (GHA), Eritrea (ERI), Uganda (UGA), Zimbabwe (ZWE), Swaziland (SWZ), Sierra Leone (SLE), Namibia (NAM), Tanzania (TZA), Mauritius (MUS), Cameroon (CMR), Equatorial Guinea (GNQ), Senegal (SEN), Mozambique (MOZ), Namibia (NAM), Morocco (MAR), Mayotte (MYT).

Table 4. MCEF results in Africa transport sector (2000-2020)

Country	region	MCEF	GCEF	TGR	Country	region	MCEF	GCEF	TGR
Algeria	1	0.228	0.754	0.308	Ethiopia	4	0.163	0.313	0.523
Egypt	1	0.256	1.000	0.256	Kenya	4	0.708	0.888	0.777
Mauritania	1	0.082	0.313	0.256	Madagascar	4	0.361	0.627	0.578
Morocco	1	0.266	0.871	0.301	Mauritius	4	0.515	1.000	0.516
Tunisia	1	0.332	0.906	0.366	Rwanda	4	0.330	0.691	0.480
Benin	2	0.152	0.320	0.573	Seychelles	4	0.161	0.895	0.192
Burkina Faso	2	0.141	0.269	0.586	Sudan	4	0.535	0.868	0.591
Cabo Verde	2	0.389	0.528	0.790	Tanzania	4	0.466	0.811	0.557
Côte d'Ivoire	2	0.635	0.949	0.661	Uganda	4	0.197	0.351	0.561
Ghana	2	0.185	0.391	0.546	Burundi	5	0.179	0.179	1.000
Guinea	2	0.147	0.471	0.415	Cameroon	5	0.483	0.495	0.985
Mali	2	0.300	0.573	0.546	Chad	5	0.656	0.656	1.000
Niger	2	0.175	0.435	0.499	Congo DR	5	0.838	0.843	0.994
Nigeria	2	0.540	0.780	0.642	Eq. Guinea	5	0.946	0.946	1.000
Senegal	2	0.222	0.456	0.545	Gabon	5	0.743	0.747	0.994
Togo	2	0.225	0.419	0.541	**Mean**				
Angola	3	0.358	0.695	0.539	**North**	**1**	**0.233**	**0.769**	**0.298**
Botswana	3	0.169	0.462	0.503	**West**	**2**	**0.283**	**0.508**	**0.577**
Lesotho	3	0.121	0.217	0.554	**Southern**	**3**	**0.323**	**0.569**	**0.583**
Malawi	3	0.511	0.919	0.545	**East**	**4**	**0.382**	**0.716**	**0.530**
Mozambique	3	0.267	0.655	0.469	**Central**	**5**	**0.641**	**0.644**	**0.996**
Namibia	3	0.101	0.160	0.631	**Africa**	**6**	**0.372**	**0.641**	**0.597**
South Africa	3	0.323	0.551	0.617					
Zambia	3	0.318	0.499	0.618					
Zimbabwe	3	0.743	0.966	0.773					

4.1.1 Trend of Meta frontier carbon efficiency

Kernel density Estimation

Established in July 2005, following the G8 Summit in Gleneagles (UK), the Infrastructure Consortium for Africa (ICA) plays a pivotal role in mobilizing funds and resources to support and enhance Africa's infrastructure, with a particular focus on the transport sector. Complementing the Program for Infrastructure Development in Africa (PIDA), the ICA contributes significantly to the development of infrastructure in recipient countries, with an emphasis on establishing key cross-border connectivity systems, including those in the transport domain. The PIDA, whose consultancy services commenced in 2010 and were officially adopted in 2012, aims to bridge the continent's infrastructure gap, with transport being one of its primary focuses. Recent progress reports highlight that a significant portion of PIDA projects is concentrated within the transport sector. Both ICA and PIDA are dedicated to fostering a more resilient and sustainable transport infrastructure in Africa (AfDB-NEPAD, 2023; AfDB, 2023).

Based on the information presented, this study follows Wei et al.'s (2019) methodology and employs Kernel density plots to analyze the MCEF for the years 2000, 2010, 2015, and 2020. As illustrated in Figure 3.1 and Table A, there is a notable leftward shift in the MCEF peaks for year 2020, indicating a downward trend in carbon efficiency performance among the 40 economies analyzed. This decline suggests challenges in realizing low-carbon transportation under the auspices of ICA and PIDA. Several factors may have contributed to this trend: funding shortfalls in PIDA's transport projects (AfDB-NEPAD, 2023; Lin and Sai, 2022b), the ripple effects of the Arab Spring (2010-2012), high energy intensity in certain African nations (e.g., Uganda, Zimbabwe, Mozambique, and Congo Dr) (World Bank Group, 2023), volatile oil prices impacting transport investments, and a lack of stringent low-carbon transport policies (UNEP, 2020). For example, by 2019/2020, only 19% of PIDA's transport projects had been completed, and Africa's high import rate of used light-duty vehicles poses a significant challenge to environmental sustainability and carbon efficiency (African Union, 2020; World Economic Forum, 2023). Additionally, the growth of the energy extractive industry in Africa between 2009 and 2014, which accounted for nearly 30% of global oil and gas discoveries, led to extensive road development for transporting fossil fuels, exacerbating pollution (IEA, 2014).

