Urban transport energy demand model for Riyadh: methodology and a preliminary analysis

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ABSTRACT

Saudi Arabia intends to reduce GHG emissions by 278 million tons of CO₂eq annually by 2030 through Nationally Determined Contribution (NDC) to UNFCCC. Among many policies, mass transit system and transit-oriented development are being developed with the expectation to reduce energy consumption and GHG emissions in Riyadh. To what extent such initiative can reduce energy consumption and GHG emission is an important question. In this paper, a methodology to systematically measure the impact of mass transit and transit-oriented development in Riyadh city on the energy demand has been developed. For Riyadh, a comprehensive travel demand model considering the impact of mass transit and transit-oriented development is still missing. To this end, this paper aims to fill the gap. This methodology considers the state-of-the-art in travel demand analysis and the local context by combining traditional four-step model and activity-based model for modal-shift. This paper describes the methodology and its application for Riyadh by analyzing modal-shift only between car and metro. The results suggest that metro can reduce energy consumption, but the reduction varies with varying accessibility, car, and metro situations. At high urban density and higher car travel cost, we may achieve as high as 13% reduction in fuel demand.

1. Introduction

Transport is a high energy-demanding sector and a significant contributor to greenhouse gas (GHG) emissions. The transport sector in GCC countries\(^1\) emitted around 220 Mt CO₂ in 2019, which was about 19% of total carbon emission from this region (Crippa et al., 2020). According to Emissions Database for Global Atmospheric Research (EDGAR; Crippa et al., 2020), Saudi Arabia’s transport sector contributed about 22% of country’s overall emissions; similarly, UAE and Oman contributed 18% each, respectively. EDGAR also suggested that carbon emission from transport sector is increasing at a faster rate in GCC countries than the world. From 2005 to 2019, the increase in carbon emission in transport sector is remarkably high in some GCC countries, for example, Oman (+366%) and Qatar (+268%). While we are expecting to decrease overall carbon emission, carbon
emissions from other GCC countries also continued to increase significantly from 2005 to 2019 – Bahrain (+47%); Kuwait (+34%); KSA (+77%); and UAE (+72%; Crippa et al., 2020). Although the emission trend in the transport sector is still upward, there is a sign of slowing down in Kuwait, UAE, and KSA in recent years. Remarkable efforts to create an energy-efficient transport system, including investment in public transport as well as oil demand management after the Paris Agreement in 2015, might have led to such changes.

Saudi Arabia is committed to the Paris Agreement. Saudi Arabia’s intends to reduce GHG emissions by 278 million tons of CO₂eq annually by 2030 through Nationally Determined Contribution (NDC) to UNFCCC. The NDC also includes promotion for mass transport systems in Saudi cities. Saudi Arabia is developing a city-wide metro system in Riyadh and intends to execute similar projects in Jeddah and Dammam along with the improvement in building energy efficiency (Government Of Saudi Arabia, 2015). Per capita energy consumption is much lower for public transport than private vehicles (Kenworthy, 2018; Kenworthy et al., 2020). Kenworthy (Kenworthy et al., 2020) reported that per capita energy consumption by private vehicle is over ten times more than that used by public transport in Swedish cities as well as in general European cities. This difference can go as high as 55 times in US cities.

According to Saudi Energy Efficiency Center, the energy consumption from Kingdom’s transport sector was around 21% in 2017, which is largely based on fossil fuel. The estimated number of vehicles within KSA is expected to reach 26 million, and daily consumption of gasoline and diesel will be around 1.86 million barrels by 2030 (Amarnath & henaki, 2019). With the expectation to reduce energy consumption and carbon emissions, the Riyadh metro system is being developed as the first major initiative to combat transportation-related emissions and climate change. According to Riyadh Metro (Riyadh Metro, 2020), this initiative is expected to reduce daily car trips by 250,000 per day. To achieve its goal, Riyadh is also implementing a bus network including Bus Rapid Transit (BRT) and other feeder and community buses in several corridors and transforming the urban context via transit-oriented development.

However, we need to understand the travel demand in a multi-modal transport system, where both private and public transports are operational instead of only private vehicles, to measure the expected outcome and to assess the achievement. Transport planners have been developing different models to understand the impact of urban transport development on the economy, society, and environment. These travel demand models work as policy analysis tools and support decision-makers in making informed decisions regarding transport planning and development. For Riyadh, a comprehensive travel demand model considering the impact of mass transit and transit-oriented development is still missing. To this end, this paper aims to fill the gap. In this paper, we develop a methodology to systematically measure the impact of mass transit and transit-oriented development in Riyadh city on the energy demand. The methodology considers the state-of-the-art in travel demand analysis and the local context. We elaborate the methodology through a preliminary analysis and result.
2. Background literature

Two main approaches in travel demand modelling and forecasting are the traditional four-step travel demand model and the activity-based model (shan et al., 2012). The majority of transport planning authorities apply four-step models. Even though activity-based models look at travel demand in detail from individual and/or household perspectives (see, e.g. Bowman & Ben-Akiva, 2001; Shiftan & Suhrbier, 2002). As a result, activity-based models help to make better informed decisions and to assess policy initiatives.

