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Discussion Paper

Decarbonizing Road Freight Transportation in Saudi Arabia

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Abstract

Saudi Arabia needs to decarbonize road freight transportation to fulfill its emission reduction commitments. In this study, we utilize the GCAM-KSA modeling framework to explore potential mitigation pathways for the Kingdom's road freight sector. We evaluate the emission implications of several announced and potential decarbonization strategies, including the modal shift to electric freight rail, fuel efficiency improvements for heavy-duty vehicles (HDV), and the adoption of zero-emission vehicles. The results suggest that achieving an economy-wide net-zero target will require policy initiatives such as replacing trucks with electric freight rail, implementing fuel economy standards for heavy-duty vehicles (HDVs), adopting zero-emission vehicles, and introducing carbon taxes. In the *economy-wide net-zero* scenario, total land freight CO_2 emissions will be reduced to 29.4 Mt by 2060. The adoption of higher carbon taxes not only curbs the overly fast growth of land freight activity, capping total land freight demand at 823 billion tkm, but also incentivizes further adoption of freight rail and zero-emissions vehicles. In 2060, rail and zero-emission vehicles (primarily battery electric vehicles – BEVs) are expected to account for 30.6% and 25.9% of total land freight activities, respectively, while internal combustion engine (ICE) vehicles make up the remaining 43.5%. Low-carbon technologies (i.e., electricity and hydrogen) are expected to play an increasingly important role in the road freight decarbonization process, with their total demand projected to reach 56.8 TWh (electricity) and 77,549 tonnes (hydrogen), respectively, by 2060. Policymakers need to be aware of the energy and emission implications of the supply of these fuels on other energy sectors so that a coordinated decarbonization pathway across the Saudi economy can be achieved.

Keywords: GCAM-KSA, Road Freight Transportation, Economy-Wide Net-Zero, Decarbonization, Heavy-Duty Vehicles, Rail.

1. Introduction

Transportation is a significant contributor to Saudi Arabia's energy consumption and carbon emissions, accounting for approximately 28% of total final energy consumption and 26% of CO_2 emissions (IEA 2023). The road sector is estimated to be responsible for the vast majority of all transportation emissions (Climate Trace 2024), which is driven by relatively low domestic petroleum prices and the lack of alternative transportation modes (Algunaibet and Matar 2018; Lopez-Ruiz, Nezamuddin, and Muhsen 2020). Within road transportation, freight trucking accounts for a significant share of the sector's oil consumption (Xu and Dua 2023).

In 2021, Saudi Arabia officially pledged to reach carbon neutrality by 2060 (Associated Press 2021). Hence, decarbonizing the Kingdom's road transportation sector has become imperative to achieve this policy target. While an official decarbonization roadmap is yet to be released, the Saudi government has implemented a series of policy initiatives that contribute to transport emission mitigation. In its first Nationally Determined Contributions (NDC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC), Saudi Arabia proposed improving efficiency standards of the transportation sector and expediting the development of public transport systems in its major cities (SLOCAT 2022). Accordingly, the Saudi Energy Efficiency Center (SEEC) introduced fuel economy standards for light-duty vehicles (LDVs) in 2016 (Kamboj et al. 2024). The Saudi government also launched multiple public transport projects across the Kingdom, which include the heavily invested metro and bus transit systems in the capital city of Riyadh (U.S.-Saudi Business Council 2023). Moreover, Saudi Arabia has taken steps to gradually rationalize its gasoline and diesel prices to curb fast-growing domestic fuel consumption (Sheldon and Dua 2021; Darasha 2024).

Although these initiatives have demonstrated the Saudi government's intention to start decarbonizing the transportation sector, most existing policy measures have focused on the passenger LDV segment, and there have been insufficient solutions to tackle the emission challenges from heavy-duty vehicles (HDVs) in the road freight sector. HDVs account for a substantial proportion of total energy consumption from road transportation and have been the backbone and major enabler of the Saudi economy (Xu and Dua 2023). Yet, it remains difficult to decarbonize due to the limited technological options currently available. However, reducing carbon emissions from road freight is essential for reaching the net-zero target, especially considering that global freight transportation demand is expected to continue to grow in the coming decades (ITF 2021). As outlined in Saudi Arabia's Vision 30 strategy, the country aspires to transform itself into a logistics hub connecting major trade routes between Asia, Europe, and Africa, while also building a diversified and sustainable economy (Saudi Vision 2030 2023; Arab News 2021). To achieve this vision and a net-zero future, the development of a low-carbon road freight transportation sector would be indispensable.

In the updated submission of its first NDC, Saudi Arabia has pledged to continue to improve the fuel economy of its transportation fleet (UNFCCC 2022). In the meantime, the Kingdom has stated on multiple occasions its plan to significantly expand the railway network to enhance its freight capabilities (Arab News 2024a: Saudi Gazette 2023). Furthermore, Saudi Arabia is aspiring to establish its clean energy value chains, which include manufacturing electric vehicles and producing low-carbon fuels such as green hydrogen for both domestic use and exporting to international markets

(Arab News 2024b, 2024c). In light of these government efforts to develop a more sustainable transport and logistics sector, in this study, we evaluate the emission implications of these policy initiatives and explore their potential mitigation benefits for the road freight sector. Apart from assessing individual decarbonization strategies, we also investigate the potential gap between these strategies and the economy-wide net-zero target to explore what additional efforts will be needed to fill the gap.

Section 2 of this paper briefly describes the methodology, while Section 3 presents the scenario design. Section 4 discusses the main results of our analysis, and the final section concludes with discussions and policy implications.

2. Methodology

In this study, we utilize the GCAM-KSA modeling framework (Kamboj et al. 2024), a modified version of the Global Change Analysis Model (GCAM). GCAM-KSA, which has been disaggregated from GCAM's Middle East region and specifically developed for Saudi Arabia, is a dynamic, recursive model that includes 33 energy-economy regions. The GCAM-KSA has been primarily used to assess various emission mitigation policies and pathways. It models energy demand across various transport sectors, including passenger (road, rail, and domestic aviation), freight (road and rail), international aviation, and international shipping. The demand for each service is influenced by the region's GDP, income levels, and population. For each type of service demand, there are competing modes of transportation. The model features a complex nested structure in passenger transport. Different modes, vehicle types, and technologies compete at various levels, guided by a logit choice mechanism (Kamboj et al. 2024). More details on the transport sector in GCAM and GCAM-KSA can be found in Kyle and Kim (2011) and Kamboj et al. (2023).

