An integrated urban-transport smart growth model around metro stations: A case of Qatar

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ABSTRACT

Urban growth strategies are incorporated for land-use planning and transportation to facilitate people's movement towards a mass transit system. This requires transport demand analysis of a particular area so that, if possible, urban re-planning can be done to support long-term sustainable use of the transportation system. The paper focuses on the study of transportation demand analysis in some stations of the recently opened metro system in Qatar. The study uses hypothetical scenarios of land use density to analyze transportation demand. A regression model is used to assess the relationship between the generated transport demand from each type of land use, which shows that the land-use type can substantially impact the ridership of a mass transit system. Based on the analysis conducted in this paper, it can be concluded that if ridership in a particular area is to be increased, its development for mixed land use might be a good option. The proposed mixed-use planning and the insights developed in the paper are expected to help urban planners in different countries with similar urban growth and development situations.

Introduction

Urban planners need to consider people's movement around the urban areas when considering sustainable land-use planning, decongesting the road network, and promoting economic growth. The planners also need to focus on retaining the social and cultural fabric in the area. However, increased vehicle ownership and lagged development of roads and associated infrastructure (like parking, side roads, and expressways) create congestion. Such a situation increases waiting time, pollution in the area, unproductive use of fuel, and the loss of economic activity due to congestion. Bilbao-Ubillos (2008) mentions that the loss depends on the cumulative value of wage, reduced vehicle speed, and the time taken to the destination of economic activity. Bilbao-Ubillos (2008) also mentions that such congestions also increase noise and emissions in the area.

One solution to avoid congestion is to strengthen the public transportation system, such as buses and metros. Examples of the metro stations in Bangkok and Singapore can be taken, where stations are integrated with economic and social activities and residential activities

in some areas. Singapore's model provides a hub and spoke transport concept for integrated bus and metro movements to reduce travel time and facilitate social and economic planning around the station. This type of planning, often called transit-oriented development (TOD), is a well-known paradigm of metro transport enhancement, urban compactness, accessibility, and interconnectivity.

This paper focuses on Qatar, where the metro system is in operation since 2019. The development of mass transit is made as a part of the Qatar National Vision 2030 (QNV-2030) adopted by the government (Tan et al., 2014). Therefore, planning for increased mobility through better land use, accessibility, and mobility around the station becomes important.

The main objective of the paper is to study the current ridership and assess the changes in the train ridership from a set of selected stations when there are changes in the land use density. The objective is important to assess transport demand around the metro stations due to the choice of land use options. The viability of the station and the ridership are important factors for the continued economic operation of the rail system. The paper considers three stations that serve

Al-Ghanem district in central Doha, which is an old locality. The study seeks to answer the question regarding the relationship between metro ridership and the implementation of smart growth plans around the stations.

The paper is structured in four sections. The first section provides the introduction, which also includes a brief review of the literature. The methods and materials, and features of the study area are mentioned in Section "Methods and Materials." The results and discussion, and scenario analysis are given in Section "Results." Finally, in Section "Discussion," conclusions, and limitations and future research directions are provided.

Literature review

The importance of mass transit in urban areas has been the focus of many researchers due to the need for faster mobility and reduced congestions, thereby reducing the need to make investments in further expansion of roads and infrastructure. However, in urban areas, due to relative economic prosperity and social stability of the population, people opt for higher ownership of vehicles, which can lead to urban problems such as pollution and congestions, thus impacting the livability in those areas (Ling et al., 2016). The integration of mass transport system and land use is important in urban areas (Babakan and Taleai, 2015); therefore, a balance of land use, livability, and mobility with economic prosperity become important in urban areas (AlSuwaidi and Furlan, 2018). For example, in Singapore urban model, the ownership of the vehicle is allowed. The country has fixed the annual growth in the number of vehicles. However, ownership is allowed only when a competitive price bid for entitlement is successful (Chu, 2015). This measure is also complemented with mass transport system development so that all areas can be accessed either through a rail system or a bus system. What is clear here is that in urban planning, mass transit is an important factor for mobility.

Smart growth and transport planning

Smart growth is associated with development and growth to the quality of life. Smart growth focuses on achieving growth sustained over the long term (Onyschuk et al., 2001). Smart growth focuses on managing and coordinating land-use planning and transportation to address social and economic aspects. For smart growth-based transportation, planners have to aim at fewer vehicle trips and less parking demand in urban areas by integrating bicycling, transit trips, or walking. Researchers have incorporated smart growth planning strategies and transit-oriented development (TOD) for urban land-use planning. In TOD, the focus is on the systematic integration of public transit and land use. Scholars such as (Li et al., 2010; Ma et al., 2018; Mosadeghi et al., 2015; Motieyan and Mesgari, 2017; Nguyen et al., 2015; Peng et al., 2017; Ren et al., 2019; Zheng and Peeta, 2015) have conducted studies on smart growth and TOD. These studies provide some common aspects of transportation: 1) integration with metro transit ridership; 2) compactness in terms of land use; 3) ease in accessibility; 4) extensive connectivity; and 5) value of real estate around the area. These aspects should be identified and analyzed for the sustainability of the transit system.

