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The Responsiveness of Fuel Demand to Gasoline Price in Passenger Transport: A Case Study of Saudi Arabia

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Key Points

Empirical estimates of fuel demand changes to price variation are based on historical consumption and prices, and can be applied as a single point estimate to a wide range of price movements. However, if fuel prices are set outside the boundaries of historical changes, policymakers may be concerned as to the validity of the empirically assessed price elasticity. We have developed a transport model to provide a techno-economic estimate of the price elasticity of fuel demand. It incorporates consumers' choices as a result of several factors, including fuel substitutes, available transport modes, income, value of time and magnitude of price change.

Our findings from the application of this transport model to Saudi Arabia show that policymakers can have confidence that the empirical estimates are broadly valid, even for large changes and if prices move outside historical variations.

In general, gasoline demand in Saudi Arabia is price inelastic due to the lack of fuel and modal substitutes. However, our approach suggests that the response may become more pronounced when the magnitude of the change increases.

The cross-price elasticity of diesel is not constant. Demand for diesel will increase if gasoline price is raised significantly. Motorists may, for example, opt for diesel-based public transport, such as trains or buses, for long distance local trips. The change in jet-fuel use is negligible.

Executive Summary

Demand for transportation fuels change as the price of these fuels fluctuate. Past empirical analyses provided estimates of a single figure for price elasticity based on historical consumption and prices. However, a concern for policymakers is that this elasticity may not remain constant as the magnitude of the price change becomes larger. A prospective price movement may well be outside of historical variation and consumers may respond more readily when the changes are significant.

Transport is seen as a service first, from which the consumption of fuel arises. Once consumers have made a decision to travel, they can then choose an available mode to satisfy that demand. These decisions to travel are based on a variety of factors, including the costs they perceive – for example, fares, time spent waiting for buses or trains, in-vehicle time, fuel and maintenance costs for private vehicles. Diesel and jet-fuel costs are not directly incurred by travelers, as they are mostly consumed by buses, trains and airplanes, although their levels of use contribute to fares.

We developed a model that considers several factors when assessing consumers' choices: the ability to substitute fuels and modes, income and spending budgets, value of time and behavior and the magnitude of price change from the initial price. We validated and calibrated this methodology in a long-run framework using Saudi Arabia data for 2013. This analysis simulates how people's choices would vary as the price of gasoline is gradually raised to 350 percent above its initial value. Figure 1 shows a long-run price elasticity curve generated by considering the aforementioned factors.

This methodology can help governments formulate more effective transport policies and provide comfort as to the validity of elasticity estimates when they want to test policies that fall well outside historical price variations. It also provides insights into how consumers may react to changes in fuel prices including substantial increases.

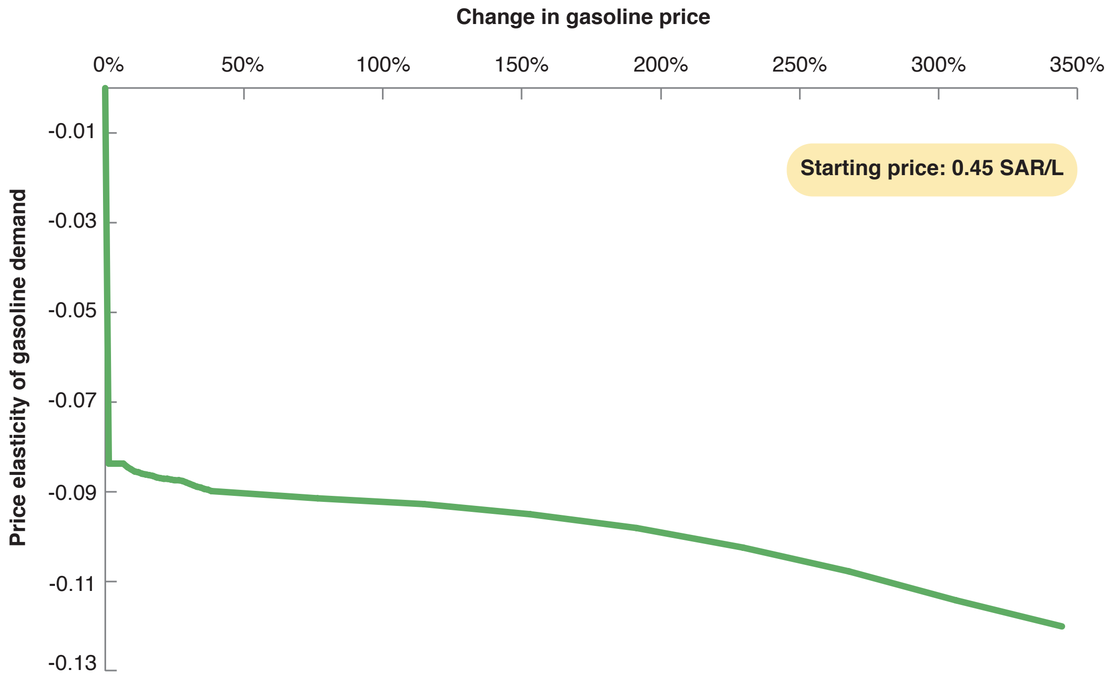

Figure 1. Own-price elasticity of gasoline demand in Saudi Arabia.

Source : KAPSARC analysis.

Transport Fuel Prices in Saudi Arabia

The prices of transport fuels in Saudi Arabia are administered by the government. The price of the lower-grade gasoline was set at 0.45 Saudi Arabian Riyals (SAR) per liter in 2007 and was raised to 0.75 SAR per liter in December 2015; a fixed nominal price over the 8-year period means it actually decreased over time once inflation is taken into account. The prices of jet fuel and diesel are also administered by the government, but they are not directly relevant for passenger transport decisions as most cars and light vehicles in the Kingdom use gasoline. Customers pay fares for trips by airplanes and diesel-powered buses and these costs are considered in the analysis.