The present study focuses only on the land-based freight transport modes (excluding international shipping) in the Kingdom. The study investigates the decarbonization potential of current initiatives, developments in the land freight transport sector, and the required efforts in freight transport for an economy-wide net-zero emissions target by 2060. (Refer to the Appendix for a brief description of GCAM-KSA.)

2.1. Scenario Design

We evaluate two decarbonization scenarios and several mitigation strategies for Saudi Arabia's land freight transport sector.

- The first is the *enhanced decarbonization* scenario, which includes the following mitigation strategies:
  a. Improvement in vehicle/truck fuel efficiency (*fuel efficiency improvement* strategy).
  b. Potential introduction of clean vehicles (e.g. electric trucks) in the road freight segment, similar to the Kingdom's current 30% electric vehicle (EV) target (for the city of Riyadh) in the passenger transport segment (*clean vehicles* strategy).
  c. Modal shift from trucking to freight rail (*modal shift* strategy).
  d. A combination of these policies.
- The second scenario is the *economy-wide net-zero* scenario, which incorporates all three mitigation strategies and adopts additional policy measures to ensure that the net emissions of the Saudi economy reach zero by 2060.

For comparison, we also include a *baseline* scenario that assumes a business-as-usual situation, with no specific decarbonization targets and no implementation of the mentioned decarbonization strategies during the modeling period. Note that the *net-zero* scenario incorporates all energy sectors and economy regions in the GCAM-KSA model, ensuring that interactions between the land freight

sectors and other sectors are properly considered. In contrast, the assessment of individual mitigation strategies, as well as the *baseline* scenario for the land freight sector, does not account for feedback from other sectors and regions. Details of the scenarios and strategies are provided in Table 1.

Table 1. Scenarios and strategies considered in this study.

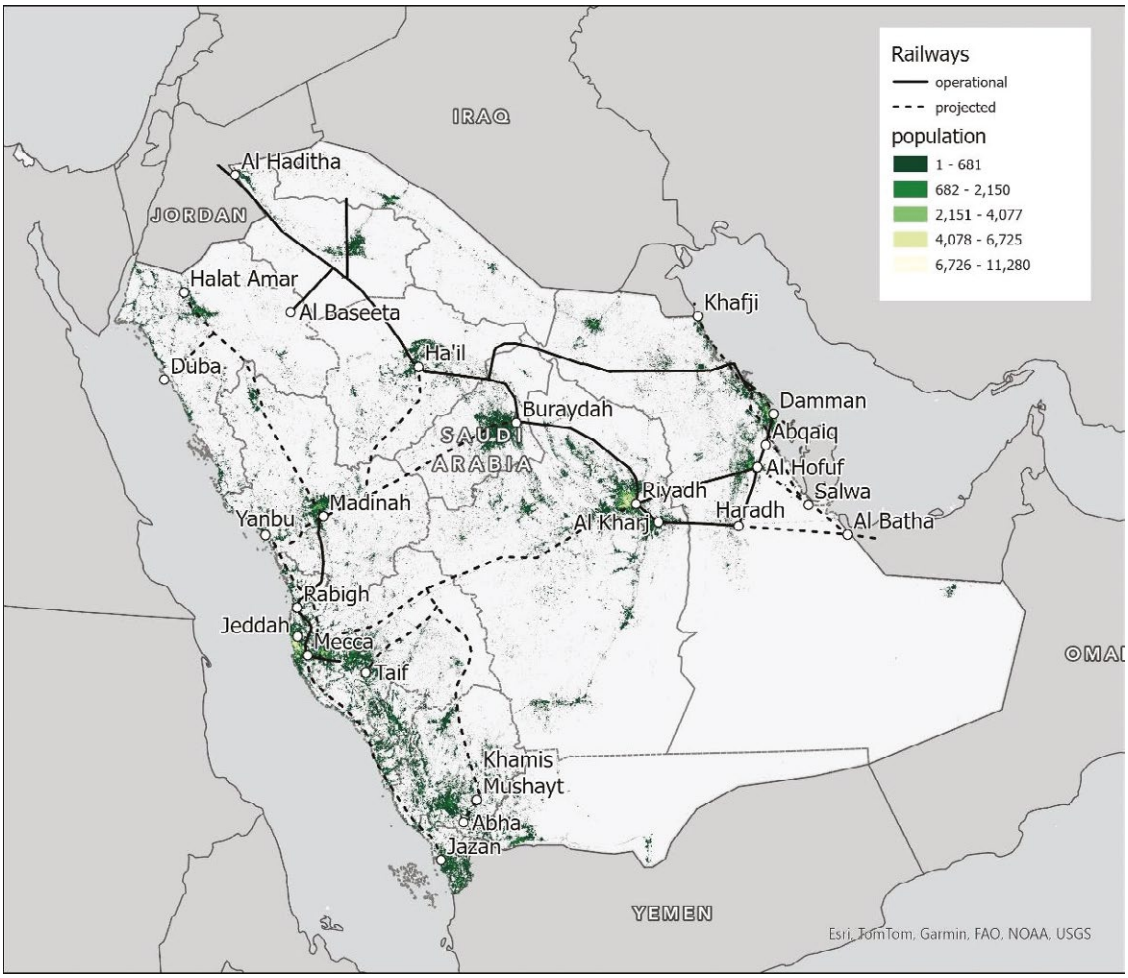
Scenario	Strategies	Implementation
Baseline		No decarbonization strategies nor decarbonization policy targets are considered.
Enhanced decarbonization	*Fuel efficiency improvement*	Consistent fuel efficiency improvement in line with IEA's Stated Policies Scenario (STEPS) (IEA 2020).
	Clean vehicles	This assumes that, with a target of achieving 30% clean vehicles among new passenger cars in Riyadh by 2030 (without further increases in ambition after 2030), the shared infrastructure can also be utilized by trucks, primarily light trucks. This is based on economic competitiveness with ICE trucks, without setting a specific target for trucks.
	Modal shift	Consistent modal shift from trucking to freight rail, with rail's total share of tkm reaching at least 20% by 2060.
	Combination	A combination of all three strategies above.
Economy-wide net-zero 2060	*Combination + additional policies*	A combination of all three strategies above, plus additional policy measures to force economy-wide net zero in 2060.