The activity-based models are more advanced than the traditional four-step models in different ways. In four-step models, disaggregate spatial information is lost, and trip characteristics are more important than activity characteristics (Mcnally, 1996). For example, the four-step models do not give spatial direction in terms of where transport policies should focus (Agrawal et al., 2018). Often, four-step models are insensitive to transit accessibility; demographic and spatial characteristics are considered uniform or constant over the Traffic Analysis Zones (TAZ); destination choices are based on trip characteristics without considering that all locations are not considered by all individuals; and mode choices are also limited to motorized vehicles (Mladenovic & Trifunovic, 2014).

Yet, the travel demand models are dominated by four-step models (Mcnally, 2007). Many cities, regions, and countries are still applying this model on their daily transport scenario analyses (e.g. (Apronti & Ksaibati, 2018; Winters et al., 2010)), both in the developed and developing world. The main reason is that the application of this model is universal and well developed. Many softwares have been developed that can be easily applied in a different context, and some may accommodate more flexibility than others to account for local needs.

As activity-based demand models are complex, these models pose a challenge in terms of data requirements. It is very context dependent, and hence, universal application is very difficult. Very few platforms are available that can accommodate different contextual aspects. Often, these models require developing tailored model structures in each spatial, social, and economic context. Application of these models in a new context requires training, which in turn requires time and money. Transport authorities that are not using such models need to spend a significant amount of time and money initially to collect data, develop the model and employ relevant experts.

Often, a timely use and financially sustainable solution are important (Xiong & Zhang, 2013). Therefore, the traditional four-step model comes in handy. Several shortcomings can be addressed to accommodate the question in need. A common solution is that to develop hybrid versions of four-step models, that were based on the availability of the data, the four-step model is modified and updated (Boyce et al., 1994; Park et al., 2020; Xuesong et al., 2009).

One of the major challenges with a four-step model is that mode choices are based on trips characteristics and not behaviorally grounded (Barff et al., 1982). Such issues can be handled separately, and the model outcome of a traditional four-step model can be improved. In an attempt to produce a cost-effective and timely solution to such problem, the Washington State Department of Transportation added an intermediate step to generate mode choices from a travel behavior model and feed them back into the four-
step model (Winters et al., 2010). Similarly, the loss of spatial information can be introduced separately. Park et al. (2020) formulated a methodology to update intrazonal trips in a four-step model using built environment characteristics and a behavioral model.

In the case of Riyadh, a traditional four-step model is only recently applied, and advanced activity-based models are not available. Traditionally, transport energy demand in KSA was based on time-series analysis of vehicle stock at the regional and national level. It was based on the sectoral economic development at the national level, where economic data are analyzed to get energy production and consumption. However, a city-level assessment of the energy demand based on disaggregated data is missing in KSA. A microlevel intervention is required to achieve the climate change goals. A microlevel assessment tool is required to help in understanding social, geographical, economic, and demographic contexts that work in favor of or against energy consumption. Therefore, there is a need for developing a travel demand model to assess new developments and changes in policies.

For KSA, a travel demand model is important to understand the impact of different initiatives cities are taking. Riyadh city authorities and relevant organizations are developing a city-wide metro system and associated bus network as part of a mass transport system to combat the energy challenges. In December 2011, the Saudi cabinet approved all phases of a $22.5 billion public transport project. The new public transit system is expected to reduce 803 million car trips per year in the city of Riyadh. To facilitate the public transport development and use, the authority also planned to encourage transit-oriented development (TOD) around metro stations and bus stops. Private cars as travel mode choice have been predominant in Riyadh for a long time, which poses an additional challenge to public transport use. How people might react and what factors might encourage or discourage the use of public transport need to be assessed to measure the success of the proposed public transport network.

The success of the proposed metro system and bus network would depend on several factors. First, Riyadh being a car dominant city, the proposed public transport system must offer a competitive service compared to the private car in terms of affordability, safety, comfort, and convenience. Distance to destination, travel time and cost, and comfort are often found important determinants of mode choice (e.g. Frank et al., 2008; Rahman et al., 2020). Therefore, mode-specific characteristics such as the cost, travel time, waiting time, connection time, number of connections, and service in general of the metro and bus system must be assessed.