Factors Influencing Consumer Transport Choices

Changing the price of a transport fuel will generally affect transport demand by consumers. The magnitude of this effect depends on several decision factors, including the flexibility of substitution, income and monetary budget, value of time and consumer's behavior as well as the initial and final prices. Substitution in this case captures the level of ease with which consumers can alternate between two or more fuels. If a consumer has a vehicle that can use multiple types of fuel, they can easily switch fuel if one becomes more costly. In addition, a consumer may also switch between different modes of travel. If gasoline price is raised, for example, a motorist may weigh the costs of driving versus taking the bus.

People's spending budget, which is dependent on income, limits how much they can spend on fuels. That is, individuals with larger income can withstand a higher fuel price than low-income households and so higher fuel prices can lead to smaller reductions in demand. Consumers also value their time when choosing which mode satisfies their desire for transport. The time element includes both in-vehicle speed and waiting time incurred when using mass transit.

Moreover, the initial fuel price faced by consumers may be so low that spending on fuels is a small fraction of their total expenditure. Thus, even a substantial price increase could yield a small reduction in demand. However, the bigger the increase in fuel price from the initial value, the larger the proportionality of the demand response.

The demand for transport fuels may therefore be viewed as a secondary demand. The primary demand is the desire for transport itself, taking into consideration the monetary costs of overall transport. That is why, for example, when the price of gasoline is increased it would be taken as a part of many costs that a consumer considers; this is represented by

$$Average\ Cost\ of\ Travel = \frac{Fuel,\ \ Operations\ and\ Fare\ Costs}{Total\ Domestic\ and\ International\ Travel\ in\ Passenger \cdot km} \tag{1}$$

A range of transport demand price elasticities were used in conjunction with the transport cost to calculate own- and cross-price demand elasticities of gasoline.

This paper aims to produce gasoline price elasticities as a function of the initial price and magnitude of the price change. The approach we have taken considers that as prices increase, the magnitude of an own-price elasticity of fuel demand rises as well. Therefore, single empirical estimates may underestimate the response when price change is large.

Description of Model

A cost-minimization approach is utilized to complement econometric methods. The total cost perceived by travelers, which includes monetary and non-monetary behavioral costs, is minimized. Considering the non-monetary behavioral costs supports this model to mimic a consumer's decision-making process. This section describes the transport model used in the analysis. Appendix C details the model equations and constraints, Appendix B describes the variables used, and Appendix A shows the model calibration.

Regional disaggregation, transport demand types and demographic groups

The model considers four geographical regions in Saudi Arabia as shown in Figure 2. Each region has two types of transport demand: short-distance and long-distance travel. Short-distance travel is limited to intra-city commutes, while long-distance travel can either be intra-regional, inter-regional or international travel. The travel demand by consumers can be satisfied by a wide range of transport modes, such as light-duty vehicles, airplanes, buses and trains. Each transport mode can have a variety of technologies (e.g., for light-duty vehicles the model can offer spark ignition and compression ignition engines along with other technologies). However, only those transport modes or technologies that in 2013 have a non-zero capacity are considered in this analysis. There are three demographic groups represented in the model: Saudi households, non-Saudi households and non-Saudi pilgrims. This distinction is made to account for the differences in travel monetary budget and value of travel time.

Figure 2. Regional transport flows represented in the model.

Source: KAPSARC analysis.

Value of time and congestion effect

Value of time is the opportunity cost incurred by travelers for the time spent in transit. If a consumer decides to save travel time by paying more, value of time can be deduced as the additional money spent over the time saved. Abrantes and Wardman (2011) found that the value of time varies with income and demand type, and thus the difference between Saudi and non-Saudi households is reflected by their respective income levels. The model also includes the level which consumers would pay to save time (Daly et al., 2014).

The value of time is also influenced by congestion, as travelers stuck in traffic would have a lower average speed that can lead to an increased perception of the value of time than those who are experiencing smooth driving. Since this model considers different geographical regions (Figure 2), the average speed for each demand type and geographical region was estimated endogenously (Greenshields et al., 1935). The congestion effect complements the value of time and captures the interactions between households.

Furthermore, following Schäfer (2015) and Gross et al. (2008), the model considers air transport system delay using the queuing systems. Passengers' waiting time in an airport can increase as air traffic grows. Such an increase in delays can lead consumers to perceive a higher value of time, which in turn may discourage them from traveling by airplane. Again, this feature of the transport model can enhance the interactions between agents, who may have different income levels and values of travel time. For instance, the desire of Saudi households to travel by airplane can discourage non-Saudi households who may not be able to cope with both the expensive fares and increase in waiting time that they would incur should they travel by airplane.

Travel time and monetary budgets

Consumers allocate a fixed amount of their daily time for traveling, known as travel time budget (Zahavi and Talvitie, 1980). Such a budget restrains travelers from taking the cheapest, yet slowest, transport mode to satisfy their transport demand, especially for long-distance travel. Although travel time budget remains constant on average, it may be higher in congested cities where waiting times are prolonged and average speeds low. Furthermore, poorer cities may have sparse transport modes, resulting in a greater travel time budget. On average, travelers in the Middle East have a travel time budget of 0.45 hours/person/day (Schäfer and Victor, 2000).

Consumers also spend a fixed proportion of their income for traveling, known as travel money budget (Zahavi and Talvitie, 1980). Travelers satisfy their transport demand by spending their money budgets on fuel, maintenance and fares. It is found that the global travel money budget ranges from 7.9 percent to 9 percent of per-capita gross domestic product (GDP), despite the changes in fuel prices and economic recessions (Schäfer and Victor, 2000).

The transport monetary cost and fuel economy

The transport monetary cost is defined as the cost of transport incurred by a passenger and it varies with the transport mode and technology. This cost includes not only fuel and maintenance costs of a private transport mode, but also the fare of a public transport mode. While fuel costs remain constant across all regions in Saudi Arabia, the use of fuels to satisfy transport demand in a specific region may vary because of different congestion levels.

Congestion levels can change the average vehicle speed, which will impact fuel efficiency. For example, road transport modes in the western region, which is typically more congested, may suffer from lower fuel economy than the south, which is not as congested. Therefore, the transport model has an endogenous fuel economy that varies with transport mode, technology, demand type, geographical region and average speed. This can enhance the interactions between agents who have different income levels. For instance, while high-income households may choose to travel by light-duty vehicles and consequently increase congestion levels, low-income households may not be able to afford such a large quantity of fuel and thus perceive other transport modes as more attractive.