2.2. Modal Share of Freight Rail

In addition to improving vehicle fuel efficiencies and introducing clean vehicles, Saudi Arabia has made ambitious plans for the development of domestic rail transportation, so a detailed investigation is warranted, as this could significantly impact future land freight activities regarding road/rail modal split. The future percentage of total freight transport demand by freight rail will depend on both government planning and the geographic/economic potential to perform modal shifts.

Compared to road trucking, rail transport has significantly lower energy and carbon intensity (Cazzola 2017). Specializing in moving cargo at long distances, rail has been promoted by countries with large geographic areas and high domestic freight transport demand as a less carbon-intensive solution for long-haul freight (Kaack et al. 2018). Rail plays an important role in fulfilling domestic land freight transport demand in many of the world's largest countries, including Canada, the U.S., India, China, Mexico, and the EU, with freight rail accounting for 17%-62% of total land freight activities (Kaack et al. 2018). As the world's 13th largest country in the area, Saudi Arabia also has significant potential for the extensive use of railways in domestic goods transportation.

Figure 1. Population distribution and railway network (current and planned) in Saudi Arabia.



Source: Authors.

Note: Population data is from Kontur Population (2023); rail network information is based on Arab News (2022a).

Figure 1 shows the population distribution and the current and planned railway networks in the Kingdom. Saudi Arabia has announced plans to more than triple the length of its domestic rail network by constructing an additional 8,000 km of new railway tracks (Arab News 2022a). As seen in Figure 1, the main population in the Kingdom is primarily concentrated in three northwest-southeast corridors in the center and along the coasts of the Arabian Peninsula, and are well served by existing and planned railway networks. Hence, given the overall sparse population distribution and the long distances between major population centers, the railway in this case serves as an ideal mode for goods transportation, especially between coastal port cities and inland industrial/ metropolitan centers.

Currently, freight rail accounts for only a small share of freight activities in Saudi Arabia. However, given the continued rise in freight rail utilization and the government's plans to expand the existing rail network, rail is expected to play a much larger role in domestic freight transportation in the future.

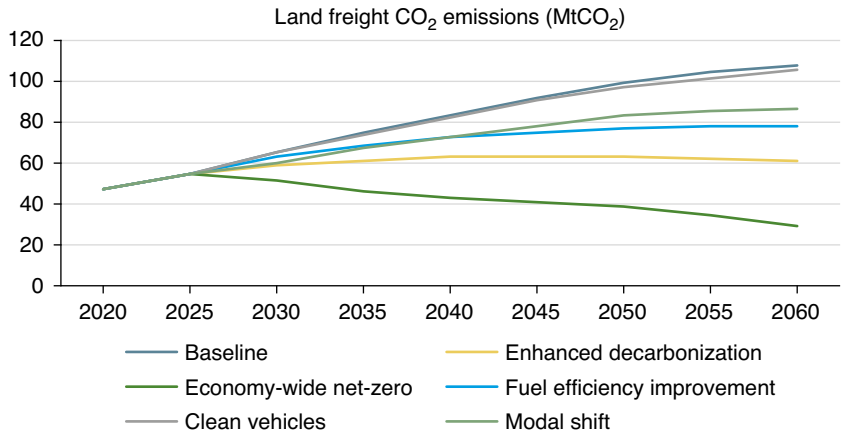
3. Results

This section presents the main results of our model analysis, including total land freight carbon emissions, total land freight demand and their modal contributions, the role of low-carbon technologies in the decarbonization pathways, and the energy demand implications due to the adoption of low-carbon technologies.

3.1. Freight CO_2 Emissions

Figure 2 shows emission trajectories for all the evaluation cases. Compared to the baseline case, which reaches over 100 Mt of CO_2 emissions by 2060, a moderate EV penetration target only slightly reduces total emissions, as electric truck activity remains negligible through 2060. On the other hand, both fuel efficiency improvements and a modal shift to rail can achieve significant emission reductions of between 20% and 30%. However, the modal shift policy seems less effective in the long term, likely because a more efficient freight rail system stimulates greater freight demand rather than substituting existing trucking demand in the absence of other policies. Combining all three decarbonization measures (*fuel efficiency improvement*, *modal shift,* and *clean vehicles*) can effectively saturate emissions by 2045 and reach a level that is about half of what is shown for the baseline case in 2060. However, the total emission reduction in the *combination* case for the *enhanced decarbonization* scenario is less than the summation of reduced emissions in the individual cases, suggesting sectoral interactions that offset some of the emission reductions. Finally, the *net-zero* scenario achieves the greatest mitigation, with total emissions peaking in 2025 and then gradually decreasing to around 30 Mt by 2060, representing a reduction of about 70% compared to the *baseline* scenario. The reason that a positive amount of emissions remains is due to the relatively high mitigation cost of the land freight sector. These remaining emissions will be counterbalanced by negative emission technologies from other energy sectors that have lower mitigation costs.

Figure 2. Total land freight emissions ($MtCO_2$), 2020-2060.

