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RESEARCH ARTICLE

Energy price reform to mitigate transportation carbon emissions in oil-rich economies

Sa'd A. Shannak[1] · **Jeyhun I. Mikayilov**[2] · **Rubal Dua**[2]

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Abstract
This study examines the impact of domestic fuel prices, population, and economic activity on transport CO_2 emissions, employing Saudi Arabia as a case study. The research uncovers statistically significant long-term associations between these variables. Despite transport CO_2 emissions demonstrating slight responsiveness to fuel price alterations, with estimated elasticity values between – 0.1 and – 0.15, the study affirms the relevance and timeliness of the Saudi government's strategy to curtail fuel incentives. Projections for a 2030 scenario, encompassing heightened economic activity aspirations and further escalations in domestic fuel prices to mirror true market costs, revealed a 1.8 percent annual reduction in transport CO_2 emissions from 2021 to 2030 compared to a scenario with unchanging fuel prices. The insights from this study bear significance not only for Saudi Arabia but also for other oil-rich nations striving to pave the way toward a sustainable transportation future.

Keywords CO_2 emissions · Climate change · Transportation · Cointegration and equilibrium correction models · Forecasting · Saudi Arabia

1 Introduction

1.1 Background

Transportation consumes around a quarter of the world's final energy and produces a similar share of direct energy-related CO_2 emissions (Ritchie and Roser 2020). Changes in transport fuel demand and associated CO_2 emissions are influenced by many factors, including population growth, economic growth, changing energy

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✉ Jeyhun I. Mikayilov
Jeyhun.mikayilov@kapsarc.org

[1] Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University-Qatar Foundation, Doha, Qatar

[2] King Abdullah Petroleum Studies and Research Center, PO Box 88550, 11672 Riyadh, Saudi Arabia

prices, new technologies, and changing behavior. This research aims to determine the factors driving the transport CO_2 emissions in economies using the case study of the Kingdom of Saudi Arabia. In particular, we analyze the long-run relationships between the CO_2 emissions from the transportation sector and drivers, including income, fuel prices, gasoline share, and population.

To deepen the understanding of these dynamics, a comprehensive literature review reveals additional insights. The global impact of urbanization and industrialization on transport energy demand and emissions is highlighted in studies by Brand et al. (2013) and Sims et al. (2014), offering a comparative perspective for Saudi Arabia's situation. Additionally, the effectiveness of policy interventions like fuel economy improvements and the adoption of electric vehicles in reducing transport sector emissions is emphasized by Schipper (2011) and Gillingham et al. (2013).

The Environmental Kuznets Curve (EKC) concept, explored in the context of Saudi Arabian transport CO_2 emissions by Alshehry and Belloumi (2017), has broader underpinnings in the works of Stern (2004) and Dinda (2004). This theoretical framework can be instrumental in understanding its applicability in Saudi Arabia. Moreover, the elasticity of fuel demand in response to price changes, particularly relevant to Saudi Arabia's energy price reform, has been studied by Hughes et al. (2008) and Burke and Nishitateno (2013).

Furthermore, the relationship between economic growth and energy consumption, a key area in the research of Alkhathlan and Javid (2015), is well-documented in studies by Poumanyvong and Kaneko (2010) and Apergis and Payne (2009). These insights provide a broader economic perspective on transport sector emissions and their drivers.

Incorporating these diverse perspectives and findings, this study aims to address gaps in the literature by presenting a holistic view of the factors affecting transport CO2 emissions, focusing on Saudi Arabia. This approach not only enhances existing knowledge but also provides actionable insights for policymakers and stakeholders in environmental sustainability and energy policy. The goal is to contribute meaningfully to the understanding of transport CO_2 emission drivers in Saudi Arabia, offering a foundation for more informed policymaking and research in this critical area of environmental and economic sustainability.

We consider Saudi Arabia as a case study because it has taken significant steps to reduce transport energy demand and, consequently, transport CO_2 emissions. First, since 2015 the Kingdom has implemented domestic energy price reform (EPR). The Saudi government has been gradually raising transport fuel prices to make transport energy consumption more sustainable and increase government revenues. This includes 91-octane gasoline, which it raised from 0.375 Saudi riyals (SAR) per liter (l) ($0.38 per gallon) in 2014 to 0.45 SAR/l ($0.45 per gallon) in 2015, then to 0.75 SAR/l ($0.76 per gallon) in 2016, 1.37 SAR/l ($1.38 per gallon) in 2018 (Sheldon and Dua 2021), and 1.99 SAR/l ($2.00 per gallon) in 2021. This policy has affected several sectors in many ways, including the transport sector. Second, another policy lever used by the Kingdom was the establishment of fuel economy standards, which sets sales-weighted average fleet fuel economy targets for automakers. In particular, the Saudi Energy Efficiency Center (SEEC) together with the Saudi Standards, Metrology and Quality Organization (SASO) began implementing the new light-duty vehicle Corporate Average Fuel Economy (CAFE) standards in 2016. This has led to a 10% improvement in the fuel economy of the new fleet (Howarth et al. 2020). In addition, strict measures were also developed to ensure imported used vehicles complied with Saudi Arabia's minimum fuel economy standards. It is anticipated that this program will lower fuel consumption by 3% on average (SEEC 2017). Third, educational and awareness programs were created to educate car owners on vehicle fuel economy through mandatory fuel economy labels (SEEC 2018). Fourth, the government has also launched several energy efficiency standards targeting heavy-duty vehicles, including a fuel economy improvement program, fuel economy labeling, and a tire resistance and grip initiative launched by the Saudi Energy Efficiency Program in 2014 and applied in November 2019. In 2019, a heavy-duty vehicle aerodynamic initiative was launched. It is anticipated that this initiative will achieve fuel savings of 5–9% (Howarth et al. 2020).

