

GIS-Based Multi-Criteria Approach for Optimizing Monorail Route Selection in Kirkuk City

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ABSTRACT

This study presents a comprehensive methodology to improve monorail route selection in Kirkuk city, Iraq using a quantitative GIS-based multi-criteria decision analysis. The primary aim of this study is to develop and apply a quantitative, GIS-based multi-criteria decision analysis framework for optimizing and objectively selecting the most suitable monorail route in Kirkuk city, Iraq, by integrating spatial, topographic, accessibility, service coverage, and economic factors in order to support sustainable and cost-effective urban transport planning in a post-conflict context. The research area covers 460.89 km², including an extensive road network of 5,533.27 km and 3,193 points of interest (POI). Four different monorail routes were analysed and evaluated using OpenStreetMap data derived from an analytic hierarchy process, digital elevation models and site suitability analysis. The approach uses weighted graph construction, various shortest path methods, and a wide range of performance metrics, including cost-effectiveness, service coverage, topographic conditions, and accessibility. Route optimization includes terrain suitability (scores from 0.50 to 0.78), elevation profile (288–393m), gradient limitations (maximum score 0.20 to 0.32), and points of interest (POIs) within a service radius of 500 m to 1 km. Based on this, Results shows Route 1 is the ideal choice as it found to be the most economical route (4.15 km, US\$214.01 million), had the highest suitability score (0.70), and required the shortest travel time (9.61 minutes). On the contrary, Route 0 had the widest service coverage (31.37 km² service area, 66.1 points of interest within 500 m).

Keywords: Monorail routes, Optimization, Open street networks, POIs, AHP, GIS.

1. INTRODUCTION

Accelerated urbanization, increased vehicular traffic, and sprawling land-use patterns exert unprecedented pressure on urban mobility networks across the Middle East (**El-Geneidy et al., 2013; Aljoufie, 2021; Khalaj et al., 2023**). Iraqi cities illustrate the operation of such pressures (**Al Jarah et al., 2019; Al-Hinkawi et al., 2021**). Their deteriorated transportation systems and considerable dependence on private vehicles have resulted in

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traffic congestion poor air quality, and inequitable access to urban possibilities (**Kang et al., 1976; Khales et al., 2013**). The constrained space in these regions hinders the expansion of conventional surface transportation systems because of insufficient rights-of-way and excessive societal costs associated with at-grade improvements. Consequently, there is increased interest in grade-separated transportation modes that occupy less space, such as monorails, which may navigate complex urban environments with less land use and minimal visual impact (**Han et al., 2019; Miller et al., 2014**). To implement monorail systems effectively, improved decision-support technologies are required to address the technical, economic, and social challenges associated with urban-transit construction. Geographic information systems (GIS) are important for reading transit routes, enabling comprehensive spatial tests that integrate topographic, demographic, land use, and community connectivity statistics (**Shaw, 2010; Norhisham et al., 2020; Patel, 2025**). Spatial analysis is increasingly more used with Multi-Criteria Decision-Making (MCDM) techniques including the analytic hierarchy process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (**Yuan et al., 2022; Sahoo et al., 2023**). These methods systematically examine trade-offs between conflicting goals together with production value, environmental impact, social equity and operational performance (**Hamurcu et al., 2018**). Network evaluation algorithms, along with the Dijkstra and A* pathfinding methods (**Foad et al., 2021; Susanto et al., 2021; Yusuf et al., 2025**), improve upon these techniques by using figuring out surest configurations that limit tour constraints at the same time as complying with spatial constraints.

Monorail is a better alternative for rapid mass transit in densely populated urban regions (**Yusuf et al., 2025**). On the opposite hand, bus rapid transit systems generally depend heavily on proper-hand separation. Monorails require much less complicated underground infrastructure and feature lower production prices than conventional subways and subway structures. They offer reliable, high-ability offerings with low environmental affects because of using electric powered traction (**El Adawy, 2017; Ahmed et al., 2021; Yildizhan and Karacasu, 2022**). Challenges inclusive of path dependence on fixed publications, special maintenance necessities, visible impact of expanded structures, and critical position of station place accessibility in influencing ridership and machine overall performance must be carefully considered in monorail making plans (**Zaghloul et al., 2024**). Urban planning in developing nations, especially Iraqi towns, affords extra methodological demanding situations because of inadequate travel survey data and the absence of professional delivery databases. OpenStreetMap (OSM) and other crowdsourced geographic facts sources provide possible answers to those records boundaries, consisting of the world over standardized schemes and extra comprehensive coverage for community modeling and accessibility assessment (**Grinberger et al., 2022; Moradi et al., 2022**). Recent advances in OSM records high-quality assessment and reconciliation have extended the reliability of open avenue networks for transportation planning, especially in areas in which conventional datasets are scarce or prohibitively expensive (**Bres et al., 2023; Belhouari et al., 2021**). This observe addressing the crucial shortcomings of Iraqi city transportation making plans with the aid of growing a comprehensive GIS-MCDM framework for optimizing monorail tracks in an open street community.

