Planning of a Metro's System in Jeddah City: Integration of Points of Interest and Station Network Analysis Using GIS

Ahmad A. Soleman, Faisal Alyhaibi

Geomatics Department, Faculty of Architecture and Planning, King AbdulAziz University, Jeddah, Saudi Arabia – Ahmad.A.Soleman@gmail.com, Faisal0alyhaibi@gmail.com

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Abstract

This paper proposes the development of a metro system for Jeddah City in the Kingdom of Saudi Arabia, with the objective of reducing traffic congestion and enhancing transportation accessibility within the urban landscape. Our goals focus not only the planning of a metro system tailored to Jeddah's unique requirements but also the identification of optimal metro station's locations. To achieve this, a methodology that includes a comprehensive database containing key information such as major roads, points of interest (POIs), and population density across Jeddah City was employed. Through data analysis, including hotspot identification and metro network analysis using Geographic information system (GIS), the study Resulted in the formulation of a metro system plan for Jeddah City. Additionally, the research identified the most suitable locations for metro stations, thus laying the groundwork for an efficient and well-integrated metro network designed to meet the city's evolving transportation needs.

1. Introduction

In this paper, we propose the design of a metro system for the city of Jeddah in the Kingdom of Saudi Arabia, aiming to enhance public transportation and alleviate the ongoing traffic congestion problems in the city. Jeddah faces significant challenges due to limited options in transportation, mainly consisting of buses and private cars. As one of the largest cities in terms of population, with 3,674,361 residents constituting 14% of the Kingdom's population [1], Jeddah also has the highest car ownership rate in Saudi Arabia, with 5,051,320 cars, accounting for 24.20% [1]. This impedes the movement of residents and hinders sustainable urban development efforts. Based on these challenges, our project seeks to design a comprehensive metro model tailored to meet the needs of Jeddah and enhance transportation in the city. Our main objectives in this paper are twofold. Firstly, we aim to design an interconnected metro network covering the entire city of Jeddah. Secondly, we aim to identify the optimal locations for stations in Jeddah, covering the entire city while minimizing the number of stations and connecting high-density residential areas with key attractions in the city, ensuring each station operates at maximum efficiency. The ultimate goal is to promote public transportation, alleviate congestion, improve infrastructure, and reduce traffic flow.

The paper by Dong Lin, Zhipeng Zhou, Miaocheng Weng, Wout Broere, (2024) [2] provides a comprehensive overview of metro systems, covering construction, operation, and their impacts on urban development. It highlights the various construction methods, safety concerns, and opera-tional aspects, including fire safety, evacuation strategies, and air quality management. The impacts of metro systems on urban development, such as increased property values and improved public health, are discussed, emphasizing their importance in promoting sustainable urban transportation. The document calls for ongoing research to address challenges and optimize metro systems' benefits for cities, stressing the need for innovative solutions in construction, operation, and integration into urban development strategies to ensure their continued success and sustainability.

The research paper by KOIZUMI, NISHIMIYA, KANEKO (2013) [3] "Urban Transportation Characteristics and Urban Mass Transit in Developing Countries" by Yukihiro Koizumi, Noriaki Nishimiya, and Motoko Kaneko delves into the relationship between urban socio-economic indi-cators and traffic patterns across over 50 cities in developing countries. Key findings highlight a correlation between higher urban density and greater public transport usage, with lower car ownership associated with higher public transport uptake, though these correlations are less pro-nounced in developing nations. The emergence of "two-wheeler cities" in Asia, characterized by a significant presence of two-wheelers in urban traffic, diverges from global trends. The timing of urban mass transit system implementation is linked to cities' socio-economic development, with larger or wealthier cities more likely to adopt metro systems Methodologically, the study utilizes existing databases such as those from the Japan International Cooperation Agency (JICA), the World Bank, and the United Nations, treating cities as urban agglomerations rather than admin-istrative units. Regression analysis aids in identifying urban transportation characteristics. In con-clusion, while overarching global trends exist in urban transportation, developing countries, nota-bly in Asia, often exhibit unique patterns. The paper underscores the importance of tailoring urban transport strategies to these specific contexts and advocates for further research focusing on diverse city types and urban indicators.