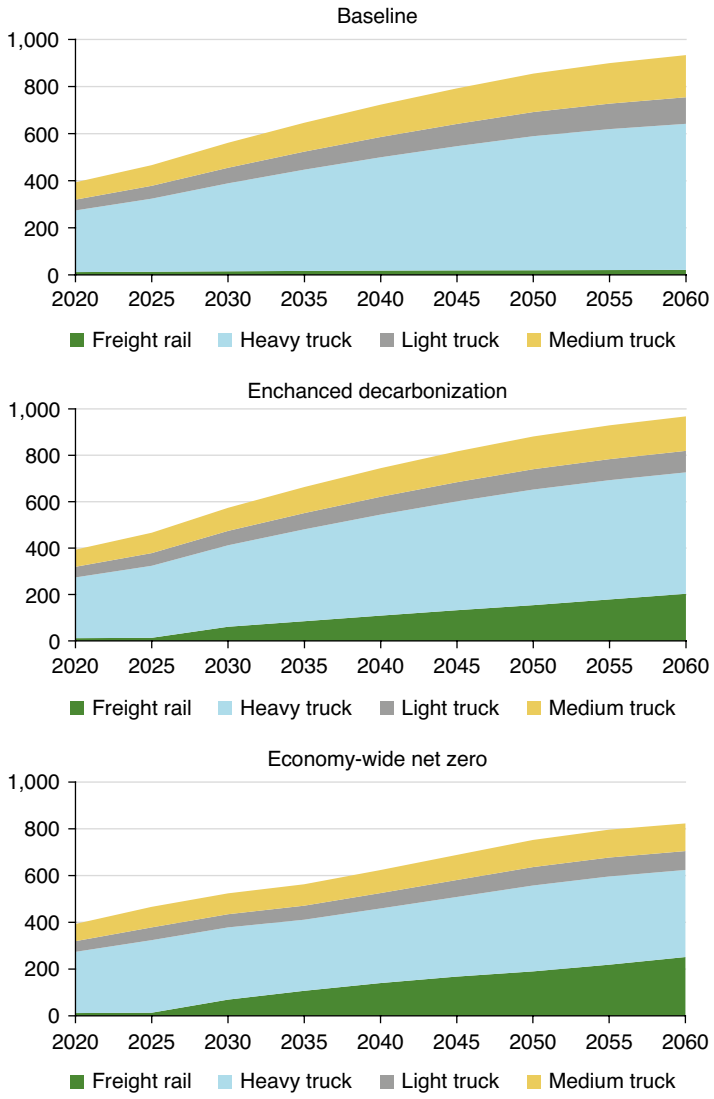


Source: Authors.

3.2. Freight Demand and Modal Contributions

Figure 3 and Figure A1 (in the Appendix) report the total freight transport demand and their modal contributions for the three scenarios and individual decarbonization strategies (under the *enhanced decarbonization* scenario). In all cases, total freight demand is expected to at least double between 2020 and 2060, growing from about 400 billion tkm to around 900 billion tkm per annum. The expansion is driven by continued population growth and economic development, which is consistent with the projection by the International Transport Forum (ITF 2021). Different decarbonization strategies have clear impacts on both the aggregate level and the structure of future freight service demand. In the absence of modal shift policies, the vast majority of new service demand will continue to be fulfilled by the trucking sector, especially heavy-duty trucks, whereas the share of freight rail will remain minimal. In comparison, in scenarios where freight is increasingly transported on the railway, freight rail will grow

Figure 3. Modal freight service demand (billion tkm) across scenarios, 2020-2060.



Source: Authors.

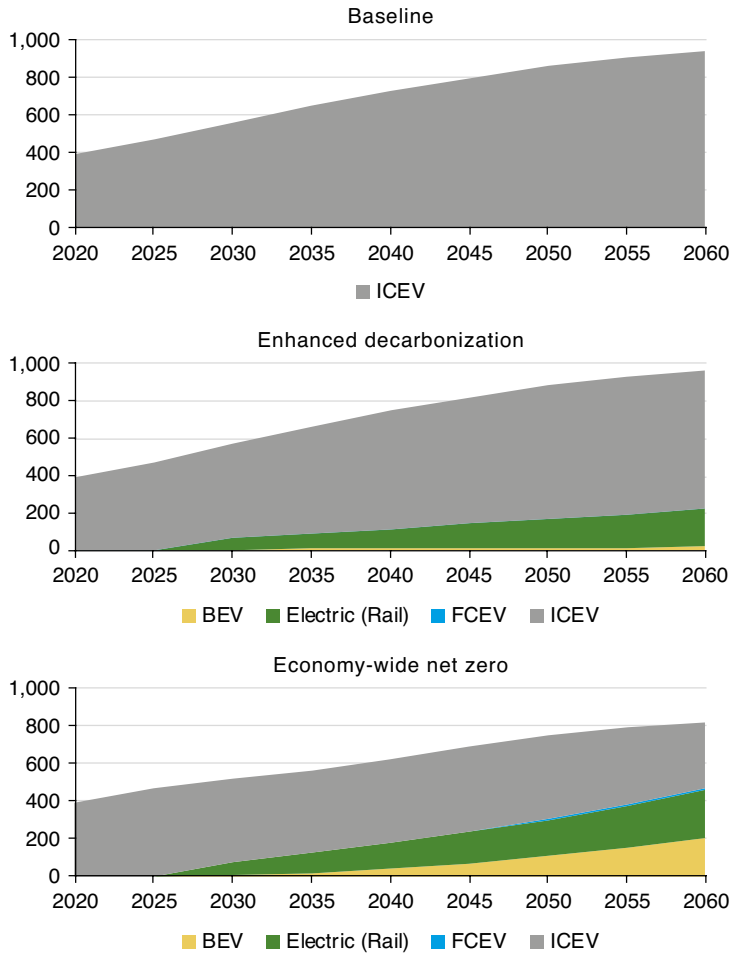
substantially and at a much faster pace than trucking, gradually substituting road vehicles in freight service supply.

In terms of total freight demand, both greater fuel efficiency and a more efficient rail system will lead to higher total service demand compared to the *baseline*, as a result of lower average freight transport prices. However, in the *net-zero* scenario, total freight demand is reduced by more than 100 billion tkm compared to the other cases. To reach the economy-wide net-zero target, freight rail will assume a further elevated role, whereas demand for trucking will be less prominent due to the introduction of higher carbon prices. In other words, not only must total freight demand be managed to remain within a reasonable level, but a significant portion of the freight services must also be carried out by low-carbon modes, such as rail, for the sector to meet its emission mitigation targets.

