Sustainable Transport in Riyadh: Potential Trip Coverage of the Proposed Public Transport Network

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Key Points

A framework has been developed to help identify the potential impact of Riyadh's public transport system.

The public transport system, the metro system alone and the metro system with bus support can potentially cover over 30%, 5% and 8%, respectively, of car- and taxi-related trips in Riyadh.

Urban sprawl is a challenge for Riyadh. It causes lower urban density, creating higher dependence on cars, which, in turn, leads to costlier infrastructure investments and higher per capita energy consumption.

Urban and land use transformation policies may be necessary to influence car-dependent behaviors.

Transit-oriented development involves creating concentrated nodes of moderate- to high-density developments, supporting a balanced mix of land uses around transit stations. Thus, it offers a solution to urban sprawl in Riyadh.

Summary

The transport sector has always had high energy demand and is a significant contributor to greenhouse gas (GHG) emissions and climate change. To improve energy efficiency and reduce GHG emissions, Riyadh is introducing an integrated public transport system. Per capita energy consumption is much lower for public transport than for private vehicles, such as cars and taxis. This study investigates the potential impact of Riyadh's proposed public transport system on car and taxi trips.

We define the potential impact as the number of car or taxi trips that can shift to public transport. We analyze the total number of trips and the geographical coverage of Riyadh's metro and bus system. Based on this analysis, we estimate the potential modal shift from cars or taxis to public transport that can be achieved with optimal planning. This study's contributions are twofold:

First, we consider the accessibility of both the origin and destination points of trips. Thus, we consider a trip as a unit. Only living or only working within an area accessible to public transport is not sufficient to make the trip between home and work via public transport.

Second, our data represent the total number of trips in Riyadh based on calibrations with real-world measurements from selected streets.

Our analysis utilizes the output of a Riyadh traffic model, geographic information about metro stations and bus stops, and guidelines on accessibility. These data show that the proposed public transport system (including both the metro and buses) covers about 30% of current car- or taxi-related trips in Riyadh. In contrast, the metro system alone covers only 5% of current car- or taxi-related trips.

In general, around a 30% modal share for public transport is a desirable outcome. However, Riyadh faces three major challenges to achieving this level of coverage:

- Urban sprawl
- Car dependency
- Residential self-selection

A potential solution to the challenge of urban sprawl in Riyadh is transit-oriented development (TOD). TOD involves creating concentrated nodes of moderate- to high-density developments that support a balanced mix of land uses around transit stations. The core aim of TOD is achieving energy efficiency. Many cities are applying this concept to address challenges such as climate change, pollution and congestion. TOD can also support transit use and the survival of the public transport system. The authorities in Riyadh have given due priority to TOD and developed a detailed plan for metro development.

However, the challenges of long-lasting car dependency and residential self-selection (i.e., a preference for car-dependent living) remain even with TOD. Several policy measures may be required to address these issues. Riyadh should not only provide incentives to use public transport but also set penalties for car use that reflect the environmental damage and energy gains. For example, pricing policies, such as parking fees and congestion charges for car users, can affect the relative costs of car and public transport use. Free trials, discounted long-term tickets and free car parking for transit users can incentivize transit use.

Introduction

In the 2015 Paris Agreement, the Kingdom of Saudi Arabia committed to reducing its greenhouse gas (GHG) emissions and adhering to climate change mitigation measures. The Kingdom pledged to reduce about 130 million tonnes of carbon dioxide equivalent by 2030. This goal was laid out in its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC 2015). In its NDC, the Kingdom promised to engage in actions and plans that would bring economic diversification and that are adaptive to the impacts of climate change. These actions and plans can help achieve sustainability goals by avoiding GHG emissions.

In this regard, two major policy initiatives have been undertaken: economic diversification to mitigate climate change, and adaptation measures. Economic diversification is focused on energy efficiency, renewable energy and alternative sources, bringing structural changes to people's lives. Adaptation measures relate to the management and planning of aspects of people's daily lives. Such measures include water and waste management, urban planning and coastal area management. Both types of policies need to focus on highly energy-intensive and GHG-emitting sectors. According to the Kingdom's NDC, about 90% of its current energy demand comes from industry, buildings and transportation (UNFCCC 2015).

The global transportation sector has always been viewed as a major energy-demanding sector that has contributed greatly to GHG emissions and climate change. It accounted for about 23% of total global carbon dioxide emissions from fuel combustion in 2014 (Santos 2017). The situation in the Kingdom is no exception. Its transportation sector produced 21% of its GHG emissions (136.9 out of 663.58 million tonnes of carbon dioxide equivalent) in 2016 (Climatewatch 2020).