The paper by Mahmoud Owais (2015) [4] "Issues Related to Transit Network Design Problem" delves into the Transit Network Design Problem (TNDP) and its multifaceted nature, spanning strategic, tactical, and operational realms of transportation planning. Mahmoud Owais highlights the intricate challenges inherent in TNDP, including its formulation complexities, combinatorial intricacies, and its NP-hard, multi-

objective nature. Despite advancements, the paper underscores the persistent need for additional research to address the unresolved issues within the TNDP do-main.

The paper by Mahmoud Owais, Abdou s. Ahmed, Ghada S. Moussa and Ahmed A.Khalil (2020) [5] "An Optimal Metro Design for Transit Networks in Existing Square Cities Based on Non-Demand Criterion" authored by Mahmoud Owais, Abdou S. Ahmed, Ghada S. Moussa from Assiut Uni-versity, Egypt, and Ahmed A. Khalil from Benha University, Egypt, presents a study focusing on enhancing transit systems in existing cities through the planning of a new underground metro network. Two models are proposed: a grid metro network and a ring-radial metro network, with emphasis placed on increasing overall system connectivity and minimizing passenger transfers. Using TransCAD software, the authors develop a methodology to optimize the cost–benefit ratio (CBR) of the transit network by minimizing transfers between stations. The results indicate that the ring-radial network model, particularly with one radial line, offers the highest CBR and enhances transit network connectivity.

The study concludes by highlighting the significance of considering both passenger transfers and capital costs in selecting the optimal metro network design. It is worth noting that the research received no external funding, and the authors declared no conflicts of interest. The methodology adopted for designing the metro relies on data collection and data integration with factors derived from literature reviews [3]. Key data include main roads, population density in district, and points of interest in Jeddah city. Ensuring the integration of these datasets, they are then stored in a da-tabase [2]. the data analysis process, focusing on analyzing population density in neighborhoods in Jeddah city, pinpointing hotspots to determine metro stations, and analyzing the metro lines net-work and connecting them to the stations [5]. Moving on to the results, the outcome entails the design of a metro network in Jeddah city and the identification of station locations.

works by emphasizing a data-driven, GIS-based approach tailored to Jeddah’s unique urban landscape.

2. Materials and Methods

2.1 Study Area

Jeddah, overlooking the Red Sea, serves as the primary gateway for travelers and pilgrims to Mecca, utilizing its international airport and seaport as the initial departure points.[5] Due to its strategic location on the Red Sea coast, Jeddah holds significant importance in the Kingdom's international trade movement, establishing itself as a central hub for business and commerce. Moreover, Jeddah is renowned for its enchanting beaches, upscale shopping centers, and diverse tourist and recreational facilities. The city sprawls along the western coast of the Kingdom, extending north and south over an area of 74,762 square kilometers [1,5], with an urban area exceeding 63,847 square kilometers.[5] As depicted in Figure 1, Jeddah boasts tourist landmarks such as the Abhor area, the northern and southern corniches, alongside artistic sculptures scattered throughout its streets. The city's population stands at approximately 3,674,316 inhabitants, constituting 14% of the total population of the Kingdom of Saudi Arabia. [1]

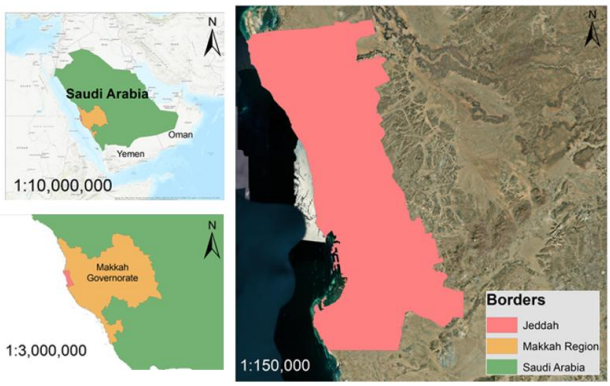

Figure 1: City of Jeddah (the study area**)**

2.2 Datasets

Acquiring relevant and reliable data is essential for conducting a comprehensive analysis for our study. We have adopted a multi-purpose approach to gather diverse datasets concerning various aspects of urban planning, infrastructure, attractions, and major roads in the city of Jeddah to facilitate the analysis and design of an integrated metro system. We have requested a set of data from reputable sources such as the Jeddah Municipality and the General Authority for Statistics in the Kingdom of Saudi Arabia These datasets encompassed a wide range of information shown in Table 1.