Second, the socio-demographic factor needs to be considered. Mode choice studies often find socio-demographic factors as a significant determinant of mode choice (Limtanakool et al., 2006). For Riyadh, Alqhatani et al. (2013) found age, income, gender, and nationality to be important factors in mode choice. Looking at the modal-shift intention to public transport in Hanoi city, Tuan (2015) found that the likelihood of modal-shift toward mass transit varied among different income groups and family structures. Hence, age, gender, income, job type, and household situation contribute to whether a person would use public transportation or not.
Finally, the transit system must be well accessible by users. People should be able to access their jobs, services, and daily necessities using the metro or bus. At the same time, metro and bus should be easily accessible from their homes. A well-planned urban structure is required to achieve a substantial number of public transport users. A high-density urban development is often suggested to increase accessibility and thereby encouraging mass transport use (Cervero & Kockelman, 1997). Therefore, urban planners often consider a modelling framework that accounts integration of land use and transportation (Waddell, 2002).

In this regard, this paper describes a methodology that accounts for socio-demographic development, accessibility improvement through TOD, and the influence of public transport development to assess the impact on energy demand. At present, there is no travel behavior data for Riyadh. Travel demand analysis is limited to 2 four-step model calibrations in 2005 and 2016. Therefore, we utilized the outcome of the traditional four-step model from 2016, which also projects the model for 2030. However, our methodology is developed to consider mode choice, vehicle choice, and accessibility factors in detail through a combination of aggregate and microlevel data so that socio-demographic, accessibility, and mode choice, including public transport, can be assessed. Therefore, this methodology can explicitly estimate the energy impact of both mass transit development and TOD.

3. Methodology

The methodology to assess the energy impact of public transport initiative and TOD on passenger transport in Riyadh is based on the combination of a four-step traffic model and discrete choice model for mode choice. The framework developed to analyze urban transport energy demand for Riyadh is shown in Figure 1. The principle of the analytical framework is to generate trip distribution based on demography, trip characteristics, and mode choices from the four-step model and then apply different factors or probabilities estimated from additional disaggregated models.

Figure 1 shows different energy demand situations – business-as-usual (BAU), and public transport impact on energy demand with or without implementation of TOD. BAU scenario is directly computable from the four-step model because the total number of trips and total vehicle kilometers traveled by current modes are already modelled and validated. A classic four-step model includes the following four steps (Fricker & Whitford, 2004; Papacostas, 1987) -

(i) Trip generation:

It calculates productions of a TAZ generally based on socio-demography of the household living in that zone; and attractions of a TAZ commonly based on nonresidential land use of that zone.

(ii) Trip distribution:
Based on certain cost factors and the calibration process, a model is developed to distribute the number of trips between TAZs. It generates an origin-destination matrix, where total trips originated in a TAZ is distributed in a number of probable TAZs in the model.

(iii) Modal split:

Based on the utilities of every operating travel mode within TAZs, the trips are distributed among the different modes.

(iv) Trip assignment:

Based on the generated O-D trip matrix and the transport network, the trips are assigned to the road network. This process utilizes different impedance/cost factors to identify low-cost routes for every pair of TAZ. The trip assignment also goes through a process of validation to match measured traffic flow within the network and further calibrated to get more accurate results over the network.

However, the total number of trips and total vehicle kilometers traveled by modes, including public transport cannot be validated. Therefore, analysis to understand the modal shift to public transport is added. The modal split in Riyadh’s four-step model only includes cars and taxis. More than 90% of the trips in Riyadh are made by cars/taxis. Although it is
possible to introduce a new public transport network and run the model to get a new modal split with public transport as an available mode, we cannot validate the model. Therefore, a mode choice model is essential to capture the willingness of the people of Riyadh to shift from car to the proposed public transport system, which is not yet operational.

In addition, public transport ridership largely depends on the accessibility to it. The four-step model is an aggregate model and accounts for aggregated accessibility at TAZ level. Accessibility analysis of the proposed public transport network is not a part of the existing four-step model and thus, is added as well. Accessibility analysis is done in two ways. At first, the current accessibility situation is determined through geographical analysis, which is explained next, and finally, accessibility at the proposed TOD situation is determined based on hypothetical scenario development.

Therefore, two separate analyses are performed to update the four-step travel demand model.

3.1. Accessibility analysis

Several researchers (Cervero, 2004; Cervero & Kockelman, 1997) suggested that transit-oriented-development (TOD) increases the chance of public transport use among the residents of TOD and is sometimes an essential catalyst for the success of a mass transit system. Among others, accessibility is the key component through which TOD affects transit ridership. How conveniently people can reach metro stations or bus stops from their origins and destinations will determine the likelihood of using public transport.