Several studies outside Saudi Arabia have employed various econometric methods to explore this complex relationship, focusing on different driving factors and their impact on transportation emissions. Hughes et al. (2008) explored the short-run price elasticity of gasoline demand using econometric analysis. They provided evidence of a significant shift in consumer response to gasoline prices over time, highlighting the importance of price mechanisms in influencing transportation emissions. Gately and Huntington (2002) utilized a demand model to assess the impact of fuel efficiency and income growth on gasoline demand in the Middle East, particularly focusing on the impact of income. Their findings suggested that gasoline demand is significantly influenced by income growth, implying that rising living standards could offset gains from increased fuel efficiency. Li et al. (2016) conducted a study on the relationship between transportation CO_2 emissions and urban sprawl in China. Employing spatial econometric models, they discovered that urban sprawl significantly contributes to the increase in transportation emissions. This study highlighted the importance of urban planning and its impact on transportation emissions. Apergis and Payne (2009) examined the relationship between CO_2 emissions, energy consumption, and economic growth across Central American countries using a panel cointegration approach. Their results indicated a positive long-run equilibrium relationship between energy consumption and CO_2 emissions, reinforcing the idea that economic growth and energy consumption are closely linked to the environment. Timilsina and Shrestha (2009) explored the factors affecting CO_2 emissions from the transport sector in Asia. They used panel data analysis and found that income, urbanization, and motorization significantly influence transport emissions. This study underscored the role of rapid economic development and urbanization in shaping transportation emissions in developing countries. Together, these studies demonstrate the complexity of factors influencing transportation emissions, ranging from economic growth and urbanization to fuel prices and efficiency. They provide valuable insights for policymakers and researchers, highlighting the need for integrated approaches that consider economic, urban, and technological factors in addressing transportation emissions.

There are two studies that we are aware of investigating transport-related CO_2 emissions in Saudi Arabia. Alkhathlan and Javid (2015), studied the impact of transport oil consumption and income on CO_2 emissions from the transport sector. Using the structural time-series modeling approach, which enables the discovery of different aspects of relationships, Alkhathlan and Javid (2015) found that the impact of oil consumption in the transport sector on transport CO_2 emissions is positive and elastic. They also found a positive monotonically increasing impact of income on transport CO_2 emissions. In addition, they found that the underlying CO_2 emissions trend[1] has been falling since 1995. This finding shows that, from the 1990s, the share of CO_2 emission-intensive vehicles in Saudi Arabia's transportation sector has been decreasing, which in turn has lessened overall CO_2 emissions from transport. Alshehry and Belloumi (2017) investigated the EKC phenomenon for transport emissions in the Saudi Arabian case. Their findings do not support the EKC for Saudi Arabian transport CO_2 emissions. Alshehry and Belloumi (2017) found the long-run income elasticity to be 0.03, and the energy demand elasticity around unity. They used energy consumption as one of the left-hand variables. Since CO_2 emissions data is calculated by multiplying the energy consumption data by conversion factors, the use of energy consumption as a driving variable in the model specification is subject to the statistical and empirical issues as discussed in Jaforullah and King (2017). The relatively smaller income elasticity might be the result of a misspecified model framework.

Alkhathlan and Javid (2015) is a valuable study that makes substantial contributions to the environmental economics literature, specifically with application to Saudi Arabia. However, there are some nuances to investigate in addition to their work. First, the study period ends in 2013, which does not allow us to see the impacts of the recent energy price reforms on CO_2 emissions from transport. Second, they used total energy (oil) consumption in transportation as one of the drivers of CO_2 emissions, which might cause some estimation issues. In particular, since carbon emissions data is not directly observable, it is calculated using energy consumption data and relevant conversion factors. Thus, the use of energy consumption, from which the emissions data is calculated, as an independent variable can result in econometric and empirical problems, as shown by Jaforullah and King (2017). However, excluding energy consumption can also lead to omitted variable bias. To avoid both issues, other measures, such as fuel share and energy intensity, are used to proxy the impact of energy consumption [see Liddle (2011, 2018) and Mikayilov et al. (2017), *inter alia*]. Third, they have not performed forecasting exercises.

1.2 Exploring the impact of energy price reforms on transport CO_2 Emissions in Saudi Arabia

This study is fundamentally driven by the research question: How do various factors, particularly ongoing energy price reforms, influence transport CO_2 emissions in an oil-rich economy like Saudi Arabia, and what are the implications for achieving a

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[1] The underlying CO_2 emissions trend (similar to UEDT = underlying energy demand trend in energy economics literature) is modeled as a stochastic trend and incorporates the deterministic trend as a special case. As with the deterministic trend it is used to capture the impact of factors such as technological changes, policy interventions etc. on CO_2 emissions.

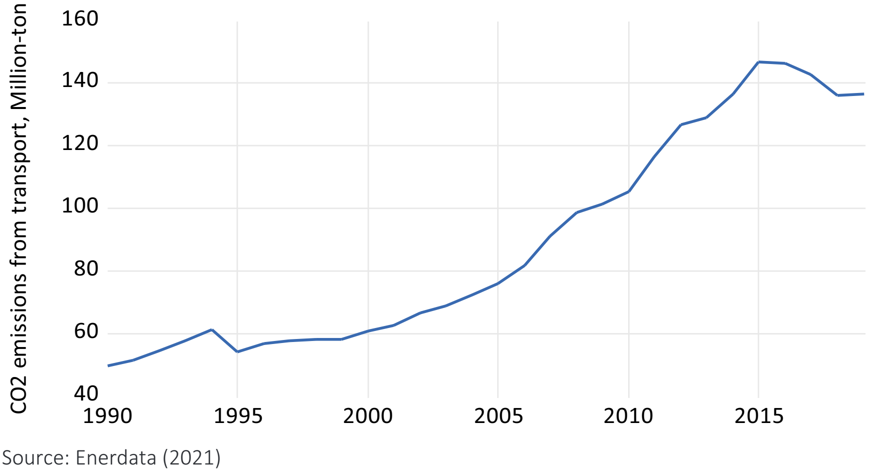
sustainable transportation sector? This question directs our focus to a critical examination of the various drivers influencing CO_2 emissions in the transportation sector, with a special emphasis on the role of energy price reforms in Saudi Arabia.