Based on recent data from the General Authority for Statistics, Amarnath and Al Henaki (2019) report that the Kingdom's transportation sector demands 22% of its energy. Of this demand, 90% comes from land transport. They also point out that the Ministry of Transport expects the number of vehicles to reach 26 million by 2030. In that case, the daily fuel consumption would be around 1.86 million barrels. The Kingdom's NDC targets reducing the transportation sector's GHG emissions and improving its energy efficiency. Saudi Arabia is therefore developing mass transportation systems in its major cities.

In line with this policy, Riyadh has made significant investments in its urban transport system to improve energy efficiency and avoid GHG emissions. The Riyadh metro system is the first major initiative to combat transportation-related emissions and climate change and improve energy efficiency. According to the Riyadh Metro (2020), the project consists of a public transit system of six main lines covering 176 kilometers (km). The system will have 85 highly equipped stations with cutting-edge technology. The Royal Commission of Riyadh City (RCRC), the authority responsible for the project, expects to reach 3.6 million passengers daily within 10 years of operation. The RCRC also expects to reduce daily car trips by 250,000, leading to reduced congestion and about 400,000 fewer liters of fuel consumption per day. To achieve these desired goals, the metro system should be able to achieve its full potential by serving a large number of people. A bus network has also been planned to support the metro system.

However, a systematic assessment of the impacts of the Riyadh metro and its supporting bus network on trips and modal shifts is needed. Such an assessment is necessary to understand the network's potentiality, measure its actual impact, monitor its progress and evaluate the project's

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success or failure. Several geographic, social and economic aspects may affect the metro and bus network's success as a public transport system. It is imperative to develop a framework to assess the importance of those aspects and take necessary steps accordingly.

The public transport system may fail to achieve its full potentiality for several reasons. For instance, it may face issues with accessibility, cost of use, be used more by men or women, or by a younger cohort. It is important to identify the key problems and take necessary actions. In this regard, an initial step is understanding the potential impact of Riyadh's public transport system. Potential impact refers to the possibility of making a modal shift from car to public transport use. An analysis should determine the number of car trips that can shift to public transport under favorable geographical, economic and social circumstances. This analysis thereby identifies the optimal number of trips using the proposed metro and bus system in Riyadh.

This potential number of trips can serve as a benchmark for measuring the efficiency of Riyadh's public transport network over time. Riyadh is unlikely to reach this benchmark immediately after the proposed public transport network's introduction. The difference between potential and actual trips after the introduction of this network therefore represents the network's efficiency. When potential and actual ridership are the same, the system has achieved full efficiency. The authorities should work toward that goal, although several policy initiatives may be necessary to achieve it. To continuously evaluate such policies' impacts and the public transport system's progress toward the benchmark, measuring the system's potential impact is imperative.

This study therefore focuses on the potential impact of Riyadh's public transport initiative. We analyze the total number of trips and the geographical coverage of the metro and bus systems in Riyadh. Based on this analysis, we estimate the potential modal shift from cars to public transport that can be achieved under optimal planning. This number can then serve as a benchmark for efficiency analyses. Such a benchmark will facilitate continuous assessment of policies and the Riyadh public transport system's progress. The contributions of this study are twofold.

First, it considers the accessibility of both the origin and destination of a trip. In other words, we consider a trip as a unit. Only living or only working within an area accessible to public transport is insufficient for travel between work and home via public transport.

Second, our data represent the total number of trips in Riyadh based on calibrations with real-world measurements from selected streets.

Methodology

We analyze the potential impact of Riyadh's public transport initiative. To do so, we calculate the number of trips that may shift from other modes to public transport (metro or bus). This methodology has two important aspects:

Trip coverage, which represents the number of trips for which the public transport system is accessible.

Potentiality, which represents the optimum probability that those trips will shift to public transport.

In this regard, potential trip coverage is defined based on access to the public transport system and the possibility of shifting to public transport. Here, we refer to trips with access to public transport as “trip coverage” and the possibility of shifting to public transport as “potentiality.”

Based on this definition, a fundamental concept in trip coverage is accessibility. We measure accessibility based on the catchment areas of metro stations and bus stops. These catchment areas are determined by geographical buffers around the stations and stops. Geographic distance is not always a good proxy for accessibility. However, the metro and bus networks in Riyadh are still under construction. Many aspects of Riyadh's metro stations and bus stops are expected to be adjusted to improve their accessibility. Consequently, it is currently very difficult to measure accessibility from network or built environment perspectives. We therefore assume that a geographic buffer is a good representation of accessibility at present.