Consumers' behavior

Our model also considers the impact of intangibles on fuel consumption. Girod et al. (2013) illustrate the role of personal and societal preferences toward transport modes and the luxury level chosen by travelers. For example, consumers in some countries may have the tendency to drive, even when roads are congested and other reliable and fast transport modes are available. We assume that a preference factor of a transport mode may change with the cost of travel.

The transport model also considers the costs associated with a traveler's perception of experiencing a crash by a transport mode. For example, by accounting for pain, grief, lost quality of life and the probability of encountering such experiences in the future (Litman, 2009). Although there are internal and external crash risks, only the internal crash risk was considered because it can have a direct impact on a consumer's decision-making process.

Results and Discussion

Own-price demand elasticity

Own-price elasticities of gasoline demand vary with gasoline price changes as shown in Figure 3. This analysis finds that the magnitude of the overall transport demand elasticity increases with rising transport cost.

The increase in gasoline price, combined with a high value of time and low efficiency caused by massive congestions, can curb demand for gasoline, which causes the sudden drop as shown in Figure 3. As the price of gasoline increases so does the cost of overall transport and consumers' willingness to reduce their overall transport demand grows. Such a reduction in the overall transport demand can alleviate congestion levels, which in turn reduces the value of time. Furthermore, lower congestion levels mean the average efficiency of light-duty vehicles increases, which can lead to a reduction in gasoline demand but with a much moderated slope.

Other transport modes become more attractive as the change in gasoline price rises beyond 250 percent. This is not only because gasoline is now more expensive, but also because of the higher average speeds at which buses can now be driven. This shift in transport demand from light-duty vehicles to other modes results in the steeper downward slope shown in Figure 3.

In general, gasoline demand in Saudi Arabia is found to be price inelastic due to the lack of fuel and modal substitutes. Even when gasoline price increases – causing the overall transport demand to decrease – consumers still have the tendency to

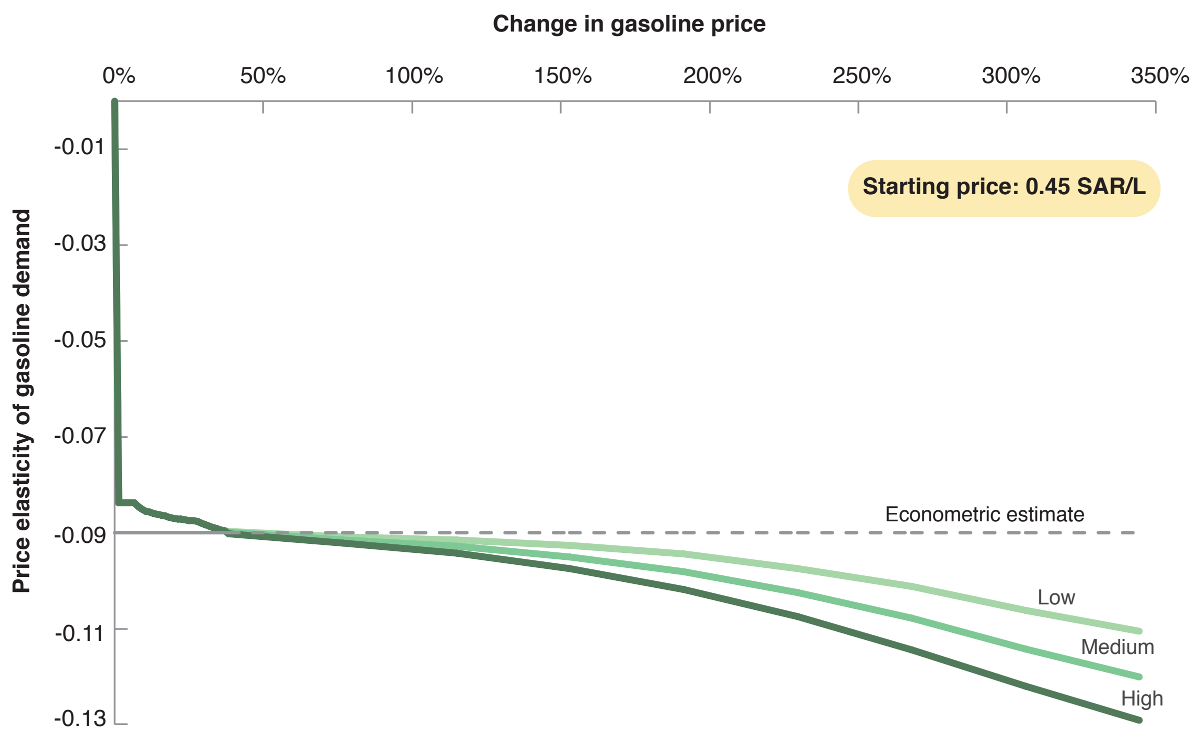

Figure 3. Own-price elasticity of gasoline demand in Saudi Arabia. Low, medium and high indicators represent the level of overall transport demand responsiveness to price changes.

Source: KAPSARC analysis.

satisfy their transport demand by using gasoline. Especially for intra-city commutes, where buses either do not exist or have a limited capacity combined with a long waiting time, lower comfort conditions and average speed.

A previous empirical study for Saudi Arabia reported an average long-run gasoline price elasticity of -0.09 (Dahl, 2012). Figure 3 also shows that consumers' response to a change in gasoline price is not constant. The elasticity is found to be aligned with the empirical estimate when the price change is within the historical boundaries and below the estimate when the price change is large. If Saudi Arabia had a diverse transport system comprised of more modes, the consumers' response may be more pronounced. Currently Saudi Arabia does not have urban train systems, and only has inter-city trains linking the eastern and central regions. If consumers had more options, they may switch to different modes of travel.

Since 1980, gasoline prices in Saudi Arabia have ranged between 0.22 and 0.90 SAR per liter. A real price change within the maximum value would correspond to the empirical estimate. If the price is raised above 0.90 SAR per liter, however, the empirical estimate would underestimate the response.