Accessibility to public transport network means access to public transport nodes such as metro stations or bus stops. Walk-time and drive-time to the stations/stops are considered as the accessibility to the public transport system. It is understood that several factors may influence accessibility to the stations/stops. Since public transport in Riyadh is currently under construction, it is difficult to consider other aspects of accessibility. For example, cycling facilities are proposed, but detailed characteristics of the proposal is not available.

Population accessibility to each metro station or bus stop was calculated using ArcGIS network analysis tool. This tool calculates reachable areas around metro stations or bus stops based on Riyadh’s street network for any specified travel times and modes. As mentioned earlier, we considered walk-time to calculate reachable areas around all metro and bus stations. A driving scenario was also considered, but only for the metro stations. The public transit network in Riyadh is expected to offer ‘Park and Ride’ spots for users to be able to arrive at the stations with their cars.

The definition for the levels of accessibility used in this paper is based on reachable areas by walking or driving within a certain time. The population within these reachable areas is then calculated as follows:

\[ N_{og} = D_{og} \times R \]  

where

- \( N \) = Number of people
- \( D \) = Number of residential dwellings
- \( o \) = Index for origin
- \( g \) = Index for levels of accessibility
\[
R = \text{Average occupancy rate per residential dwelling}
\]

The estimation is performed per TAZ basis and then aggregated to generate the total number of people living with a particular accessibility level from public transport, i.e. \( N_g = \sum_o N_{og} \). This eventually is used to generate accessibility factor as the proportion of the population for each level of accessibility

\[
\phi_g = \frac{N_g}{\sum_g N_g}
\]  

(2)

where

- \( \phi = \text{Accessibility factor} \)
- \( N = \text{Number of people} \)
- \( g = \text{Index for levels of accessibility} \)

To be noted, \( N_g \) is irrespective of trip purposes and, hence, \( \phi_g \) is applied to all purposes analogously.

### 3.2. Modal-shift analysis

The modal shift estimation model is based on a choice experiment. Choice experiment analyses how people make their choice among different alternatives based on the attributes of those alternatives. We used a discrete choice model to analyze people’s choice. A discrete choice model estimates the probability of choosing an alternative given the attributes of the possible alternatives as well as given people’s personal characteristics such as socio-demographic characteristics, trip characteristics, and spatial attributes. The discrete choice model applied in this analysis is based on utility maximization theory. We considered the binary formulation of the discrete choice model because the survey data asked respondents whether they were willing to shift their current mode to public transport (here, to metro, or to the bus).

We applied the binary logit model to investigate travelers’ modal shift (to public transport). The binary logit model is widely and commonly used in travel behavior analysis – for example, to analyze car ownership changes (Oakil et al., 2014, 2016b) and modal-shift to bicycle (Oakil et al., 2016a). The model is also analytically convenient due to its simplicity in nature for exploring the relationships between modal shift response and explanatory variables (Pan et al., 2019; Ren et al., 2020). In the context of mode choice, the model assumes that travelers connect with the disutility to each mode of alternatives, and then they choose a mode from the choice set that provides maximum utility. Thus, estimating the effects of potential factors determine the choice.

The dependent variable is whether the respondent shifted their travel mode to the public transport or not. Mathematically, modal shift (S) and no modal shift (NS) are the two alternatives in the binary choice set of each individual, then the utility function of alternative \( i \) (either modal shift or not) to the \( n \)th individual can be defined as (Ben-Akiva & Bierlaire, 1999)

\[
U_{in} = V_{in} + \epsilon_{in}
\]  

(3)
\[ V_{in} = \sum_{i=1}^{k} \beta_i x_i \]  

(4)

where

\[ U_{in} = \text{Utility of the alternative } i \text{ (shift mode or not) to the } n\text{th individual}, \]
\[ V_{in} = \text{Deterministic or observable portion of the utility estimated to the } n\text{th individual} \]
\[ \varepsilon_{in} = \text{Error term of the unknown utility to the } n\text{th individual} \]
\[ x_i = \text{Vector of independent variables (demographic and trip characteristics)} \]
\[ \beta_i = \text{Vector of estimated coefficients} \]

When \( \varepsilon_{in} \) is independent and identically (i.i.d.) Gumbel distributed, the modal shift probability that the \( n \)th individual will choose to shift the current mode can be written as (Ben-Akiva et al., 1985; Satiennam et al., 2016)

\[ P_{S_n} = \frac{1}{1 + e^{-V_{S_n}}} = \frac{e^{V_{S_n}}}{e^{V_{S_n}} + e^{V_{NS_n}}} \]  

(5)

where

\[ V_{S_n} = \text{Observable portion of the utility for modal shift} \]
\[ V_{NS_n} = \text{Observable portion of the utility for no-modal shift} \]

This paper considered many trip attributes such as travel time, travel cost, walk time and wait time, and socio-demographic characteristics of travelers such as age, employment, education, family size in the utility function. The estimated probability is then used to estimate the new mode share situation given public transport is operational. We applied this modal-shift probability to the current mode situation to introduce public transport as an additional modal share.