Therefore, this study makes use of the town of Kirkuk as a case study to illustrate the demanding situations of urban transportation in Iraq the usage of a combination of holistic feasibility evaluation, graph-based wayfinding algorithms, and multi-standards assessment to generate and examine a capability monorail configuration in Kirkuk. The approach



provides a reproducible workflow that reduces reliance on proprietary datasets at the same time as preserving analytical rigor through a dependent selection-making and sensitivity analysis framework. This study demonstrates the usage of open facts and spatial analytics in transition planning in complicated city environments, laying the muse for sustainable and equitable mobility investments that can be tailored to comparable contexts across regions.

2. METHODOLOGY

2.1 Overview

As shown in **Fig. 1**, the research design employed in the current study is sound and evidence-based and aims at investigating and analyzing the optimal monorail routes in Kirkuk city. It is a synergistic network and spatial analysis approach that incorporates multi-factor decision making analysis. The four key steps of the process are illustrated in four steps: (1) data collection and preparation, (2) building a weighted graph, (3) building a path and (4) evaluation and ranking. The study was done using a set of various geographic data. The primary inputs include a digital elevation model (DEM), site suitability raster, study area boundaries and setup options. One of the significant elements of the Analytical Hierarchy Process (AHP) is a site suitability raster. In this test, different geographical and socio-economic factors are taken into account to ascertain the suitability of a place where the monorail infrastructure should be installed. DEM also offers valuable terrain elevation information, which can be vital in the cost and limitations analysis of the slope construction. The initial process of data preparation requires the development of a simple transportation network graph using open street map (OSM). There are a number of measures that can be undertaken in order to enhance this unpublished network. First, the method of geocoding was utilized to incorporate the locations and the points of interest (POIs) in the queries. The OSM graph was narrowed down to the categories of roads that were appropriate to the planned monorail line. Small residential streets and walkways were cleared off. The graph was simplified and redundant entries were eliminated to make sure that the subsequent studies could be easily carried out.

When the core network is prepared, the analytical components are introduced to enhance realism in routing. This stage entails three simultaneous activities: first of all, it takes into account the main areas of interest (POIs), including shopping centers, transport centers, and residential areas. The nodes and the edges of the network graph were simultaneously sampled by merit and height values of multiple raster inputs. This method effectively integrates the suitability of buildings and the gradient of the terrain on the network. The second step was to estimate the number of individuals who are interested in cycling at each node. This depends on the quantity and the nature of the local points of interest and demographics. Edge weighting is then done, which is an important operation. The network contains a cost of travel weighted along each edge of the network. This weight is not just a measure of distance; It also depends on many other criteria, such as length of section, score on building difficulty, and slope of terrain created in the DEM.

This mechanism of absolute weighting guarantees the routing algorithm to be able to choose a route that is not only the shortest, but also economical and simplified to construct. The approach leads to the building of a fully weighted graph and terminals or main access points, depending on a highly-demanded node. The second step was to create the weighted graph, which was the design of a feasible monorail line. The list of the possible terminals is utilized to choose the key hub that can serve as the central point of the monorail system. Such hubs



are then prudently built to create a group of origin-destination (O-D) pairs, which are the key links of the network.