Addressing gaps in the existing literature, this study meticulously explores the complex interplay between energy pricing policies and transportation emissions in an economy heavily reliant on oil. It aims to delineate how changes in energy pricing, a key policy tool, impact CO_2 emissions from transportation. This is particularly pertinent given Saudi Arabia's position as a major oil producer and its recent initiatives in energy price reforms. Our findings are intended to guide policymakers and researchers in understanding the nuanced relationship between energy price reforms and transport CO_2 emissions in greater detail. By unraveling this relationship, the study offers valuable insights into the potential of such reforms in mitigating the anticipated increase in transport-related CO_2 emissions. Ultimately, the conclusions drawn from this research will not only contribute to the academic discourse but also inform policy decisions aimed at fostering a sustainable transportation sector in oil-rich economies like Saudi Arabia. This research, therefore, holds significant implications for environmental policy and sustainable development within the context of the Kingdom's ongoing economic and energy transformations.

The rest of this paper is structured as follows. The data is presented in Sect. 2. Sections 3and 4 describe the functional specification and econometric methodology, respectively. Sections 5, 6 and 7 contain empirical estimation results, associated discussions, and forecasts, in that order. Finally, Sect. 8 summarizes the study's major findings and policy implications.

2 Data sources

This paper uses annual time-series data from 1990 to 2019. The span is chosen based on data availability. The used variables are defined as follows. Transport emissions (emitra) are CO_2 emissions from transport, in a million tonnes of CO_2 and retrieved from Enerdata (2021); gross domestic product (GDP) is real GDP, million Saudi riyals, in 2010 constant prices, taken from the General Authority for Statistics (GaStat) (2020); average fuel price (pfuel) is the weighted average price of transport fuel. It is calculated using gasoline, diesel, and kerosene consumption data for the transport sector as weights and corresponding fuel prices, in SAR per tonne of oil equivalent (toe). In other words, using each fuel type's consumption share as a weight multiplied by the corresponding price data and summing up the results, the weighted energy price data for the transport sector is calculated. Gasoline, diesel, and kerosene consumption data for the transport sector are taken from the International Energy Agency (IEA 2020), and corresponding price data is retrieved from different royal decrees (see Hasanov et al. 2023). The calculated price data was converted to real terms using a GDP deflator. The GDP deflator is calculated based on the nominal and real GDP numbers from GaStat (2020). The gasoline share is the percentage share of gasoline consumption in total energy consumed by the Kingdom's transport sector. It is calculated based on data taken from the IEA (2020).



Source: Enerdata (2021)

Fig. 1 Transport CO_2 emissions in Saudi Arabia, Million-ton of CO_2

Population (pop) is the total population in persons. It is taken from the United Nations database (UN 2021).

The transport CO_2 emissions in Saudi Arabia increased between 1990 and 2015 (see Fig. 1). The growing trend in emissions changed at the beginning of 2015. Fuel emissions were 146.94 million tonnes of carbon dioxide equivalent ($MtCO_2e$), before dropping to 142.9 $MtCO_2e$ in 2017 (Fig. 1).

3 Functional specification

The main objective of this study is to investigate the driving factors of carbon emissions in Saudi Arabia's transportation sector and find the long-run relationship between studied variables and carbon emissions from 1990 to 2019, utilizing a partial equilibrium framework. For this purpose, we have used the following functional specification:

$$emitra = b_0 + b_1 gdp + b_2 pop + b_3 gasshare + b_4 pfuel + u \tag{1}$$

Here, *emitra* is carbon emissions from the transport sector, *gdp* is gross domestic product, *pop* is the total population, *gasshare* is the share of gasoline consumption in total transport energy consumption. *pfuel* is the average transport fuel price, *u* the error term, b_0, b_1, b_2, b_3, and b_4 are regression coefficients of the long-run relationship. All variables in Eq. (1) are in logarithmic expression hence the coefficients can be directly interpreted as elasticities.

The choice of the potential drivers of carbon emissions from transport is based on related literature. Income and population have been the most used drivers of environmental degradation since the early studies devoted to environmental pollution modeling based on IPAT identity (Enrlich and Holdren 1971) and then those dealing with the pollution-income relationship (Grossman and Krueger 1991; Shafik and Bandyopadhyay 1992; Panayotou 1993, *inter alia*), and later those using the STIRPAT framework (Dietz and Rosa 1994; 1997, *inter alia*). The coefficients b_1 and b_2 are thus expected to have positive signs. Increasing fuel prices, on the other hand, are expected to reduce CO_2 emissions from transportation, and thus, b4 is expected to have a negative impact.

Energy consumption is one of the main sources of CO_2 emissions (Baiocchi 2010, *inter alia*). Carbon emissions data, in particular, are calculated using energy consumption data and relevant conversion factors because they are not directly observable. As demonstrated by Jaforullah and King (2017), using energy consumption as an independent variable to model emissions can result in econometric and empirical issues. Excluding energy consumption, on the other hand, can result in omitted variable bias. To avoid both issues, other measures such as fuel share, *gasshare* in our specification, and energy intensity are used to proxy the impact of energy consumption (see Liddle 2011, 2018; Mikayilov et al. 2017, inter alia).