Data	Spatial Object	Format	Complete	Size
Main Street Network	Line	Shp.	Available	243KB
District	Polygon	Shp.	Available	122KB
Population Density	-	Exe.	Available	24KB
POIs	Point	Shp.	Available	3KB

Table 1: Master Data list

Additionally, before analysis, we evaluated the quality and reliability of acquired datasets. This involved a data compatibility analysis **Table 2** assessing data to ensure the integrity of our findings and conclusions.

Main Type of Conflict	Sub-category of Conflict	Redundancy	Compatibility Description	Resolved
Spatial	Geometric coherence	Fully	Different reference systems	Fully
	Topological coherence	Partially	Some Distracts are on top of each other	Fully
Semantic	Names Consistency	Partially	Multiple Polygons had the same Distract name	Partially
Temporal	-	None	-	-
Quality	-	None	-	-

Table 2: Compatibility Analysis

2.3 Database

The database should be organized according to the relationships between the data and cate-gorized as depicted in **Figure 2** for ease of search, access, sharing, and simplified development of the data.

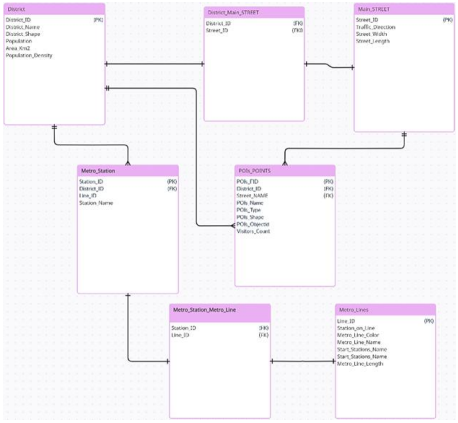

Figure 2: The workflow illustrates the classifications of the database

2.4 Methodology

(1) At the outset of the methodology, data was Acquisition, and key factors were identified from the literature reviews [2,3,4,5] to initiate the project. The data was narrowed down to the following variables: Points of Interest (POIs), Districts in Jeddah city, main streets, and population density of the city.

(2) Subsequently, the data integration process ensues, ensuring its compatibility to consolidate it into a comprehensive database.

(3) The data analysis process was conducted to identify the required criteria to meet the conditions for determining the locations of stations and the network of lines for the metro. These analyses involved determining the population density in each District in Jeddah city Figure 4, This process was conducted using the equation depicted in Figure 6. categorizing the main streets and analyzing their locations Figure 5, followed by identifying hot spot points. Subsequently, the validation and accuracy of the data were verified.

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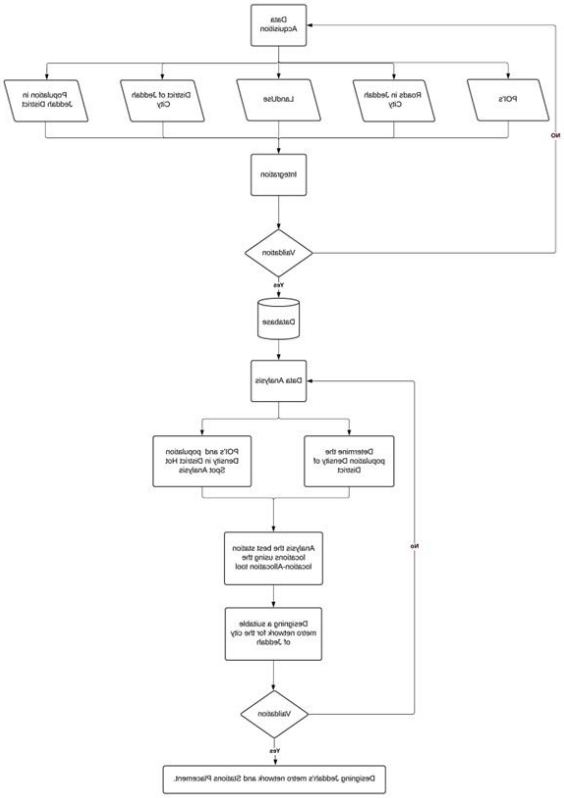

Figure 3: Methodology Workflow

3. Data Acquisition

In adherence to established methodologies and regulatory criteria, the incorporation of this design mandates the solicitation of the ensuing data parameters:

3.1 Main Streets

Data was obtained from the Jeddah Municipality

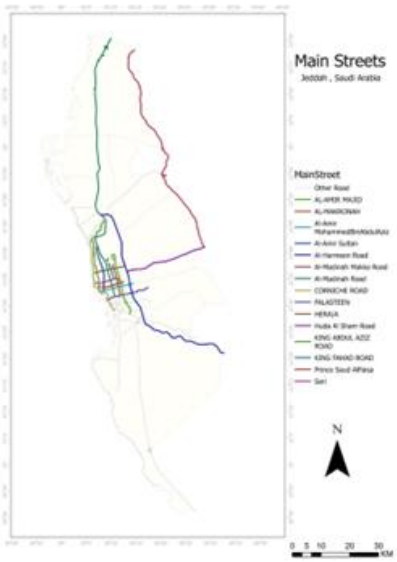

Figure 4: Main Streets

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3.2 District of Jeddah city

Data was obtained from the Jeddah Municipality

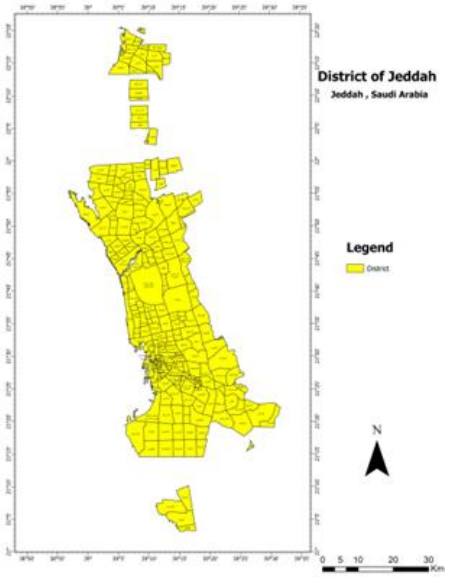


Figure 5: District of Jeddah

3.3 Population

Data was obtained from the General Authority for Statistics.

Total	Females +65	Females 15-65	Females 0-14	Males +65	Males 15-65	Males 0-14	Neighborhood Name
237,663	3,803	103,806	30,107	4,703	103,855	31,179	Al-Safa
127,771	1,999	54,321	15,099	1,902	54,702	15,736	Al-Marwah
117,175	1,959	18,084	4,808	1,738	17,878	4,765	Al-Rahma

Table 2: Population in Jeddah 2022

3.4 Interest point in Jeddah:

Attraction points in the city were identified based on their locations and the number of visitors in the area, using data from the Jeddah Municipality website.

Some areas lack clear information, but their relevance to Vision 2030 or government-designated locations has been acknowledged.