Cross-price elasticity

Figure 4 shows cross-price elasticities of diesel and jet-fuel demand that vary with the responsiveness of overall transport demand to price changes. As the gasoline price increases, consumers tend to

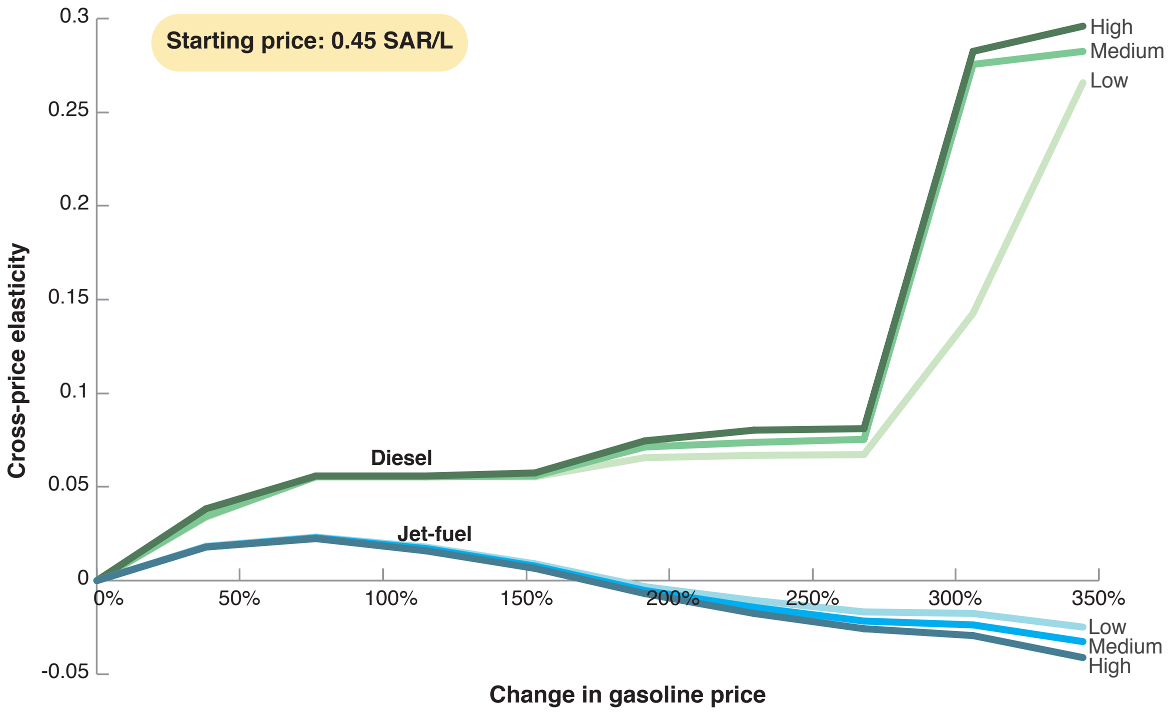

Figure 4. Cross-price elasticities of diesel and jet-fuel demands in Saudi Arabia. Low, medium and high indicators represent the level of overall transport demand responsiveness to price changes.

Source: KAPSARC analysis.

shift to buses, especially for long-distance domestic travel. However, this shift is not significant following a small increase in the price of gasoline because congestion levels are relatively high, which in turn may maintain the high value of time. Once the rise in gasoline price is beyond 250 percent, combined with the alleviated congestion levels as a result of the reduction in the overall transport demand, buses become far more attractive. This is represented in Figure 4 by the steep upward slope.

Jet-fuel demand for domestic travel remains constant, despite an increase in gasoline price. This is explained by high domestic demand for airplanes and limited capacity even before the increase in gasoline price since such a transport mode has the lowest time cost in comparison to other modes. Internationally, however, airplanes have higher fare costs and thus an increase in gasoline price can limit consumers' total travel money budgets, resulting in a limited shift to buses for nearby destinations. This will enable them to cope with the high gasoline prices, especially for intra-city commutes, where buses are not an attractive option. Figure 4 shows that the cross-price jet-fuel demand elasticities are close to zero and therefore indicates that the demand for jet-fuel has a negligible response to changes in gasoline price.

The implications of cross-price elasticity

Past econometric techniques may have estimated cross-price elasticity for diesel demand using its own price series. However, fare costs, which consumers directly face when they choose to travel by public transport, are sometimes administered and may not necessarily be impacted by an increase in the diesel price. Therefore, this methodology, which only takes into account what a consumer perceives when making a decision (e.g., fare costs, waiting time and average speed), can generate representative cross-price elasticities (Figure 4).

Conclusion

Empirical methods, which depend on historical fuel consumption and prices, have been heavily utilized to estimate price elasticity for transport fuels. In applying such estimates, policy analysts often make the simplifying assumption that consumers' responsiveness to fuel price change is constant. The response to a price movement can, however, vary according to the magnitude of that change; a consumer may react more readily when the change is substantial. Therefore, we developed a methodology that uses an optimization-based model to simulate a consumer's decision-making process. It considers the flexibility of substituting fuels and modes, income and monetary budget, value of time and consumer's behavior and magnitude of change from initial price.

Accordingly, we assess the potential impact of gasoline price change on transport demand and fuel consumption in Saudi Arabia. Different response levels in the overall transport demand were used to illustrate the drop in consumers' transport demand with the changing cost of transport. A consumers' ability to shift to other transport modes and fuels was also considered.

Our analysis shows that gasoline demand in Saudi Arabia is price inelastic due to the lack of fuel and modal substitutes. The results also find that previous empirical estimate is in line when the price change is within historical variations, and may slightly underestimate the response when the price change is large. If this methodology is applied to regions that have more diverse transportation systems, the response may deviate more drastically from the empirical estimates for that region.

We also showed that cross-price elasticities of other fuels are unlikely to be constant when the price of gasoline rises. Consumers will probably shift toward diesel more rapidly as the change in gasoline price increases. Moreover, consumers in Saudi Arabia will probably have a higher tendency of satisfying their domestic long-distance travel demand using buses if the change in gasoline price grows significantly. On the other hand, consumers may prefer to satisfy their intra-city travel by light-duty vehicle, even as the change in gasoline price increases, because of the limited capacity of urban buses, long waiting time, low comfort conditions and the scarcity of other transport modes (e.g., metro). One possibility is that consumers may slightly reduce their international transport budget with the occasional switch to buses for nearby destinations instead of airplane; this would help boost their travel budgets to satisfy their intra-city transport demand by light-duty vehicle.