3.3. The Role of Low-Carbon Technologies

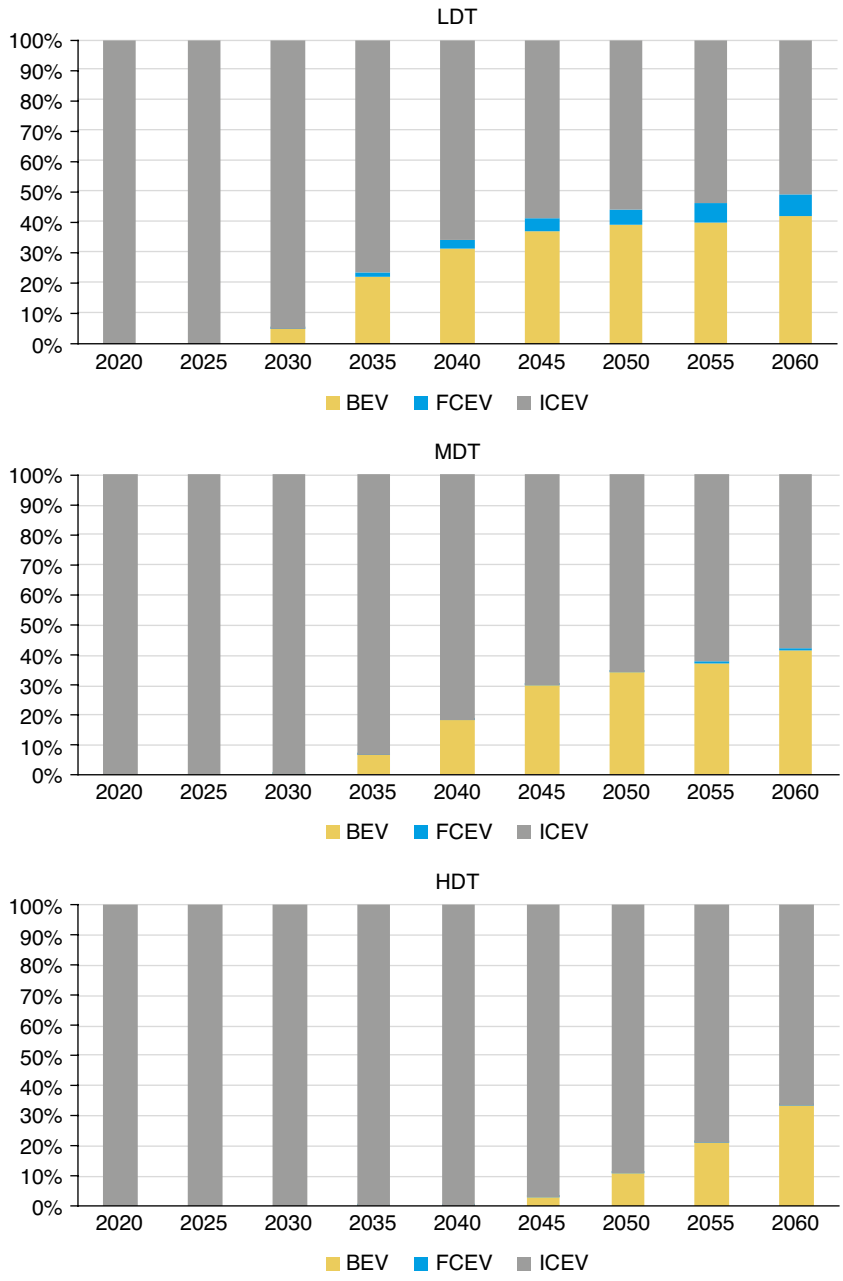
To rapidly decarbonize road freight transportation, low-carbon technologies will play an important role in the future. Figure 4 and Figure A2 (in the Appendix) show that, in cases involving mitigation policies for road trucking, the primary energy source will remain liquid fuels (i.e., diesel) through 2060. Furthermore, only a small percentage of freight activities will be carried out by electric trucks after 2050 under the *clean vehicles* strategy. In contrast, when a modal shift to rail is implemented as a decarbonization strategy, its activity will grow rapidly over the next few decades, reaching over 200 billion tkm by 2060. Assuming all future locomotives are electric, this means electricity use from freight rail will account for more than 20% of total land freight activity by the end

Figure 4. Land freight service demand (billion tkm) by fuel types across scenarios, 2020-2060.



Source: Authors.

Figure 5. Structure of new vehicle sales for light-duty trucks (LDTs), medium-duty trucks (MDTs), and heavy-duty trucks (HDTs), 2020-2060, under the *economy-wide net-zero 2060* scenario.



Source: Authors.

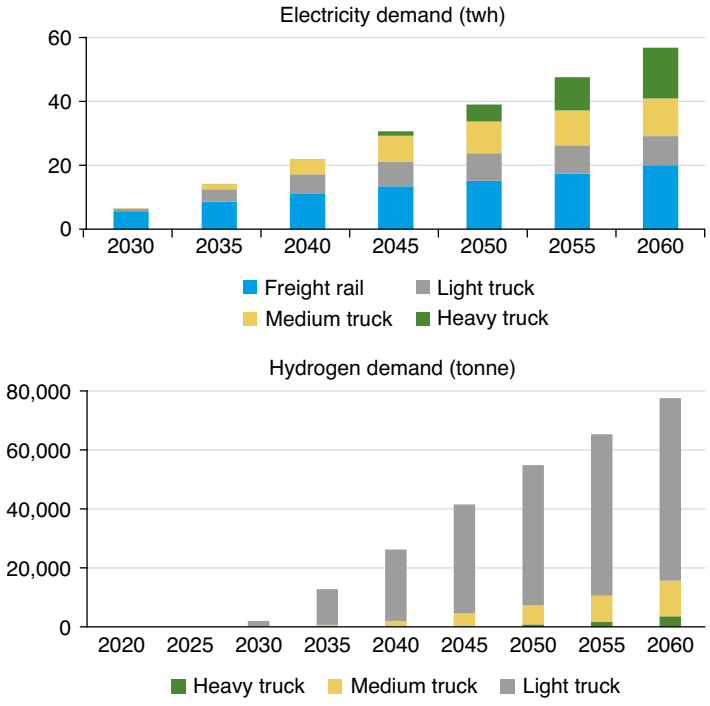
Reaching the economy-wide net-zero target will also require a substantial proportion of road vehicles to be electrified. Combined with electricity use from rail, electricity will surpass diesel to become the largest share of land freight activities in Saudi Arabia by 2060 (Figure 4). Figure 5 breaks down the progression of zero-emission technologies (electric trucks and hydrogen trucks) penetration in new vehicle sales. Among the three vehicle classes, light- and medium-duty trucks will witness the fastest adoption of

low-carbon powertrains, particularly battery electric vehicles (BEVs). BEV sales will accelerate in 2035 and 2040 for LDTs and MDTs, respectively, reaching around 20% of the new vehicles and accounting for more than 40% of the new market sales by 2060. BEVs penetration in the HDV segment is much slower, reaching about 33% of new vehicles by the end of the period, highlighting the challenges of EVs in long-haul freight applications. On the other hand, fuel cell electric vehicles (FCEVs) are primarily used in the LDT segment for urban freight, with their share not exceeding 10% of new vehicle sales by 2060.

