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مركز الملك عبدالله للدراسات والبحوث البترولية

King Abdullah Petroleum Studies and Research Center

Estimating Regional Variation in Saudi Arabia's Energy Usage and Carbon Emissions

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June 2023

Doi: 10.30573/KS--2023-DP13

About KAPSARC

KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

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Key Points

Estimates of regional energy consumption and carbon emissions could be useful for agencies investigating the effects of regionally targeted investments and policy interventions. Using gasoline consumption in Saudi Arabia as a case study, we develop two approaches for estimating the regional variation in gasoline consumption in Saudi Arabia: a sector-specific approach and a generic econometrics-based approach. Our findings reveal that Riyadh and Makkah, which account for 60% of the nation's population and economic activity, consume 58% of the country's gasoline. In contrast, the Eastern Region accounts for 22% of economic activity but only 11% of gasoline consumption, in line with its population concentration of approximately 15%. Furthermore, the correlation between the sector-specific and generic econometrics-based approaches suggests that the latter may be a good proxy for estimating regional variations in energy consumption.

As the econometrics-based approach is generic, it can be extended to estimate regional variations in areas other than energy consumption, such as emissions, as well as sectors other than transportation, for example residential electricity. Accordingly, we use it to estimate regional variations in the consumption of other fuels. These include diesel for heavy-duty trucking and kerosene for aviation; carbon dioxide (CO_2) emissions from transportation; and residential electricity consumption. In the case of residential electricity consumption, the estimated variation is similar to the actual regional variation, where actual regional-level consumption data is available.

Case Study of Gasoline Consumption

Background

Our previous work estimated the size of passenger car fleets in the Kingdom of Saudi Arabia (Dua 2020). However, the variations in fleet size and the corresponding gasoline consumption across regions are unclear. Therefore, this study addresses this gap by estimating passenger car fleets by region. It also provides approximate distributions of the (i) passenger car fleet fuel economy over time and (ii) passenger car fuel consumption across the different regions in the Kingdom. In doing so, it adopts the sector-specific and generic econometrics-based approaches.

Methodology

The sector-specific approach uses regional data to estimate the regional fuel consumption. The total regional car fleet size is divided by the average fuel economy of the car fleet and multiplied by the average annual distance driven per car. Conversely, the generic econometrics-based approach establishes the relationship between national-level energy consumption or emissions and their determinants using time-series data, before extending it to the regional level.

Sector-Specific Approach

The General Authority for Statistics' (GaStat 2007, 2016) demographic survey data provide information on the number of passenger cars owned by Saudi households in 2007 and 2016. The data show that Saudi households had 4.14 and 5.37 million passenger cars in 2007 and 2016, respectively. We estimated the average number of cars per household by region by dividing the total number of passenger cars by the total number of Saudi households (see Table 1).

Table 1. Average number of cars per Saudi household by region.

Region	Cars per Saudi household 2007	Cars per Saudi household 2016
Riyadh	1.71	1.89
Makkah	1.26	1.44
Madinah	1.13	1.44
Qaseem	1.63	1.84
Eastern Region	1.49	1.53
Aseer	1.35	1.53
Tabouk	1.29	1.29
Hail	1.73	1.67
Northern Borders	1.49	1.42
Jazan	0.87	1.19
Najran	1.36	1.31
Baha	1.58	1.53
Jouf	1.54	1.50

Source: KAPSARC analysis.

At the country level, the average car ownership per household was 1.42 and 1.51 for 2007 and 2016, respectively. Our estimate is close to the average number reported in the Household Environment Survey (GaStat 2019), which estimated 1.38 cars per household on average in 2019.

The only data available for foreign households is the number by region in 2007 (GaStat 2007). To estimate the number of passenger cars by region for foreign households in 2016, we first estimated the total number of foreign households. We assumed a similar regional growth in the number of Saudi and foreign households (Table 2). We assume the same average number of cars in foreign and Saudi households by region to estimate the total number of passenger cars for foreign households in 2007 and 2016. We thus obtained an estimate of the total number of private passenger cars by region in 2007 and 2016. In addition, we estimated the number of taxis by region. In 2015, Saudi Arabia had approximately 0.1 million taxis, with 0.04 and 0.035 million taxis estimated in Riyadh and Jeddah, respectively (Careem 2015; Al-Bogami 2016). We assumed that the total number of taxi medallions in these regions, and in Saudi Arabia as a whole, has remained relatively constant around these values. We estimated the distribution of the remaining taxis across various regions in proportion to their populations. Combining the number of private passenger cars and taxis, we obtained the regional estimates for passenger cars in 2007 and 2016, as shown in Figure 1. Using these estimates, we calculated the compounded annual growth rates by region (Figure 1). Assuming continuous growth, we estimated the total number of passenger cars in Saudi Arabia to be 8.79 million in 2019.