Urban-Transportation planning in Qatar

Qatar has experienced rapid urban growth in the last two decades. Qatar has adopted the principles of sustainability, diverse transportation systems, and compact mixed-use areas in the city (Eiraibe et al., 2015) for urban development or redevelopment. Qatar aims to build a series of megaprojects designed to encourage global investment and tourism (Salama and Wiedmann, 2016), necessitating integrating the built environment with the transport system (Hubschneider, 2011). Such integrated planning should also focus on the individual's perception of transportation dynamics (Warith et al., 2020).

Qatar has adopted the Qatar National Master Plan (QNMP) 2032, which includes sustained development of transportation systems through railways, public bus transportation services, and highways. Qatar plans to develop 300 km of a light rail system with four lines and 98 stations that connect the international airport, stadiums, and urban areas. This development is in line with the Qatar National Vision 2030 (Alsaeed et al., 2018). Since 2019, three lines and 37 stations are in operation (Fig. 1). The new development in transportation is expected to increase the mass ridership towards the public transport system in urban areas (Litman, 2012).

Methods and materials

The methodology used in this paper is described in Fig. 2, which shows the identification of the research problem as the first step. In the next step, the indicators to be used for the analysis are identified based on the literature review. The case area for the application of the method is described in brief in the following step. Data required for the analysis are collected from Qatar Rail (QR), the Ministry of Transportation and Communications (MOTC), and the Ministry of Municipality and Environment (MME). Scenarios are generated for the assessment of land-use planning and transportation demand. Recommendations are made at the end of the study for the implementation of the study's outcomes.

Identification of indicators

There are four smart growth indicators identified in the literature: land use density, metro transit ridership, compactness level, and accessibility. Most of the authors consider at least three of the indicators, as shown in Table 1. The type of land use around the station impacts the generation of metro ridership. Compactness refers to the similarity of land use around a given area. Hence, higher compactness means more homogenous land use, which may have a different metro ridership than those with lower compactness. Accessibility is measured by the trips generated and attracted around the study area (Ma et al., 2018). Accessibility depends on the travel time, the road's capacity, and the traffic generated or attracted by the road. The accessibility models consider the travelers' perceptions of the opportunities that are closer and more desirable (Geurs and van Wee, 2004). However, due to the focus of the study and the data availability, only two indicators, land-use density, and metro ridership, are used here.

Land-use density

Land-use density is an important parameter for integrated urban and public transportation planning. Motieyan and Mesgari (2017) mention that higher land-use density in an area generally leads to a higher potential to increase walkability and cycling by the neighborhood residents. Land-use density (D_i) is calculated with Eq. (1). However, in this paper, the land-use is clustered into five (i = 5) types, 1: residential, 2: commercial, 3: mixed-use, 4: public spaces, and 5: undeveloped.

$$D_i = \frac{\text{Area for land use } i}{\text{total area}} \tag{1}$$

Metro transit ridership

Cervero and Kockelman (1997) mention three factors as important for increasing the metro's ridership. They mention that land-use density leads to transportation accessibility, diversity of land use, the population from around the area, roads, walkability, and parking availability as important criteria. The authors mention that increasing land-use density helps increase the trips generated from around the metro station and trips attracted by the metro station. Metro trips
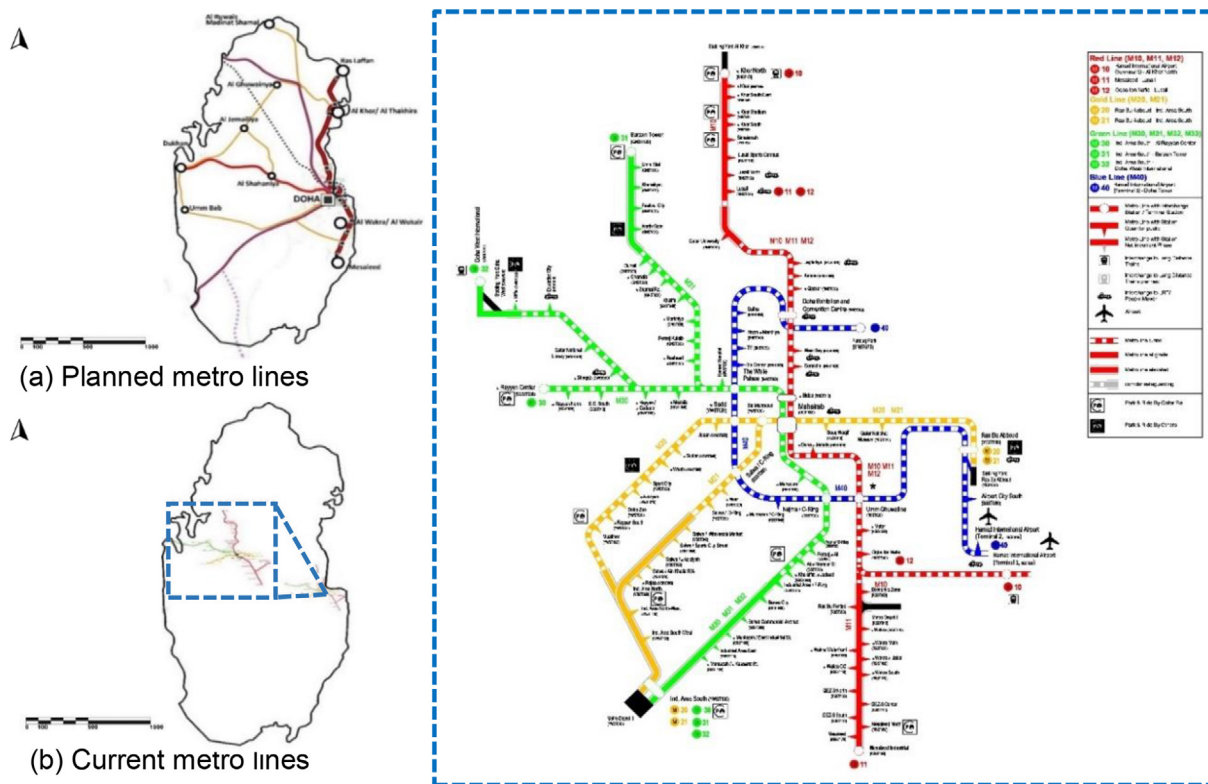
Fig. 1. Qatar Metro lines and stations (Source: corp.qr.com.qa).