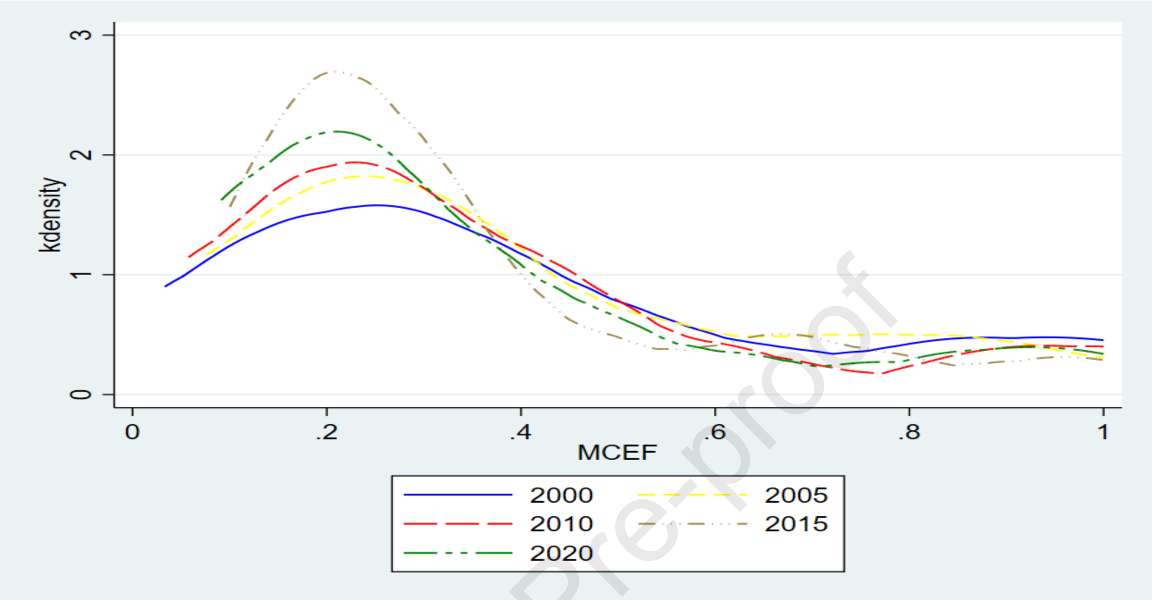

Fig. 3.1 Kernel density estimate of MECF from 2000 to 2020

Annual MCEF trend of selected economies

In Fig.3.2, we selected countries with a large share of CO2 emissions (ZAF, EGY, DZA, NA) and top performers in their groups (CIV, KEN, ZWE, GNQ, TUN) to assess TGR trends over the sample period. Côte d'Ivoire’s (CIV) TCE trend was influenced by political unrest from 2002 to 2011, with major declines during the 2008 global economic crisis and the latter part of the civil war (2010-2011). The improvements followed the implementation of economic recovery measures(IMF, 2016a). Egypt (EGY) and Algeria (DZA) exhibit a low, stable TGR trend due to fuel subsidies, which keep gasoline and diesel prices among the lowest in Africa, combined with high energy use and weak emission regulations (Fattouh and El-Katiri, 2013; UNECA, 2024). Both countries were impacted by the 2008 global economic crisis and the 2010/2011 Arab Spring. South

Africa’s (ZAF) TGR trend reflects deteriorating transport infrastructure and high fossil fuel consumption, which has been consistently among the highest in Africa (UNECA, 2024). In 2021, 30% of the country’s paved roads were reported to be in poor condition (INP, 2021). Zimbabwe (ZWE) saw a relatively high TGR trend during the sample period, supported by strong copper prices that boosted government infrastructure investments, though it faced similar economic distortions as other countries(IMF, 2010). Nigeria's (NGA) gradual TGR rise from the early 2000s is attributed to robust economic growth, averaging 9.2% between 2004 and 2010, fueled by rising oil prices. However, growth slowed to an average of 4.7% from 2011(IMF, 2016b). Kenya’s (KEN) decent carbon efficiency performance in early years was due to the induction of “Roads 2000" strategy, which focused on partial rehabilitation to counter the lack of road maintenance(Wasike, 2001). However, the sharp decline in efficiency followed the 2008 removal of import taxes on local motorcycles. After 2010, with reduced political tensions, motorcycle numbers surged from 3,800 in 2005 to over 120,000 in 2012 (Uzim and Dixon, 2024). Equatorial Guinea (EQ) is one of Africa's more developed economies, maintaining a stable yet high investment share of GDP, averaging 54% between 2004 and 2015 has influenced its trend.

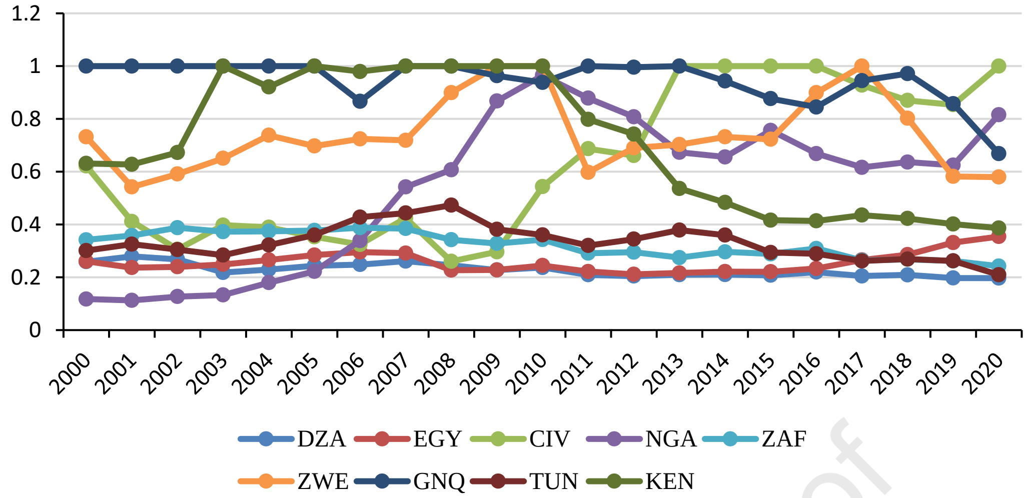

Fig. 3.2 Annual MCEF trend of selected economies from 2000 to 2020

4.1.2 Technology gaps ratio

Utilizing Equation 9 (*eq9*), we calculate the Technology Gap Ratios (TGR), which measure how far the evaluated entities in different technological categories are from their respective potential technical frontiers (Du et al., 2014). The country-specific average efficiencies of TGR are depicted in Table 4, while the annual trends are graphically represented in Figures 4 and 5 (detailed data can be found in Table C of the supplementary materials). As evidenced in Figure 4 and 5 and Table 4, a majority of the Central African countries exhibit higher TGR scores, indicating their values are close to 1. This suggests that the technological frontiers of Central African countries, such as Chad, Burundi, and Equatorial Guinea (each with a TGR score of 1), are closely aligned with the meta-production frontier technology, in contrast to countries in other regions. Conversely, North African countries demonstrate the lowest average TGR values, with an average of 0.298. Despite Seychelles from East Africa recording the lowest individual TGR score (0.192), it is predominantly North African countries like Egypt (0.256), Mauritania (0.256), and Morocco (0.301) that feature among the lowest TGR scores.