Finally, our methodology can support governments make effective transport policies, especially when historical fuel prices and consumption are not readily available, or when they want to test policies that fall well outside historical price variations. It can also provide insights into how consumers may react to a significant change in fuel prices. For example, consumers may redistribute their transport money budget between demand types in order to satisfy their overall transport demand. As part of future work, this transport model will be integrated into the KAPSARC Energy Model for Saudi Arabia.

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Appendix A : Model Calibration

According to Schäfer and Victor (2000) the travel money budget should be constant, in spite of the change in fuel prices or economic recession, where each person has a travel money budget between 7.9 percent and 9 percent of income (GDP/Cap). Therefore, this paper estimates the travel money budget limit for Saudi Arabia to be around 8.5 percent of income. Thereafter, such a budget is distributed between regions and household types based on their transport budget shares and population published by General Authority for Statistics (GASTAT) (2013).

Gasoline consumption in 2013 from the Saudi Arabian Monetary Agency (SAMA) (2015) was used to calculate the total transport demand by light-duty vehicles in passenger km using energy intensity. The energy intensity was calculated for Saudi Arabia based on the load factor and average efficiency for light-duty vehicles published by International Energy Agency (IEA) (2009) and Alabbadi (2012). The total transport demand for light-duty vehicles is distributed between short- and long-distance travel based on the shares of urban and non-urban travel (IEA 2009). Thereafter, the short- and long-transport demands is distributed between geographical regions and household types based on the transport budget shares published by GASTAT (2013). Figure A.1 shows the calculated gasoline consumption by the model, and it has been calibrated to the actual consumption in 2013 published by SAMA (2015).

The total transport demand for buses, airplanes and trains in passenger km were obtained from Saudi Arabia Public Transport Company (SAPTCO) (2015), International Civil Aviation Organization (2013) and GASTAT (2014), respectively. They were then distributed between geographical regions and household types based on their respective transport budget shares published by GASTAT (2013).

Bus, air and train fare prices were obtained from SAPTCO (2015), Saudia (2015) and Saudi Railways Organization (SRO) (2015), respectively.

The operation and maintenance cost for gasoline-powered cars was obtained from Krishnan et al. (2015). Bus, airplane and train domestic capacities were obtained from Al-Ohaly (2015), Saudia (2013), Flynas (2015) and SRO (2015), respectively. Bus international capacity was obtained from the annual report published by SAPTCO (2015), and evenly distributed between geographic regions. Inter-, intra-regional and international distances were obtained from the Statistical Yearbook published by GASTAT (2014). The full set of data used for each mode is shown by Table A.1.

Following Litman (2009), the value of time for domestic travel was assumed to be 25 percent of the hourly wage rate of each household. While for international travel, it was assumed to be 75 percent of the hourly wage rate of each household (Belenky 2011). The average wage rates of Saudi and non-Saudi households were obtained from the Ministry of Labor (2013), and the number of working hours per week obtained from GASTAT (2013).

Congestion levels for each region and demand type may influence vehicle speeds. Congestion levels were estimated following the work of Greenshields et al. (1935). The length of paved roads is required to estimate the traffic density and this was obtained from Ministry of Municipal and Rural Affairs (2013). Annual km per light-duty vehicle and annual km per bus were obtained from IEA (2009) and SAPTCO (2015), respectively, to estimate the total number of vehicles for each region and demand type. The passengers' delay time requires the total airport capacity in passenger-km that was estimated using arrival delay data (FlightStats, 2013).

The preference factor of each transport mode was reported by Girod et al. (2013). The total internal crash risk for Saudi Arabia was obtained from Jacobs et al. (2000). Then, the methodology used by Litman (2009) was followed to estimate the crash risk for each road-transport mode.