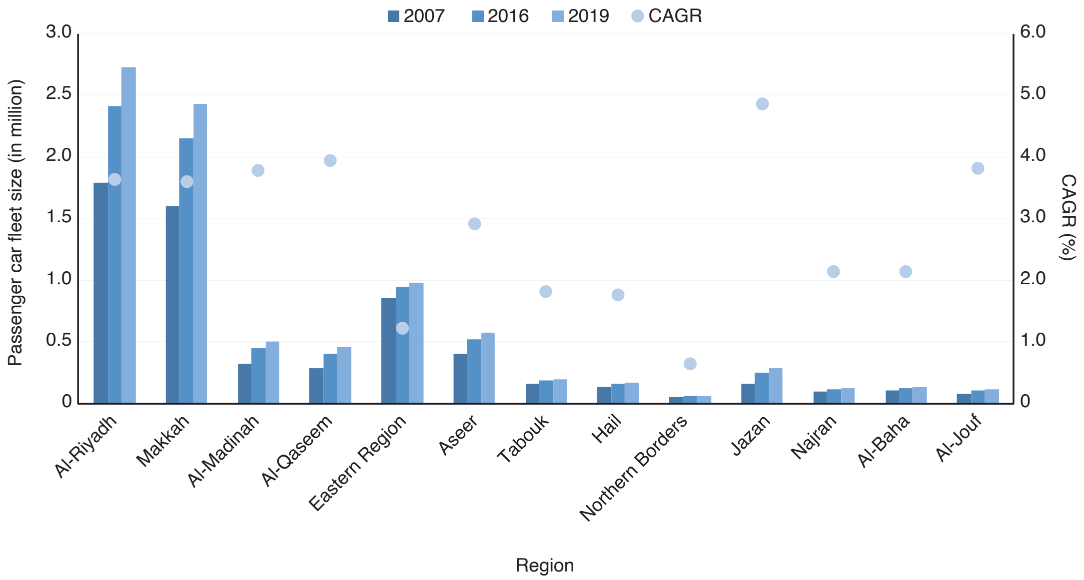
Furthermore, we attempted to estimate the evolution of the passenger car fleet fuel economy

Table 2. Growth in the number of Saudi households between 2007 and 2016.

Region	Growth in the number of Saudi households (%)
Riyadh	23
Makkah	18
Madinah	9
Qaseem	25
Eastern Region	8
Aseer	14
Tabouk	17
Hail	21
Northern Borders	10
Jazan	11
Najran	25
Baha	24
Jouf	42

Source: GaStat (2007, 2016).

Figure 1. Passenger car fleet size and compounded annual growth rate (CAGR) in car fleet size by region.



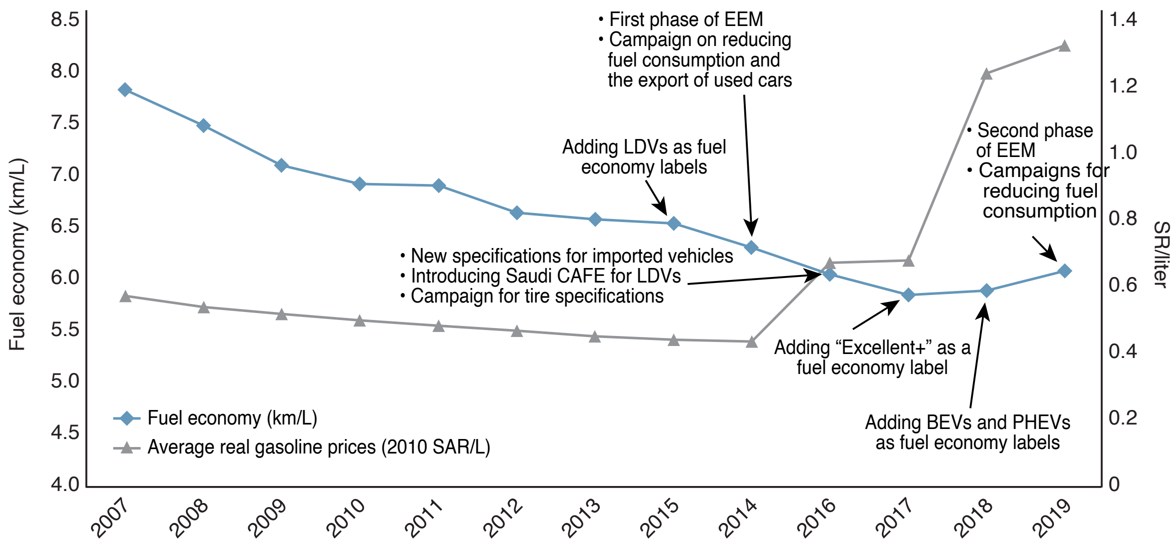
Source: KAPSARC analysis.