We define the walkable distances from metro stations and bus stops as their buffers in this study. Specifically, we consider an 800-meter buffer for metro stations and a 400-meter buffer for bus stops as walkable distances. Zielstra and Hochmair

(2011) suggest that a substantial proportion (75%-80%) of trips that meet these criteria can shift to public transport. However, both the origin and the destination of a trip must be within the aforementioned catchment areas of metro stations or bus stops. Thus, a trip must both start and end within a catchment area. In addition, we need to know the number of trips that are made within these catchment areas. We define this number as the system's trip coverage.

To calculate the number of trips, we use trip generation information from the RCRC's traffic model. This traffic model is based on traffic analysis zones (TAZs), as shown in Figure 1. Thus, our data only indicate the aggregate trip generation from each TAZ. It is very likely that the geographical buffer around a station or stop may not completely cover a particular TAZ. In that case, we consider the estimated number of trips to be proportional to the coverage area of a metro station's buffer within a TAZ. For example, if 50% of a TAZ's area is within 800 meters of a metro station, then 50% of trips to that TAZ are considered accessible by metro. Thus, the total number of trips that can be accessed by metro, bus or a combination of both is as follows:

$$Trip_{coverage} = \frac{Coverage_{origin}}{Area_{origin}} \times \frac{Coverage_{destination}}{Area_{destination}} \times Trip_{origin,destination}$$

The above equation estimates the public transport system's total trip coverage. However, it is unlikely that 100% of these trips will shift to public transport. The characteristics of the built environment and the sociodemographics of the catchment areas determine a public transport system's potentiality. Thus, the potential trip coverage is as follows.

$$\begin{aligned} Trip_{potential\ coverage} &= Trip_{coverage} \\ &\times Trip_{potentiality\ factor} \end{aligned}$$

The potentiality factor is an important tool for calculating potential trips. Here, this factor reflects the probability of using public transport under favorable conditions. From design principles, it indicates public transport ridership in an ideal situation. Riyadh's conditions may not currently be ideal, and the potentiality factor is not meant to reflect what Riyadh will achieve when the system is introduced. Instead, it is meant to measure the potentiality of the Riyadh public transport system in an ideal situation.

Because the ideal situation is theoretical rather than a practical scenario, the potentiality factor should represent a common but best-case scenario. According to Zielstra and Hochmair (2011), "The most common standard measures of walking distance to transit stations used in the public transit industry to generate service areas are 400 meters (0.25 miles) buffers around bus stops and 800 meters (0.5 miles) around rail stations with most passengers (75%-80%) walking the given distances or less."

To determine best-case scenarios, we looked into some success stories of public transport development. Singapore's Land Transport Authority (2011) provides an overview of major cities that depend on public transport and their modal shares. One success story is the mass transit system (bus and bus-rapid-transit) of Bogota, Colombia. In 2000, Bogota implemented an integrated, extensive mass transit system covering almost the entire city. Mass transit was used for 62% of all journeys in the city in 2008 (Land Transport Authority 2011) and around 80% of all motorized journeys.

In contrast, the public transport network in Paris, France, which dates back to 1900, is advanced and developed. It also covers the entire city, and public transport was used for 62% of all journeys in 2008 (Land Transport Authority 2011). Paris has a high share (33%) of cars and taxis, and public transport accounted for about 65% of all motorized journeys. Tokyo, Japan, is also well developed and well served by public transport. Although mass transit constituted only 52% of all journeys in 2009 (Land Transport Authority 2011), it was used for more than 80% of motorized journeys. Tokyo has a high share (37%) of non-motorized journeys.

Under optimal conditions, we assume that public transit is used for 80% of motorized travel when made within walkable distance from metro or bus stations. This is the best possible outcome. Thus, we use the 80% figure to estimate the number of trips that can shift from cars and taxis to public transport. It would be unrealistic to assume that all trips within walkable distance of public transport would shift to public transport.

A multimodal transport network, such as a combination of trains, metro lines and buses, can help expand the catchment areas of the public transport system (Guo and Wilson 2011; Cheng and Tseng 2016). Thus, our analysis focuses on three potential outcomes. First, we analyze the metro system's coverage. Then, we differentiate among metro users by including the possibility of transferring from a bus to the metro, or vice versa. Finally, we analyze the extension of public transport coverage by considering Riyadh's public transport system as a multimodal system that combines metro and bus transport. The results represent the following outcomes:

- Trip coverage of metro stations

■ Trip coverage of metro stations including potential transfers from buses

■ Trip coverage of public transport based on both metro stations and bus stops

These three separate analyses of trip coverage are important for understanding the contributions of different transport modes to the multimodal public transport system.