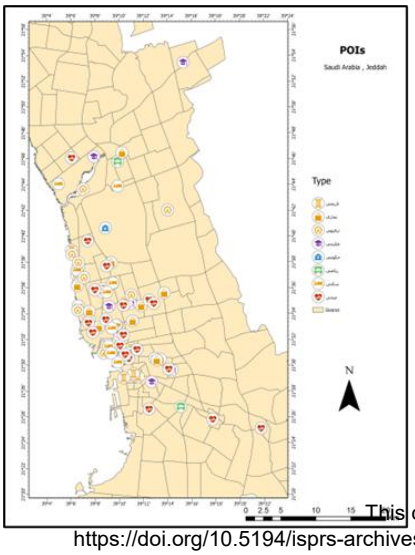


Figure 6 : POIs in Jeddah City

3.5 Land Use in Jeddah city

Data was collected from previous projects at the college

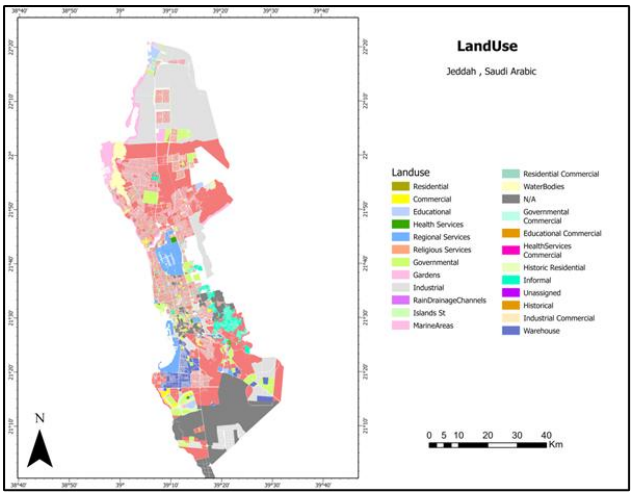


Figure 7 : LandUse in Jeddah City

4. Data Analysis

Determine the population Density of District Figure 8,9

$$\text{Population Density} = \frac{\text{People}}{\text{Area}}$$

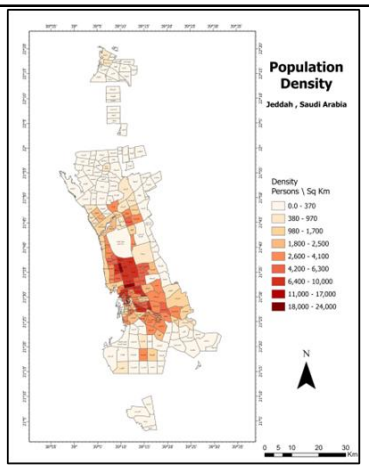


Figure 8: Population Density in Jeddah City

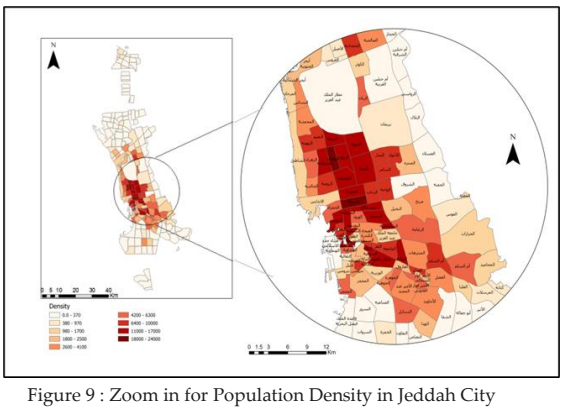


Figure 9 : Zoom in for Population Density in Jeddah City

4.1 POIs and population Density Hot Spot Analysis

We require a hotspot analysis to identify high-density population areas and Points of Interest (POIs) to accurately determine theoptimal locations for stations Figure 9.10

$$Gi* = (X - \mu) / (\sigma * d)$$

X: is the value of the attribute for each feature.
μ:is the mean value of the attribute for all features.
σ: is the standard deviation of the attribute for all features.
D: is the distance or spatial weight between each feature and its neighboring features.

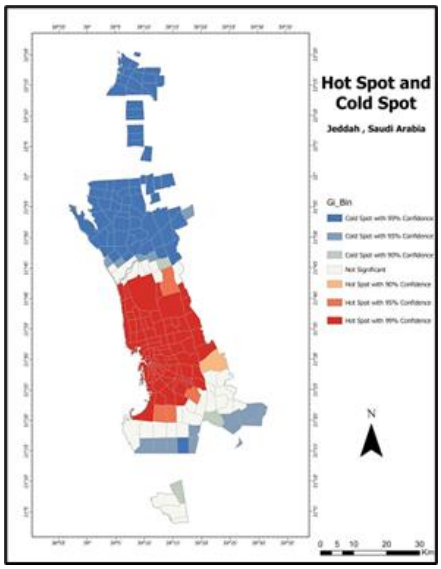


Figure 10 : population Denly

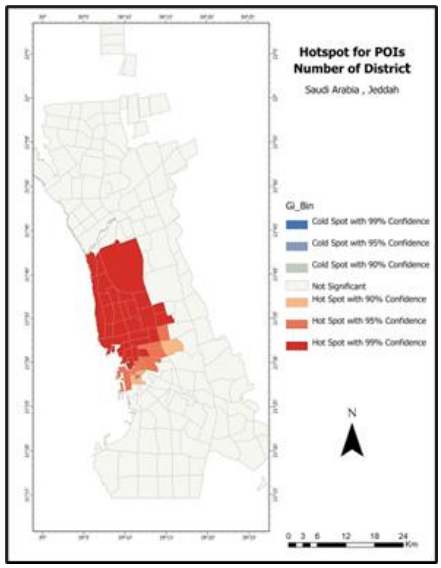


Figure 11: HotSpot number of POIs

4.2. Analysis the best Stations Location

Normalization formula often used in various scientific and engineering disciplines. It is used to scale a value within a specific range. Figure 11,12

$$N = \frac{PI - PI_{min}}{PI_{max} - PI_{min}}$$

PI: is the current value of the parameter being normalized.
PImin: is the minimum value of the parameter in the dataset.
PImax: is the maximum value of the parameter in the dataset.
N: is the normalized value, typically ranging from 0 to 1.