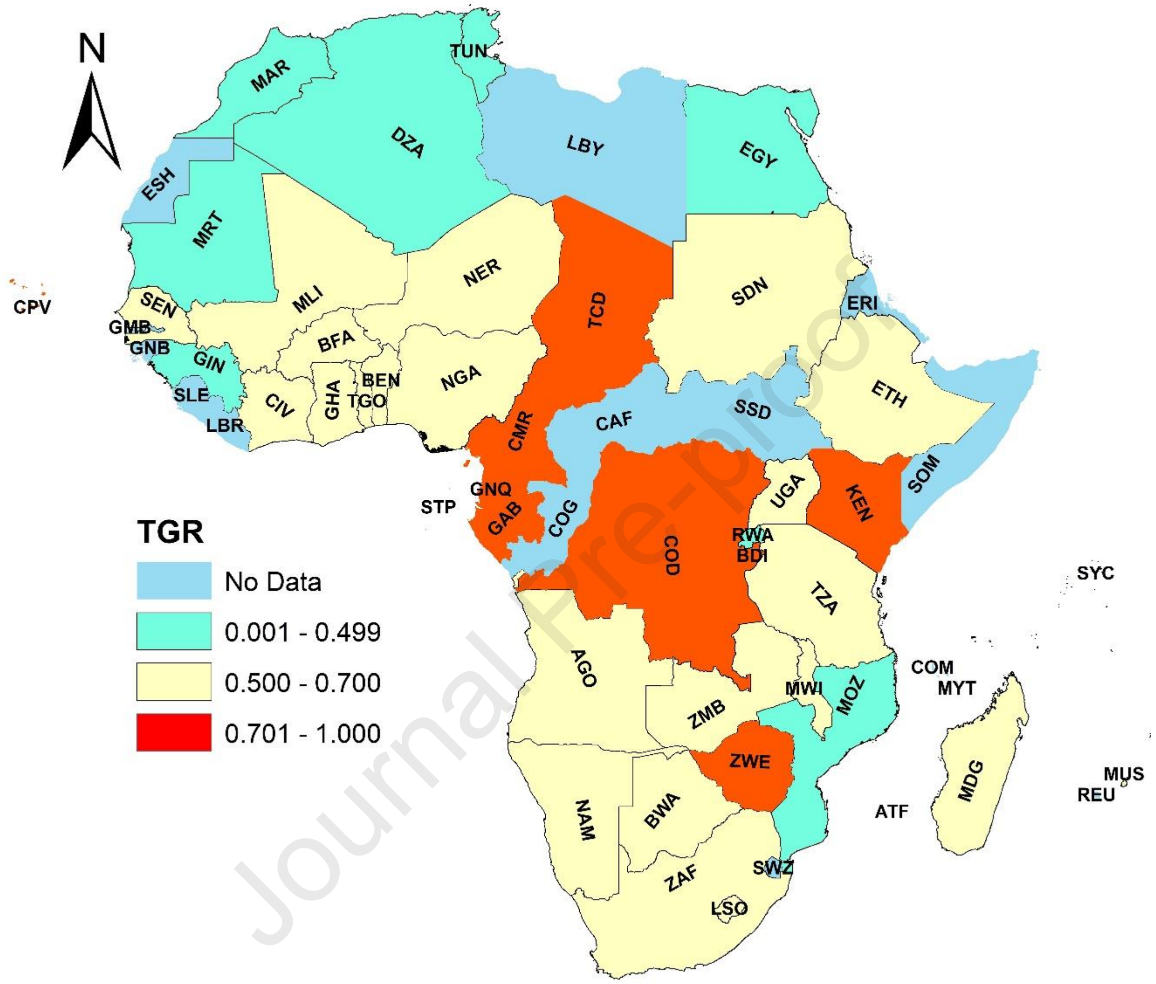

Fig.4 Average TGR by country from 2000 to 2020[6]

The trend analysis of the Transport Technology Gap Ratio (TGR[7], as depicted in Figure 5, reveals noticeable declines during significant periods such as the 2007/2008 financial crisis, the Arab Spring (2010-2012), and the periods of oil price volatility starting

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[6] **Note:** refer to Fig 2 for country full names

[7] see Fig A in the supplementary material for Annual TGR trend in selected economies from 2000 to 2020

from 2014. These downturns likely stem from governments facing fiscal challenges and prioritizing immediate economic stabilization over long-term investments in green transport technologies, including innovation funding and research and development efforts (IEA, 2014; Lin and Sai, 2022b). In North Africa, the continued adaptation to low oil prices, Arab Spring and regional conflicts influenced their efficiency trends.

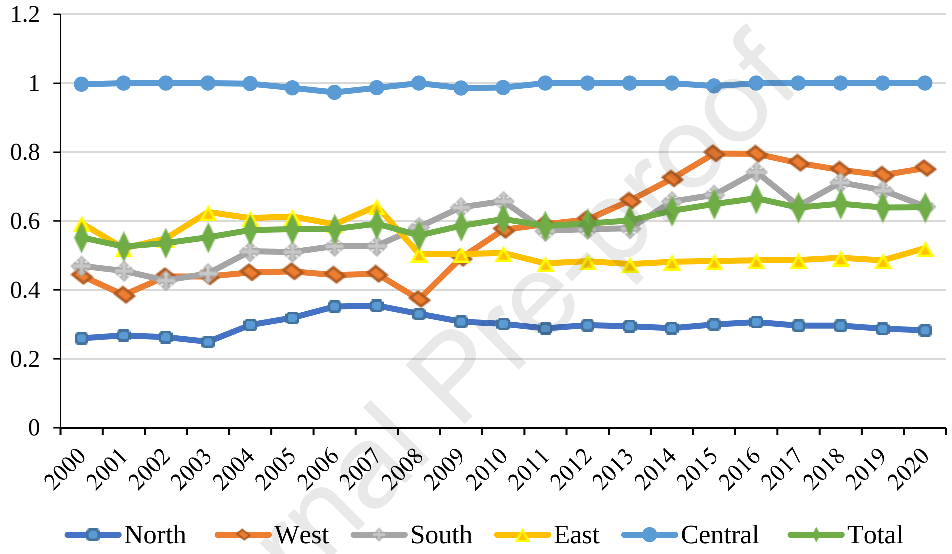

Fig. 5 Annual average TGR trend of the five regions

4.2. Potential contraction of CO_2 emission-Meta production frontier

Section 4.2 and 4.2.1 delves into the potential transport CO_2 emission reduction potentials (TCP) and sources of TCP. The results, detailed in Tables 5 and illustrated in Figure 6 (with comprehensive data available in Tables D and G of the supplementary material), present the average values and percentages for TCP across the African continent. The findings indicate that, on average, Africa's total annual CO_2 emissions could potentially be reduced by 5583.650 kt over the period from 2000 to 2020, which accounts for 74.479% of the total emissions. This suggests that each country, on average, has the capacity to reduce its CO_2 emissions by approximately 139.591 kt annually.

Geographically, North Africa emerges as the region with the highest average TCP, with a staggering 17180.794 kt, accounting for 90% of its average CO_2 emissions over the study period. At the country level, Tunisia exhibits the lowest percentage of TCP relative to average CO_2 emissions at 87.8%, while Mauritania leads with a notable 97.56%. On average, North African economies exhibit the highest TCP percentage at 92.794% compared to other regions. Following North Africa, Southern Africa shows a significant TCP of 5117.358 kt, which is equivalent to 77.639% of the region's average CO_2 emissions from 2000 to 2020. Namibia and Botswana top the list in this region with the highest potential reduction percentages of 92.79% and 92.22%, respectively, whereas Zimbabwe records the lowest at 42.75%. In terms of TCP quantity, South Africa stands out with the highest figure at 35205.972 kt, followed by Angola with 3729.783 kt. Malawi, on the other hand, has the lowest at 218.191 kt. West Africa ranks third in TCP with a total of 3191.188 kt. Nigeria, Ghana, and Benin have the largest average TCPs in the region at 20587.518 kt, 4523.402 kt, and 3089.629 kt, respectively. Guinea (94.032%), Benin (92.665%), and Niger (91.343%) and Burkina Faso (91.043%) showcase the highest TCP percentages, whereas Nigeria (57.670%) and Côte d'Ivoire (33.336%) present the smallest. In East Africa, with a total TCP of 2047.391 kt, Sudan, Ethiopia and Tanzania and record the largest average TCPs at 5697.913 kt, 3326.792 kt, and 2892.237 kt, respectively. Kenya, however, stands out for its relatively lower TCP share of 52.868% compared to its CO_2 emissions. Central Africa, with the lowest TCP amount of 381.517 kt, sees Cameroon leading in TCP quantity at 1385.607 kt, and Equatorial Guinea at the other end with the lowest share of 6.002%. Burundi tops the region with a TCP percentage of 82.844%.