Data Description

The analysis is based on three data sources:

- The output of the RCRC's Riyadh traffic model for 2016.
- Geographic information about metro stations and bus stops from the RCRC.
- Guidelines on accessibility and potential public transport users from the literature.

Trip information is based on the traffic model deployed by the RCRC's transportation modeling group.¹ The RCRC divided Riyadh into 1,492 TAZs in 2016 (Figure 1).

The RCRC's traffic model is a classic four-step model, as follows.

- Trip generation: The model calculates total trips originating from or ending in each TAZ. Originating trips are generally computed as a function of sociodemographic parameters represented by the households in each TAZ. The trips ending in a TAZ are commonly determined based on the zone's non-residential land use.
- Trip distribution: Based on certain cost factors and a calibration process, a model is developed to distribute the number of trips across TAZs. This model generates an origin-destination matrix in which the trips originating in a TAZ are distributed among a number of probable TAZs.

Figure 1. The RCRC's TAZs in Riyadh.

Source: RCRC.

¹ This group was previously known as the Arriyadh/Riyadh Development Authority.

- **Modal split:** Based on the utilities of every operating travel mode within the TAZs, the trips are distributed among the different modes.
- **Trip assignment:** Based on the generated origin-destination trip matrix and the transport network, the trips are assigned to the road network. This process utilizes different impedance and cost factors to identify the lowest-cost route for every pair of TAZs. The trip assignment also undergoes a validation process to match the measured traffic flow within the network. The model is further calibrated to obtain more accurate results over the network.

Based on the trips originating from and ending in each zone, an origin-destination matrix that indicates the number of daily trips between TAZs has been developed. As of 2016, no transit system was operating in Riyadh. Thus, the matrix represents

trips made by cars and taxis. About 6% of trips are made via group transport, such as company buses and vans (Ministry of Municipal and Rural Affairs 2017). However, the RCRC's traffic model excluded those trips. In many cases, these trips represent the movement of low-income workers within Riyadh, and excluding them is not ideal. However, our intention is to understand the potential shift from car to public transport use. We therefore calculate the car trips that can shift to the new public transport system.

Trips can be categorized by mode and the nationality of the traveler. Figure 2 shows the distributions of different types of trips by nationality in Riyadh. In general, most car trips (about 70%) are made by Saudis. According to the General Authority for Statistics, Riyadh's population comprised 44% non-Saudis and 56% Saudis in 2017. Thus, Saudis are more likely to make car trips than non-Saudis. In contrast, non-Saudis make more taxi trips than Saudis, indicating the higher dependency of non-Saudis on taxis.

Figure 2. Trip distribution in Riyadh by nationality in 2016.

Source: RCRC's traffic model output for 2016.

Data Description

The traffic model further categorizes Saudi nationals' trips into six purposes. These are home-based work, home-based secondary school, home-based post-secondary school, home-based shopping, home-based other and non-home-based. Here, home-based means that a trip either originated or

ended at home. An example of a non-home-based trip is going shopping straight from work. The model also categorizes non-Saudis based on gender. Figures 3 and 4 show the trip descriptions and statistics for the eight different segments and two modes (i.e., car and taxi trips).

Figure 3. Distribution of car trips in Riyadh by purpose in 2016.

Source: RCRC's traffic model output for 2016.

Figure 4. Distribution of taxi trips in Riyadh by purpose in 2016.

Source: RCRC's traffic model output for 2016.

Figure 3 shows that in Riyadh, non-Saudi men make the most car trips, and Saudis make most of their car trips for home-based work purposes. Most non-Saudi men work in the Kingdom and, thus, most of their car trips are likely to be work trips as well. Notably, car trips made by non-Saudi women represent car trips made as passengers because women were not allowed to drive cars in 2016.

Figure 4 shows that non-Saudis also make a large number of taxi trips. However, Saudis do not make as many taxi trips as non-Saudis. The reason that non-Saudis use taxis more often may be because car ownership differs between Saudis and non-Saudis. Non-Saudis may be less likely to own a car than Saudis, possibly owing to their temporary

residential status in the Kingdom. Saudis tend to use taxis more often for school trips. The data may reflect mothers bringing their children to school by taxi because women could not drive in 2016.

As mentioned earlier, no active transit system currently operates in Riyadh. However, Riyadh has proposed and made significant investments in building a public transport network. This network includes a metro system, a bus-rapid-transit system, and community and feeder bus services. These services are intended to cover a large area of the city and serve most of its residents. Figure 5 depicts the geographic coverage of the proposed public transport system.