4 Econometric methodology

First, the used variables are tested for unit-root properties, following the conventional procedure for time series data estimations. Second, if all variables are integrated of the same order, the long-run common movement—the cointegration relationship should be tested. After confirming the cointegration relationship, the long-run relationship can be estimated.

For testing stationarity features of the variables, the widely used augmented Dickey-Fuller (ADF) (Dickey and Fuller 1981) test is utilized. The null hypothesis of the ADF test states the non-stationarity of the variable. To test the cointegration relationship between a dependent variable (*emitra*) and independent variables (*pfuel, pop, gasshare, and gdp*), Banerjee et al. (1998), and bounds tests (Pesaran and Shin 1999; Pesaran et al. 2001) are used. For both tests, the null hypothesis is the nonexistence of the cointegration relationship. Since both the ADF and utilized cointegration tests are widely used in similar studies, they are not detailed here. Interested readers are referred to the above-mentioned literature.

For the estimation of the long-run relationships, and to see if different techniques produce similar results, we used different estimation techniques. Although the data-generating process (DGP) does not depend on the methodology used, in the case of the small sample, it is preferable to ‘dig’ with different estimation tools to ‘reveal the behavior’ of the corresponding DGP. The general-to-specific modeling approach (Gets, Davidson et al. 1978; Hendry et al. 1984; Campos et al. 2005, *inter alia*) is used as the main technique, since it provides wider options to consider. The Gets modeling approach has been performed using the Autometrics tool, a multi-path block-search machine learning algorithm. The modeling procedure under the Gets framework consists of two steps. In the first step, the algorithm searches for intervention dummies, assigning impulse, step, blip (differenced impulse), and break-in-trend dummies to all sample points. In the first phase, the theory-related variables do not enter into the search process. The initial model with all the selected dummies and theory-related

Table 1 Unit root test results

	Level		Differenced
	i	i&t	i
emitra	– 0.698	– 1.143	– 5.016***
pfuel	– 1.156	– 0.956	– 4.471***
pop	– 1.486	– 0.859	– 1.210
gasshare	– 3.638**	– 2.543	– 4.230***
gdp	– 0.583	– 1.770	– 5.515***

i = intercept only; i&t = intercept and trend case. In the unit-root specification, the maximum lag is set to two and the optimal lag number is chosen based on the Schwarz information criterion

“**” and “***” stand for a rejection of the null hypothesis at the 5% and 1% significance levels, respectively

variables is referred to as the General Unrestricted Model (GUM). The search process is realized using a multipath-block search algorithm. In the second step, the Autometrics algorithm searches for theory-related variables, excluding the selected intervention dummies from the search process. The selection process in the second step relies on the congruency principle, no loss of information going from GUM to the final model, and a battery of diagnostic tests (Hendry and Doornik 2014).

In addition, the fully modified ordinary least squares (FMOLS) (Phillips and Hansen 1990; Hansen 1992a, 1992b), dynamic ordinary least squares (DOLS) (Saikkonen 1991; Stock & Watson 1993), and canonical cointegration regression (CCR) (Park 1992) methods, the bounds testing approach to auto-regressive distributed lag (ARDLBT) (Pesaran and Shin 1999; Pesaran et al. 2001) and Structural Time Series Modeling (STSM, Harvey 1989) approach were employed for the long-run estimations for robustness. The rationale behind utilizing the CCR, DOLS and DOLS approaches is to check if the cointegration-oriented techniques will produce similar results to the utilized Gets approach. The ARDLBT approach is similar to the Gets approach regarding the initial dynamic specification but differs in the way it selects the final model. Hence, it is used to robustify the results from the Gets approach. The STSM approach allows treating the parameters of the relationship to vary over time. Therefore, it is used to test the parameters for potential variation.

5 Empirical estimation results

Following the time series modeling methodology, the unit root properties of variables have been examined using the ADF test (Dickey and Fuller 1981). The results of the ADF test are presented in Table 1.

As Table 1 demonstrates, all the variables are integrated in the first order, except the population variable. In addition to the ADF test, we utilized the Kwiatkowski-Phillips-Schmidt-Shin (1992) test, which concluded the stationarity of the population variable at the first difference. From the table, it might seem *gasshare* variable is stationary, but the additional investigation also supports its non-stationarity.

Table 2 Cointegration tests' results

Cointegration tests		
Test	PcGive	BT
Test value	– 11.476**	28.829***

Null hypothesis of both tests is "series are not cointegrated"

"**" and "***" stand for a rejection of the null hypothesis at the 5% and 1% significance levels, respectively.

Hence, we conclude that all variables are I(1). That is, their first differences are stationary. Therefore, one can test the variables for the cointegration relationship. The Banerjee et al. (1998) test, also called the PcGive test, and bounds (BT) cointegration tests (Pesaran and Shin 1999; Pesaran et al. 2001) were used for this exercise, and the results are reported in Table 2.

As can be seen in Table 2, both tests conclude the existence of a cointegration relationship among the studied variables. For the next step, the long-run estimations were carried out. The detailed estimation results from the *Gets* approach in the dynamic form are provided in Table 3. As can be seen from Table 3, the estimated model in dynamic form satisfies all the diagnostic tests (Panel B). Moreover, the coefficients of the selected terms (variables) are statistically significant (Panel A of Table 3). The initial search process selected a few intervention dummies (see Table 3). Namely, the following interventions have been selected: I2014 = pulse dummy taking 1 in 2014 and 0 otherwise; and three step dummies, S12004, S12005, and S12017. The step dummy takes 1 from the first observation until time T and 0 otherwise. The results from the *Gets* approach were then converted into static long-run form, and are given in Table 4. Table 4 also demonstrates the long-run estimation results from the CCR, DOLS, FMOLS, ARDL, and STSM approaches, which serve as a measure of the robustness of the long-run results.