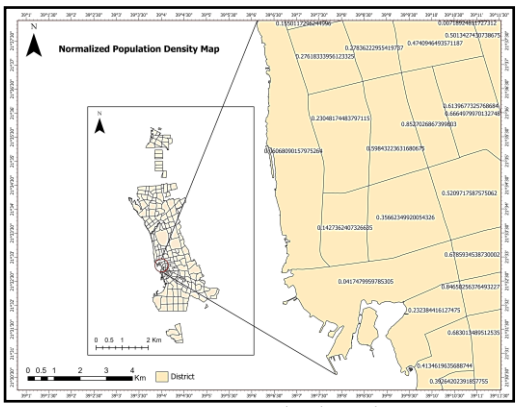


Figure 12 : Normalized Population

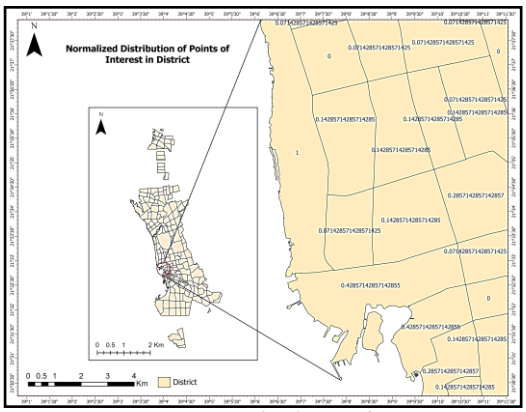


Figure 13 : Normalized Point of Interest

4.3 Analysis the best Stations Location

After applying the equations, a feature extraction process to points should be conducted to initiate the location allocation process

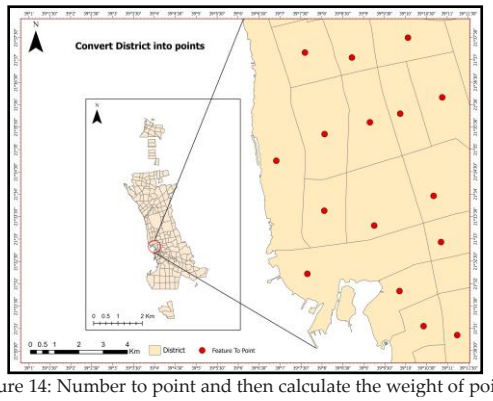


Figure 14: Number to point and then calculate the weight of points according to the district.

Figure 13: Number to point and then calculate the weight of points according to the district.

4.4 Location-Allocation Analysis

$$\text{Minimize} \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij} x_{ij}$$

dij : is the distance or travel cost between demand point *i* and facility *j*.
xij: is a binary variable that equals 1 if demand point *i* is allocated to facility *j*, and 0 otherwise.
m : is the number of demand points.
n : is the number of facilities.

$$\sum_{j=1}^{n} y_j = p$$

yj : is a binary variable that equals 1 if facility *j* is selected, and 0 otherwise.
P : is the total number of facilities to be located.

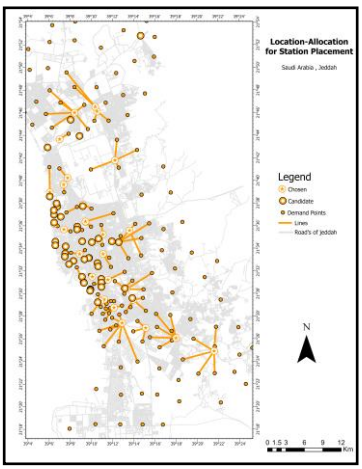


Figure 15 : The figure shows the proposed point distribution.

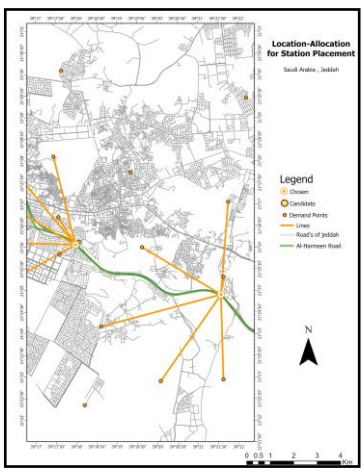


Figure 16 : Figure showing the selected locations in Jeddah city.

4.5 Analysis Best Routes

After identifying the station areas, the next step is to determine the optimal routes connecting these stations, ensuring they cover and integrate the previously identified factors.

$$_{i,i+1}\text{Minimize} \sum_{i=1}^{n-1} C$$

Ci,i+1 represents the cost of traveling from point *i* to point *i*+1.
n is the total number of points or stops.