Figure 5. Geographic representation of metro station (yellow) and bus stop (green) locations and catchment areas in Riyadh.

Source: KAPSARC analysis.

Data Description

Our methodology defines 800-meter buffers around metro stations and 400-meter buffers around bus stops as catchment areas. As Figure 5 shows, most of Riyadh will be served by the public transport initiative proposed by the government. A few peripheral areas will not be served. However, those areas are still developing and are largely vacant.

Nonetheless, our main focus is on understanding the coverage of the public transport system in terms of trips rather than area. In this regard, we need to analyze the coverage of Riyadh's public transport system in terms of TAZs. Figure 6 offers a detailed view of the metro stations' geographic coverage and their coverage within TAZs.

Figure 6. Example catchment areas within 800-meter buffers of metro stations in relation to TAZs.

Source: KAPSARC analysis.

Results

Based on our methodology, we first investigate metro coverage alone. Second, we consider total metro coverage, including trips involving bus transfers but excluding trips made solely by bus. Third, we investigate public transport coverage including trips made by metro, bus or a combination of both.

Potential trip coverage of the metro system

Figures 7 and 8 present the metro system's trip coverage. Coverage is defined as the area within an 800-meter distance of a metro station. Trip coverage is the total number of trips that start and end within coverage areas. The potential trip coverage is the number of trips that can potentially shift to the metro from other modes (i.e., cars or taxis). Here we define the number of trips that can potentially shift to the metro as 80% of the metro's total trip coverage. Thus, the percentages shown in the figures

represent the proportion of total trips that could shift to the metro. We refer to "potential car trip coverage" when we consider only car trips and to "potential taxi trip coverage" when we consider only taxi trips.

Figure 7 shows the metro system's potential car trip coverage. About 4% of total car trips for all purposes could shift to the metro. In other words, about 4% of all car trips start and end within 800 meters of metro stations. Thus, the total potential trip coverage for cars is 4%. For Saudis, the potential car trip coverages for many trip purposes are less than that for all trips (4%). Non-home-based car trips are more likely (4%) to be covered by the metro than trips for other purposes are. In general, however, trip coverage by the metro system does not substantially differ across different purposes. Moreover, the potential car trip coverage is higher for non-Saudis (6% for women and 5% for men) than for Saudis. This result indicates that non-Saudis make car trips near metro stations more often than Saudis do and, thus, are more likely to shift to the metro.

Figure 7. Potential car trip coverage of Riyadh's metro system.

Source: RCRC's traffic model output for 2016.

Results

Figure 8. Potential modal shift from taxi trips to metro trips in Riyadh.

Source: RCRC's traffic model output for 2016.

Figure 9. Potential modal shift to the metro by current mode and nationality.

Source: RCRC's traffic model output for 2016.

Likewise, Figure 8 shows the public transit system's potential taxi trip coverage. In total, about 7% of taxi trips could shift to the metro, meaning that the total potential taxi coverage is 7%. This coverage is much higher than the total potential car trip coverage. This result means that taxi trips more often start and end within 800 meters of metro stations. Thus, taxi trips are more likely than car trips to shift to the metro.

Figure 8 shows that taxi trip coverage ranges from 4% and 6% depending on a trip's purpose. Saudis are more likely to shift from taxi trips to the metro for non-home-based and post-secondary school trips. Work trips and shopping trips are next, with trip coverages of about 5%.

As in the case of car trips, we find that non-Saudis make more taxi trips within the catchment areas of metro stations than Saudis do. Hence, the potential taxi trip coverage for non-Saudis is generally higher than that for Saudis. To better understand this distinction, we illustrate the potential trip coverage by nationality in Figure 9. Indeed, non-Saudis have greater potentiality to shift to the metro from both cars and taxis. Overall, non-Saudis are almost twice as likely to shift their trips to the metro.

However, the overall trip coverage by metro stations in Riyadh is not very high. On average, metro stations cover about 4% of total trips (4% and 7% of car and taxi trips, respectively). To facilitate metro use and increase public transport ridership, however, the Riyadh metro is designed with an integrated bus network.

Potential trip coverage of the metro system including bus transfers

As the prior analysis shows, a substantial modal shift from cars and taxis to mass transit is unlikely when only the metro is considered. To increase ridership, Riyadh needs to extend its metro stations' coverage. One way of doing so is integrating other modes of transport into the metro system. Riyadh's bus network can play a vital role in this respect. Thus, we extend our analysis by considering trips that combine metro and bus use. In other words, people may use buses to reach the metro or travel from metro stations to their final destinations by bus. Here, we consider potential trip coverage not only based on walking distance but also based on bus ride distance.