in Saudi Arabia. To do so, we divided the total distance traveled by the passenger car fleet by its total fuel consumption. The Joint Oil Data Initiative (JODI) oil world database was used to obtain the total fuel consumed by the passenger car fleet (JODI 2021). We only considered the gasoline consumption numbers from the JODI oil database, given the limited share of diesel passenger cars in the Kingdom. To estimate the total distance traveled, we first approximated the evolution of the average annual car mileage, also known as the vehicle kilometers traveled (VKT) over time. We used the national average VKT of 25,000 kilometers (km) per car in 2013, based on Sheldon and Dua's (2020) data on new vehicle buyers in Saudi Arabia. To consider the change in the average VKT before and after 2013, we used its elasticity with respect to income and the average real gasoline price[1]. Given the lack of local data for estimating these elasticity values, and the absence of local literature, we based our elasticity assumptions on global studies. In particular, we assumed the elasticities of average VKT with respect to fuel price and income to be approximately -0.15 and 0.3, respectively (Brand 2009; Gillingham 2010; Goodwin, Dargay, and Hanly 2004; Hymel, Small, and Van Dender 2010; Small and Van Dender 2007). To estimate the evolution of the average VKT (Appendix A), we considered a linear relationship between the natural logarithms of average VKT, fuel price and income. Using the assumed elasticity values, we estimate the constant for this linear relationship so as to match the known 2013 data point. Based on the relationship between average VKT and its drivers—fuel price and income—and these drivers' evolution over time, we estimated the evolution of average VKT. Additionally, we assumed the average VKT for taxis to be 5.42 times higher than that for private passenger cars, which is similar to the ratio in the United States (Schaller Consulting 2006). Finally, we combined the estimated average VKT and fleet size to obtain the total distance traveled by the passenger car fleet, including private cars and taxis. By dividing the total distance traveled by the total fuel consumed, we obtain the average fleet fuel economy.

Figure 2 shows the evolution of the estimated fuel economy of the passenger car fleet. From 7.84 kilometers per liter (km/L) in 2007, it declined to 6.32 km/L in 2015. Leading up to 2015, it was anticipated that the vehicle fleet would continue to expand, and fuel consumption would nearly double between 2010 and 2030 without significant policy intervention (Alabbadi 2013). Correspondingly, the Saudi government implemented several policies to slow the growth of or even reduce the gasoline consumed by its passenger car fleet. Demand-side policies included raising fuel prices, and supply-side policies included the setting of fuel economy standards by the Saudi Standards, Metrology and Quality Organization (SASO) and Saudi Energy Efficiency Center (SEEC 2015-2019). As highlighted in Figure 2, the SEEC implemented various other campaigns and initiatives to improve the fuel economy of passenger cars (both new and used) imported into the Kingdom. The combined effect of these programs appears to have reversed the decreasing trend of the average fleet fuel economy.

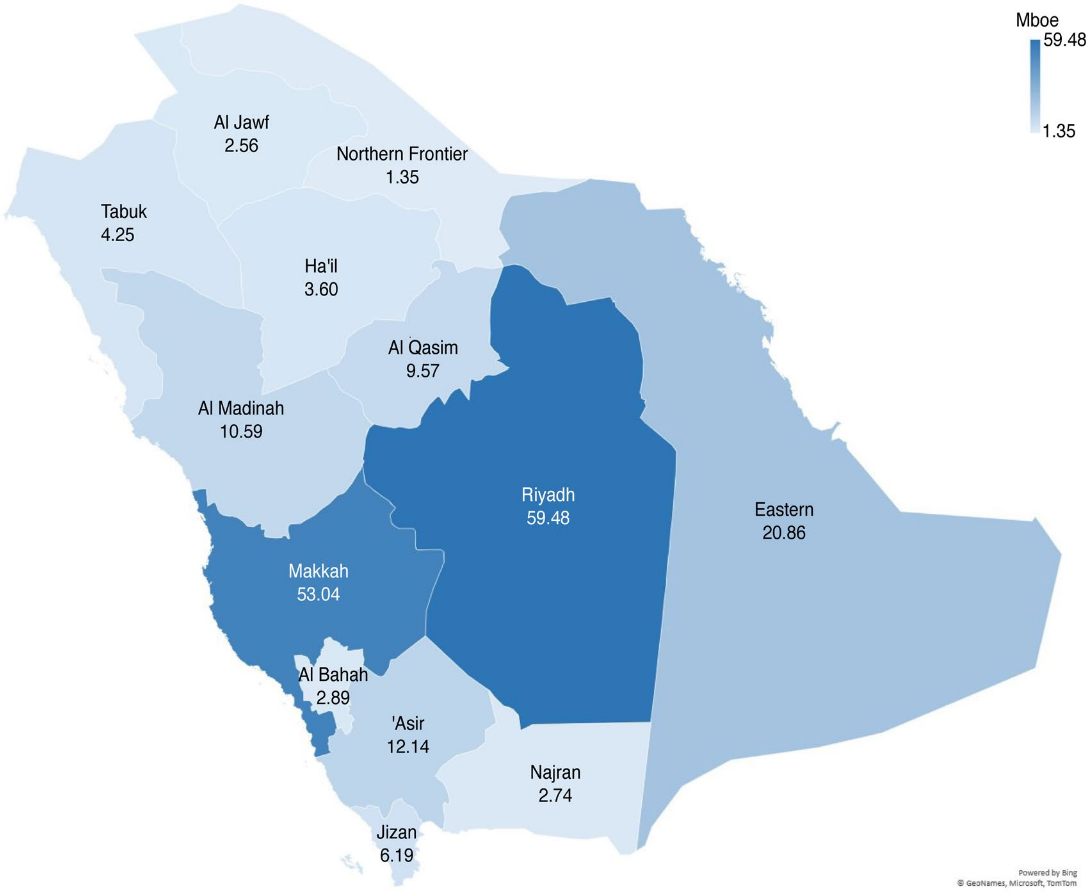
We further explored the approximate distribution of the fuel consumed by passenger cars across different Saudi regions in 2019. We assumed a regional parity in the estimated average fleet fuel economy and average VKT. Another assumption was that the variation in fleet fuel consumption was because of the variations in the passenger car fleet size across regions. Figure 3 shows the distribution of gasoline consumption (in million barrels of oil equivalent [Mboe]) in Saudi Arabia in 2019, totaling approximately 189 Mboe. We found that 59.5% of the gasoline fuel was consumed in Riyadh and Makkah, which account for approximately 60% of the population and economic activities. In absolute terms, the combined passenger car fleets for Riyadh and Makkah were estimated to consume 112.52 Mboe. Interestingly, in the Eastern