are based on the rate of trip generation, trip attraction, and land-use density. Therefore, based on Ma et al. (2018), the formulation given in eq. (2) calculates the ridership for different land uses. Motieyan and Mesgari (2017) also mention transit-oriented trip generation based on land use in an area.

$$Total\ Ridership = \sum_{s \in S} \sum_{i \in I} (O_s + d_s)D_i \tag{2}$$

where (O_s) refers to trip generation for a station (s), and (d_s) refers to trip attraction due to particular land-use density (D_i).

Smart growth principles

Researches have incorporated smart growth planning strategies for station areas to assess transportation demand. Common principles observed in the research are; 1) rail transit ridership, 2) compactness, 3) accessibility, 4) connectivity, and 5) property values. Most of the research focuses on mixed-use municipalities and neighborhoods to assess smart growth in an area. Transit planning becomes important in the study area as some parts of the current land use planning for smart growth are still emerging.

Study area

Al Ghanim (Zone 16), Fig. 3, is located within Doha's central city. The district area is about 34,000 sq. m. with a population of approximately 126,000. It is amongst the older Doha area with an attractive urban fabric based on the building styles and the allotted plots (Doha Metro project, 2020).

The chosen location consists of old Al Ghanim (Zone 16), Zone 17, and Zone 6. These are considered as one of the oldest areas in Doha, where Souq Waqif (traditional bazaar), one of the most known traditional markets in the State of Qatar, is located. The area is close to

two significant projects: 1) Msheireb Properties' development, and 2) Qatar National Museum. Ras Abu Aboud street in the study area offers a high degree of accessibility and connectivity to many focal points around it. The roads support walkability and the direct flow of movement, with linkage to visitors attractions such as Gold Souq (bazaar), Souq Waqif, and old Dar Alkutub. Other older neighborhoods, AlAsmakh (Zone 4) and AlNajada (Zone 7), also share similar characteristics. Zone 6 also has a public bus interchange station, which provides connectivity to other city areas. Fig. 3 shows the Gold underground metro line section with the three stations within the study area. It is worth mentioning that Msheireb station is the central station of the Gold Line.

Data collection and analysis

The data on metro ridership were collected from Qatar Rail (QR), and spatial data related to metro land use and its density were obtained from the Ministry of Transportation and Communications (MOTC) and Ministry of Municipality and Environment (MME). The data on ridership were collected in February 2020, and approximately 5000 records were collected before the COVID-19 pandemic situation in Qatar.

Land use density

The land use in the study area is given in Fig. 4. The land-use density in the study area is given in Table 2. It is worth mentioning that the residential area - highlighted in yellow - has the largest density, followed by the commercial areas. As noted in Fig. 4, some of the residential areas are also used for commercial purposes.