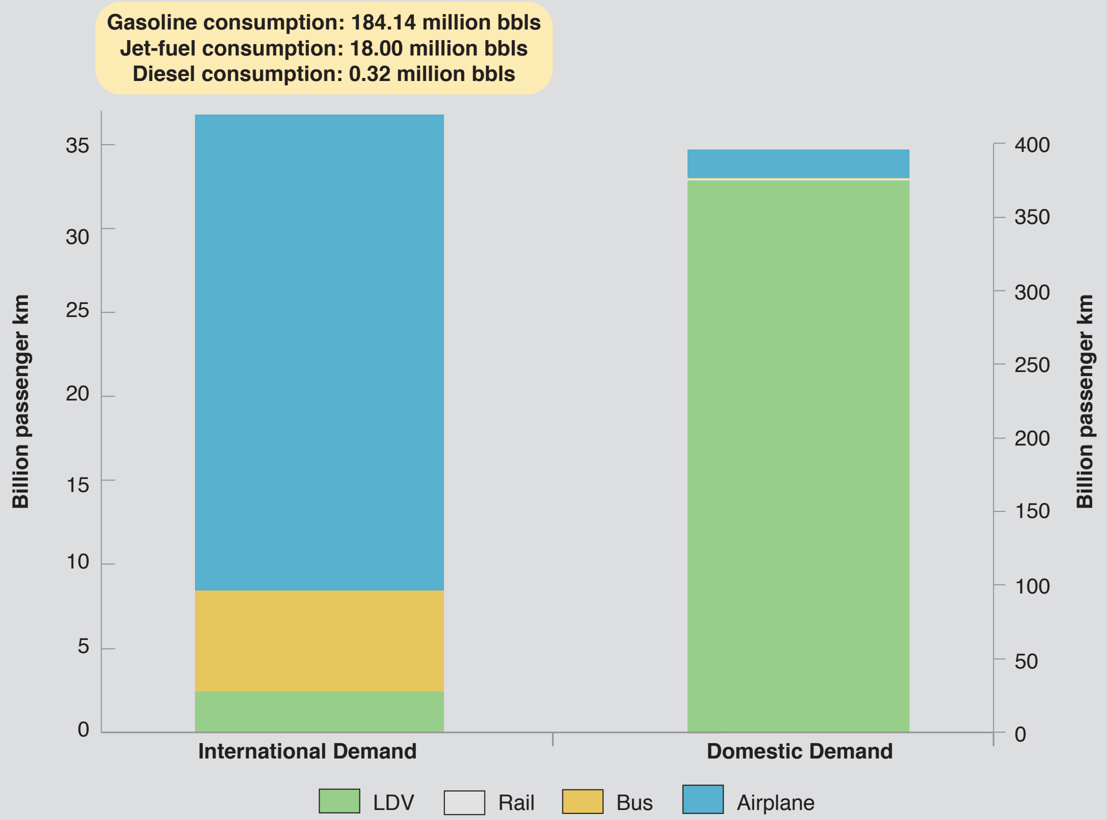

Figure A.1 Total demand by transport by mode and type in the calibration year.

Source: KAPSARC analysis.

Table A.1 Transport modes in the model and their fuel use, occupancy, operational cost, free-flow speed and waiting time.

Transport mode	Fuel use (L/vehicle-km)	Occupancy (passengers / vehicle)	Operation & maintenance cost (USD/ vehicle-km)	Free-flow speed (km/hr)	Waiting time (hr)
Gasoline-powered car	Endogenous	1.6	0.0975	60 (long-distance); 41 (short-distance)	-
Diesel locomotive (Long-distance)	1.25	298	-	100	1
Bus (Long- and short-distance)	Endogenous	35 (long-distance); 25 (short-distance)	-	50 (long-distance); 35 (short-distance)	1
Airplane	12.12	200	-	1000	Endogenous

Source: Bigazzi and Kelly (2015), Srivastava et al. (2006), Aircraft Commerce (2005), IEA (2009), and Krishnan et al. (2015).

Appendix B: Parameters and Variables

Sets	
TPd	types of travel demand.
TPo and TPoo	travel options.
TPe	fuel used for transportation.
HH	type of households.
r and rr	regions.

Parameters and variables	
Valueoftime:	value of time in USD per passenger hour.
TPAPe(TPe,time,r)	administered energy price in USD per L or kWh.
TPbudget(HH,time,r)	household budget for transportation in million USD for all households per year.
Efficiency(TPo,TPe,TPd)	Fuel use in million L per million km traveled.
LoadFactor(TPo,TPd)	occupancy in passenger per vehicle.
TPomcst(TPo,TPd)	non-fuel operations and fare cost in USD per vehicle km.
TPdomfarecst(TPo,TPd,r,rr)	fare costs for public transport domestically in USD per passenger per trip.
TPintlfarecst(TPo,TPd,r)	fare costs for international public transport in USD per passenger per trip.
uf(TPo,TPd,time)	free-flow speed for transport modes in km per hour.
TPwaittime(TPo)	waiting time in hours per trip for transport modes (zero for private transport options).
TPdemvaldom (HH,TPd,time,r,rr)	regional demand for domestic transportation service in million passenger km per year.
TPdemvalintl (HH,TPd,time,r)	regional demand for international transportation service in million passenger km per year.
TPexistcap (TPo,TPe,TPd,r,rr)	existing capacity of transport modes in million passenger km per year.
TPRFconv(TPe)	conversion factor from million L to million metric tons.
TPdistanceintl(r)	distance between departure region and international destination in km.
TPdistancedom(TPd,r,rr)	distance between domestic regional nodes in km.

alpha0(TPo,TPe,TPd)	fitted parameter for the endogenous efficiency equation.
kj(TPo)	length of the vehicle in km per vehicle.
annualkm(TPo)	annual km driven per vehicle per year.
paved(TPd,r,rr)	length in km of paved roads within and between regions.
pavedint(r)	length in km of international paved roads.
capairport(t)	capacity of Saudi airports in 2013 in million PKM.
crash(TPo)	crash cost in USD per VKM by transport mode.
Totperceivedcost	total perceived cost as the sum of monetary, time costs and intangible aspects.
TPdomtravel(TPo,TPd,TPe,HH,t,r,rr)	total demand for domestic travel in million PKM.
TPintltravel(TPo,TPd,TPe,HH,t,r)	total demand for international travel in million PKM.
TPexistcp(TPo,TPe,TPd,t,r,rr)	existing domestic capacity for various transport modes.
TPopandmaint(t)	total maintenance costs incurred by households.
TPtimeinvest(TPo,TPd,t,r,rr)	travel time investment costs incurred by households.
TPeconsump(TPe,TPo,HH,t,r)	amount of energy used by HH in each region in million units of energy.
TPtimecst(t)	time cost for travel by different modes.
TPk(TPo,TPd,t,r,rr)	domestic traffic density in vehicle per km.
TPuac(TPo,TPd,t,r,rr)	corrected domestic average speed in km per hr.
TPuacint(TPo,TPd,t,r)	corrected international average speed in km per hr.
TPtotdom(t)	total domestic demand for air only in million pkm.
TPtotint(t)	total international demand for air only in million pkm.
TPdelayair(t)	fraction of the exogenous waiting time caused by air traffic.
TPeffdom(TPo,TPe,TPd,t,r,rr)	domestic efficiency in units of L per km.
TPeffint(TPo,TPe,TPd,t,r)	international efficiency in units of L per km.
TPkint(TPo,TPd,t,r)	international traffic density in vehicle per km.
TPcrash(t)	crash risk perceived by consumers in USD.

Appendix C: Equations and Constraints

The model was solved using PATHNLP. The solver linearizes the non-linear terms in the equations then solves the model. We also manually linearized the equations and ran a linear version of the model, which produced almost exactly the same result we obtained from the non-linear version.