3.4. Energy Demand Implication for Other Sectors

The economy-wide net-zero pathway necessitates an increased use of electricity and hydrogen fuel in land freight transportation, leading to a rapid growth in electricity consumption from both rail and trucking, as well as hydrogen consumption from FCEVs (Figure 6).

Figure 6. Total electricity and hydrogen demand from land freight transport, 2030-2060.



Source: Authors.

Note: Hydrogen demand is converted from EJ according to IEA (2024).

With the expansion of railway networks in the Kingdom and new freight services coming online, electricity consumption from freight rail is expected to grow steadily starting in 2030, surpassing the consumption of any single truck category. On the other hand, the growth of electricity consumption across truck categories follows a more of a "phased" pattern. While LDTs and MDTs begin to show significant electricity use around 2035 and 2040, respectively, HDTs do not reach 5 TWh of electricity consumption until 2050. Combining all subsectors, total electricity consumption from land freight transportation grows from 6.6 TWh in 2030 to 56.8 TWh in 2060. To put this in perspective, electricity demand from trucking and freight rail by 2060 is expected to account for nearly 20% of KSA's total electricity production (289 TWh) in 2020 (GASTAT 2021). This will require a significantly higher

electricity supply from the power generation sector, along with corresponding emissions mitigation measures to ensure the production of low-carbon electricity.

In the meantime, hydrogen fuel demand will grow rapidly starting in 2035, with annual consumption exceeding 10,000 tonnes. By 2060, total hydrogen demand is expected to reach nearly 80,000 tonnes, with the majority of the consumption coming from LDTs. To ensure that the hydrogen used is truly low-carbon from a life-cycle perspective, “green” hydrogen produced using renewables and “blue” hydrogen produced with carbon capture and storage methods must be the primary sources of fuel for land freight transportation.

4. Discussions

Overall, to reduce carbon emissions in the road freight transportation sector and reach the economy-wide net-zero target, Saudi Arabia must implement a range of policy initiatives, as no single policy can serve as a silver bullet for emissions mitigation. Our analysis in this study suggests that shifting freight demand from trucking to rail, improving vehicle fuel efficiency for existing and future vehicle stock, and adopting low-carbon fuels such as electric and hydrogen, are all potentially viable strategies to decarbonize road freight transport.

At present, the Saudi government has already been actively pushing for some of these policies. For instance, ongoing and planned railway additions include the Landbridge project that will connect Riyadh with Jeddah on the Red Sea coast. The GCC Railway project will connect all six GCC countries, passing through several Saudi cities on the coast of the Arabian Gulf. Several other railways will connect densely populated regions in west Saudi Arabia and along the Red Sea coast (Arab News 2022a). As the Kingdom seeks to significantly expand the exploration of its abundant mineral resources, the new rail capacity is expected to provide key logistical support for the growth of the mining sector and related industrial sectors, as well as enable low-carbon freight transportation to replace truck trips on the road (Arab News 2023, 2024a). From this perspective, developing an efficient multi-modal freight transport system – utilizing rail for long-distance cargo transportation between major logistic hubs and trucks for regional and last-mile deliveries – could be an effective strategy for reducing vehicular travel demand and related emissions.

On the other hand, while the Kingdom has implemented fuel economy standards for light-duty vehicles (including light trucks), it has yet to release a similar standard for heavy-duty vehicles, such as heavy-duty trucks. Saudi Arabia currently imports the majority of its trucks from abroad. Relevant regulations include an age restriction, which stipulates that imported trucks must be no older than five years (Saudi Gazette 2022), as well as a requirement for the Euro 5 standard to ensure that imported trucks have low emissions of pollutants (Saudi Gazette 2024). Around the globe, an increasing number of countries and regions are setting fuel economy standards for heavy-duty vehicles (Basma 2024). As internal combustion engine (ICE) trucks are expected to continue to play a significant role for the coming decades in Saudi Arabia through its net-zero journey, establishing relevant energy and emission regulations would be an important approach to decarbonizing the trucking sector and achieving climate change mitigation goals.

Further, the introduction of electric and hydrogen fuel-cell trucks could benefit from existing policy and market momentum, helping to kickstart an EV value chain in the Kingdom. Saudi Arabia has set ambitious plans to establish a large EV manufacturing sector and produce electric passenger vehicles domestically (PIF 2023a; Lucid Motors 2023). In this context, policymakers may also consider manufacturing electric trucks (e.g. light electric trucks to begin with) to leverage both the economy of scale and economy of scope. In the meantime, the Saudi Electricity Company (SEC) and PIF are seeking to establish a massive EV charging network in Saudi Arabia by 2030 (PIF 2023b).

Recent studies have shown that charging stations for light-duty passenger EVs could also accommodate the charging needs of small- and medium-sized electric trucks without significant infrastructure upgrades (Borlaug et al. 2021). Hence, the increasing charging infrastructure availability could help the adoption of light- and medium-duty electric trucks, which are most likely to have early market penetration based on our analysis. On the other hand, with the ongoing construction of the world's largest green hydrogen project, Saudi Arabia is actively pushing

for the creation of a new hydrogen value chain (Saudi Gulf Projects 2023; Air Products 2024). Having one of the lowest production costs of green hydrogen in the world (Arab News 2022b), Saudi Arabia has substantial potential to develop a hydrogen economy in the course of building a sustainable society and net-zero future. Hence, as a hard-to-abate sector, road freight transportation is ideal for starting pilot projects to incentivize more hydrogen utilization on the demand side.