Bus and metro trips can be combined if a bus stop is in close proximity to a metro station to enable

transfers between the two. However, people may not take the bus to the metro if the bus ride itself is too long. In line with these principles, we set two criteria for combining metro and bus trips:

- First, the distance between the bus stop and the metro station at the transfer point should be no more than 100 meters.
- Second, the bus ride from the origin to the metro station or the metro station to the destination should be no longer than 2 km.

Furthermore, not all bus trips involve the metro, and we exclude trips that solely involve buses from this analysis. However, we do not have precise data on the frequency of such trips. Thus, we assume that trips are equally likely to involve only bus travel or to involve both bus and metro travel. Finally, we exclude feeder poles because they involve double transfers by design (a feeder bus to a community bus and then to the metro). Generally, the probability of public transport use falls as the number of transfers increases.

Based on these additional criteria, we recalculate the potential trip coverage. Figure 10 shows the potential car trip coverage when the metro and bus networks are integrated. In this case, the potential car trip coverage increases from 4% to 8% (Figures 7 and 10). The metro's potential car trip coverage therefore doubles when the bus network is integrated compared with when we only consider the metro service. The bus network increases coverage the most for non-home-based trips (from 4% to 9%) and home-based school trips (from 3% to 7%). As mentioned earlier, these trips are very important. Not only do they constitute a large share of trips in Riyadh, but they also influence work trips and car ownership.

Results

Figure 10. Potential car trip coverage of the metro system with bus system support in Riyadh.

Source: RCRC's traffic model output for 2016.

Figure 11. Potential taxi trip coverage of the metro system with bus system support in Riyadh.

Source: RCRC's traffic model output for 2016.

Figure 11 shows that the potential taxi trip coverage increases from 7% to 13% when we incorporate the possibility of bus transfers. With respect to taxi trip purposes, non-home-based and home-based school trips are more accessible from metro stations.

A general finding is that taxi trips have more transit accessibility than car trips. One reason for this may be that people typically go to places with multiple

options, such as malls, when using taxis. This behavior increases the efficiency of these trips in terms of taxi cost. Because metro stations are designed to connect multipurpose activities, taxi trips are more likely to start and end in such areas. In addition, trips made by non-Saudis are more easily shifted to the metro than trips made by Saudis (Figure 12). However, the difference between the two groups is not as high as that for just the metro system (Figure 9).

Figure 12. Potential modal shift to the metro (with bus system support) by current mode and nationality.

Source: RCRC's traffic model output for 2016.

Potential trip coverage of the public transport system

We further analyze the potential trip coverage of public transport when we consider accessibility to all metro stations and bus stops. To reiterate, we define accessible distances for metro stations and bus stops as 800 meters and 400 meters, respectively. The potentiality factor is 80%.

As in the previous analyses, figures 13 and 14 illustrate the potential car trip and taxi trip coverage, respectively, of the public transit system. Figure 15 shows the potential modal shift to public transport by current mode and nationality.

According to Figure 13, the potential car trip coverage of the public transport system for all trip purposes is about 29%. Thus, the bus network provides about 25% of total car trips access to the public transport system in Riyadh. The potential to shift to public transport increases substantially when the bus network is considered. This result means that the success of Riyadh's public transport relies more on the bus network than on the metro system. In terms of trip purposes for Saudis, non-home-based

and home-based secondary school trips are the most influenced by incorporating the bus network. Home-based post-secondary school trips are the least affected.

The potential taxi trip coverage is 39%, which is higher than the potential car trip coverage (Figure 14). The bus network provides about 32% of taxi trips access to Riyadh's public transport network. Looking at the effects of incorporating the bus network on taxi trip coverage by trip purpose for Saudis, we find similar results as for car trips. Non-home-based and home-based secondary school trips are the most affected trips, and home-based post-secondary school trips are the least affected.

In general, the bus network increases access to schools and non-home-based activities more than it does to other activities. Having good access to schools and non-home-based activities is important for reducing car trips and car ownership. People often use cars because they need to combine trips to drop off or pick up children from school with trips to work. If schools are easily accessible by public transport, we may expect better results in terms of the modal shift from cars and taxis to the metro and buses.

Results

Figure 13. Potential car trip coverage of the public transport system in Riyadh.

Source: RCRC's traffic model output for 2016.

Figure 14. Potential taxi trip coverage of the public transport system in Riyadh.

Source: RCRC's traffic model output for 2016.