Following Daly et al. (2014) and Krishnan et al. (2015), the objective is to minimize total cost perceived by household (units in million USD):

Note: Only energy directly purchased by households appears in the cost function to be minimized.

$$\min Perceived\ Total\ Cost = \sum_{t}(TPtimecst_t + TPopandmaint_t + TPcrash_t) + \sum_{(TPe,TPo,t,HH,r)} TPeconsump_{TPe,TPo,HH,t,r} TPAPe_{TPe,t,r}$$

This equation calculates the domestic door-to-door speed after taking into account the congestion effect (units in km/hr):

Note: Only for light-duty vehicles and buses.

$$TPuac_{TPo,TPd,t,r,rr} = uf_{TPo,Tpd,t} \times \left(1 - \left(\sum_{TPoo} kj_{Tpoo} * TPk_{TPoo,TPd,t,r,rr}\right)\right)$$

This equation calculates the domestic traffic density (units in vehicle/km):

Note: Only for light-duty vehicles and buses.

$$TPk_{TPo,TPd,t,r,rr} = \sum_{(TPe,HH)} \frac{TPdomtravel_{TPo,Tpd,TPe,HH,t,r,rr} \times 10^6}{LoadFactor_{TPo,TPd} \times annualkm_{TPo} \times paved_{TPd,r,rr}}$$

This equation calculates the international door-to-door speed after taking into account the congestion effect (units in km/hr):

Note: Only for light-duty vehicles and buses.

$$TPuacint_{TPo,TPdL,t,r} = uf_{TPo,TpdL,t} \times \left(1 - \left(\sum_{TPoo} kj_{Tpoo} * TPkint_{TPoo,TPdL,t,r}\right)\right)$$

This equation calculates the international traffic density (units in vehicle/km):

Note: Only for light-duty vehicles and buses.

$$TPkint_{TPo,TPd,t,r} = \sum_{(TPe,HH)} \frac{TPdomtravel_{TPo,Tpd,TPe,HH,t,r} \times 10^6}{LoadFactor_{TPo,TPd} \times annualkm_{TPo} \times paved_r}$$

This equation calculates the fraction of the exogenous waiting time caused by air traffic:

Note: This fraction is multiplied by the exogenous waiting time, in the *T P timebudget* and *T P timecst$_t$* equations, to calculate the total added waiting time caused by air traffic.

$$TPdelayair_t = \frac{1}{2} \times \left[\frac{\frac{TPtotdom_t + TPtotint_t}{capairport_t}}{1 - \frac{TPtotdom_t + TPtotint_t}{capairport_t}} \right]$$

This equation sums all the domestic travel demand by air (units in PKM):

$$TPtotdom_t = \sum_{TPo,TPdL,TPe,HH,r,rr} TPdomtravel_{TPair,TPdL,TPe,HH,t,r,rr}$$

This equation sums all the international travel demand by air (units in PKM):

$$TPtotint_t = \sum_{TPo,TPdL,TPe,HH,r} TPinttravel_{TPair,TPdL,TPe,HH,t,r}$$

This equation calculates the domestic fuel economy (units in L/km):

Note: The first term is applicable for light-duty vehicles and the second term is applicable for buses.

$$TPeffdom_{TPo,TPe,TPd,t,r,rr} = \sum_{TPo,TPe,TPd,t,r,rr} \left\{ \left[\left[\frac{1}{0.43 \times \sum_{i=0}^{i4} \exp\left\{ alpha_{TPo,TPe,TPd_i} \times \left[\frac{TPuac_{TPo,TPd,t,r,rr}}{1.6} \right]^i \right\}} \right] \right] + \left[\left[\frac{1}{0.43 \times \left\{ -0.003 \times \left[\frac{TPuac_{TPo,TPd,t,r,rr}}{1.6} \right]^2 + \frac{0.214 \times \left[TPuac_{TPo,TPd,t,r,rr} \right]}{1.6} + 0.972 \right\}} \right] \right] \right\}$$

This equation calculates the international fuel economy (units in L/km):

Note: The first term is applicable for light-duty vehicles and the second term is applicable for buses.

$$TPeffint_{TPo,TPe,TPdL,t,r} = \sum_{TPo,TPe,TPdL,t,r} \left\{ \left[\left[\frac{1}{0.43\times \sum_{i=0}^{i4} \exp\left\{ alpha_{TPo,TPe,TPdL_i} \times \left[\frac{TPuacint_{TPo,TPdL,t,r}}{1.6}\right]^{i} \right\}} \right] \right] + \left[\left[\frac{1}{0.43\times \left\{ -0.003\times \left[\frac{TPuacint_{TPo,TPdL,t,r}}{1.6}\right]^{2} + \frac{0.214\times\left[TPuacint_{TPo,TPdL,t,r}\right]}{1.6} + 0.972 \right\}} \right] \right] \right\}$$

This equation sums the crash risks imposed by transport mode (units in USD):

$$TPcrash_t = \sum_{TPo,TPd,TPe,HH,r} \left\{ \frac{TPintltravel_{TPo,TPd,TPe,HH,t,r} \times crash(TPo)}{LoadFactor_{TPo,TPd}} + \sum_{rr} \left[\frac{TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr} \times crash(TPo)}{LoadFactor_{TPo,TPd}} \right] \right\}$$

This equation sums all the operational costs associated with transport modes (units in million USD per year):

Note: *TPintltravel* $_{\mathrm{TPo,TPd,TPf,HH,t,r}}$ is only for long-distance travel.

$$\begin{aligned} TPopandmaint_t &= \sum_{TPo}\sum_{TPe}\sum_{TPd}\sum_{HH} \left[TPomcst_{TPo,TPd} \sum_{r} \left(TPintltravel_{TPo,TPd,TPe,HH,t,r} + \sum_{rr} TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr} \right) \right] \\ &+ \sum_{TPo}\sum_{TPe}\sum_{TPd}\sum_{HH} \left(\sum_{r}\sum_{rr} \frac{TPdomfarecst_{TPo,TPd,r,rr}}{TPdistancedom_{TPd,r,rr}} TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr} \right) \\ &+ \sum_{TPo}\sum_{TPe}\sum_{TPd}\sum_{HH} \left(\sum_{r} \frac{TPintlfarecst_{TPo,TPd,r}}{TPdistanceintl_{TPd,r}} TPintltravel_{TPo,TPd,TPe,HH,t,r} \right) \end{aligned}$$

This equation calculates the cost attributed to waiting and commute times (units in million USD per year):