After incorporating accessibility and modal-shift situation, estimation of energy consumption is based on the vehicle kilometer traveled by each mode and energy consumption per kilometer per mode. So, the estimation of energy consumption is simply

- Calculation of vehicle kilometer traveled, that is,

\[ VK_m = T_m \times D_m \]

where \( VK \) is the vehicle kilometers traveled, \( T \) is the number of trips, and \( D \) represents distance per trip in kilometers by \( m \) mode.

- To calculate the energy consumption, we need to multiply the vehicle kilometers by fuel economy of each mode –

\[ E = \sum_{m} V_{km} \times F_{m} \]

where \( E \) is the total energy consumption, \( V_{km} \) is the vehicle kilometers traveled by mode \( m \) and \( F \) is fuel economy of mode \( m \).
4. A preliminary analysis: Energy impact of the proposed Riyadh metro

This is a preliminary analysis for data availability reasons. For this analysis, we focused on the proposed metro network and excluded the proposed bus network. Because the stated preference survey did not have sufficient information regarding modal shift to bus. In addition, there is no vehicle choice data. These limitations led to limited analysis for the methodology. Nonetheless, the framework is designed to include any update as simply as possible.

This analysis is based on the data from the Royal Commission for Riyadh City (RCRC), who developed the four-step traffic model in 2005 and 2016 and a projection for 2030. The baseline data were from 2016, based on which different scenarios were developed. The timeframes and the definition of the scenarios with respect to the methodology are elaborated in Table 1. The timeframes chosen for this analysis are based on data availability for both current and projected situations.

There is a baseline scenario for which timeframe differs. Because the baseline depends on the available data. Whereas RCRC’s traffic model was built for 2016, a stated preference survey for the willingness to use public transport was carried out in 2013. To analyze the modal shift, this survey is the most recent data. So, the estimation results came from the baseline scenario. BAU, public transport scenario, and TOD scenario were developed for 2030 using the estimation results from the baseline. Therefore, BAU differs from the baseline on the basis of data projection and the relationships among demography, travel and accessibility remain as per the baseline scenario.

| Scenarios               | Scenario description                                                                 | Timeframe         |
|-------------------------|--------------------------------------------------------------------------------------|-------------------|
| Baseline scenario       | The baseline scenario represents the period when data were collected, or a survey was conducted. Data for the four-step traffic model are from 2016; however, modal-shift data are from a stated preference survey in 2013. | 2016/2013         |
| BAU scenarios           | This scenario represents the projected travel and energy situation without the public transport system and transit-oriented development (TOD) being implemented. | 2030              |
| TOD scenarios           | This is the projected travel and energy situation with the public transport system being implemented. | 2030              |
| Development scenarios   | This is the projected travel and energy situation with both the public transport system and TOD being implemented. | 2030              |

4.1 Data description

The methodology is developed to assess transport energy demand for 2030. The preliminary analysis and results illustrate data and results for BAU, public transport, and TOD scenarios. Five data are important – trip data, accessibility data, current mode choice data, modal-shift data, and fuel economy data. The fuel economy data is the average fuel economy in the KSA.
4.1.1. Trip data

The source of the trip data in the outcome of traditional four-step traffic model from RCRC (Royal Commission for Riyadh City). The data contain information at TAZ level. Riyadh city was divided into 1492 TAZs. Every TAZ contains information regarding age structure, gender, and nationality. Based on RCRC trip rates per demographic criteria, we created the trip data.

This trip production in the RCRC’s traffic model was categorized into eight groups. The trips made by Saudis were divided into six groups based on trip purposes: home-based work trip (HBW), home-based trips to secondary school (HBSch), home-based trips to post-secondary school (HBSchP), home-based trips to shopping (HBShp), other home-based trips (HBO), and non-home-based trips (NHB). Here, home-based means that a trip is either originated or ended at home (an example of non-home-based is going to shopping from work). Additional two groups are for non-Saudis based only on gender – non-Saudi male (NSM) and non-Saudi female (NSF). Trip data by demographic characteristics from this model are shown in Table 2.