Metro transit ridership

The ridership data of the trip generation and trip attraction for Msheireb (downtown area), Souq Waqif, and National Museum sta-
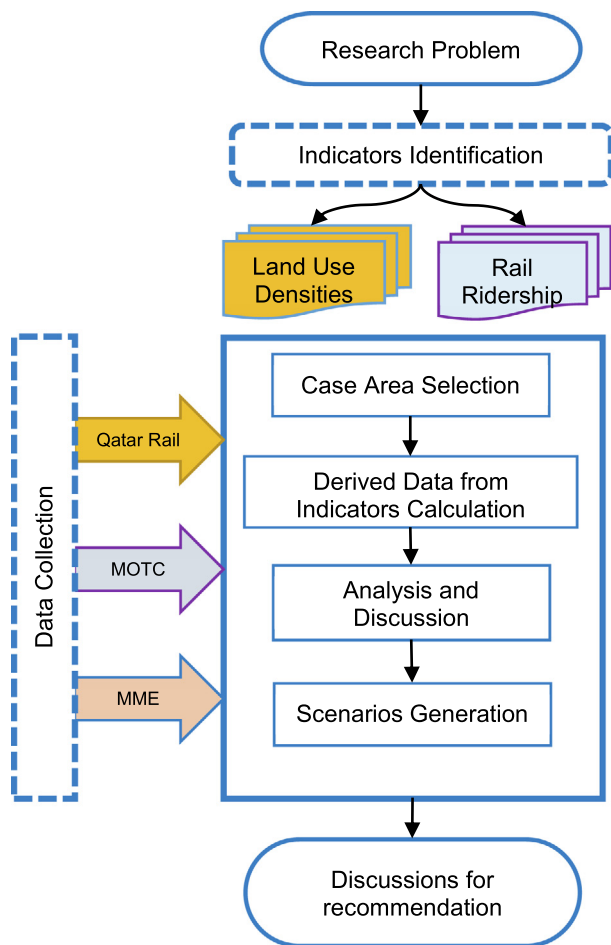
Fig. 2. Methodology Framework.

Table 1
Land use density.

Land use	Area (sq. m.)	Density
Residential	11,560	0.34
Commercial	10,200	0.30
Mixed-use	6,120	0.18
Public Spaces	3,740	0.11
Undeveloped	2,380	0.07
Total	34,000	1

tions were collected in Feb 2020, before the COVID-19 related closure is illustrated in Fig. 5. The trip pattern shows that the ridership generated in Msheireb in the morning is almost double that for Souq Waqif station. Also, it shows that the trips related to the National Museum are low at all times. The reason could be that the museum is recently opened to the public, and people can visit this during working hours only.

Table 3 shows the total monthly ridership for Msheireb (S_1), Souq Waqif (S_2), and National Museum (S_3) stations. The number of monthly ridership in the Souq Waqif station is slightly higher than Msheireb station, while it is least at the National Museum in all periods. As mentioned earlier, commuters travel to the National Museum station to visit the national museum area. However, commuters traveling to Msheireb station can also go to Msheireb downtown and the Corniche (tourist area). It is worth mentioning that Souq Waqif and National Museum stations started operation in November 2019 Table 4.

Results and discussion

Based on eq. (2), the trip ridership generation for the residential, commercial, mixed-use, and public space land uses are the highest for Msheireb, followed by Souq Waqif and National Museum. The lowest rate of ridership is for the National Museum station. This outcome shows a relationship between the number of trips generated in each station and the land use densities. For instance, Musheireb station has the highest number of trips, with the highest density of residential land use.

Scenario generation

The potential impacts of smart growth planning on land use and transportation for sustained transit-oriented development are discussed here. Miller and Hoel (2002) mention that smart growth principles application enhances the neighborhood's diverse urban activity. In this paper, three hypothetical scenarios are developed (using random numbers) for land use density to assess metro ridership (Table 5). The scenarios are generated based on a hypothetical random selection of land-use densities and are used as inputs to calculate rail ridership per land use. Scenario (1) considers the current land-use density. Scenario (2) considers equal land-use density for mixed residential and commercial activities with adjustments in other land use. Scenario (3) considers reduced residential land-use density but increased density for other land uses. The planners can evaluate different scenarios to integrate urban transport with land use to maximize ridership and land utilization.

Table 6 illustrates the results generated for the three scenarios for different land uses around the stations (S1, S2, and S3). It is found that scenario (3), which has the highest land-use diversity, is the best scenario to apply smart growth principles in the study area since it provides the highest land-use diversity and results in the highest metro ridership.

A regression model (eq. (3)) was developed to examine the relationship between total ridership and ridership per land-use type. The results from the regression analysis shown in Table 7 illustrate a significant correlation between ridership per land use and total ridership at a 0.05 level of significance.

$$TR = a + b(O_s + d_s)D_i + \varepsilon \qquad (3)$$

where; (TR): total ridership, (O_s):trips generated, (d_s):trips attraction, (D_i):land use density, (a): intercept, (b):slope, (ϵ):residual value.

Residential ridership explains 94.4% of the variability of the total ridership. Similarly, commercial ridership, mixed ridership, and public spaces ridership represent 96%, 92%, and 94% of the variability of total ridership. Fig. 6 shows the regression between ridership per land use and total ridership.