Table 4 shows that all utilized estimation techniques provide close results. All the variables were found to have relevant signs and are statistically significant. All utilized techniques produce quite close results for the price and population elasticities. Regarding income elasticity, all approaches produce similar results, except the DOLS and ARDLBT. The latter two estimation techniques produce results that are close to each other. When it comes to the gasoline share elasticity, FMOLS and CCR produce similar and relatively smaller values, while all others produce quite close results. Considering slightly different elasticities in some cases, in the discussion section, we provide intervals for the corresponding elasticities.

It is important to note that in the literature, it is not clear which income measure, GDP or non-oil GDP, is a better proxy for transport-related energy consumers' income (Atalla et al. 2018). Consequently, the same can be said in terms of transport-related CO_2 emissions. Hence, as an additional check, we used non-oil GDP as an income measure, and the results are provided in Table 5 in the appendix. One can see from Table 5 that the results with non-oil GDP are not substantially different from the results with GDP.

Table 3 Estimation results of the *Gets* approach in dynamic form

Panel A: Final model specification results in ADL form

Variable	emitra (-1)	pfuel	gdp(-1)	pop(-1)	gasshare	gasshare(-1)	constant	I2014	S12004	S12005	S12017
Coefficient	0.3648	– 0.0971	0.2508	0.8331	– 0.8981	0.4666	– 14.6055	– 0.0304	0.0373	0.0272	0.0502
p-value	0.0000	0.0000	0.0003	0.0000	0.0000	0.0002	0.0000	0.0106	0.0052	0.0492	0.0002

Panel B: Diagnostic tests' results for the final model specification

Test	AR 1–2 test	ARCH 1–1 test	Normality test	Hetero test	RESET23 test	R-square	Adjusted R-square
Test statistics	3.2551	0.9752	2.7375	1.7043	0.5073	0.9999	0.9994
p-value	0.0652	0.3322	0.2544	0.1803	0.6115		

Dependent variable is emitra

AR = autocorrelation test (Godfrey 1978), *ARCH* autoregressive conditional heteroscedasticity test (Engle 1982), *Normality test* Doornik and Hansen (1994) normality test, *Hetero test* heteroscedasticity test (White 1980), *RESET23* Regression Specification Test (Ramsey 1969), *I2014* pulse dummy taking 1 in 2014 and 0 otherwise, *S1T* step dummy taking 1 from the first observation until time T and 0 otherwise

Table 4 Long-run estimation results

	DOLS	FMOLS	CCR	ARDL	STSM	*Gets*
gdp	0.172***	0.391***	0.398***	0.178**	0.396***	0.395***
pfuel	– 0.150***	– 0.137***	– 0.115***	– 0.152***	– 0.153***	– 0.153***
pop	1.561***	1.253***	1.080***	1.554***	1.311***	1.312***
gasshare	– 0.788***	– 0.416***	– 0.360***	– 0.787***	– 0.677***	– 0.679***

The dependent variable is *emitra*; "***" stands for the rejection of the null hypothesis at the 1% significance level

In addition, using the STSM approach (Harvey 1989), we also investigated if the level and slope of the trend of the relationship are stochastic. The estimation results revealed no statistical evidence of these parameters changing over time (Figure 3 in the appendix). In other words, the slope is found to be constant, and the level change is negligible. Overall, there is a slight decrease of less than 1 percent in the underlying CO_2 emissions trend, which can be attributed to efficiency improvements.

6 Discussion of the results

In this section, we discuss the results of our empirical findings. Our empirical findings, indicating that a 1% increase in fuel prices leads to a 0.12–0.15% decrease in transport-related CO_2 emissions, have significant implications when considered in the context of Saudi Arabia's energy price reform. This reform, which involves gradually aligning domestic fuel prices with international levels, is a crucial component of the Kingdom's strategy to reduce its carbon footprint. The energy price reform in Saudi Arabia acts as a pivotal economic mechanism to incentivize reductions in CO_2 emissions. By increasing fuel prices, the reform directly discourages excessive use of personal vehicles, leading to a decrease in overall fuel consumption. This, in turn, contributes to a reduction in CO_2 emissions from the transportation sector, aligning with the country's broader environmental goals. Furthermore, this reform is instrumental in encouraging the adoption of energy-efficient technologies and vehicles. Higher fuel costs make the use of fuel-efficient vehicles more economically attractive for consumers. This shift is particularly significant for Saudi Arabia, given its previous position as a country with some of the lowest fuel prices in the world due to extensive subsidies. The reform also aligns Saudi Arabia's domestic fuel pricing policy with its commitments to global climate change initiatives. By reducing subsidies and increasing fuel prices, the Kingdom is taking a proactive stance in the global effort to combat climate change, showcasing its role as a responsible player in the international community. In essence, the energy price reform in Saudi Arabia is not just an economic policy but a crucial environmental strategy. The correlation between fuel price increases and reductions in CO_2 emissions, as evidenced by our study, underscores the effectiveness of this reform in steering the country towards a more sustainable and environmentally friendly future.

Our analysis suggests that a 1% increase in income is associated with an increase of 0.17–0.40% in transport-related CO_2 emissions in the long run. This finding accords with the literature. Several prior studies confirm that income is positively correlated with transport emissions (Baiocchi et al. 2010; Brand and Boardman 2008; DEFRA 2008; Druckman and Jackson 2008; Fahmy et al. 2011; Gough et al. 2011; Weber and Matthews 2008, *inter alia*).