| Nationality | Gender | Age | Population * 000 | Trip * 000 | Trip rate |
|-------------|--------|-----|------------------|------------|-----------|
| Saudi       | Female | 0–17| 1165            | 1076       | 0.924     |
|             |        | 18–24| 507             | 507        | 1.000     |
|             |        | 25–44| 885             | 1319       | 1.490     |
|             |        | 45–65| 398             | 216        | 0.543     |
|             |        | 66+  | 71              | 17         | 0.245     |
| Male        | 0–17   | 1213| 1156            | 0.953      |
|             | 18–24  | 619 | 1474            | 2.381      |
|             | 25–44  | 817 | 3878            | 4.746      |
|             | 45–65  | 507 | 1976            | 3.897      |
|             | 66+    | 106 | 252             | 2.377      |
| Non-Saudi   | Female | 0–17| 187             | 61         | 0.324     |
|             |        | 18–24| 70              | 38         | 0.548     |
|             |        | 25–44| 319             | 133        | 0.417     |
|             |        | 45–65| 52              | 25         | 0.483     |
|             |        | 66+  | 6               | 0          | 0.000     |
| Male        | 0–17   | 280 | 311             | 1.111      |
|             | 18–24  | 130 | 175             | 1.340      |
|             | 25–44  | 710 | 1565            | 2.206      |
|             | 45–65  | 252 | 835             | 3.315      |
|             | 66+    | 11  | 33              | 3.014      |
| Total       |        | 8305| 15,048          | 1.812      |

Source: RCRC’s traffic model output for 2030.

4.1.2. Accessibility data

Although the accessibility is measured as walk and drive time to stations, we are considering only walk time. Because the data for modal-shift analysis did not include drive time accessibility and therefore, modal-shift cannot be assessed for different accessibility situation by car. So, the accessibility data represent the walk time to and from the metro stations. We counted reachable dwelling units within different walk times and multiplied the number of dwelling units by occupancy rate to get the number of people within the reachable area. The occupancy rate per residential dwelling was measured based on average household size per dwelling in Riyadh. According to RCRC, the average household size across Riyadh in 2016 was 5.7. Walk time categories
were developed based on the categories used for modal-shift analysis so that the results of modal-shift analysis can be applied directly. An example showing the areas within 0–5, 5–10, and 10–15 min from the metro station is presented in Figure 2.

![Figure 2](image_url). An example of the areas within different walk times from the metro stations.

Based on the number of people within the areas defined by different walk times, we get the proportion of the population for each level of accessibility ($\phi_{og}$) as per equation 2. To be noted, the accessibility is analyzed at TAZ-level, i.e. how many people living within a certain accessibility level for a TAZ. Later, it is aggregated to calculate accessibility factor by demography in Riyadh. Applying this factor to the trip data, we generate trips distribution by accessibility levels. In Figure 3, population distribution by accessibility levels is illustrated.
4.1.3. **Current trip characteristic data**

Using the O-D matrices, trip characteristic data were generated. Trip characteristics include trip purpose, travel mode, time, distance, and cost. All the attributes were taken from RCRC’s traffic model outputs, which was based on TAZ. However, the data were aggregated at the attribute level. Since this represents a huge amount of data, we only show an example table with example data in Table 3. Trip characteristics were generated for each age, gender, and nationality separately. Thus, the percentages are based on demographic characteristics.

| Trip mode | Trip distance | Trip time | Trip cost | Number of trips | Percentage by demography |
|-----------|---------------|-----------|-----------|----------------|--------------------------|
| Car       | 20.5          | 20        | 3         | 12,000         | 90%                     |
|           | ...           | ...       | ...       | ...            | ...                     |

4.1.4. **Modal-shift data**

Modal-shift data come from a stated preference survey conducted by RCRC in 2013. In the survey, a choice experiment was performed to understand people’s preferences regarding the metro and bus. In total, 164 car users were asked about their willingness to shift to metro. The survey constructed nine hypothetical situations based on different travel times, fares, wait times, walk times, and transfer requirements. After considering non-response and missing values, the sample size remained 148 individuals leading to 1332 observations. A detailed description of the survey and the sample can be found in our previous study (Anwar et al., 2021). Based on a mixed logit estimation, influential factors affecting the model shift to metro were identified. Several variables were considered including choice-specific attributes and socio-demographic characteristics. The results (adjusted from our previous study (Anwar et al., 2021)) are shown in Table 4.

The results were used to generate car and metro choice probabilities by using the estimated coefficients to the current trip characteristics, car attributes, and hypothetical metro attributes. As mentioned earlier, the current trip characteristics and other attributes came from RCRC’s traffic model. However, the metro attributes and accessibility are not possible to determine since the metro and TOD are yet to implement. Therefore,
the hypothetical scenarios were used for accessibility and metro attributes to calculate choice probabilities for car and metro. Choice probabilities at the current accessibility and without metro represent the BAU scenario.