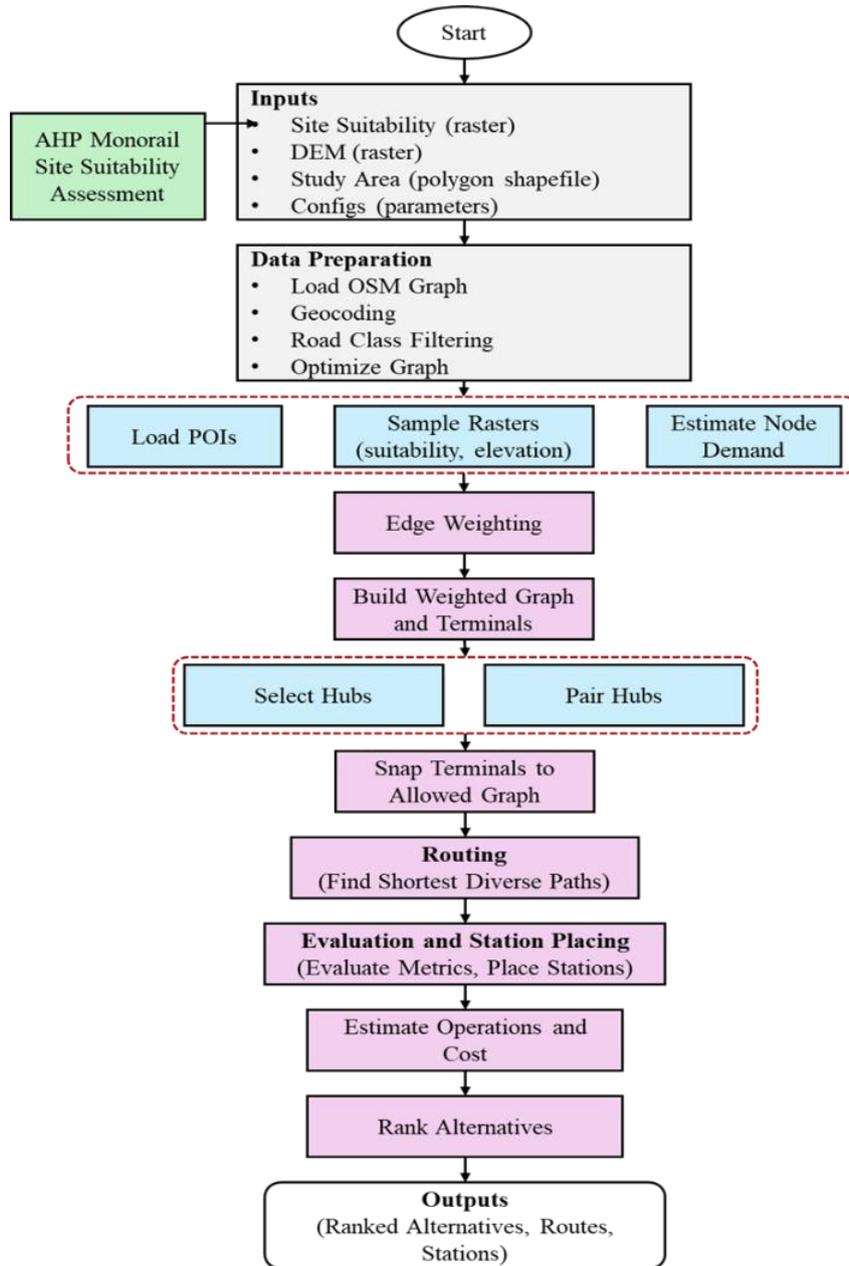


Figure 1. Flowchart of the proposed methodology for optimizing alternative monorail routes.

It is a complex algorithm of routing each origin-destination pair to calculate the shortest and most efficient path. The possibility to find shortest divergent paths is an important characteristic of this approach. The algorithm determines some of the perfect paths between two hubs. Here, the term shortest is used to describe the path that has the minimal weight of all the edges, meaning the combination of distance, cost, and construction feasibility. The approach gives decision makers a number of options and not only one. Before routing, the

terminals were selected and tied to clear graphs cautiously so that they are well placed. An overall analysis of the suggested route alternatives was conducted. The possible routes were given performance indices, and optimal points between the stations were chosen to make the performance as high as possible and reach as many points as possible. Then the full cost estimation stage is followed, where the initial capital cost of the building, the long-term operation and maintenance cost of the building are estimated for each possibility. The rest of the routes were ranked based on an evaluation matrix and a compilation of estimated costs. This last step was to present an effective list of prioritized monorail corridors to the stakeholders so that they could make informed decisions on the basis of a comprehensive evaluation of the performance, cost, and feasibility.

2.2 Study Area Description

The study site is located in northern Iraq, extended for a 461.22 km² and centered on the city of Kirkuk (**Fig. 2**). It lies between 44 ° 18' and 44 ° 30' East longitude and 35 ° 18' and 35 ° 42' North latitude and thus it is an important urban and peri-urban area of northern Iraq. There are a number of major areas in the domain research, and Kirkuk is one of the largest of urban centers situated to the south.