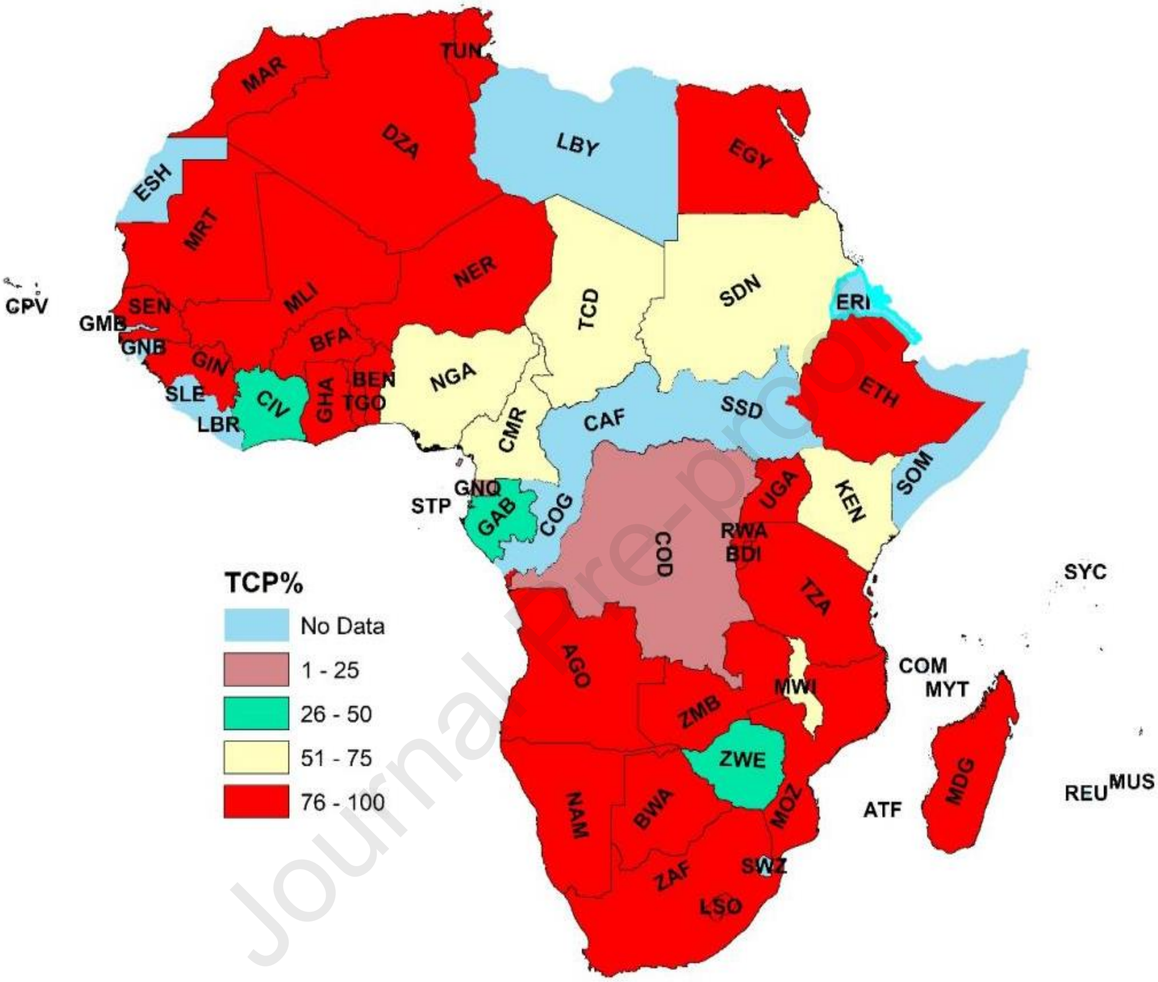

Fig. 6 Average percentage of CO$_2$ emission potential contraction[8] (2000-2020)

4.2.1. Potential sources of CO$_2$ emission contraction

This section (**4.2.1.**) explores the sources of estimated CO$_2$ emission reductions potentials. In this regard, the inefficiency in CO$_2$ emissions performance was computed using equation 13, in the context of MIFF and TGIFF. To discern the underlying factors contributing to

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[8] See Tables C, D, E, F in the supplementary material for detailed annual results

TCP, it is essential to separate it into two key components: management inefficiency ($TCPMIFF$) and technology gap inefficiency ($TCPTGIFF$), as delineated under the meta production frontier framework. Focusing on CO_2 emission potential contraction due to management failures, the study provides insights into the annual average quantities of CO_2 emission contraction through Table 5 and Table E in the supplementary material. At the regional level, North Africa emerges as the area with the most significant management inefficiency, contributing to a TCPMIFF of 13944.514 kt. In stark contrast, Central Africa records the least amount at 376.517 kt. Intriguingly, when considering the percentage of TCPMIFF, Central Africa exhibits the highest inefficiency at 99.165%, with East Africa displaying the lowest at 80.361%. On a country-by-country basis, South Africa leads in TCPMIFF, followed sequentially by Egypt, Algeria, Nigeria, and Morocco in terms of quantity. The predominance of these countries in North Africa underscores the critical role of fossil fuel consumption in their energy mix and weak diesel sulphur content regulation as a major contributor to their elevated TCPMIFF (Jong, 2022).

When evaluating the CO_2 emission potential contraction attributable to the technology gap (TCPTGIFF), as delineated in Table 5 and Table F in the supplementary material, notable regional disparities emerge. The Central region exhibits the lowest contraction potential, amounting to a mere 5 kt on average. In stark contrast, North Africa (NA) displays the highest potential, with an average of 3236.279 kt. Remarkably, Burundi and Chad achieved consistent efficiency throughout all the years under review. This can be attributed to their early commitment to low sulfur content in diesel (Jong, 2022). On a national scale, Egypt stands out with the highest average reduction potential of 7601.781 kt, closely followed by Nigeria at 5531.536 kt and South Africa at 5283.668 kt. Algeria and Morocco also feature prominently, with reduction potentials of 4985.988 kt and 2362.213 kt, respectively. In terms of percentages, the East records 19.639 %, North Africa 17.203 %, Southern Africa 15.432 %, Western Africa 11.729 %, and Central Africa a minimal 0.835 %. These figures underscore significant regional variations in the potential for CO_2 emission reduction due to technology gaps.

Table 5 Average of TCP and its components from 2000 to 2020 by region

Region	CO_2(kt)	TCP(kt)	TCP% of CO_2	TCPMIFF (kt)	TCPTGIFF (Kt)	TCPTGIFF % of TCP	TCPMIFF %of TCP
North	18517.450	17180.794	92.794	13944.514	3236.279	82.797	17.203
West	4833.764	3191.187	80.589	2573.685	617.502	88.271	11.729
Southern	6419.348	5117.358	77.639	4349.764	767.594	84.568	15.432
Eastern	2767.293	2047.392	79.294	1642.310	405.082	80.361	19.639
Central	946.412	381.517	42.077	376.517	5.000	99.165	0.835
Africa	6696.853	5583.650	74.479	4577.358	1006.291	87.032	12.968

TCP=Total CO_2 emission potential contraction, TCPMIFF= TCP due to management failure, TCP due to technology gap inefficiency/failure, Av=Average.