Figure 2. Estimated fuel economy of passenger cars over time and SEEC campaigns.



Note:
EEM – Energy efficiency measures, LDVs – Light-duty vehicles, BEV – Battery electric vehicles, PHEV – Plug-in hybrid electric vehicles, and SR – Saudi riyals.
Source: KAPSARC analysis.

Figure 3. Regional variation in gasoline consumption across Saudi Arabia.

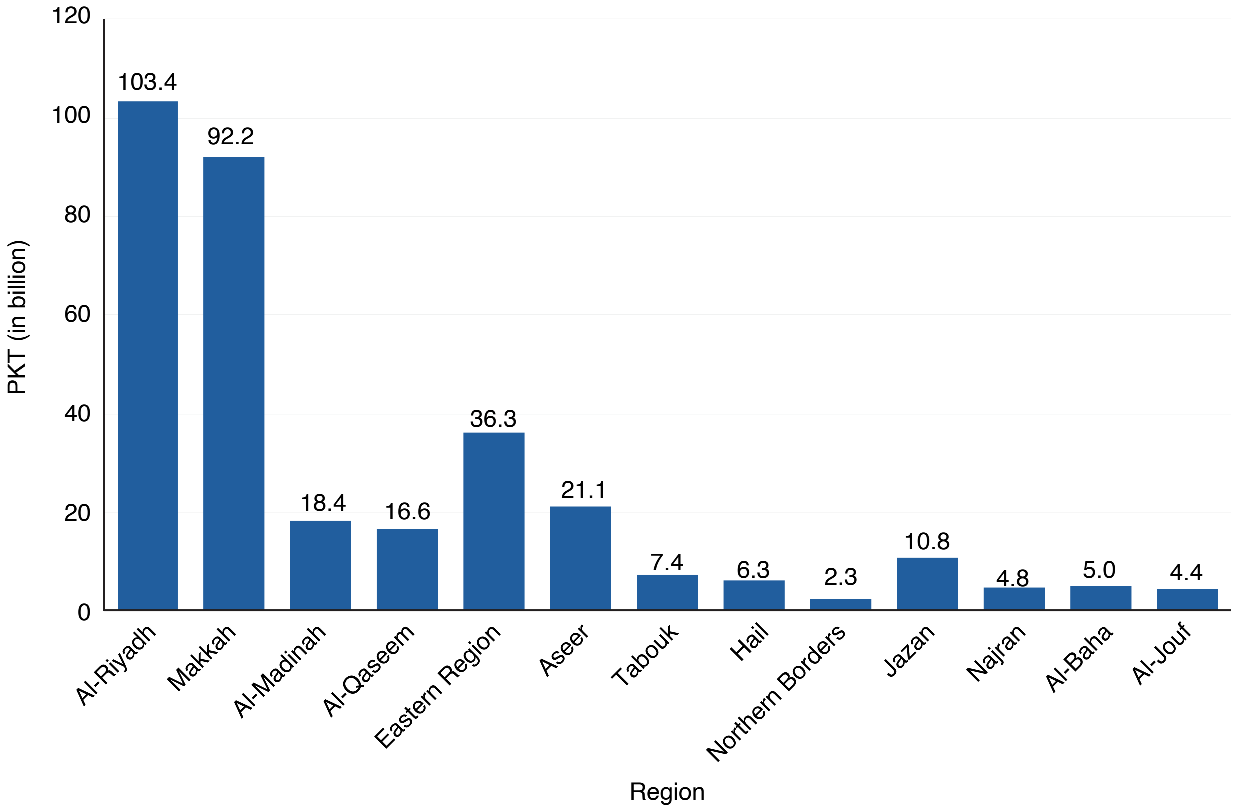


Source: KAPSARC analysis.
Note: Mboe = million barrels of oil equivalent.

Region, with 22% of economic activity (Lopez-Ruiz, Blazquez, and Hasanov 2019), passenger cars accounted for 11% of the total gasoline consumption. This is somewhat proportionate to its population ratio of approximately 15%.