In terms of structural differences across nationalities, we find similar outcomes (Figure 15) as in the previous analyses (figures 9 and 12). The public transport network including both the metro and buses will cover more trips made by non-Saudis than trips made by Saudis. This result implies that non-Saudis make more trips within the catchment

areas of the public transport network. One reason for this outcome may be that many non-Saudis live or work near metro stations or bus stops, possibly because non-Saudis live in high-density areas. Thus, a small catchment area can cover a large number of trips for non-Saudis.

Figure 15. Potential modal shift to public transport by current mode and nationality.

Source: RCRC's traffic model output for 2016.

The findings suggest that potential trip coverage relies more on the bus network in Riyadh. Relying more on buses can increase the system's vulnerability because they are more useful for short distances than for long distances. Riyadh's bus network is also designed as a set of community bus services and feeder buses. With the exception of bus-rapid-transit, its buses serve short distances.

The most frequent trips in the city are work trips, which often are not confined to a single community. People must combine bus and metro trips via transfers to travel between communities. The analysis in section 4.2 provides a better overview of this type of trip. Unfortunately, the potential trip coverage of metro use with bus transfers is not very high (8%).

Discussion: Challenges to Achieving the Potential Trip Coverage

Our analysis shows that bus support is essential for increasing overall transit use in Riyadh. The metro system alone covers only about 5% of car and taxi trips. However, with the support of the bus network, the metro system's coverage may increase to 8% of trips. Finally, the overall public transport network, including the metro and the entire bus network, may cover 30% of current car and taxi trips in Riyadh.

In general, a 30% modal share for public transport is a desirable outcome. Major cities served by public transport typically achieve this goal. The public transport shares for New York City, London, Toronto and Sydney are 33%, 37%, 24% and 27%, respectively (United States Census Bureau 2015; Transport for London 2017; Statistics Canada 2016; Loader 2017). Paris has exceptionally good public transit use, registering a public transport modal share of 62% in 2008 (Land Transport Authority 2011). The very high public transport use in Paris can be attributed to its lower fare price compared with the other cities mentioned above. However, a common attribute of all these cities is high density. Their public transport systems can cover a large number of people within walking distance.

Urban density is necessary to achieve the goal of covering more than 30% of trips with public transport. The trip coverage measured in this analysis is based on the assumption that sociodemographic and geographic conditions are favorable to metro use. In other words, at present, 30% of car and taxi trips can shift to public transport under ideal conditions. Specifically, this outcome arises if everybody wants to use public transport and all geographic, economic, demographic and social factors are conducive to using public transport.

Urban density often receives significant attention as a major geographic driver of higher public transport use. After active transport use (Cervero and Kockelman 1997) and a lower probability of car ownership (Oakil, Manting, and Nijland 2016), it is the most important factor. However, urban density presents a great challenge for Riyadh. To address the increasing need for space to accommodate economic growth and activity, Riyadh has been growing rapidly for decades. This growth, together with motorization, created low density and sparse settlements in Riyadh, as in many urban regions. This phenomenon is often called 'urban sprawl.'

Although urban expansion was a convenient solution to Riyadh's rapid growth, this development was not efficient. Urban sprawl has created many challenges for the city and for public authorities, including in transport. On the one hand, it creates a high dependency on cars, leading to high per capita energy consumption. On the other hand, urban sprawl makes the development of public infrastructure very costly.

In addition, Riyadh has a long-standing dependency on cars. This car dependency may impact the potential success of TOD. Furthermore, the sociodemographic composition within the public transit system's coverage area may present a challenge. People who do not want to use public transport may live within the trip coverage area, and they may continue to use their cars. This issue is referred to as residential self-selection (Cao, Mokhtarian, and Handy 2009).

Residential self-selection suggests that people tend to live in areas that satisfy their travel preferences. According to Cervero and Duncan (2008), people living near existing train stations tend to commute

by rail more often than residents newly served by a rail network. This finding is very relevant for Riyadh, which has no transit system and a strong dependence on cars. Thus, people living within the coverage areas may not use the metro or bus system.

Although Riyadh's overall demographics may change in the long run, they will not change automatically. If residential development is not dense and supportive of public transport, people

who prefer to use cars will not relocate to places that are more conducive to cars. In turn, people who prefer public transport will not get a chance to move to trip coverage areas. Land use transformation and population redistribution are required to achieve that goal. Thus, urban density has two associated challenges. The first is the high car dependency of Riyadh's residents, and the second is the preference for car-dependent living that renders residential densification less effective.

Conclusion: Future Research

This study's main objective was to set a benchmark for Riyadh's public transport system. We analyze the number of potential trips that may shift from cars to public transport. From a design perspective, Riyadh's public transport network has the potential to cover as many as 30% of all car trips. However, there are challenges in achieving this goal, and it is not unreasonable to assume that the goal will not be achieved.