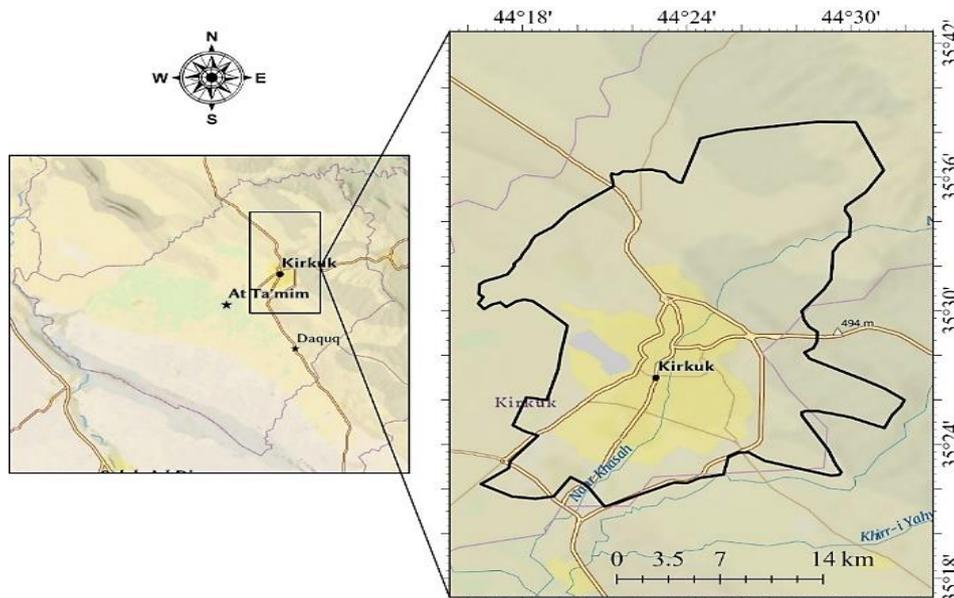


Figure 2. Location map of the study area: Kirkuk, Iraq.

The topography of the landscape is diverse, with the elevations being above 330 m above sea level. The area is principally flat, which can be used to build a transportation infrastructure, but it is surrounded by diverse terrain, which can present engineering difficulties in future monorail constructions. The canal system is one of the hydrographic factors that have to be considered carefully in the planning of routes and the eco-impact assessment. The research site well illustrates the current road network that supports key transportation and links among localities. The existing corridors may be used as the criterion to optimize the monorail routes and make it easier to build them when implementing the project. The Kirkuk Governorate research area is a region with a lot of economic and geopolitical value in Iraq. This background gives a relevant case study to explore sustainable mobility alternatives in the reconstruction and development of the country in the post-



conflict area of post-conflict reconstruction and urban development. The size of the area and its urban structure offer an apt foundation for assessing the possibility of a monorail system as an alternative mode of transportation to conventional transport modes of a similar metropolitan setting in the Middle East.

2.3 Monorail Site Suitability Assessment

2.3.1 Datasets

A comprehensive multisource geospatial dataset was compiled for the study site to examine urban planning and infrastructure. The input consists of a 30 m SRTM DEM; 10 m Sentinel-2 land use/land cover, produced by Impact Observatory, Microsoft and ESRI using ESA imagery; 400 m hex contour population estimate; OpenStreetMap routes and points of interest; Here real-time traffic flow and events received from the Traffic API; FAO/UNESCO Global Land; and high-resolution Google Earth imagery for verification and digitization of features such as airports and bridges. The Kirkuk Urban Planning Department and the Department of Transport have integrated job centers, open spaces and public transport routes into the municipal framework. All datasets were aggregated, analyzed and visualized using ArcGIS Pro, which also provides base maps and supplementary layers.

Monorail site suitability was assessed using a GIS-based multi-criteria decision framework that effectively incorporates topographic, urban, social and environmental considerations into the decision-making process. Key elements discussed include demographics and destination accessibility; Integration of bus networks with existing rail systems, expanded by road capacity and potential feeder services; land use patterns and prospects for transition-oriented development; environmental constraints and mitigation strategies; factors related to terrain, soil, flooding and seismic activity; and conflicts involving existing or proposed utilities and infrastructure. Twenty-four variables were categorized into six unique groups: Demography, Transportation, Land Use, Environment, Topography, and Infrastructure. Each variable was classified as either a benefit or cost criterion based on its relationship with the project objectives.

Standardized inputs for analysis and mapping in spatial processing. Continuous variables were normalized to a range of 0–1 using min-max scaling, applying direct transformations to the benefit criterion and inverse transformations to the cost criterion. Categorical variables, including land use and soil, were reclassified into appropriateness scores using expert-established weights. The final transit suitability surface was generated by harmonizing all layers, maintaining uniformity in resolution and projection, and employing the MCDA methodology.