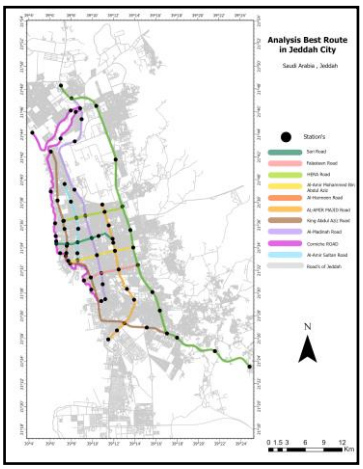


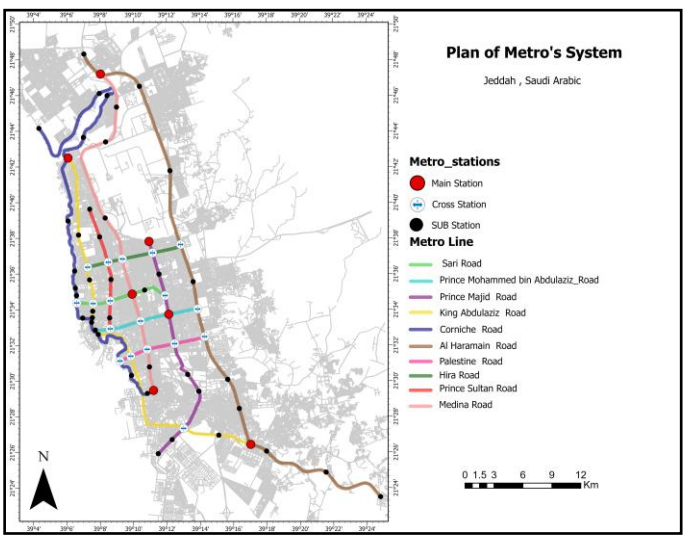
Figure 17: Location of stations and the line connecting them

5. Results

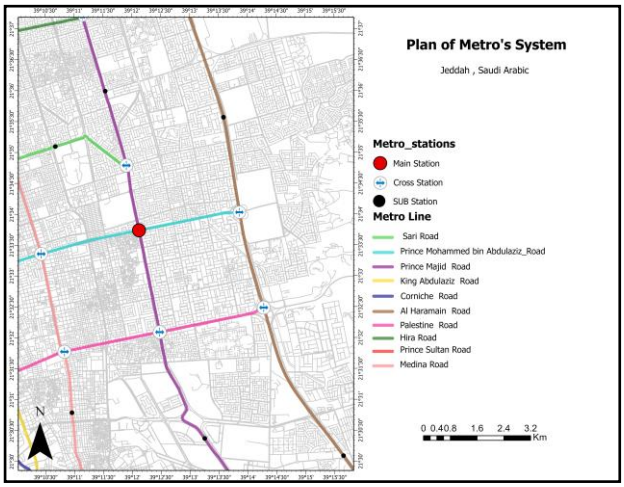
After conducting the hotspot analysis, we successfully identified areas of peak population density and key Points of Interest (POIs). This analysis enabled us to accurately determine the optimal locations for metro stations.

Following the application of relevant equations, we performed a feature extraction process to convert the data into points, initiating the location allocation process. This step was crucial for the precise placement of the metro stations.

Subsequently, we determined the optimal routes connecting the identified stations. These routes were designed to ensure comprehensive coverage and integration of all previously identified factors, including population density and POIs. This strategic planning guarantees that the metro system will effectively serve the highest demand areas, providing efficient and convenient transportation solutions for the residents of Jeddah City.



5.1 Lines Information



Cross Stations	Stations	Line Length	Name
5	6	9.7Km	Sari Road
5	5	10.9Km	Prince Mohammed bin Abdulaziz Road
5	11	24.8Km	Prince Majid Road
6	11	41.9Km	King Abdulaziz Road
7	16	56.2Km	Corniche Road
4	14	62.4Km	Al Haramain Road
5	5	9.1Km	Palestine Road
5	5	10.Km	Hira Road
7	3	12.7Km	Prince Sultan Road
10	5	36.8Km	Medina Road

Table3: The following table provides information on the interconnected lines and all their analyses

5.2 Stations Information

The following table provides information on the interconnected Stations and all their analyses.