Discussion

The relationship between the transportation network and land use is critical in maintaining the well-being of the entire community. It is worth mentioning that metro stations have led to a higher occupancy rate of the buildings. Therefore, it is only prudent to seek the possibility of locating the activities and the residential sector close to the stations. Currently, most of the areas around the stations are either being demolished or redeveloped. It is proposed that those areas near the stations be developed as residential areas (Fig. 7). These residential areas can also allow mix-use, like in Singapore, where lower levels in some residential complexes are used for commercial and community activities and serve as the transit stations for rails and buses. Such a mixed development can eliminate additional transport costs, thus saving on living costs (Leinberger, 2008; McCann, 2000). Hence, this will create transit trips evenly throughout the metro operation time.
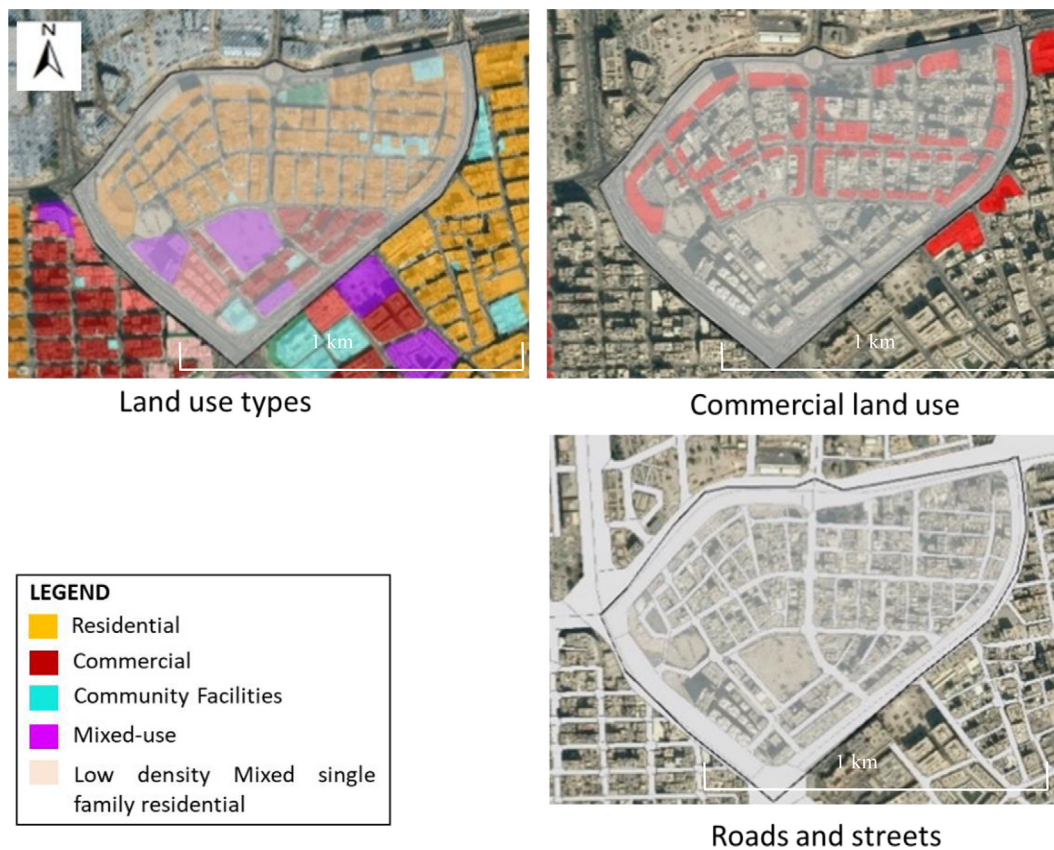
Fig. 3. The study area.

Fig. 4. Al-Ghanim district land use.

To increase the activities, however, urban planners should also focus on the affordability of the property in the area. When properties around the station are not affordable, then they might be occupied just by one type of activity, for example, commercial, and would not create regular transportation demand. For smart growth planning, livability in the area becomes important. To increase livability, on the other hand, affordability of the area becomes impor-

tant. When an area is relatively affordable, it can create sustained demand for various services, including transportation. Livability and availability of transportation facilities would become like a watershed creating mobility around the area, thus making mass transportation a viable option. However, to implement such a concept, urban planners may consider some of the following approaches.

Table 2
Monthly ridership in the three stations (Source: Qatar Rail).

Month	Msheireb (S_1)	Souq Waqif (S_2)	National Museum (S_3)
May 2019	46,399	0	0
Jun. 2019	72,808	0	0
Jul. 2019	45,793	0	0
Aug. 2019	59,131	0	0
Sep. 2019	52,281	0	0
Oct. 2019	83,501	0	0
Nov. 2019	96,313	29,962	11,882
Dec. 2019	201,013	227,689	72,056
Jan. 2020	217,148	207,917	74,512
Feb 2020	193,433	199,074	74,358

Table 3
Ridership Generation for stations per land-use (trips/m²).