Finally, despite the above decarbonization strategies, total road freight transport demand is still expected to more than double between 2020 and 2060. The surging freight activity is the result of a growing population, higher living standards, and increasing demand for online retail and their fast delivery (ITF 2021), posing significant challenges for the sector to reach its emission mitigation target. Therefore, additional policy measures must be implemented to slow the rapid growth of freight transport activity. Common policy options in this regard include monetary policies, such as fuel tariffs and other price-based mitigation strategies like area charges, congestion charges, and parking charges, as well as non-monetary policies, such as sales bans and vehicle use/parking permits (Axsen, Plötz, and Wolinetz 2020). As Saudi Arabia introduced energy price reforms for the road transport sector in recent years, research has shown that increasing fuel prices could reduce related transport emissions and prompt the adoption of more fuel-efficient vehicles in the Kingdom (Shannak, Mikayilov, and Dua 2024; Sheldon and Dua 2021). As such, policymakers could continue to raise diesel prices to disincentivize the use of less energy-efficient ICE trucks by shippers and fleet operators. In the meantime, incentives may be provided to accelerate the adoption of clean vehicles and technologies. Together with other strategies, these policy measures will help to ensure that the Kingdom reaches its net-zero and environmental sustainability targets.

5. Conclusion

Decarbonizing the hard-to-abate road freight transportation sector is essential for Saudi Arabia to meet its climate commitments and achieve its logistics development targets. In this paper, we used the GCAM-KSA modeling framework to assess the climate implications of several policy initiatives. Some of these initiatives have already been announced by the Saudi government, such as the massive expansion of the domestic railway network for long-haul freight transportation. Other potential strategies, which have yet to be adopted and implemented, include enacting fuel economy standards for HDVs, promoting zero-emissions trucks (BEVs and FCEVs), and further raising diesel prices and carbon taxes.

We conducted scenario analyses to assess the individual and combined climate impacts of these mitigation strategies. We also examined the scenario in which Saudi Arabia achieves its 2060 economy-wide net-zero target. The results show that, under all scenarios, total land freight demand will more than double, reaching over 800 billion tkm by 2060. On the other hand, although implementing stringent HDV fuel economy standards, replacing vehicle trips with cargo transport on electrified railways, and moderately adopting zero-emissions vehicles could all contribute to decarbonization, these initiatives alone are insufficient to support Saudi Arabia's economy-wide net-zero target. Together, they would reduce less than 50% of road freight emissions by 2060 compared to the baseline case.

To bridge the gap between these policy efforts and deep decarbonization of the road freight sector, as required by economy-wide carbon neutrality, policymakers need to consider additional mitigation strategies, such as carbon taxes. In the economy-wide net-zero scenario, total land freight CO_2 emissions are reduced to 29.4 Mt by 2060, a 72.8% reduction compared to the *baseline* scenario. The adoption of higher carbon taxes not only curbs overly fast growth of land freight activity, capping total land freight demand at 823 billion tkm, but also incentivizes further adoption of freight rail and zero-emissions vehicles. By 2060, rail and zero-emission vehicles (primarily BEVs) are expected to account for 30.6% and 25.9% of total land freight activities, respectively, while ICE vehicles will make up the remaining 43.5%.

Low-carbon technologies (i.e., electricity and hydrogen) are expected to play an increasingly significant role in road freight decarbonization. However, policymakers must consider the energy and emission implications for other energy sectors. Our analysis shows that, to achieve deep decarbonization in line with the net-zero target, total demand for electricity and hydrogen in the land freight sector will reach 56.8 TWh and 77,549 tonnes, respectively, by 2060. Supplying these energies using low-carbon fuel sources will become a new challenge but is crucial for achieving a coordinated decarbonization process across the Saudi economy.