4.3 Discussion of transport CO_2 emission efficiency, reduction potential and sources

The findings from this study highlight several key observations about the transport sector in Africa. Firstly, the sector displays a consistently low level of carbon efficiency throughout the study period, with marked technology gaps among the different geographic regions of the continent. Central Africa leads in the technology gap ratio, indicative of the continent's most advanced green production technology, closely followed by Southern Africa. This suggests that regions or economies that rely heavily on low-carbon energy sources (eg. DR Congo) and exhibit elements of economic prosperity, such as Gabon and Equatorial Guinea, demonstrate higher efficiency in production technology. The observed decline in carbon efficiency can be attributed to several factors, including poor road conditions, an increasing trend in used vehicle ownership, and lax sustainable transport regulations (Jong, 2022; UNEP, 2020). Moreover, many African countries provide subsidies for fossil fuels used in transport, leading to increased diesel consumption. In the global context, Africa ranks as the top importer of gasoline for transport and second only to Europe in diesel imports (IEA, 2019).

Secondly, Africa as a whole exhibit a significant potential for CO_2 emission reduction in its transport sector, amounting to 74.479 % of its total transport emissions. Analyzing the average annual TCP of 5583.649 kt from 2000 to 2020, we find that this amount exceeds the 2020 transport CO_2 emissions of relatively moderate emitters like Côte d'Ivoire and Cameroon. This indicates a substantial scope for emission reduction in Africa's transport sector. This is unsurprising given that many vehicles in Africa are older and less fuel-efficient, leading to higher energy consumption and emissions compared to modern vehicles, as noted by the IEA (2022, 2014), UNEP (2020) and Namahoro et al. (2021). Regionally, North Africa leads in terms of both the amount and percentage of TCP, while Central Africa also shows commendable performance. Contrarily, the Southern region exhibits the lowest percentage of TCP.

Third, management failures contributed over two-thirds to Africa's total potential emission reduction from 2000 to 2020 (see Figure 7). This finding underscores the prevalent inadequacies in transport human capital and institutional structures across most African countries, hindering the delivery of sustainable transport services (Josephine Foundation, 2012; UNEP, 2020; World Economic Forum(WEF), 2017). These results resonate with Ayetor et al. (2021), who established the existence of weak monitoring and institutional capacity in the region. At country level, among Africa's top five transport CO_2 emitting countries (South Africa, Nigeria, Egypt, Algeria, and Morocco), Nigeria and

South Africa are comparatively ahead in moving towards zero transport emissions, with TCP shares of 57% and 79% respectively, which are lower than the 90% observed in other economies.

Regionally, a key factor contributing to TCP results, particularly in **North Africa**, is the region's high reliance on fossil fuel production combined with less robust energy efficiency frameworks, despite having a high number of countries that completely ban (three out of five in Africa) the importation of used cars. This situation likely leads to increased transport CO_2 emission intensity. Supporting this observation, Wang et al. (2020b) identified a substantial potential reduction rate of 54.97% in Egypt's transport sector.

In contrast, **Central Africa's** economies exhibit superior carbon efficiency in the transport sector compared to other regions. The low TCP observed in these economies can be credited to the relatively advanced development of some countries (such as Gabon and Equatorial Guinea) and a stringent focus on environmental management in the implementation of their natural resource policies (AU, 2021).

Southern Africa (SA) stands as the second most proficient region in TCP among all African regions. This notable performance is largely attributed to the region's solid financial and monetary integration, which are key factors in attracting investments in low-carbon initiatives (AU, 2021). In 2021, Southern Africa led with $42 billion in FDI, while West Africa followed with $14 billion, part of which was committed to green fields (UNCTAD, 2022). Additionally, transport policies have played a pivotal role in SA's performance. For instance, South Africa's green transport policy is geared towards expanding road infrastructure with lower carbon resilience, aiming to abate total greenhouse gas emissions in the sector by 5% by 2050 (DoT, 2018). Moreover, Zimbabwe and Malawi have also made strides in environmental protection by implementing transport taxes and engine capacity restrictions.

In **West Africa**, Nigeria's notable improvement in TCP can mainly be credited to the implementation of Euro 3 standards and the elimination of government fuel subsidies. Additionally, the UK's commitment to provide £150 million for clean transport projects in Nigeria, aimed at fostering greenhouse gas resilient practices, is a significant contributory factor (Chikwendu et al., 2015). This investment addresses the escalating issue of vehicle congestion and associated emissions. However, other West African countries exhibit high TCP rates, partly due to lax vehicle emission import policies. Countries like Mali, Senegal, Cape Verde, and Burkina Faso, for instance, lack stringent vehicle importation regulations. The introduction of standardized fuels and vehicle regulations (compliance with Euro 4 emissions standards) by 15 West African nations in 2020 is expected to significantly reduce transport emissions in the region (UNEP, 2020; World Economic Forum, 2023).

In **East Africa**, economies such as Ethiopia, Madagascar, Uganda, and Tanzania fall under the category of having weak institutional frameworks for light-duty vehicles (UNEP, 2020; Urgaia, 2018). Notably, three of the six leading importers of used cars in Africa are from this region, which explains their high TCP rates (Muigua, 2022).

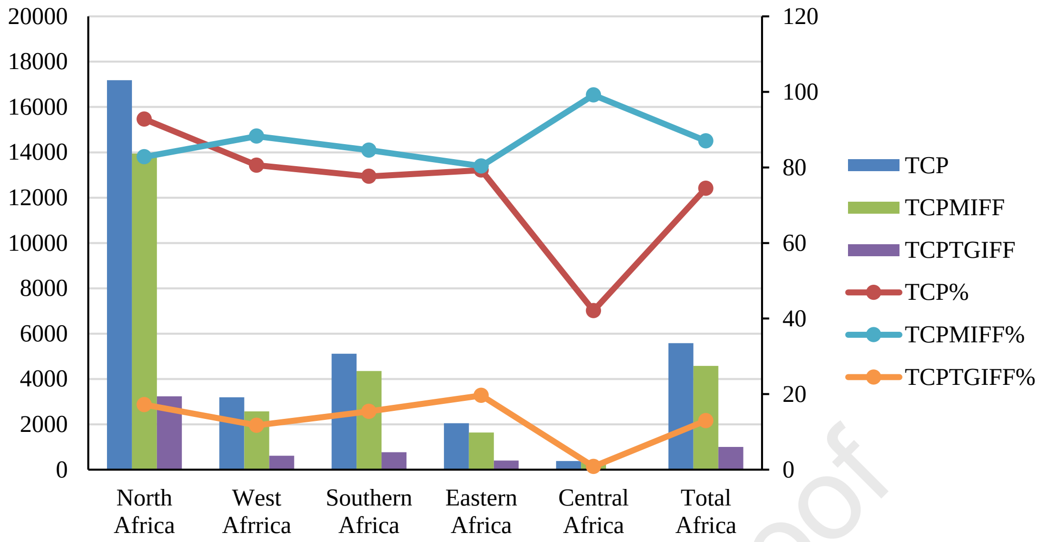

Fig. 7 Average TCP and its sources from 2000 to 2020 by region

4.4 Analysis of external influencing factors using panel regression

To develop more targeted policies, policymakers need to understand the external causes of transport carbon efficiency performance. The fixed effects outcomes based on the Hausman test are presented in Table 6. The P value (0.000) indicates that the individual fixed effect is not zero, leading to the rejection of the null hypothesis. Therefore, the findings support using the fixed effects model. Besides, the average VIFs (see Table I) of the variables(2.20) are below 5, indicating no multicollinearity, which is below the recommended threshold of 10 (Lin et al., 2011; Zhang et al., 2022). The correlation coefficients (see Table H- supplementary material) were less than 0.5, suggesting a modest level of correlation between the variables.