To determine whether the benchmark is achievable, we need to investigate the actual impact of the public transport system in terms of modal shift. Thus, our future research will first focus on the *impact of the proposed integrated public transport network on mode shares and the energy demand in Riyadh*. We suspect that the actual ridership of public transport will be less than its potential ridership because of three major challenges. These challenges are urban sprawl, car dependency and residential self-selection. Several policy instruments are available to address these challenges.

One potential solution to urban sprawl in Riyadh is Transit Oriented Development (TOD). TOD involves creating concentrated nodes of moderate-to-high-density developments supporting a balanced mix of land uses around transit stations. TOD encourages compact growth within a five to ten minute walk from quick and efficient public transit. The concept promotes the ideal of living, working, playing, shopping and learning in a pedestrian-friendly environment without the need for a car. The core aim of TOD is improving energy efficiency. Its major benefits include increased transit ridership, reduced traffic congestion and pollution, and more walkable and livable neighborhoods.

The core concept of TOD is density. Thus, it affects transit ridership directly by bringing more people within walking distance of public transit, increasing

the system's potentiality. However, TOD involves not only high-density development but also the integration of transport and land use. TOD leads to more walkability and less car ownership, resulting in greater use of public transit. It brings many activity destinations within walking distance of public transit, which facilitates its use by increasing travelers' activity options. The city authority has prioritized and developed a detailed plan for TOD around metro development in Riyadh. In this regard, our next aim is to investigate the impact of the proposed TOD development on mode shares and energy demand.

However, TOD's success in achieving a desired level of public transport ridership also hinges on two associated challenges. These challenges are car dependency and a preference for car-dependent living. Riyadh's long-lasting dependency on car use as the main travel mode is a major challenge. In addition to TOD, several other policy measures may be required to break that dependency. Riyadh must focus not only on providing incentives for using public transport but also on setting penalties for using cars. These policies should reflect environmental damage and energy gains. The basic principle is to apply different pricing policies to affect the relative costs of using cars and public transport. For example, parking fees, tolls or congestion charges can be levied on car users. Free trials, discounted long-term tickets and free car parking can be offered to transit users. These policies are designed to affect mode shares by increasing the system's efficiency rather expanding its coverage.

Car parking fees and tolls are designed to influence car use at particular times and places. In contrast, fuel prices affect car use nationwide and are not specific to a particular time or location. Any policy that tends to increase the cost of using cars may discourage their use. Households tend to respond to increasing costs by reducing unnecessary or less

important car trips. They may also consider shifting to public transport if it is available.

Car parking fees may not affect car trips made with a personal driver. The driver may drop the passenger off at the destination and return later to pick them up. Many of the car trips considered in our analysis were made using a personal driver in Riyadh, especially because women could not drive in 2016. However, women can now drive, meaning that car parking fees may be a more useful policy. In addition, free public transport trials are helpful for acquainting people with the system. Discounted long-term tickets are useful for encouraging people to use public transport for longer periods. Thus, we aim to analyze the impacts of changes in car and public transport costs on mode shares and energy demand in Riyadh.

Finally, preferences for car-dependent living need to be addressed. Within the concept of residential self-selection, users' preferences or attitudes are thought to have a strong influence on their choices (Bohte, Maat, and Van Wee 2009). People may be less likely to change their decisions and, thus, are less likely to be influenced by TOD policies. However, research also suggests that people's travel attitudes change in the long run after they relocate to high-density areas (De Vos, Ettema, and Witlox 2018). Often, various soft measures, such as motivation and awareness regarding public transport, can be used to affect such preferences. However, soft measures are difficult to assess before they are implemented. Thus, Riyadh may need to act to influence travel attitudes or preferences and facilitate and ease public transport use.

High-density and walkable neighborhoods and pricing policies are essential to encourage a modal shift toward public transport. Our subsequent research will assess the impacts of these initiatives from mode-share and energy-demand perspectives.

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A green geometric graphic consisting of several overlapping triangles and polygons, located in the top-left corner of the page.

Notes

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About the Project

This study is part of the ongoing project, KAPSARC Spatial Urban Energy System. The project comprises two components: an urban energy model and a spatial economic model. It also has three objectives. The first is to improve energy efficiency through transit-oriented development (TOD) in the transportation and electricity sectors. The second is to gain additional efficiencies by realizing the potential opportunities of TOD's innovative and smart technologies. The third is to investigate the energy and economic impacts (including on real estate development) of transportation, land use and urban planning interventions in Riyadh.

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