2.3.2 Analytical Hierarchy Process (AHP) for Weight Derivation

The diverse panel of ten experts was formed in order to ensure a wide expertise in all the relevant areas of monorail infrastructure planning, which include: The respondents were academic scholars in the field of transportation engineering and planning, individuals with practical experience in the field of transportation infrastructure construction, senior executives who participated in large scale infrastructural projects, and practitioners in the field of urban development and land use planning. Expert in the field of transportation infrastructure design, with a specific focus on integrated urban systems and the development of smart cities. A Geographic Information Systems professional, with expertise in geographical analysis, surveying, mapping, and spatial data management, but with a focus



on data processing and statistical analysis of transportation systems. Such a diverse composition ensures a fair representation of academic, industrial, and technical perspectives, providing complete coverage of the areas of knowledge that should be relevant to the evaluation of the monorail location appropriateness.

For each pairwise comparison matrix A , where a_{ij} represents the relative importance of the criterion i over criterion j . The following properties hold for each pairwise comparison matrix A , where a_{ij} represents the relative importance of criterion i over criterion j . The following properties apply according to Eq. (1) **(Li, 2008)**:

$$a_{ij} = \frac{1}{a_{ji}}, a_{ii} = 1, a_{ij} > 0 \quad (1)$$

The weight vector w is obtained by solving the eigenvalue problem, and according to Eq. (2) **(Wan et al., 2025)**:

$$Aw = \lambda_{\max} w \quad (2)$$

Where λ_{\max} is the largest eigenvalue of matrix A . The weight vector is normalized as follows, and according to Eq. (3):

$$\sum_{i=1}^n w_i = 1 \quad (3)$$

The consistency of expert judgments was evaluated using the Consistency Ratio (CR) according to Eq. (4) **(Liu et al., 2023)**:

$$CR = \frac{CI}{RI} \quad (4)$$

where the Consistency Index (CI) is calculated as in Eq. (5) **(Liu et al., 2023)** :

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (5)$$

The RI is the Random Index corresponding to the matrix size n . Pairwise comparison matrices with $CR \leq 0.10$ were considered acceptable for inclusion in the analysis.

The individual expert weights were combined using the geometric mean method to maintain the mathematical integrity **(Llaudet and Imai, 2023)** according to Eq. (6):

$$w_{\text{geometric}} = \left(\prod_{k=1}^m w_k \right)^{1/m} \quad (6)$$

where w_k represents the weight from the expert k , and m is the number of experts. The geometric mean approach preserves the reciprocal property of AHP matrices and provides robust weight estimates when expert opinions vary.

2.4 Optimizing Monorail Route Alternatives

Table 1 summarizes the parameters, weights, and operational assumptions used in the proposed GIS-based multi-criteria route optimization model. The weighting coefficients (α , β , γ , δ) represent the relative importance of terrain suitability, grade penalty, road-class bias, and demand, respectively, ensuring that spatial feasibility, engineering constraints, and



service performance are jointly considered. Grade constraints are introduced using soft and hard slope thresholds (τ_s, τ_h), while penalty terms (P_h, P_{NaN}) are applied to discourage routes that cross excessively steep terrain or areas with missing/undefined grade values. Accessibility is modeled through the service radius R (500 m), the number of candidate paths per origin–destination pair k (4), and the maximum number of pairs P (3), which together allow exploration of feasible alternatives while controlling computation. To avoid producing nearly identical solutions, an overlap threshold θ (0.7) is imposed, and the search is focused on the top N hubs (10). Practical feasibility is further controlled by route length bounds ($D_{min}, D_{max} = 3\text{--}100$ km) and station spacing constraints ($T, T_{min}, T_{max} = 1000, 800, 1500$ m), consistent with realistic monorail planning requirements. Operational performance is estimated using the cruise speed v (35 km/h) and dwell time Δ (25 s). Economic evaluation is included through unit costs c_g and c_s (\$40 million/km and \$8 million), enabling cost comparison across alternatives. Finally, road hierarchy preferences are incorporated by limiting considered highway classes H (trunk, primary, secondary, tertiary) and applying class factors r_e (0.9–1.7; lower is better) to bias routing toward higher-order corridors. Collectively, the parameters in Table 1 provide a transparent and reproducible basis for ranking alternative monorail routes within the GIS-based MCDA framework.

The proposed methodology for optimizing monorail route alternatives is an end-to-end pipeline implemented to generate, evaluate, and rank alternative monorail alignments using open street networks, raster suitability and elevation data, and point-of-interest (POI) proximity signals. The pipeline integrates data acquisition, raster sampling, demand estimation, edge cost modeling, hub selection and pairing, k -diverse shortest path search, station siting, and multi-criteria evaluation/selection.