Our analysis suggests that a 1% increase in the gasoline share (gasoline consumption divided by total energy consumption in the transport sector) is associated with a 0.36–0.79% decrease in transportation emissions in the long run. The share of gasoline in transport fuels is representative of the fuel consumption within the Kingdom's light-duty vehicle sector. This is because diesel and kerosene are mainly used in the heavy-duty vehicle and aviation sectors, respectively. Historically, the penetration of diesel vehicles in the light-duty vehicle sector has been low because of the high sulfur content of diesel fuel in the Kingdom. All else being equal, it could be argued that an increase in the share of gasoline in the Kingdom's transport fuels has historically been associated with higher fuel demand from the light-duty vehicle sector, which is inherently more efficient than the heavy-duty vehicle and aviation sectors. This could explain why the elasticity of transport CO_2 emissions with respect to gasoline share in transport fuels has historically been negative, for a given amount of energy used in the transport sector.

Finally, the population was found to have a significant impact on transport-related CO_2 emissions. A 1% increase in the total population was found to be associated with a 1.08–1.56% increase in transport-related CO_2 emissions in the long run. This finding is consistent with economic theory: Population growth is a major driver of increased transport demand and, eventually, transport emissions.

It is also worth mentioning that the employed STSM approach, which treats the parameters of the relationship to vary over time, did not find substantial evidence for the variation in the elasticities. In other words, the elasticities are found to be constant for the estimation period. Therefore, the income elasticity of the transport CO_2 emissions is found to be constant, indicating the linear relationship between transport CO_2 emissions and income. This finding, with a linear relationship, negates the validity of the so-called Environmental Kuznets Curve phenomenon for the Saudi Arabian transport CO_2 emissions. Although, the slightly varying level of the trend of the relationship can be considered indicative of some efficiency gains, transport-based CO_2 emissions trajectory needs some time to follow the Environmental Kuznets Curve path.

7 Forecasting transport emissions

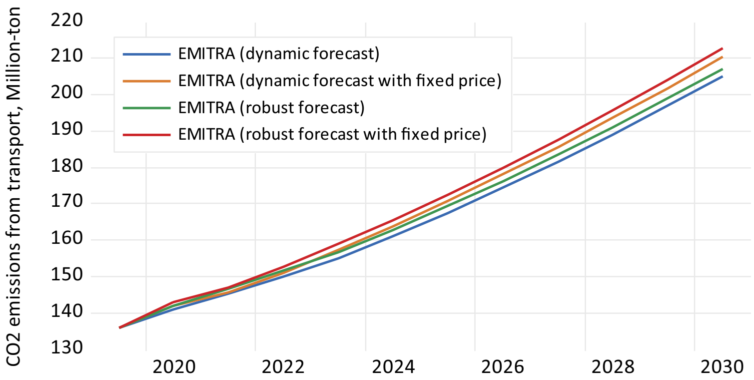
7.1 Forecasting assumptions

This section first discusses the forecast assumptions and then develops a forecast for the 2020–2030 horizon. In forecasting exercises, we used two scenarios, based on price assumptions. In the first case, we fixed prices to the 2019 value. All other assumptions are the same for both scenarios. For the second scenario, the production cost is taken as a target. That is, using Matar and Anwer's (2017) finding on the cost of different transport fuel types, we assume that in 2030, the prices of transport fuels will reach their production costs. Namely, we assume that in 2030, the prices will be 1.94 SAR/l, 1.98 SAR/l, 0.65 SAR/l, and 1.89 SAR/l for gasoline-91, gasoline-95, transport diesel, and jet fuel, respectively. Starting in 2021, transport fuel prices are increased each year by the same rate to reach the 2030 target prices. For the GDP assumptions, we used a 2030 target that has been discussed among policymakers (see Saudi Gazette 2021) as nominal GDP value. Then, the GDP values are increased by the same percentage to achieve the 2030 number. Population size forecast assumptions are made using UN population data for Saudi Arabia (UN 2021). Considering the discussion in the previous section, the share of gasoline is assumed to be constant over the forecast horizon and equal to the sample average (52%). Some readers might question this assumption, though, considering the potential penetration of alternative low- or zero-carbon transport fuels including 'green' electricity and hydrogen. The assumption is based on the logic that the potential for an increase in the penetration of low- or zero-carbon transport fuels would reduce the share of gasoline as a percentage of transport fuels. This could mean that the growth in total transport CO_2 emissions could be reduced and even reversed. Given the lack of policies in the Kingdom supporting the penetration of alternative fuel vehicles at this point, the likelihood of the share of gasoline used in transportation decreasing significantly by 2030 due to the rising share of alternative fuels remains low. Furthermore, since we do not have any further information about the future evolution of gasoline as a share of transportation fuel, we assume it remains at its historical average. Our assumptions for the forecasting exercises are provided in Table 6 of the appendix.

7.2 Forecasting results

Utilizing the estimated models and assumptions made in the previous sub-section, we performed forecasting runs. In these runs, we used all the estimated model results, and the models produced very close results. To avoid having several figures, we only report the *Gets* forecasting results for the forecast horizon (other forecasting results are presented in Fig. 4 of the appendix). We used dynamic forecasts and a robust forecasting device (Hendry and Doornik 2014). As can be seen from Fig. 2, both techniques produced very similar results.

Based on the applied assumptions and robust device results, the transport CO_2 emissions in 2030 are forecasted to be 207 million tons for the fuel price increase scenario. Using the same methodology for the fixed fuel price scenario, this figure is forecasted to be 213 million tons in 2030. In comparison to the fixed fuel price scenario, the rising fuel price scenario reduces annual transportation emissions by 1.8 percent on average over the 2021–2030 period.