Ridership per land use (trip/m²)			
	S_1	S_2	S_3
Residential land use trips	4409	4216	1752
Commercial land use trips	3891	3720	1546
Mixed-use land use trips	2335	2232	928
Public Spaces land use trips	1427	868	567

- Increase the land use density within the district to reduce unit land costs
- Promote mix-use as it will help to create more uniform transportation demand in the area.

- Increase the diversity in the afforded housing options (apartments over shops, hostels); this will make the area attractive to multiple family types and create vibrancy in the area.
- If applicable, eliminate or reduce taxes on the development due to the long term impact of such development
- Cross subsidize mass transportation, if necessary
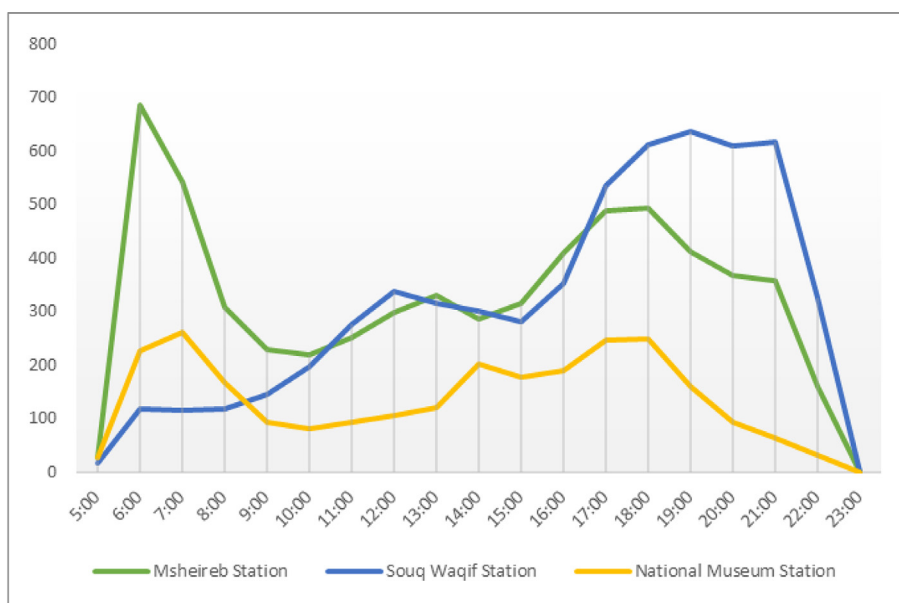
Trips generation
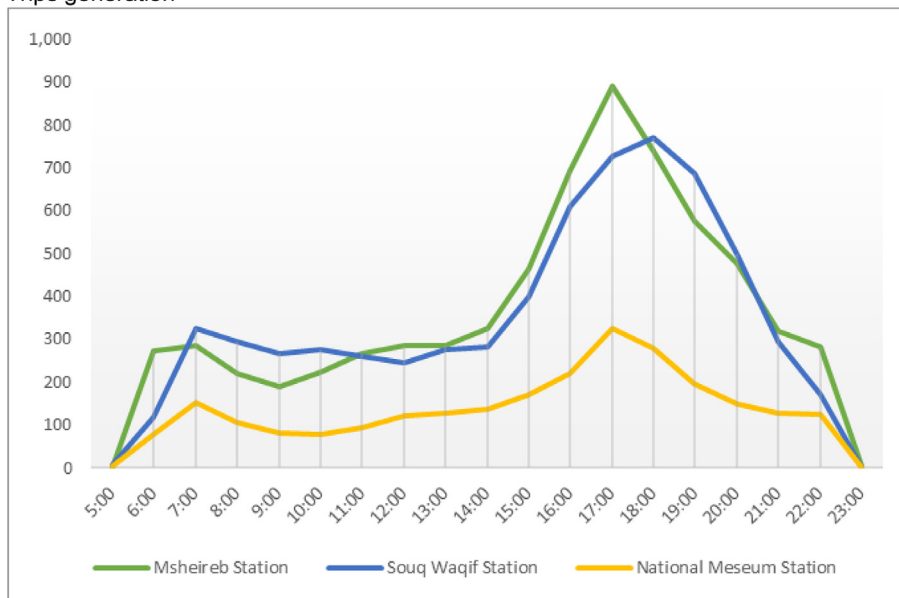
Trips attraction

Fig. 5. Ridership frequency.

Table 4
Indicators from the literature.

Reference Variable	Li et al., 2010	Ma et al., 2018	Bautista-Hernández, 2020	Riggs et al., 2020	Ren et al., 2019	Peng, Li, and Choi, 2017	Nguyen et al., 2015	Zheng and Peeta, 2015	Zhou et al., 2014	Ercan et al., 2017	Al-Mosaind, 2018	Moeckel and Lewis, 2017	Muley, 2011	Foth et al., 2013	Johansson et al., 2017	Alotaibi and Potoglou, 2018
Land-use density	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Metro Transit Ridership		✓		✓	✓		✓		✓	✓	✓	✓	✓		✓	
Compactness	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Accessibility	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓

Table 5
Scenarios for land-use smart distribution.