The study denotes the projected (planar, metric) road network as an undirected graph $G = (V, E)$ obtained from OpenStreetMap (OSM). For node $i \in V$ we store coordinates (x_i, y_i) , sampled suitability $s_i \in [0, 1]$, elevation z_i (meters), and a demand proxy $d_i \in [0, 1]$. For an edge $e = (u, v) \in E$ we use length l_e (meters), highway class factor r_e , average suitability s_e , average demand d_e , grade g_e , and a composite cost $w_e > 0$. Route alternatives are simple paths $p = (v_0, \dots, v_m)$ between terminal nodes.

2.4.1 Data and Pre-processing

The OSM drive network for the study area was retrieved using OSMnx and projected it to a local CRS in meters. Edges are filtered by OSM highway classes in $H = \{\text{trunk, primary, secondary, tertiary}\}$ and the largest connected component is retained. Edge geometries are preserved, and edges are flattened to columns $\{u, v, \text{key}\}$ for downstream processing. POIs are obtained from OSM tags (e.g., aeroway:aerodrome, railway:station, amenity:bus_station, amenity:hospital, amenity:university, shop, office, tourism*). Non-point geometries were centroided. The POIs were re-projected to the network CRS.

Two rasters are used: (i) suitability raster S (dimensionless, higher is better), and (ii) a digital elevation model (DEM). The node coordinates were transformed to each raster's CRS via pyproj and the cell values were sampled using rasterio. NoData values are mapped to NaN, with robust handling to avoid the propagation of non-finite values. For all nodes $i \in V$, the suitability and elevation are sampled according to Eq. (7):

$$\begin{aligned} s_i &\leftarrow \text{sample}(S, x_i, y_i), \\ z_i &\leftarrow \text{sample}(\text{DEM}, x_i, y_i). \end{aligned} \tag{7}$$



2.4.2 Demand Estimation from POIs

The POI proximity was converted into a normalized node demand proxy. Let P be the set of POIs with weights $w_p > 0$ derived from OSM tag-specific priors (e.g., aerodrome=5.0, railway:station=4.0, university=3.0, shop:*=1.5). For each node i we aggregate the weights of POIs within a radius R meters using a Ball Tree for efficiency according to Eq. (8):

$$d_i = \sum_{p \in P} I \{ \| (x_p, y_p) - (x_i, y_i) \| \leq R \} \cdot w_p, d_i = \text{scale}(d_i). \quad (8)$$

Default $R = 500\text{m}$. This construction favors alignments traversing POI-dense areas while retaining flexibility through the radius and weights.

2.4.3 Edge Features, Grade, and Composite Weight

For each edge $e = (u, v)$ we compute:

$$\begin{aligned} l_e & \quad \text{geometry length in meters,} \\ s_e & \quad 1/2(s_u + s_v), \\ d_e & \quad 1/2(d_u + d_v), \\ g_e & \quad \frac{|z_u - z_v|}{l_e} \text{ (dimensionless grade).} \end{aligned}$$

A soft/hard threshold grade penalty g_e^p enforces comfort/constructability while retaining network connectivity by default:

$$g_e^p = \left\{ \begin{array}{ll} 0, & g_e \leq \tau_s, \\ \frac{g_e - \tau_s}{\tau_h - \tau_s}, & \tau_s < g_e \leq \tau_h, \\ P_h, & g_e > \tau_h, \\ P_{\text{NaN}}, & g_e \text{ undefined (DEM gap).} \end{array} \right\}$$

Defaults: $\tau_s = 0.04$, $\tau_h = 0.06$, $P_h = 1.0$, $P_{\text{NaN}} = 0.15$. Optionally, edges with $g_e > \tau_h$ or NaN can be forbidden.

We incorporate a highway-class factor r_e from a lookup (lower is preferred): {trunk:0.9,primary:1.0,secondary:1.1,tertiary:1.2,residential:1.6,service:1.7}. We normalize it to $[0,1]$ by Eq. (9) (Aroyo et al., 2011) :

$$r_e^{\text{norm}} = \frac{r_e - a}{b}, \text{ with } a = 0.9, b = 0.8 \quad (9)$$

The edge composite dimensionless penalty combines the suitability deficit, grade penalty, class bias, and demand deficit according to Eq. (10):

$$c_e = \alpha \cdot (1 - s_e) + \beta \cdot g_e^p + \gamma \cdot r_e^{\text{norm}} + \delta \cdot (1 - d_e), \quad (10)$$

with default weights $(\alpha, \beta, \gamma, \delta) = (0.5, 0.2, 0.1, 0.2)$.