4.2. Results

Two important outcomes of the analysis are the impact of the proposed metro on vehicle kilometers traveled and the gain in fuel consumption due to the proposed metro. The gain was estimated as the change in energy consumption due to the shift from car to metro. The net energy gain was not possible to be assessed because we do not know the energy consumption by the metro. However, cars in Riyadh depend mostly on hydrocarbon sources. Whereas the metro is electric based and, hence, creates opportunities to use alternative renewable sources. The gain in car fuel consumption would have a direct impact on the crude oil demand in the KSA and significant positive consequences from a greenhouse gas emission perspective. From that perspective, the gain can be seen as a reduction of fuel consumption from hydrocarbon sources.

According to the methodology, there are two steps to get energy demand:

4.2.1. Vehicle kilometers traveled

The source of trip distance is the RCRC traffic model output. The distance is based on network distance between TAZs, which is available from the O-D matrix. Therefore, distances are also at the aggregate level. Taking midpoints of TAZs as origins or destinations distances were measured. According to RCRC, vehicle occupancy rate was
1.6, which was also considered in the vehicle kilometer traveled estimation. In Figure 4, the impact on total car traveled distance at the different metro, car, and accessibility situations is shown.

![Figure 4. Impact of Riyadh metro on vehicle kilometer traveled.](image)

To be noted, change in accessibility leads to different demographic distribution and thus, different trip distribution. This generates differences in the total number of vehicle kilometers traveled. For instance, the total vehicle kilometers traveled by Saudis decreases from 130.2 million km at BAU scenario to 126.6 million km at the last scenario with accessibility as density twice as high as the current density near station, whereas the total number of vehicle kilometers increases for non-Saudis (from 31.2 million to 34.0 million).

The results suggest that there will be a shift of 9.7 mil vehicle kilometers (7.1 + 2.6) if the metro is implemented at 3 SAR ticket fare and at the current accessibility situation and car travel cost. This number will increase to 11.5 mil vehicle kilometers if we introduce a car parking charge of 5 SAR. This accounts for an increase from 6% to 7.1%. Furthermore, this percentage increases to 12.7% for the hypothetical scenario where population density within 10 min walk from the station is doubled the current density. An interesting finding is that the total vehicle kilometers traveled is also reduced from 161.4 to 160.6 mil kilometers. This implies that people will need to travel less distance given the current job and other trip attraction locations. However, it is understood that the land-use will transform as well due to metro development, which is not considered for this analysis.

4.2.2. Fuel economy and energy consumption

Energy consumption is based on standard energy use by different types of vehicles. Types of vehicles can be classified based on different criteria of built and model. However, vehicle stock information in Riyadh as well as in the KSA based on built and model is not available. In general, most of the vehicles in Riyadh are gasoline driven. Although IEA (2020) finds much regional differences in fuel consumption, the average fuel
consumption statistics of the KSA was used because of data limitation. According to Saudi Arabia’s Energy Efficiency Center (SEEC), the average fuel consumption in 2015 was 12.5 km/l for light duty vehicles in the KSA.

Based on this average data, the energy consumption for the given vehicle kilometers traveled was calculated. Total fuel consumption is equivalent to total fuel consumption by car, whereas vehicle kilometers traveled by metro do not add to the total fuel consumption. Therefore, the equivalent fuel consumption for the kilometers traveled by metro was considered as the reduction in fuel consumption. In Figure 5, it is differentiated by the orange color in the columns. To simplify, the reduction in fuel consumption in the figure is estimated by multiplying metro kilometers by the average fuel economy of cars in the KSA.

![Figure 5. Impact of Riyadh metro on total fuel consumption.](image)

According to this result, it is possible to reduce energy consumption by 1.7-million-liter equivalent of gasoline per day, if the population density within 10 min walk is twice than the current density, and metro fare is 3 SAR and car cost is increased by 5 SAR parking charges. This is almost 13% reduction from the current fuel demand coming from very car oriented.

5. Conclusions and future works

This paper develops a travel demand model for Riyadh, the Kingdom of Saudi Arabia. The model can be considered the first initiative to assess systematically the impact of new development that may affect travel mode usage and choice, and, hence, travel demand. This model accounts for socio-demographic changes, new infrastructure development, changes in the built environment, and policies that affect the cost of different modes.
The results only show metro costs and accessibility situation. The results found from the analysis cannot be used as a reference for Riyadh since the analysis did not include bus travel decisions. The main purpose of the analysis was to operationalize the model and get preliminary results. It is intended to deliver the comprehensive result through a data visualization interactive portal. Many scenarios based on metro, car, and accessibility situations can be tested, which are difficult to present in a paper or document.