		Land use i	Density D_i	Area (m2)
Scenario 1 (current)	1	Residential	0.34	11,560
	2	Commercial	0.3	10,200
	3	Mixed-use	0.18	6,120
	4	Public spaces	0.11	3,740
	5	Undeveloped	0.07	2,380
		Total	1	34,000
Scenario 2	1	Residential	0.33	11,220
	2	Commercial	0.33	11,220
	3	Mixed-use	0.17	5,780
	4	Public spaces	0.16	5,440
	5	Undeveloped	0.01	340
		Total	1	34,000
Scenario 3	1	Residential	0.27	9,180
	2	Commercial	0.31	10,540
	3	Mixed-use	0.2	6,800
	4	Public spaces	0.22	7,480
	5	Undeveloped	0	0
		Total	1	34,000

Table 6
Ridership generation per land-use using smart growth principles.

	Scenario 1			Scenario 2			Scenario 3		
	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
Residential	4410	4216	1752	4280	4092	1700	3502	3348	1391
Commercial	3891	3720	1546	4280	4092	1700	4020	3844	1597
Mixed-use	2335	2232	928	2205	2108	876	2594	2480	1031
Public Spaces	1428	868	567	2075	1984	824	2853	2728	1134
Total	12,062	11,037	4792	12,840	12,278	5101	12,970	12,401	5153

Table 7
Regression Statistics.

|	Residential	commercial	Mixed-use	Public spaces
Multiple R	0.971929	0.980006	0.960893	0.970142
R Square	0.944646	0.960412	0.923316	0.941175
Adjusted R Square	0.944401	0.960237	0.922977	0.940914
Standard Error	150.114	126.948	176.6844	154.7494
Observations	228	228	228	228

Conclusions

This study is developed as an initiative to implement smart growth development principles around rail stations by focusing on the two important indicators, which are land use density and rail transient ridership. This is not to neglect the importance of the other two indices, which are accessibility and compactness in the study context. For transit-oriented development, it is necessary to create an environment that promotes transportation demand and increases livability. It is shown in this work that the selection of land use around an area has a direct bearing on the transit demand and, therefore, the long-term sustained use of mass transit systems. However, the area should have a rational level of compactness and focus more on different land uses.
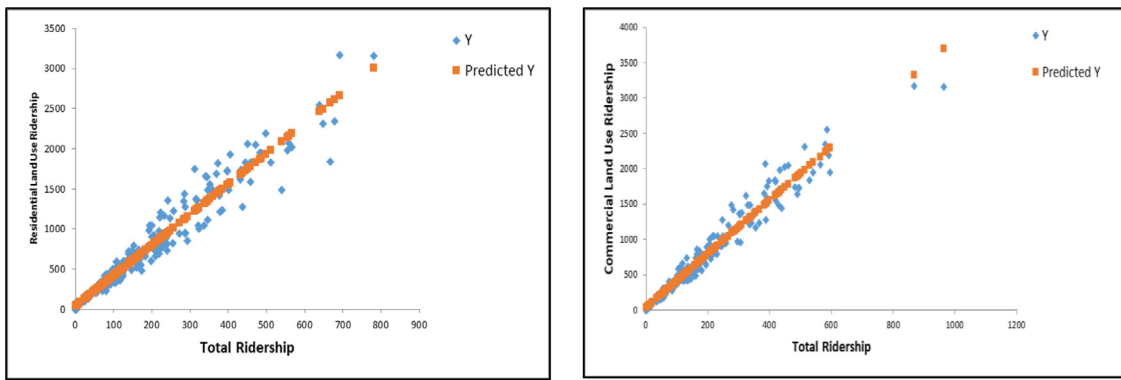
Regression for residential land use

Regression for commercial land use
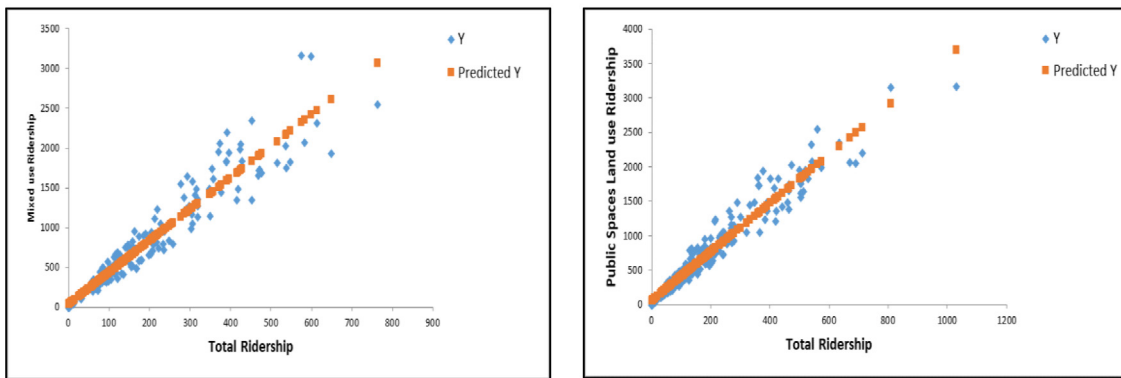
Regression for mixed land use