Note: $TPdelayair_t$ is only applicable to airplanes.

$$TPtimecst_t = \left\{ \sum_{TPd} \sum_{TPo} \sum_{r} \sum_{rr} \sum_{HH} Valueoftime_{HH} \times TPtimeinvest_{TPo,TPd,HHt,r,rr} \right.$$
$$+ \sum_{TPo} \sum_{TPd} \sum_{HH} \sum_{TPe} Valueoftime_{HH} \left(\sum_{r} \left[\frac{\sum_{rr} TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr}}{LoadFactor_{TPo,TPd}} \right. \right.$$
$$\left. \cdot \left(\frac{1}{TPuac_{TPo,TPd,t,r,rr}} + \frac{TPwaittime_{TPo} \times (1 + [TPdelayair_t])}{TPdistancedom_{TPd,r,rr}} \right) \right]$$
$$+ \sum_{r} \left[\frac{TPintltravel_{TPo,TPd,TPe,HH,t,r}}{LoadFactor_{TPo,TPd}} \right.$$
$$\left. \left. \left. \cdot \left(\frac{1}{TPuacint_{TPo,TPd,t,r}} + \frac{TPwaittime_{TPo} \times (1 + [TPdelayair_t])}{TPdistanceintl_{TPd,r}} \right) \right] \right) \right\}$$

This constraint imposes a monetary budget limit for transportation services (units in million USD per year):

Note: Only energy and operational costs directly incurred by households appears in the monetary budget constraint.

$$\sum_{TPo} \sum_{TPe} \sum_{TPd} \left[TPomcst_{TPo,TPd} \left(TPintltravel_{TPo,TPd,TPe,HH,t,r} + \sum_{rr} TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr} \right) \right]$$
$$+ \sum_{TPo} \sum_{TPe} \sum_{TPd} \sum_{rr} \frac{TPdomfarecst_{TPo,TPd,r,rr}}{TPdistancedom_{TPd,r,rr}} TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr}$$
$$+ \sum_{TPo} \sum_{TPe} \sum_{TPd} \frac{TPintlfarecst_{TPo,TPd,r}}{TPdistanceintl_{TPd,r}} TPintltravel_{TPo,TPd,TPe,HH,t,r}$$
$$+ \sum_{TPe} TPeconsump_{TPe,TPo,HH,t,r} TPAPe_{TPe,t,r} \leq TPbudget_{HH,t,r}$$

This constraint calculates how much energy is used for passenger transport (units in GWh or million L per year):

Note: TPeffdom only applies to private or bus transport modes. Efficiency only applies to air and rail transport.

$$TPeconsump_{TPe,TPo,HH,t,r}$$
$$- \sum_{TPd} \left(\sum_{rr} \left(TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr} \right. \right.$$
$$\left. * \frac{(TPeffdom_{TPo,Tpe,Tpd,t,r,rr} + Efficiency_{TPo,Tpe,Tpd})}{LoadFactor_{TPo,TPd}} \right) + TPintltravel_{TPo,TPd,TPe,HH,t,r}$$
$$\left. * \frac{(TPeffint_{TPo,Tpe,Tpd,t,r} + Efficiency_{TPo,Tpe,Tpd})}{LoadFactor_{TPo,TPd}} \right) = 0$$

This constraint ensures demand for domestic travel is satisfied (units in million passenger-km per year):

$$\sum_{TPo}\sum_{TPe} TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr} \geq TPdemvaldom_{HH,TPd,t,r,rr}$$

This constraint ensures demand for international travel originating domestically is satisfied (units in million passenger-km per year):

$$\sum_{TPo}\sum_{TPe} TPintltravel_{TPo,TPd,TPe,HH,t,r} \geq TPdemvalintl_{HH,TPd,t,r}$$

The two constraints below are used to impose modal capacity restrictions for domestic and international travel, respectively (units in million passenger-km per year):

For example, rail capacity is only available between two regions, and airplane seat capacity is limited.

Note: The capacity is indexed by fuel to allow for distinct electricity-powered or diesel-powered rail capacities.

$$TPexistcp_{TPo,TPe,TPd,t,r,rr} - \sum_{HH} TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr} \geq 0$$

$$-\sum_{HH} TPintltravel_{TPo,TPd,TPe,HH,t,r} \geq -TPexistintlup_{TPo,TPe,t,r}$$

This constraint imposes a time budget limit for passengers (units in million hours per year):

Note: The time budget is restricted to time spent in motorized transport modes, as discussed by Schäfer and Victor (2000). $TPdelayair_t$ is only applicable to airplanes.

$$\sum_{TPo}\sum_{TPd}\sum_{HH}\sum_{TPe}\left(\sum_{r}\left(\sum_{rr}\frac{TPdomtravel_{TPo,TPd,TPe,HH,t,r,rr}}{LoadFactor_{TPo,TPd}} \cdot\left(\frac{1}{TPuac_{TPo,TPd,t,r,rr}}+\frac{TPwaittime_{TPo}\times(1+[TPdelayair_t])}{TPdistancedom_{TPd,r,rr}}\right)\right) + \frac{TPintltravel_{TPo,TPd,TPe,HH,t,r}}{LoadFactor_{TPo,TPd}} \cdot\left(\frac{1}{TPuacint_{TPo,TPd,t,r}}+\frac{TPwaittime_{TPo}\times(1+[TPdelayair_t])}{TPdistanceintl_{TPd,r}}\right)\right) - \sum_{TPo}\sum_{TPd}\sum_{r}\sum_{rr}\sum_{HH} TPtimeinvest_{TPo,TPd,HH,t,r,rr} \leq TPtimebudget$$

Notes

Notes

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About the Project

We developed the KAPSARC Energy Model for Saudi Arabia (KEM-SA) to understand the dynamics of the country's energy system. It is a partial equilibrium model formulated as a mixed complementarity problem to capture the administered prices that permeate the local economy. KEM-SA has been previously used to study the impacts of various industrial fuel pricing policies and improved residential efficiency on the energy economy. The passenger transportation model presented in this paper helps understand more of the end-use energy demand, and it is being integrated into KEM-SA.

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