Total Stations	
7	Main Station
18	Cross Station
42	SubStation
67	Sum

Table4: Number and types of stations

District	Number of POIs	Number of Stations
Al-safa	4	5
Al-Marwah	2	4
Al-Shatti	14	11
AL WAHAH	4	2
AL NUZHA	2	3

Table5 : Number of stations in the district

5.3 Main Stations Information

The main stations were identified based on land use and land area, ensuring that the stations connect all directions and routes. The following table provides details of each main station, including its direction and relevant information.

Land type	Number Of POIs	Cross	Main Station
NA	3	Medina Road with Al-Haramain	1
residential commercial&	4	King's Road with Corniche	2
NA	2	Airport	3
NA	7	Tahlia Road with Prince Majid	4
NA	8	Medina Road with Al-Balad	5
residential commercial&	5	Medina Road with Sari	6
NA	2	King's Road with Al-Haramain Road	7

Table6: Number of main stations and land uses at each main station

6. Discussion

The findings of this study highlight the critical role of an integrated metro system in reducing traffic congestion and improving urban mobility in Jeddah. By leveraging Geographic Information Systems (GIS) and network analysis, the study successfully identified optimal metro station locations and designed a comprehensive metro network tailored to the city's transportation needs. The results indicate that high-density residential areas and major points of interest (POIs) play a crucial role in determining station locations, ensuring maximum efficiency and accessibility. Optimizing the metro network contributes to reducing reliance on private vehicles, enhancing sustainability, and fostering better integration with urban infrastructure, ultimately improving the overall quality of life in the city.

The methodology employed in this study, which involved hotspot analysis, location-allocation modeling, and network analysis, has proven to be effective in metro system planning. Identifying high-density population areas through spatial analysis enabled strategic placement of stations in locations with the highest demand. These findings align with previous research, such as Koizumi et al. (2013), which emphasized the correlation between urban density and public transit use, and Owais et al. (2020), which proposed optimizing metro design to minimize transfers and enhance network efficiency. These comparisons validate the proposed metro system for Jeddah and underscore the importance of data-driven decision-making in urban planning.

Despite the positive results, several factors must be considered to ensure the successful and sustainable implementation of the metro project. This study did not extensively address economic factors and implementation costs, which are crucial elements in infrastructure decision-making. Integrating cost-benefit analysis (CBA) in future research will help assess the financial feasibility of the project, evaluating construction, operational, and maintenance costs, as well as the economic impact on the city. Additionally, future studies should explore potential funding models, such as public-private partnerships (PPP), government financing programs, and revenue generation

strategies from reduced congestion and increased economic efficiency.

Moreover, developing advanced models for metro demand forecasting based on demographic shifts and economic growth will be essential for long-term planning. Incorporating real-time traffic data, transit demand forecasting, and investment return evaluations can enhance planning accuracy and decision-making. Furthermore, conducting environmental and social impact assessments will provide additional insights into how the metro project will affect local communities, land use, and sustainability.

Overall, this study demonstrates that utilizing GIS and spatial analysis in metro system planning provides a practical and efficient approach to enhancing transportation infrastructure in Jeddah. By incorporating economic considerations, cost analyses, and financing strategies in future research, the metro project can be executed in a more sustainable and effective manner. To ensure long-term success, continuous evaluations and updates should be conducted, considering urban development trends, financial constraints, and the evolving public transportation needs of Jeddah.

7. Conclusion

The study of urban transportation characteristics and the implementation of public transportation systems in developing countries provides critical insights into the unique challenges and potential solutions for enhancing urban mobility. By focusing on the specific needs and conditions of developing cities, this research highlights the importance of tailored approaches to public transit implementation.

Through a comprehensive methodology that includes literature reviews, resident surveys, expert interviews, and data analysis using both quantitative and qualitative methods, the study identifies key factors that influence the success of urban transportation systems. These include socio-economic conditions, infrastructure development, policy frameworks, and public perception.

The findings emphasize the need for integrated and sustainable transportation solutions that consider the diverse aspects of urban development. Effective public transportation can significantly improve urban mobility, reduce congestion, and contribute to overall economic and social development. By addressing the identified challenges and leveraging the proposed solutions, developing countries can achieve more efficient and resilient urban transportation systems.

In conclusion, this research underscores the vital role of context-specific strategies in advancing urban transportation in developing countries. By fostering collaboration among stakeholders and prioritizing sustainable practices, cities can build more robust public transit systems that meet the growing demands of urban population

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