Regression for public space

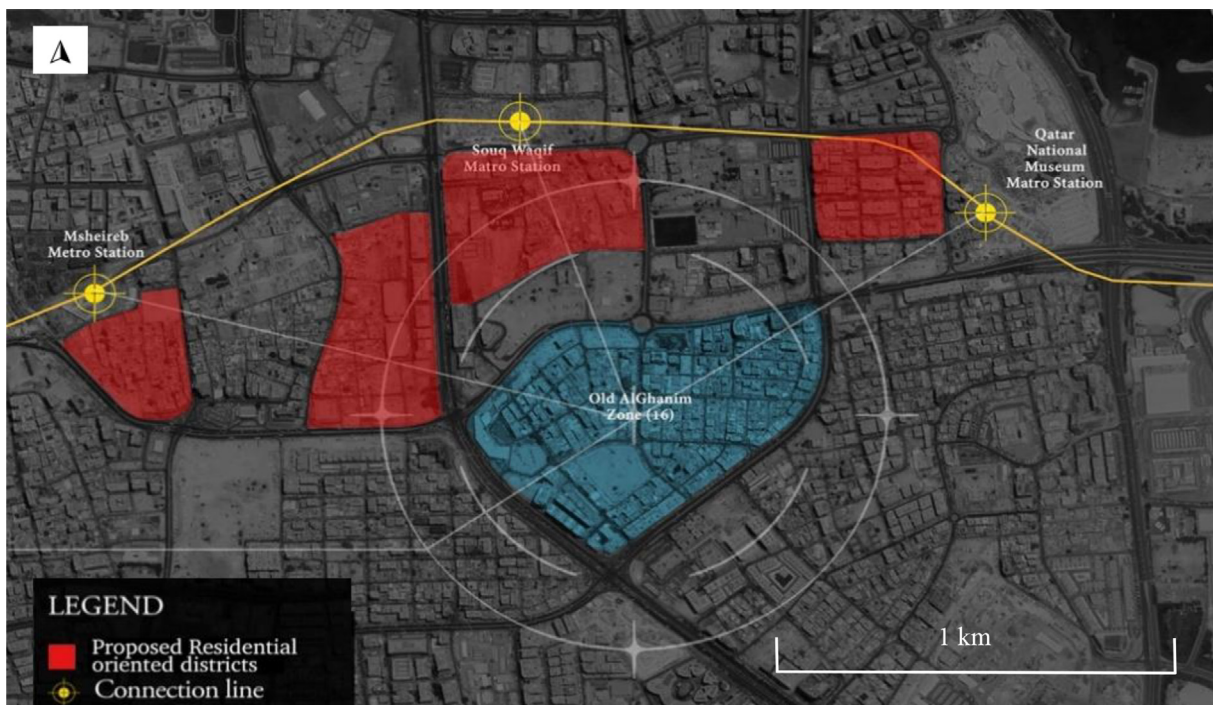**Fig. 6.** Regression of ridership for different land use.

Fig. 7. Proposed residential developments.

The paper uses the case of the Al-Ghanim district. The analysis shows that, if there is an opportunity, focusing on the diversity of land use can create a more sustained daily transportation demand than focusing only on one type of land use or only one type of attraction in that area. When land-use type is homogenous, it will create demand only at a certain time of the day; therefore, land-use compactness also becomes an important factor for metro transit ridership. It is to note that the planners/municipality can adopt certain strategies to promote the occupation of the area by residents and attract businesses. Whether temporary or permanent, additional attractions can be added in the area for people to visit and enjoy it. This will increase the attractiveness of the area and increase the ridership of mass transit.

Limitation and future work

This research study is limited by considering two indicators. The data used in this study is based on the data collected for a limited period, although they are complete for the considered time. The assumption on the future land use is made on hypothetical scenarios, which may be used by the planners, as the area around the stations is still under development. Therefore, the results obtained from the analysis should be taken as the basic and preliminary work.

Since the metro in Qatar is new and the city is in the re-planning stage, this research can be extended in a couple of directions.

- This research can be extended to include accessibility and compactness. This will require further data collection and development of different models, some of which are also mentioned in Ma et al. (2018).
- The research can also be extended to study the impact of socioeconomic and cultural aspects as well. As most of the citizens in Qatar own vehicles, increasing the ridership only through mixed land use can be challenging.
- The third aspect is the climatic factor, which many authors have ignored to study. Qatar generally has very hot weather for two to three months a year. Therefore, the impact of such a high temperature may cause a problem going to or moving out of the stations. Therefore, mixed-use land planning may have to be supported by planning for the mobility of the people (walking or bicycling) from their location to the stations. The impact of such mobility to and from the station on the ridership can be another direction of research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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