Furthermore, we combined the regional data on the number of cars with the average VKT and vehicle occupancy to calculate the passenger kilometers traveled (PKT) by region. Regional PKT figures could be used, among other things, to estimate passenger flows between regions. We estimated vehicle occupancy in the Kingdom using the New Vehicle Buyer Survey, which includes a representative sample of the new vehicles purchased in Saudi Arabia and individual-level sociodemographic characteristics. Vehicle occupancy in Saudi Arabia was estimated to be 1.69 (see Appendix B for more details) compared to approximately 1.67 in the United States (Federal Highway Administration 2017). In 2019, the PKT totaled more than 329 billion passenger kilometers. The Riyadh region accounted for 31% of the total PKT, followed by the Makkah region. Figure 4 depicts the regional PKT (in billion) in Saudi Arabia in 2019.

Figure 4. Passenger kilometers traveled (PKT) by region in 2019.



Source: Authors.

Generic Econometrics-Based Approach

We developed another generic econometrics-based approach to estimate gasoline consumption across the different Saudi regions. We first developed a national-level time-series model to estimate the relationship between gasoline consumed by passenger cars and its associated drivers using annual data for 1992-2017. As our ultimate objective was to estimate gasoline demand at the regional level, we used the drivers for which both national- and regional-level data were available. To estimate the national-level model, we considered three variables: population, gasoline price and luminosity, a proxy for gross domestic product (GDP). Luminosity, a measure of nighttime light intensity from space, was used as the proxy for two reasons. First, data on luminosity were available at both the national and regional levels. Second, the literature has established luminosity as a reasonable proxy for GDP (Chen and Nordhaus 2011).

For the national-level time-series model estimation, the augmented Dickey-Fuller test showed that all three variables were I(1), i.e., integrated of order 1 (Table 3). Next, we used an econometrics approach based on Pellini's (2021) novel error correction model to estimate the long-run cointegrating relationship after accounting for outliers and breaks.

The estimated coefficient of the error correction term was negative and statistically significant at the 1% level (-0.721***; see Table 4). Therefore, the model indicates the presence of cointegration or a long-run relationship (Pellini 2021).[2] The elasticities of gasoline demand with respect to population, luminosity and gasoline price were estimated as 1.47, 0.018 and -0.15, respectively, all significant at the 1% level. The signs and magnitudes appear consistent with our expectations and the literature.

Next, we assume that the long-run cointegrating relationship estimated at the national level holds true at the regional level. Additionally, we impose a constraint that the sum of the estimated regional-level gasoline demand numbers sums up to the national level. Our assumption is consistent with that in Lopez-Ruiz, Blazquez, and Hasanov's (2019) study. The authors estimated regional-level GDP using national-level GDP data, albeit by using a simple ordinary least squares estimator on non-stationary national-level time-series data. Moreover, Lopez-Ruiz, Blazquez, and Hasanov (2019) appear to have assumed that regional-level GDP would be directly proportional to regional night lights, whereas the national-level model estimation appears to have been performed using the logarithmic form of both variables. We enhanced these aspects using two approaches. First, we utilized an estimator that is compatible with non-stationary time series. Second, we used the same logarithmic form when estimating regional-level variation, while still constraining the regional-level sum to equal the national total. Figure 5 shows the distribution of gasoline consumption across different Saudi regions using sector-specific and generic economics-based approaches. The estimated regional distributions derived from these two approaches appear to be in the same range. Thus, arguably, the estimates reasonably represent the regional distribution of gasoline consumption in Saudi Arabia.

Furthermore, the correlation between the results from both approaches illustrates that the generic econometrics-based approach is a decent proxy for estimating sectoral-level spatial variation in energy consumption. Its applicability extends beyond the realm of fuel demand and the transportation sector.

Table 3. Dickey-Fuller unit root test results using national-level time-series data.

Variable	Form	Test statistic
Logarithm of population	Level	0.201
	First difference	-3.011**
Logarithm of luminosity	Level	0.625
	First difference	-4.423***
Logarithm of gasoline price	Level	-1.434
	First difference	-3.908***
Logarithm of gasoline consumption	Level	0.482
	First difference	-3.815***

Source: Authors.
Note: ** and *** represent a rejection of the null hypothesis at the 5 and 1 significance levels, respectively.

Table 4. Estimated error correction model automatically selected by Autometrics for gasoline demand using national-level time-series data.