Table 6 Regional regression results of influencing factors affecting transport carbon efficiency (*MCEF)*

Variable	NA	WA	SA	EA	CA
lnTVP	.129***	.304***	.371***	.374***	.238***
	(.032)	(.03)	(.041)	(.035)	(.045)
lnUB	-.268***	-.324***	-.438***	-.012	.85***
	(.071)	(.099)	(.109)	(.048)	(.158)
lnHC	.41***	.01	.124**	-.028	-.165***
	(.114)	(.022)	(.053)	(.06)	(.053)
lnFDI	-.015	.002	-.022	.067*	.021
	(.014)	(.016)	(.015)	(.038)	(.015)
lnNRT	-.002	-.034***	.004	.008	.031
	(.006)	(.013)	(.016)	(.008)	(.025)
lnBR	-.01	.051*	-.03	-.209***	.23***
	(.018)	(.03)	(.04)	(.069)	(.026)
lnSC	-.166***	.052*	-.011	.009	.029
	(.053)	(.028)	(.043)	(.06)	(.036)
lnTRE	-.002	-.023***	-.033***	-.183***	-.115**
	(.011)	(.009)	(.012)	(.019)	(.045)
lnTEI	-.474***	-1.424***	-.104	-.048	-4.162***
	(.107)	(.162)	(.173)	(.159)	(1.149)
lnIC	-.112***	.14***	-.12	-.004	.118
	(.037)	(.047)	(.077)	(.084)	(.084)
SfD	-.345***	1.075***	-.338**	-.318***	.708***
	(.108)	(.257)	(.15)	(.05)	(.179)
Cons	2.859***	2.951***	5.669***	2.744***	-5.2***
	(.725)	(.911)	(1.094)	(.685)	(1.138)
Observations	105	210	189	168	105
R-squared	.942	.904	.9	.905	.951
Country FE	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES
Hausman Test Chi2 111.44 Prob > Chi2 = 0.0000					

*Robust errors are in parentheses, *** p<.01, ** p<.05, * p<.1, dependent variable is lnMCEF, NA=North Africa, WA=West Africa, SA=Southern Africa, EA=East Africa, CA=Central Africa, Transport Value-added per capita (TVP), human capital (HC), Sulphur content (SfC), urbanization (UB), and institutional capacity (IC) are selected. FDI as a share of GDP, energy intensity (TEI), business regulation (BR), structural change (SC), natural resource rent (NRT), renewable energy (TRE).*

Table 6 presents the panel regression model results of all five regions. In **North Africa (NA)**, carbon efficiency in the transport sector is improved by higher TVP per capita and skilled HC, whereas UB, SC, TEI, IC, and SfD impede its growth. The positive effect of TVP corresponds with the region's commitment to large infrastructure investments, including transport. Algeria (38.5%), Mauritania (31.7%), and Morocco (27.8%) are among Africa's top eight economies with the highest fixed capital share of GDP between 2010 and 2020, reflecting their capacity to invest in transport efficiency (World Bank Group, 2023). However, it is important to note that while TVP improves transport carbon efficiency in North Africa, the region's reliance on fossil fuels and the slow adoption of cleaner energy technologies are reflected in the low carbon efficiency levels discussed in section 4.1. This result aligns with Lin and Sai (2022a) for 23 SSA economies. Moving on, the increased effect of human capital (HC) highlights the region's relatively strong human development. With an average Education Development Index of 6.49 between 2010 and 2020, the region ranked second, just behind Southern Africa's 6.8 (UNDP, 2024). A higher accumulation of human capital promotes the shift to energy-efficient technologies, the adoption of low-carbon fuels, and innovations in energy conservation. The results align with Khan et al. (2021) for seven OECD nations.

For the inhibitory factors, UB in countries such as Algeria, Tunisia, and Morocco surpass the global average of 57% urban population (OurWorldInData, 2024). This urban growth with poor public transport systems can negatively influence traffic congestion, increased private vehicle ownership, and transport demand, ultimately resulting in higher fuel consumption and emissions. This findings align with Haouraji et al. (2021), where urbanization raises emissions by 2.76% for four North African countries. Next variable is SC, which recorded a negative impact on TCE and could be due to the slow transition to sustainable transport modes like electric vehicles (EVs) and public transport in the region and across Africa. The electric vehicle market share in Morocco, and Tunisia remains less than 0.1%; as a result, internal combustion engine vehicles continue to dominate, leading to sustained high demand for gasoline and diesel (Khan et al., 2022). This result is consistent with Onanuga et al. (2021) for 31 SSA countries. Further, the negative effect of TEI aligns with NA's high energy intensity and fossil fuel subsidy levels. In 2017, Algeria (4.02%), Egypt (6.27%), and Tunisia (2.91%) were among top nine highest in fossil fuel subsidies as a percentage of GDP in Africa (UNECA, 2024). Egypt, Algeria, Morocco, and Tunisia ranked among the top 12 energy-intensive economies in Africa from 2010 to 2020 (EIA, 2024), indicating inefficient energy use and resulting in higher carbon emissions. This result concurs with Sai et al. (2023) for 35 Africa economies. The inhibitory effect of institutional capacity (IC) is evident in large, cheaper adulterated fuels being sold on informal markets due to limited IC levels and resources for fuel monitoring and testing (Naré and Kamakaté, 2017). This is compounded by weak sulfur regulation standards (SfD), with countries like Algeria (2,500 ppm) and Egypt (6,000-7,000 ppm) struggling to implement effective emission controls (Jong, 2022). Obobisa et al. (2022) affirmed the negative effect of IC on 25 African economies, while Ayetor et al. (2021a) highlighted the issue of poor fuel quality across Africa.

In **West Africa (WA)**, carbon efficiency in the transport sector is driven by higher TVP, BR, SC, SfD, and IC. However, UB, NRT, TRE, and transport TEI present challenges. The positive impact of TVP is linked to increased investments in infrastructure and logistics, as seen in Ghana, Nigeria, and Cote d'Ivoire, which recorded average transport output growth of 7.4%, 9.4%, and 19% from 2010 to 2020 (UNECA, 2024), indicating more optimized operations and potential in energy consumption reductions. These findings align with Lin and Sai (2022a) for 23 SSA economies. The region's Centre for Renewable

Energy and Energy Efficiency (ECREEE), established in 2010, has played a crucial role in enhancing IC and SfD's positive impact on carbon efficiency by promoting incentives for low fuel consumption transport systems and emission standards (ECREEE, 2024). The findings regarding IC align with those of Karim et al. (2022) for 30 SSA countries, while the results related to SfD are consistent with P. Li et al. (2020) on China. The positive effect of BR reflects significant reforms in business practices, with Nigeria implementing nine reforms and Senegal and Togo seven each between 2018 and 2019 (World Bank, 2019). Regulations that promote clean business activities, including in transport, can enhance efficiency, as noted by Ugwu et al. (2022). The positive effects of SC are associated with a strong shift in economic activities driven by digitalization, as evidenced by the rise of e-commerce and teleworking, which has reduced the need for mass travel. West Africa leads Africa in mobile money adoption, accounting for 36% of registered accounts (GSMA, 2024). Notably, eight of the top 20 African countries with the highest infrastructure investments as a share of GDP, including transport, are in West Africa, contributing to improved logistics and connectivity (ICA, 2017). These findings also align with Dappe and Lebrand (2024) in the Horn of Africa and Lake Chad region.