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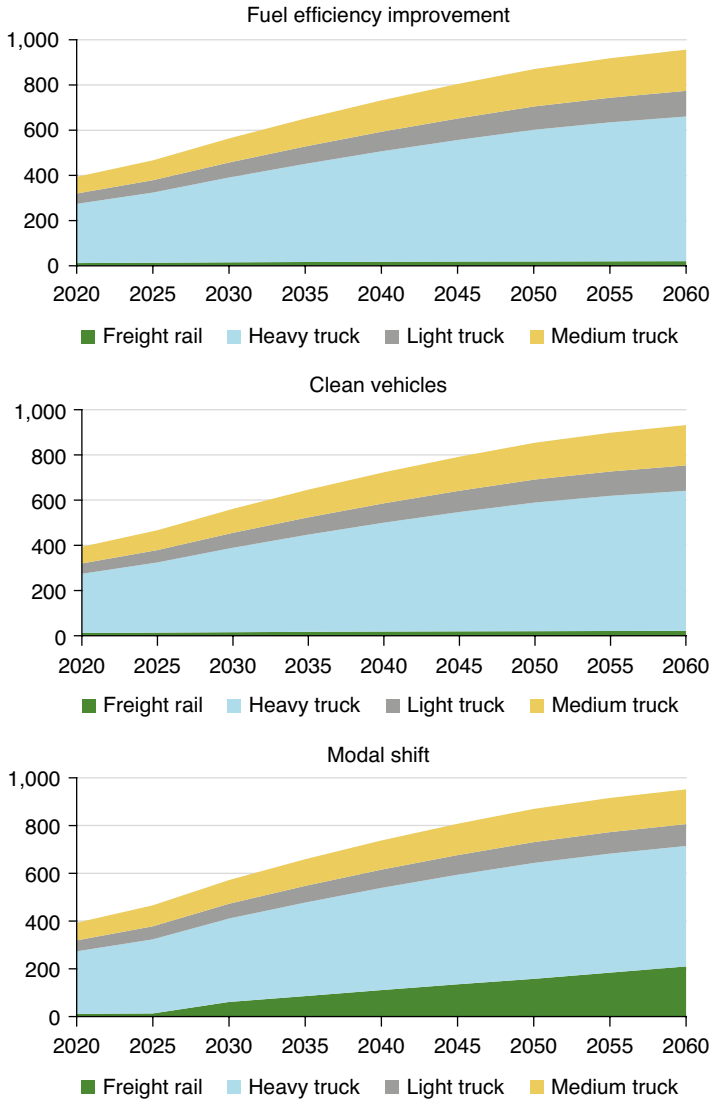
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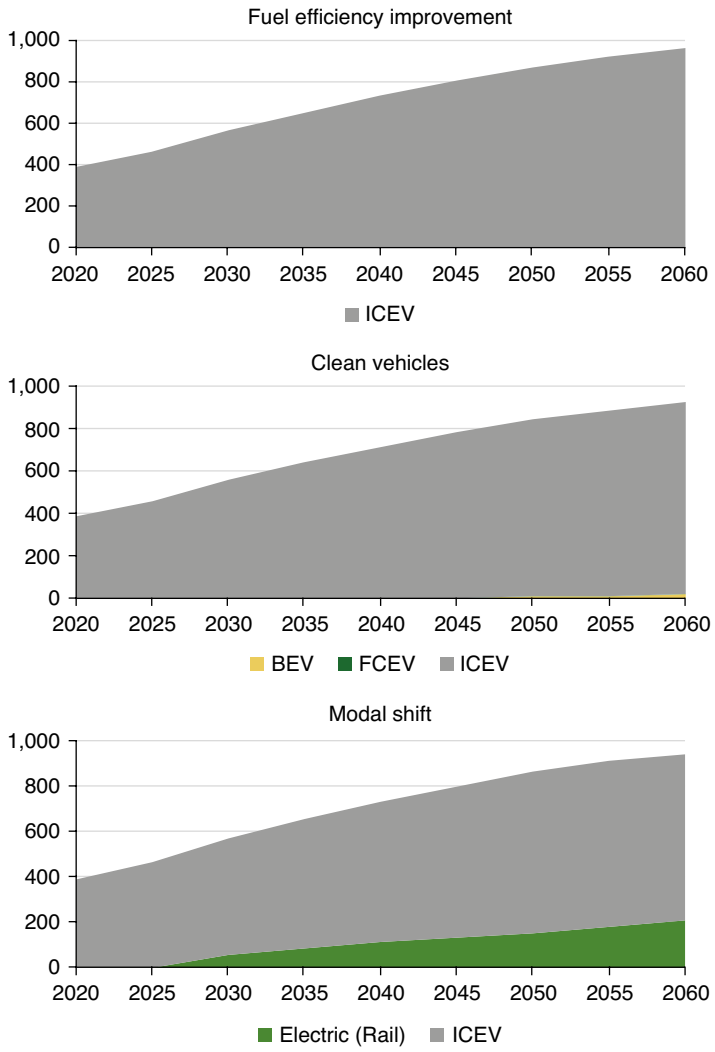
Appendix

Figure A1. Modal freight service demand (billion tkm) under separate decarbonization strategies in the *enhanced decarbonization* scenario.



Source: Authors.

Figure A2. Land freight service demand (billion tkm) under separate decarbonization strategies in the *enhanced decarbonization* scenario.



Source: Authors.

GCAM-KSA

Total Land Freight Demand

GCAM-KSA is a dynamic recursive model that operates in five-year time intervals from 2015 to 2100 (Kamboj et al. 2024). Total land freight transport demand is calculated using the following equation:

$$D_f^t = \sigma_{t-1}(GDP_l^t)^{\alpha'}(P_l^t)^{\beta'} \quad (1)$$

where D_f^t is the demand for freight transport at the time period (t), σ is the calibration parameter from the previous time period (t-1), GDP_l is the index for GDP (PPP basis) of region (r) represented as the ratio of GDP in the time period (t) to the ratio of GDP in the time period (t-1), and P_l is the index of price of transportation (cost to carry goods) aggregated across all modes and technologies and calculated as the ratio of price in the time period (t) to the price in the previous time period (t-1). α' and β' are the income and price elasticities of freight demand (Kyle and Kim 2011).

Modal Share of Vehicle Classes

Given the shares of rail and road freight demand, the choice over different vehicle classes is determined

endogenously by the model using the logit choice function (Clarke and Edmonds 1993; Mishra et al. 2013). Three vehicle classes are considered in this study: light-duty trucks (LDTs), medium-duty trucks (MDTs), and heavy-duty trucks (HDTs). The following equation is used to calculate the market share of a given vehicle class (S_i) based on the economic cost of travel:

$$S_{i,t} = \frac{(SW_i)(P_{i,t})^{\lambda}}{\sum_i^n (SW_i)(P_{i,t})^{\lambda}} \quad (2)$$

where *SW* is the share weight, P_i is the cost of transport service, λ is a cost distribution parameter or logit exponent, and *n* is the number of modes in the given sector. The share weight is a calibration parameter, and the cost distribution parameter regulates the degree to which future price changes will be reflected in modal shifts.

The total cost of any vehicle class (P_i) and time period *(t)* is calculated as follows:

$$Cost\ of\ vehicle\ class, P_{i,t} = \frac{(FP_{i,t})(I_{i,t}) + NFP_{i,t}}{LF_{i,t}} \quad (3)$$

where *FP* is the fuel price, *I* is the vehicle fuel intensity, *NFP* is the levelized vehicle non-fuel price (measured in $/vehicle-kilometer), *LF* is the load factor (tonnes per vehicle).

About the Authors



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About the Project

The “Decarbonizing Road Transportation in Saudi Arabia” project aims to address the need for long-term emissions reduction in Saudi Arabia’s road transport sector, the second-largest source of CO_2 emissions in the Kingdom. The project seeks to establish a benchmark for analyzing energy consumption and greenhouse gas (GHG) emissions in road transport while providing decision-makers with insights into potential decarbonization pathways. Using an integrated assessment modeling framework, the project attempts to maximize synergies between the transport sector and other sectors of the Saudi economy, while evaluating various decarbonization strategies in a holistic manner. It investigates energy efficiency improvements, modal shifts, electrification, and a range of other policy initiatives to support Saudi Arabia’s transition toward a net-zero future.



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