	Coefficient	Standard error	t-value	t-prob	Part.R^2
DI:2002	0.003	0.001	2.610	0.031	0.460
DI:2004	0.018	0.002	10.600	0.000	0.933
DI:2009	-0.011	0.002	-4.910	0.001	0.751
I:2005	0.041	0.003	15.300	0.000	0.967
S1:1999	-0.006	0.002	-3.020	0.017	0.533
T1:2008	0.038	0.004	9.650	0.000	0.921
T1:2009	-0.061	0.005	-12.300	0.000	0.950
T1:2011	0.027	0.002	14.500	0.000	0.964
Δ(Logarithm of gasoline price)$_t$	-0.102	0.002	-45.500	0.000	0.996
Δ(Logarithm of gasoline price)$_{t-1}$	0.020	0.003	6.140	0.000	0.825
Δ(Logarithm of population)$_t$	0.525	0.100	5.230	0.001	0.774
Constan$_t$	-16.204	1.317	-12.300	0.000	0.950
(Logarithm of luminosity)$_{t-1}$	0.013	0.001	10.600	0.000	0.933
(Logarithm of population)$_{t-1}$	1.058	0.082	12.900	0.000	0.954
(Logarithm of gasoline price)$_{t-1}$	-0.112	0.004	-25.700	0.000	0.988
(Logarithm of gasoline consumption)$_{t-1}$	-0.721	0.033	-21.700	0.000	0.983

Source: Authors.
Note: The final selected model is a congruent and parsimonious error correction model. The selected impulse and step indicator dummies, including DI, I, S1, T1, capture anomalous events, i.e., outliers and breaks in the demand in a particular year or time period.

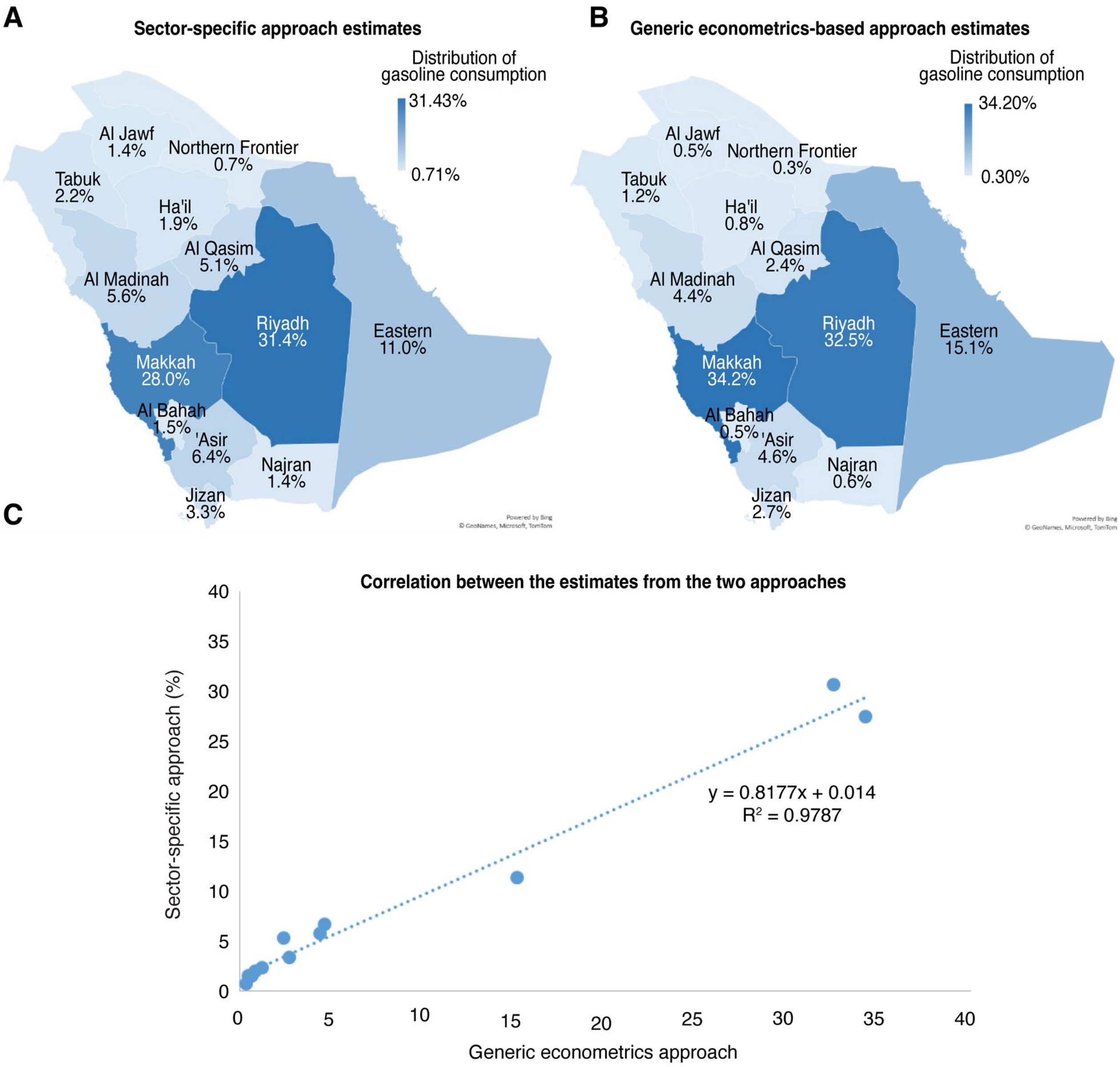
Table 5. Estimated long-run elasticities

	Coefficient	Standard error	t-value	t-prob
Luminosity	0.018	0.002	10.000	0.000
Population	1.467	0.063	23.100	0.000
Gasoline price	-0.155	0.004	-38.900	0.000

Source: Authors.