On the negative effect variables, UB’s inhibitory impact stems from high peak population densities and slow urban capital investment, which contribute to poor urban design and long commutes or congestion, ultimately raising energy consumption (Lall et al., 2017). Côte d'Ivoire and Togo have over 18% and 20% of their populations living in urban agglomerations of more than 1 million, with about 56% and 51% residing in slums (OurWorldInData, 2024). Urban sprawl in these cities offsets the advantages of urban concentration, largely due to congestion costs and the presence of informal sector operators with minimal regulation. The negative impact of NRT on TCE is evident in the reliance on mineral revenues for basic needs. For instance, Nigeria's GDP growth fell from 6% in 2014 to -1.6% in 2016 due to declining oil prices, resulting in a 38% decrease in infrastructure investment (World Bank Group, 2023). TRE and TEI negative's influence on TCE can be attributed to the reliance on used diesel and gasoline vehicles and inadequate clean vehicle infrastructure, resulting high fossil energy consumption. In 2019, Nigeria (62.12%), Ghana (8.96%), and Benin (15.37%) together accounted for 86% of used vehicle imports from the USA (ITF, 2024). Similarly, Ayetor et al. (2023) noted that the EV (plug-in) import to charging infrastructure ratio is 103.7 in Senegal and 2,518.9 in Nigeria compared to 4.3 in Morocco. All findings regarding the inhibitory factors are consistent with previous studies: Ali et al. (2019) on urbanization (UB) for 47 developing countries, **Afolabi (2023)** on natural resource rent (NRT) for 41 economies in Africa, Lin and Abudu (2020) on transport renewable energy (TRE) for MENA economies, and Sai et al. (2023) on transport energy intensity (TEI) for 35 African countries.

In **Southern Africa (SA)**, carbon efficiency in the transport sector is enhanced by higher TVP per capita and HC. However, UB, TRE, and SfD hinder efficiency. TVP's positive effect on TCE can be attributed to the advanced nature of some economies in the region. Namibia, Botswana, and South Africa are ranked among Africa's top eight for transport infrastructure (AFDB, 2022), which can influence logistics efficiency. South Africa's ban on used car imports allows for effective regulation of domestically produced vehicle efficiency (UNEP, 2020). For the negative effect variables, Human capital's impact on TCE reflects regional efficiency levels. Botswana, South Africa, and Namibia, classified as efficiency-driven economies by the Global Competitiveness Index (GCI), emphasize quality education, labor market efficiency, and advanced technology adoption (WEF, 2017). Besides, South Africa produces cars locally and offers cheaper app-based electric three-wheeler taxis compared to ICE taxis (Roychowdhury et al., 2023). Both Namibia and Botswana allocate 8-9% of their GDP to education, ranking among the top in Africa (UNECA, 2024).

UB’s negative impact is reflected in countries like Namibia, Zambia, Zimbabwe, and Angola, which have over 30% of their populations residing in large cities (among the highest in Africa), marked by severe congestion and unregulated shared transportation options (OurWorldInData, 2024). Persistently low paved network ratio, with Zambia at 15.4%, Mozambique at 27%, Namibia at 17.4%, and South Africa at 21% is also a major factor (IRF, 2024). The SFD limits TCE can reflect in having four countries in the top ten for energy intensity (MJ per $2017 PPP GDP) (World Bank Group, 2023) countries in Africa with weak regulatory ranking of on used cars and status (UNEP, 2020). TRE's negative impact is tied to the region's heavy dependence on fossil fuels and the slow pace of renewable energy transitions (Kessides, 2020). For instance, South Africa relies on fossil fuels for 94% of its primary energy consumption as at 2019 (Global Change Data Lab, 2022a). The findings are consistent with prior research. With the improving variables, Lin and Sai (2022a) 's findings align with VP in 23 SSA economies, and human capital is supported by the results of Iorember et al. (2021) in South Africa. Conversely, the inhibitory urbanization is align with the results of Oladunni et al. (2022) in nine provinces of South Africa. Lin and Abudu (2020) agrees with the negative effect of TRE in MENA economies. The work of Naré and Kamakaté (2017) and Ayetor et al. (2021b) support the negative effect of high sulfur diesel on TCE in African countries.

In **East Africa (EA)**, carbon efficiency is hindered by high sulphur diesel use (SfC), ineffective BR, and TRE. SfC: some economies (e.g., Seychelles, Ethiopia) still rely on high-sulphur fuels (up to 5,000 ppm), while old, polluting vehicles dominate fleets (Jong, 2022). In 2019, Kenya, Uganda, and Tanzania accounted for 67.5% of used vehicle imports from Japan (ITF, 2024). BR's negative impact stems from weak vehicle import regulations. In 2018, imported used vehicles in Rwanda and Uganda averaged over 15 years old (UNEP, 2020). Besides, TRE use remains insufficient to adequately support the transportation sector in CA (Sadiq and Chidi, 2024). With FDI, Mauritius, Rwanda, and Kenya consistently secure spots among the top five SSA economies for their strong business climates (World Bank, 2019). This favorable business climate positioned East Africa as a leader in foreign direct investment (FDI), attracting 143 projects worth $19.4 billion in 2016. As part of this initiative, Kenya initiated the 480 km Standard Gauge Railway Project in May 2017, which cost $3.8 billion (AnalyseAfrica, 2017). The results for FDI, BR, TRE, and TVP align with the findings of Adams et al. (2020) on FDI for 19 SSA countries, Rieger (2019) on BR for 104 developing nations, Lin and Abudu (2020) on TRE for MENA economies, Lin and Sai (2022a) on TVP 23 SSA economies, and Ayetor et al. (2021b) on SfC for African countries, accordingly.

In Central Africa (CA), carbon efficiency in the transport sector is positively supported by factors such as TVP, effective UB, stringent BR and low sulphur content in fuels (SfC). However, HC, TRE, and TEI hinder efficiency. TVP promotes TCE because in Central Africa, mining dominates construction activities, driving infrastructure improvements that enhance logistics and reduce carbon emissions. For instance, in 2010, when mining share of GDP grew from 9% to 18% in 2011, fixed capital investment grew from 14% to 28.7% (UNSD, 2024; World Bank Group, 2023). UB enhances TCE through improved public transport, shared mobility, and spatial planning. With 23.76% of DR Congo's population in large urban areas, shared infrastructure and lower transport costs can enhance carbon efficiency (Global Change Data Lab, 2022b). BR enhances TCE due to high environmental and regional integration index scores, driven by green development investments (AU, 2021). SfC's positive impact stems from early sulphur content restrictions in diesel (500ppm) in Chad and DR Congo (Jong, 2022). HC's negative impact is attributed to the fact that many economies lack the personnel with the specialized skills needed for modern transport systems and management practices. Cameroon and Chad ranked among the bottom 12 in the 2017 Africa Capacity Index (ACBF, 2017). TRE's negative impact stems from the limited adoption of renewables in its transport sector, with challenges in scaling production and grid reliability, leading to reliance on imported diesel and gasoline. More so, the negative effect of TEI could result from an aging vehicle fleet and longer travel times due to poor road conditions (e.g., Burundi's paved network ratio was 14.38% in 2020, while Gabon's was 21.54% in 2017 (IRF, 2024) have led to increased fuel consumption and a higher transport carbon footprint. The results align with previous studies. On the positive effect variables, TVP results in CA conform with Lin and Sai (2022a) in SSA economies, UB align with Adams et al. (2020) for 19 SSA countries, BR is consistent with Ugwu et al. (2022) for 30 SSA economies. In contrast, the negative impact variables, SfC, align with findings by Li et al. (2020) on China. For the inhibitory factors, the results of TEI and HC concur with Asane-Otoo (2015) for 45 African countries, and TRE supports Lin and Abudu (2020) in MENA economies.