Time	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Dynamic	140.93	145.26	150.06	155.17	161.07	167.51	174.36	181.55	189.05	196.87	205.00
Dyn (f)	142.06	145.76	151.10	157.22	163.81	170.76	178.03	185.63	193.56	201.83	210.45
Robust	141.89	146.62	151.60	156.81	162.80	169.31	176.24	183.51	191.09	198.99	207.21
Rob(f)	143.03	147.13	152.65	158.88	165.56	172.59	179.95	187.63	195.65	204.00	212.72

Fig. 2 Forecasts for CO_2 emissions from the transport sector. *Dyn (f)* dynamic forecast with fixed price, *Rob (f)* robust forecast with fixed price

8 Concluding remarks and policy implications

We have examined the long-run impact of income, fuel prices, population, and the share of gasoline in transportation fuel on Saudi transportation CO_2 emissions. We employed different estimation methods to achieve more robust results and, as a result, well-grounded policy recommendations. Our empirical analysis shows that the studied variables have long-term effects on transportation CO_2 emissions in Saudi Arabia. The estimation results we derived from different methods are very similar, which indicates the robustness of the results obtained.

Our empirical findings suggest that raising fuel prices is a viable policy option for policymakers to consider in order to reduce transportation CO_2 emissions. In other words, the empirical analysis results support Saudi Arabia's 2016 energy price reform policy, which included a gradual phase-out of energy incentives. However, the low degree of responsiveness of transport CO_2 emissions to fuel price, with estimated elasticity values ranging from – 0.1 to – 0.15, highlights the need for additional policy options if policymakers want to reduce transport CO_2 emissions further. This is especially crucial given that economic activity is found to drive transport CO_2 emissions, with estimated elasticity values ranging from 0.17 to 0.4, and the expected increase in economic activity under the Saudi Vision 2030 (Saudi Vision-2030 2019). Simulating a scenario that included this expected increase in economic activity and a further increase in fuel prices to reflect actual market prices resulted in an average reduction of 1.8 percent in annual transportation CO_2 emissions from 2021 to 2030 relative to a fixed price scenario.

In addition, rising fuel prices could prompt greater interest in fuel-efficient vehicles (Sheldon and Dua 2021; Bansal et al. 2021; Bansal and Dua 2022). Furthermore, increasing fuel prices to reflect actual market prices will reduce the energy incentives given and will make additional resources available to the government. These saved resources could be utilized to fund the transition to a more sustainable transportation future, including the development of high energy efficiency modes like rail and transit, envisioned under the Kingdom's National Transport and Logistics Strategy (Arab News 2021).

Appendix

See Tables 5 and 6, Figs. 3, 4.

Table 5 Long-run estimation results with non-oil GDP

	DOLS	FMOLS	CCR	ARDL
gdp	0.152***	0.264*	0.306**	0.150*
pfuel	– 0.135***	– 0.097***	– 0.098***	– 0.135***
pop	1.408***	1.069***	0.974***	1.415***
gasshare	– 0.689***	– 0.437***	– 0.400***	– 0.704***

Dependent variable is *emitra*; "***","**","*" stand for rejection of the null hypothesis at the 1%, 5% and 10% significance levels, respectively

Table 6 Forecasting assumptions

	GDP mln SAR, 2010 prices	Average Fuel Price SAR/TOE	Population, persons	Gasoline share, ratio
2020	2,784,921.41	1391.08	34,813,867	0.52
2021	2,938,008.54	1438.99	35,367,883	0.52
2022	3,099,510.87	1488.63	35,930,716	0.52
2023	3,269,890.98	1540.05	36,502,505	0.52
2024	3,449,636.89	1593.32	37,083,394	0.52
2025	3,639,263.43	1648.52	37,673,527	0.52
2026	3,839,313.74	1705.72	38,273,051	0.52
2027	4,050,360.82	1764.99	38,882,115	0.52
2028	4,273,009.15	1826.41	39,500,872	0.52
2029	4,507,896.46	1890.06	40,129,476	0.52
2030	4,755,695.53	1956.03	40,768,083	0.52

mln million, *SAR* Saudi riyals, *TOE* tonne of oil equivalent

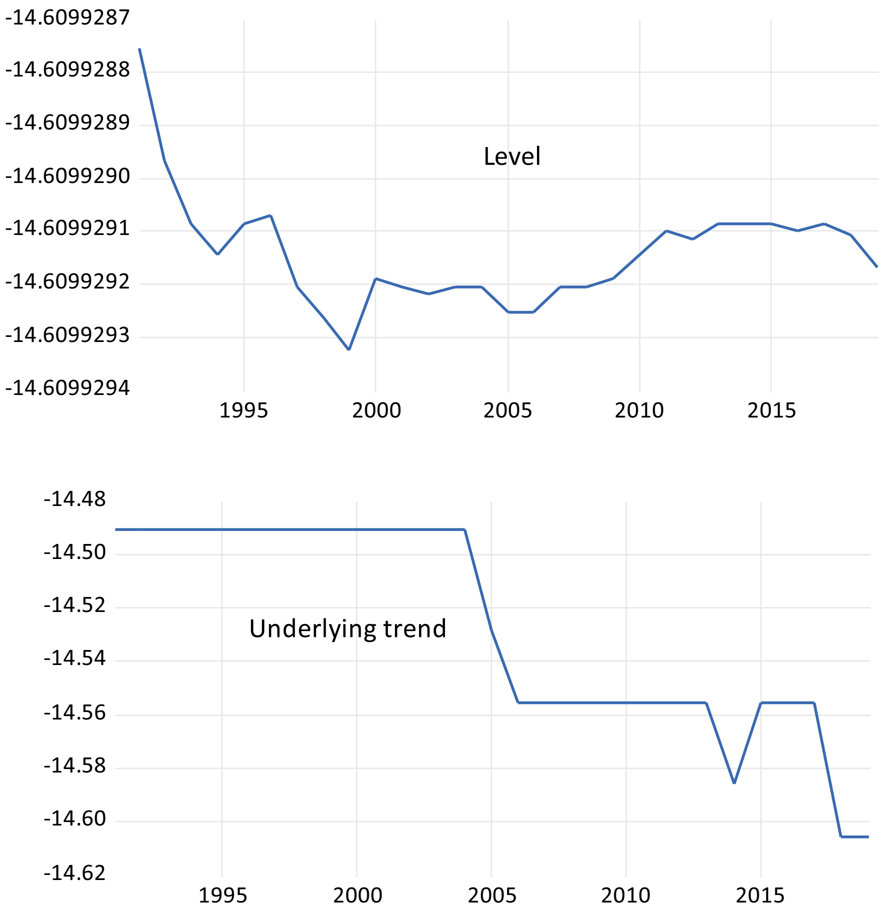


Fig. 3 Level and underlying trend of the transport emissions (logarithmic scale)