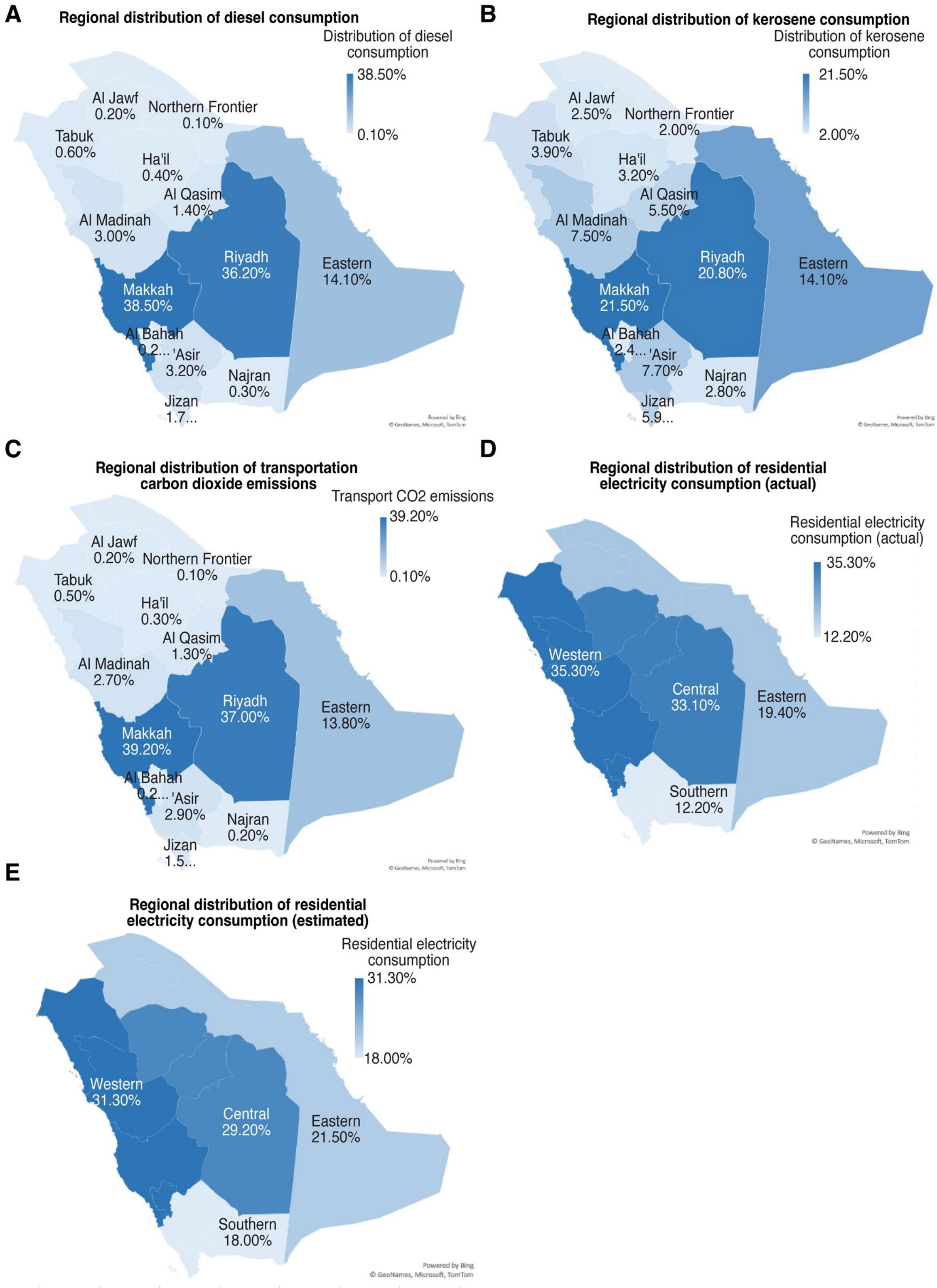
Accordingly, we estimated the regional variations in demand for other fuels, including diesel and kerosene, carbon dioxide (CO_2) emissions from the transportation sector and the demand for residential electricity (Figure 6).[3] In the case of residential electricity consumption, for which actual regional-level data is available, the estimated regional variation is found to be similar to the actual variation.

Figure 5. Regional distribution of gasoline consumption in Saudi Arabia based on the sector-specific and generic econometrics-based approaches.



Source: KAPSARC analysis.
Note: Appendix C contains the tabulated values corresponding to Figures 5a and 5b.

Figure 6. Regional variations in the demand for diesel, kerosene and residential electricity and transportation carbon dioxide emissions.



Source: KAPSARC analysis.