4.5 Robustness test

To confirm the robustness of the panel regression results, we follow Zhang et al. (2015) and performs robustness tests by re-estimating the dependent variable using a non-directional distance function. In Table J, the indicators' directions and significance levels remain largely unchanged, confirming the reliability of the original conclusions.

5. Conclusion and policy implications

The transportation industry has emerged as a primary source of emissions in Africa, highlighting its crucial role in realizing the sustainable future envisioned in the "Africa We Want" blueprint. Evaluating transport CO_2 emissions efficiency is crucial for Africa's emission reduction targets, energy conservation, and regional development, yet it remains largely uncharted. Therefore, taking regional heterogeneity into account, this research employs a non-parametric metafrontier method to assess the transport carbon efficiency, potential emission reductions, and the sources of emission reduction across forty African economies from 2000 to 2020. External factors influencing MECF across various geographical regions are also analyzed.

The key findings of the study are as follows:

1) Carbon efficiency levels across Africa are generally low, with significant technology gaps observed across the continent’s five geographical regions throughout the study period. Central Africa stands out with the highest technology gap ratio, indicating its leading adoption of optimal green production technology in Africa, closely followed by Southern Africa.

2) The carbon efficiency distribution density shows a declining trend over time, indicating diminishing effectiveness in current approaches towards environmental sustainability in the transport sector.

3) The continent has considerable potential for CO_2 emission reduction, accounting for 74.479 % of total transport emissions, averaging 5583.649 kt annually. North Africa exhibits the most significant potential for reducing CO_2 emissions, both in terms of volume and percentage, suggesting a low decoupling effect between fossil fuel use and CO_2 emissions. Conversely, Central Africa demonstrates the least potential for emission reduction, indicative of effective environmental policy implementations.

4) The majority of the CO_2 emission reduction potential, amounting to 87% of the total, is attributed to management inefficiencies. Central Africa shows the highest percentage of potential emission contraction due to management inefficiencies, while North Africa records the lowest.

5) Influencing factors on transport carbon efficiency (TCE) exhibit regional heterogeneity. Transport value-added positively supports TCE in all regions, while Transport energy intensity and renewable energy diminishes it. Human capital improves TCE in only in NA and Southern region. FDI only improves it in East Africa and Natural resource rent hinders it West Africa. Urbanization, business relations, structural change, institutional quality and sulphur content in diesel have mixed effects.

Policy implications: The study bears some important policy implications for developing climate response strategies and sustainable transport policies.

Given Africa's low carbon efficiency, it's crucial to boost the continent's climate resilience fund, focusing on green transportation investments. Key areas of investment should include railway development, mass rapid transit systems, promotion of electric vehicles, and supporting non-motorized transport. Fiscal measures like fuel taxes and road pricing can incentivize public transport use. Reforms should phase out internal combustion vehicles, reduce non-renewable energy subsidies, and promote eco-friendly alternatives like transitioning from jet fuels to biofuels and efficient traffic management.

To address technological disparities, sustainable transport planning should be customized to each region's needs. Central Africa, with low emission reduction potential but high management inefficiency, requires tailored strategies for each region or country, promoting mutual learning and adaptation of successful transport resilience tactics across regions. Regions with high emissions, like North and Southern Africa, need updated and robust green transport policies and energy frameworks, as well as investment in artificial intelligence algorithms to improve transport management and energy efficiency. West and East Africa, with lower carbon efficiency, should focus on reforming transport systems and integration of advanced technology solutions. In general, the African Union should implement uniform green transport standards and support innovation in low-carbon transport solutions (eg E-mobility, rail etc) through research funding and green incentives.

The primary driver of CO_2 emission potential contraction in the transportation industry is attributed to management inefficiencies. To counter this, we propose establishing green public-private partnerships (PPPs) and comprehensive driver training programs to enhance technical capacities for climate change mitigation. Creating Green Transport Advisory and Research Service Centers in each nation is essential to foster knowledge and competency. Governments should also implement rigorous vehicle inspection and maintenance programs, including emission testing, fuel system checks, exhaust system inspections, and air filter evaluations. Additionally, collaboration across regional blocs and with international partners is vital to leverage a diverse pool of experts in transport sustainability. These efforts are crucial for enhancing management practices and reducing CO_2 emissions in the transportation industry.

The regression results suggest that differentiated policies are needed across all regions to improve transport CO_2 efficiency. Incentives should be provided to shift toward mass public transportation schemes, transition entirely to zero-sulfur diesel fuels. Economic measures like tax incentives, road pricing, and parking fees can be implemented to regulate transport-related emissions. Rapid integration of clean energy sources as transport fuel alternatives and prioritizing quality production processes in value addition are recommended. Governments should strengthen green business regulations and support sustainable natural resource management. The incorporation of development plans with transport infrastructure and traffic management strategies is encouraged. Promoting industrial agglomeration programs with increased capital investment and green urban planning measures can enhance the net benefits of urbanization, human capital, and FDI. Similarly, governments should regulate and provide training informal sector operators as well as streamline uncoordinated transit systems.

This study's **limitations** are important to acknowledge. Firstly, a non-parametric approach was employed, which did not account for statistical inferences. Additionally, the research considered two internal and eleven external factors influencing emission reduction potential. Future studies could benefit from including a broader range of other environmental impact factors, such as agglomeration, infrastructure investment intensity, intra-trade, spatial spillovers, and industrial structure upgrading, to gain a more comprehensive understanding of CO_2 emission efficiency. Another limitation is that this study focused solely on static CO_2 efficiency within the production framework, overlooking dynamic aspects. Future research could explore these dynamic features for a more nuanced analysis. Lastly, it is suggested that future studies use passenger numbers as an output measure when data becomes available, as the value added can be significantly influenced by fluctuations in traffic ticket prices.

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Highlights

- Transport carbon efficiency performance and its determinants are investigated.
- Used non-parametric meta-frontier technique to account for regional heterogeneity.
- Results exhibit low carbon efficiency levels and considerable technology gaps.
- Potential CO_2 reduction is estimated at 74.49%, primarily attributed to management inefficiency.
- Regression-influencing factors exhibit regional heterogeneity.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

We declare hereafter that, this manuscript with title ‘‘**Evaluation of transport carbon efficiency, reduction potential, and influencing factors in Africa**’’ has not been previously published, is not currently submitted for review to any other journal and will not be submitted elsewhere before one is made. Thank you so much.

Signed
Rockson Sai
12 Oct., 2024