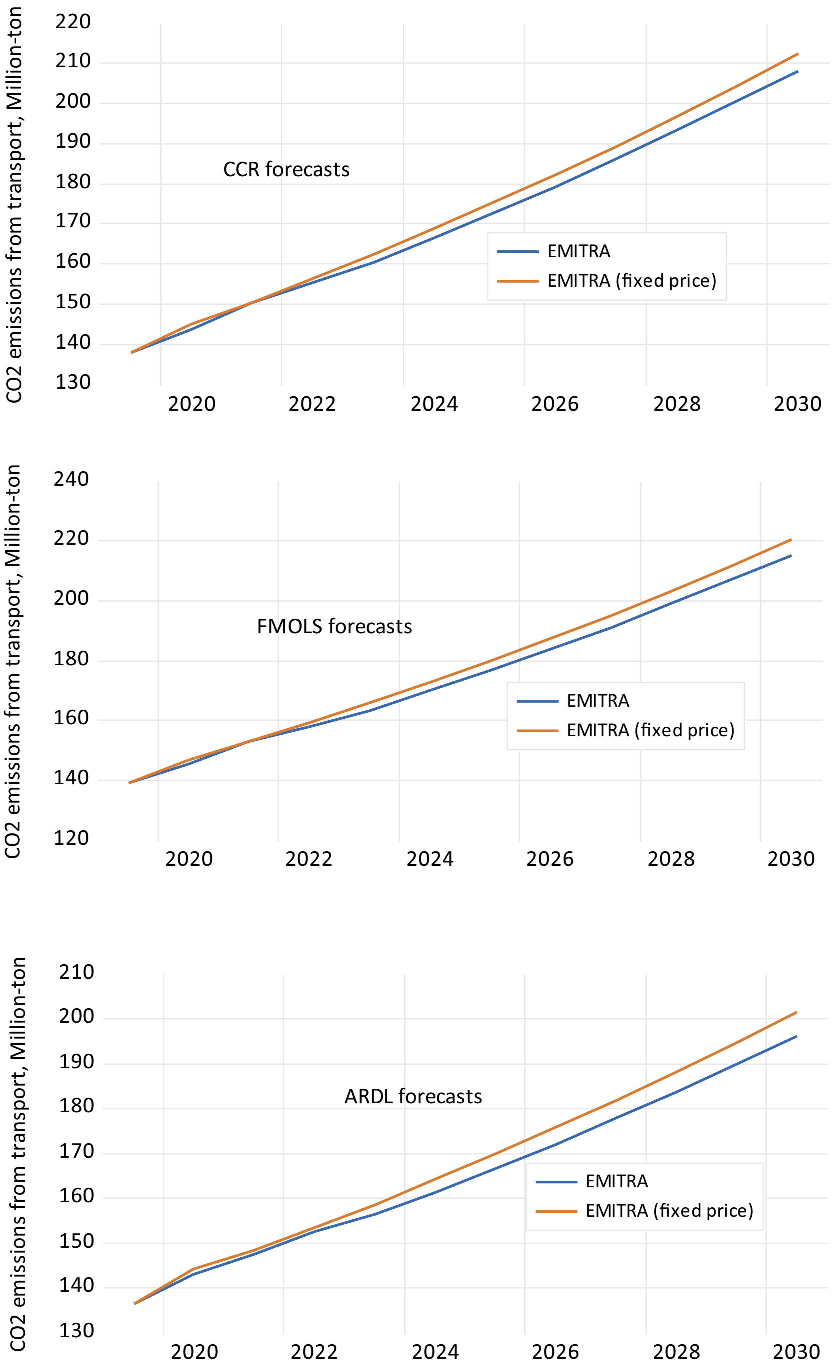


Fig. 4 Forecasting results of the CCR, FMOLS, ARDL and DOLS approaches

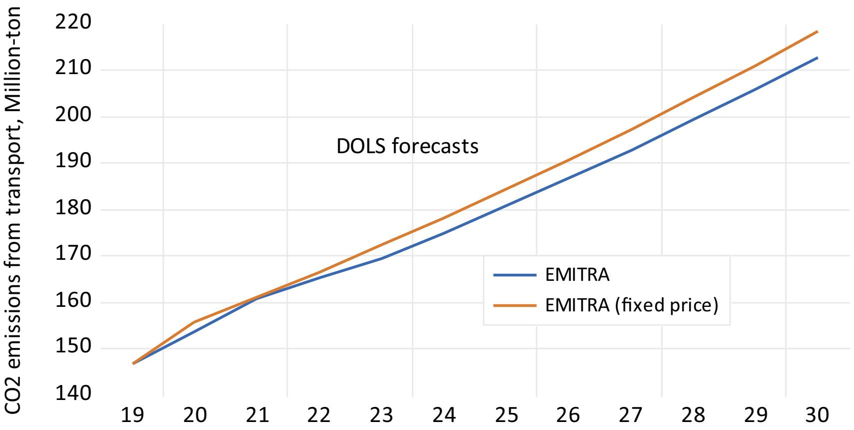


Fig. 4 (continued)

Data availability Data is available from authors upon the request.

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