Concluding Remarks

In most countries, energy consumption and emissions differ by region. However, data on regional differences are typically difficult to obtain, particularly in Saudi Arabia. To estimate the regional variation in gasoline consumption, we developed a generic econometrics-based approach. The results showed regional variations similar to the highly aggregated regional-level data for electricity consumption. Furthermore, the regional variation in gasoline consumption estimated using the generic approach was positively correlated with that estimated using a sector-specific approach. Overall, the findings indicate that the generic approach is a good proxy for estimating regional differences in energy consumption. The findings of this study could be used by government agencies when planning investments in energy-related projects or implementing policy interventions to identify regions with the greatest potential impact on emissions mitigation.

Endnotes

[1] Average real gasoline prices were drawn from Aldubyan and Gasim (2021)

[2] Autometrics, the software used for model estimation, runs a battery of diagnostic tests before selecting a valid model. These include the error autocorrelation test (Godfrey 1978), auto-regressive conditional heteroscedasticity test (Engle 1982), normality test (Doornik and Hansen 1994), heteroscedasticity test (White 1980) and regression equation specification error test (Ramsey 1969).

[3] The same method was used to estimate regional variations in these areas. The long-run cointegrating relationships were estimated at the national level and assumed to hold true at the regional level. We set the constraint that the sum of the estimated regional-level numbers equaled the national total. Appendix Table D1 depicts the corresponding long-run elasticities.

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Appendix A

Table A1. Average annual vehicle kilometers traveled (VKT) over time in Saudi Arabia.

Year	Average annual VKT (private cars)	Average annual VKT (taxis)
2007	24,253	131,507
2008	24,311	131,820
2009	23,800	129,047
2010	23,930	129,756
2011	24,547	133,098
2012	24,855	134,766
2013	25,000	135,555
2014	25,181	136,535
2015	25,366	137,537
2016	23,717	128,600
2017	23,445	127,123
2018	21,433	116,215
2019	21,093	114,370
2020	24,253	131,507

Source: Authors.

Appendix B

Vehicle Occupancy in Saudi Arabia

Vehicle occupancy for private cars in Saudi Arabia was estimated using two questions from the New Vehicle Buyer Survey. This survey contains a representative sample of new vehicle purchases in Saudi Arabia, with approximately 7,500 observations representing 1% of all new vehicle purchases.
The first and the second questions were about the frequency of car usage with rear-seat passengers and front-seat passengers, respectively. The drivers could choose between five possible responses: almost daily, at least once per week, at least once per month, less than once per month and never. We obtained the distribution shown in Table 6 using a cross-analysis of these two variables.

We used this distribution to estimate the total number of passengers, including drivers (n = 12,677). We then divided this number by the total sample size (n = 7,500) to calculate the vehicle's occupancy (1.69).

Table B1. Cross-analysis of the two variables.

	Frequency of car usage with front-seat passengers				
Frequency of car usage with rear-seat passengers	Almost everyday	At least once a week	At least once a month	Less than once a month	Never
Almost everyday	782	450	324	206	251
At least once a week	662	487	329	222	307
At least once a month	436	352	194	139	153
Less than once a month	320	279	257	119	179
Never	336	239	196	121	162

Source: New Vehicle Buyer Survey.

Appendix C

Table C1. Regional distribution of gasoline consumption in Saudi Arabia based on the sector-specific and generic econometrics-based approaches.

Region	Sector-specific approach (%)	Generic econometrics-based approach (%)
Riyadh	31.43	32.50
Makkah	28.03	34.20
Al Madinah	5.60	4.40
Al Qassim	5.05	2.40
Eastern Region	11.02	15.10
Asir	6.42	4.60
Tabuk	2.25	1.20
Hail	1.90	0.80
Northern Borders	0.71	0.30
Jizan	3.27	2.70
Najran	1.45	0.60
Al Bahah	1.53	0.50
Al Jawf	1.35	0.50

Source: Authors.

Appendix D

Table D1. Estimated long-run elasticities.

	Diesel	Kerosene	Electricity	Transportation carbon dioxide emissions
Luminosity	0.030**	-0.002	0.016***	0.042***
Population	1.813***	0.757***	0.534***	1.8892***
Fuel price	-0.229**	-0.165***	-0.132***	-0.365***

Source: Authors.
Note: ** denotes the 5 significance level; *** denotes the 1 significance level.

About the Authors

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Abdulrahman is a research associate at KAPSARC working on the future of transport energy demand. He previously worked as a lecturer at the College of Engineering at Muhammed Ibn Saud University and as a traffic engineer at the Riyadh Metro project. His interests are transport economics and efficiency, energy security, and renewable energy policy and regulation.

Rubal Dua

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About the Project

Promoting the adoption of energy efficient vehicles has become a key policy imperative in both developed and developing countries. Understanding the impacts of various factors on adoption rates forms the backbone of KAPSARC's efforts in the light-duty vehicle demand field. These factors include (i) consumer-related factors—demographics, behavioral, and psychographics; (ii) regulatory factors—policies, incentives, rebates, and perks; and (iii) geotemporal factors—weather, infrastructure and network effects. Our team is currently developing models at different levels: microlevel models using large-scale data comprising new car buyers' profiles, and macrolevel models using aggregated adoption data to understand and project the effects of various factors affecting the adoption rate of energy efficient vehicles.

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