Urban sprawl in Riyadh is a major source of energy inefficiency. It leads not only to more vehicle kilometer travels, more fuel consumption, and more air pollution but also to inefficiencies in infrastructure provision. De-densification of residential and commercial districts causes an increase in both energy services and construction materials. Following this realization, the RCRC released its new strategic plan for Riyadh metropolitan called MEDSTAR (Metropolitan Development Strategy Arriyadh) in 2003. The major component in this spatial plan is the concept of reorienting the city from car-based infrastructure to public transit-oriented infrastructure through TOD connected by metro rail.

The pattern of land use and accessibility to metro has profound impact on urban transport energy demand. The challenge of Riyadh city revolves around planning, designing, and managing urban growth in mixed as well as compactly manner. To contain the impact of mass transit development on energy demand, this paper proposed a methodology, which is comprised of estimating trip distribution based on demography, trip characteristics, and mode choices from the four-step model. Accordingly, it assessed the likelihood of vehicle kilometer traveled reduction by introducing Riyadh metro and TOD, which resulted in reduced fuel consumption, broadly energy demand. The TOD concept is planned to be implemented in Riyadh city and is designed to increase fuel efficiency as well as the accessibility. The TOD promotes a new urban form; therefore, policy interventions in urban form considered with an emphasis on accessibility would have significant impact on individual travel patterns given that the proposed TOD is in place.

Considering the simulation results, the most effective strategy to reduce the energy consumption was found the strategy of adapting TOD focusing on accessibility doubled near the stations, which contributed to reduced vehicle kilometer traveled. Thus, the policy must be aimed at reducing vehicle kilometer traveled while increasing transit ridership. This study uses few indicators such as parking fees, metro fare and accessibility as control and assess the future energy demand, which result in the reduction of fuel consumption.

Understandably, the economic and spatial aspects would not solely determine the metro ridership. Many factors influence public transport ridership, which are often multifaceted, interrelated factors and can be conscious or unconscious (De Witte et al., 2013). Higher number of public transport ridership is not easily achieved. There are many barriers to public transport use that can be categorized as hard, soft and complementary (Blainey et al., 2012). Importantly, the hard barriers are more related to indicators and interventions on the supply side of the transport system such as travel cost, time, or frequency, whereas the soft barriers are more related to the demand side including psychological and behavioral aspects (Queiroz et al., 2020).
For example, car dependency can be unfavorable to public transport use. In general, such behavior may create an inertia towards car use and discourage metro use (La Paix et al., 2022). Riyadh is a car-dominated city (Aldalbahi & Walker, 2016). About 85% of Riyadh’s eight million daily trips are taken by car, whereas just 2% of its trips are taken by bus (Al-Fouzan, 2012; Alqahtani et al., 2012). In addition, Riyadh’s urban infrastructure does not favor public transport system (Aldalbahi & Walker, 2016; Al-Mosaind, 2018). Moreover, Riyadh’s Islamic culture and conventions regarding privacy might play a significant role. Less than 9% of the total trips were made by women using Saudi Arabia Public Transport Company (SAPTCO). The main reasons are the privacy issue as well as availability of private cars and drivers (Aldalbahi, 2018). Thus, the public transport is culturally unattractive to female users in Saudi.

Whereas hard barriers such as cost, land-use, and accessibility can be overcome by designing the metro system carefully, the soft barriers and complementary barriers are culturally and geographically embedded in the society. It is understood that Riyadh needs to create a favorable condition for public transport, both from infrastructure perspective and from cultural and geographical perspectives. To achieve sustainable urban mobility, the current transport system, which favors automobile travel, must evolve. The new system should prioritize energy efficiency, environmental sustainability, and an overall better quality of urban life (Businge et al., 2019).

This model is the first step to consider socio-economic factors, accessibility, and travel characteristics such as cost and time. The methodology is based on robust application of four-step travel demand model, where modal-shift, accessibility and vehicle choice can easily be incorporated. Information on the soft barriers such as psychological, cultural, and other geographical issues like weather are not considered yet. A more innovative and advance method requires rigorous collection of data. For example, an agent-based model or an activity-based travel demand model needs travel diary data including not only travel and socio-economic factors but also psychological factors such as attitude and preference. Therefore, future research will focus on data collection and enrichment to incorporate more information detail regarding accessibility, travel, and demography as well as attitude and preference regarding travel modes, environment, and other values. Given the rapid changes in socio-economic as well as in urban context of Riyadh and scarcity of appropriate data, the traditional four-step model promises an in-time solution for policy making and informed decision support. The results from this research will be collated into a data visualization portal, where different hypothetical scenarios can be tested. It will serve as a policy evaluation tool.

Note

1. Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

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