Finally, the additive path cost uses length-weighted penalty according to Eq. (11):

$$w_e = l_e \cdot c_e, \quad (11)$$

A weighted undirected graph is constructed from all non-forbidden edges. If filtering completely disconnects the graph, the method retains all edges to preserve solvability.



2.4.4 Hub Selection and Terminal Pairing

The nodes for hub candidacy were scored by combining demand with proximity to major interchanges (airports and rail/bus stations). Let b_i be a normalized bonus assigned to the nearest node to each major POI. The hub score is according to Eq. (12):

$$h_i = 0.7 \cdot d_i + 0.3 \cdot b_i. \quad (12)$$

The top- N Nodes are selected by h_i with a simple farthest-point spacing constraint of at least 1 km between selected hubs (default $N = 10$).

Terminal pairs (i, j) are then formed, subject to distance bounds D_{min} and D_{max} (defaults: 3 km and 100 km). Candidate pairs are scored to favor demand while discouraging excessively long corridors as follows Eq. (13):

$$\phi(i, j) = \frac{(d_i + \epsilon)(d_j + \epsilon)}{dist(i, j) + \epsilon}, \epsilon = 10^{-6} \quad (13)$$

If no pair meets the bounds, the farthest pair is used as a fallback. The top P pairs (default $P = 3$) was retained.

2.4.5 k-Shortest Diverse Paths

For each terminal pair, simple paths with a non-decreasing total cost were enumerated, using the `shortest_simple_paths` generator of NetworkX (a best-first variant akin to Yen's algorithm **(Aroyo et al., 2011)**). To promote spatial diversity, a path p is accepted only if it does not overlap too much with previously accepted paths. Let $E(p)$ denote the set of undirected edges in path p , then the overlap ratio is as Eq. (14):

$$\rho(p_1, p_2) = \frac{|E(p_1) \cap E(p_2)|}{\max\{|E(p_1)|, 1\}} \quad (14)$$

A candidate is accepted if $\rho(p, p) \leq \theta$ for all previously accepted p , with default $\theta = 0.7$. Up to k alternatives per pair are kept (default $k = 4$).

2.4.6 Station Siting along a Path

Given a path $p = (v_0, \dots, v_m)$, cumulative distances D_j are computed along the path using edge lengths. Stations are seeded at terminals and then placed greedily near the target spacing with demand-aware refinement: (1) Use a target spacing T (default 1000 m), with minimum and maximum spacing $[T_{min}, T_{max}]$ (defaults 800 m, 1500 m), (2) For each target $t \in \{T, 2T, \dots\}$ along $[0, D_m]$, consider nodes within a window of $\pm 200m$ and choose the node maximizing $\sigma(n) = 0.7 \cdot d(n) + 0.3 \cdot deg(n)$, where $d(n)$ is a local demand proxy (here approximated by path-average demand) and $deg(n)$ is node degree in the edge set, (3) Enforce T_{min} from the last station; if violated, slide the target forward by 100 m, and (4) If any consecutive station gap exceeds T_{max} , insert intermediate nodes closest to multiples of T within the gap.

2.4.7 Route Metrics and Multi-criteria Ranking

For each alternative, the following is computed:

$$L_{km} = \frac{(\sum_{e \in p} l_e)}{1000},$$

$$s = \frac{1}{|p|} \sum_{e \in p} s_e, \text{High-suit share} = \frac{1}{|p|} \sum_{e \in p} I\{s_e > 0.7\},$$

$$d = \frac{1}{|p|} \sum_{e \in p} d_e, g(\%) = 100 \cdot \frac{1}{|p|} \sum_{e \in p} g_e, g_{max}(\%) = 100 \cdot g_e.$$



Operational time with cruise speed v (km/h) and per-station dwell Δ (s) is according to Eq. (15) (Deng et al., 2025) :

$$T_{min} = 60 \cdot \frac{L_{km}}{v} + N_{st} \cdot \frac{\Delta}{60} \quad (15)$$

A first-order CAPEX model combines guideway and station costs as Eq. (16):

$$CAPEX[\$/M] = c_g[\$/km] \cdot L_{km} + c_s[\$] \cdot N_{st}, \quad (16)$$

with defaults $v = 35\text{km/h}$, $\Delta = 25\text{s}$, $c_g = \$40\text{M/km}$, $c_s = \$8\text{M/station}$.

Curvature risk is flagged if sharp turns (interior angle 90° at consecutive nodes) exceed 3 per km as in Eq. (17):

$$Risk = \left(\frac{\{sharp\ nodes\ in\ p\}}{L_{km}} \right) > 3 \quad (17)$$

Finally, the alternatives are ranked by a normalized composite score favoring demand and suitability while penalizing cost as in Eq. (18):

$$Score(a) = 0.5 \cdot scale(d_a) + 0.3 \cdot scale(s_a) - 0.2 \cdot scale(CAPEX_a) \quad (18)$$

Table 1. Primary parameters and default values.

Description	Symbol	Default
Suitability weight	α	0.5
Grade penalty weight	β	0.2
Road-class bias weight	γ	0.1
Demand weight	δ	0.2
Soft/hard grade thresholds	τ_s, τ_h	0.04, 0.06
Hard/NaN grade penalties	P_h, P_{NaN}	1.0, 0.15
Demand radius	R	500 m
k paths per pair	k	4
Max pairs considered	P	3
Overlap threshold	θ	0.7
Top hubs, spacing	N	10
Pair distance bounds	D_{min}, D_{max}	3, 100 km
Station spacing	T, T_{min}, T_{max}	1000, 800, 1500 m
Cruise speed, dwell	v, Δ	35 km/h, 25 s
Costs	c_g, c_s	\$40M/km, \$8M
Highway classes	H	trunk, primary, secondary, tertiary
Class factors	r_e	0.9–1.7 (lower better)

2.5 Software Stack

The proposed methodology is implemented in Python programming language. The street network and POIs were retrieved from OSM using OSMnx with standard tag filters (Boeing, 2017). A number of geospatial tools were used including GeoPandas/Shapely for geometry (Liu et al., 2022); Rasterio for rasters (Gillies, 2025); pyproj for CRS transforms; scikit-learn BallTree for proximity (Kramer, 2016); NetworkX for path enumeration (Scellato, 2013). The suitability raster prepared as continuous values (higher preferred). The DEM raster is externally provided elevation in meters used to derive edge grades. All



computations were performed in a projected CRS (meters). Random seeds (default 42) were set for reproducibility, where applicable.

3. RESULTS AND DISCUSSION

3.1 Results of Monorail Site Suitability Analysis

The outcomes of the AHP show that Table 2 priorities are population-centered and focused on development. The most significant ones were demographics (0.391), land use (0.243) and transportation (0.140). The following were infrastructure, terrain and environment with weights 0.108, 0.064 and 0.054, respectively, and it indicates that the physical and environmental limitations are viewed as solvable obstacles. Demographically, the impact of population density (0.700) is bigger than that of employment centers (0.300). Land use underlines the significance of land-use classification (0.364) and building density (0.171); Commercial and recreational areas had moderate benefits, whereas green space (0.116) and heritage sites (0.091) incurred cost, whereas industrial areas produced the minimum amount of value (0.051). The significance of transport presents the significance of connectivity and demand. The positive factors were road network density (0.264, cost), traffic volume (0.193), and travel time (0.166), and access to the public transport was also labeled cost (0.150). Hospitals (0.311) and universities (0.243) are the most important infrastructures, whereas electricity networks (0.172) and bridges (0.099) added complexity. Topographical slope with a value of 0.822 was higher than the elevation slope with the value 0.178. This environmental subscale indicated that it favored the protection site (0.444) over archeological site (0.194) but the overall environmental load was low. The plan may work well in line with reconstruction efforts of the post-conflict periods in Kirkuk because it focuses on socio-economic advantage and service provision. Nevertheless, it puts a strain on the sustainability goals, which explains the necessity to adhere to the transparent approaches to the derivation of weight and the necessity to re-prioritize the focus to the particular contexts.

The AHP techniques of examining monorail site appropriateness show that the spatial growth potential of Kirkuk city is of different pattern, which indicates that quantitative and equi-interval methods of classification bear significant differences. The quantile approach (**Fig. 3**) indicated a polarized distribution of compatibility classes with concentrated regions of very high suitability (dark green) to the central-western region of the study area with vast regions of very low suitability (red) in the north and south-eastern areas of the study area. This hierarchical order of classification brings out the comparative order of areas, which encourages equal representation within all the competency areas. In both the classification methods, the urban center turned out to be the most appropriate site to develop monorails.

Table 2. AHP weights of the main criteria used for monorail route site zoning.

Criterion	Weight
Demography	0.391
Environment	0.054
Infrastructure	0.108
Land Use	0.243
Topography	0.064
Transportation	0.140



Table 3. AHP weights of secondary criteria used for monorail route site zonation.

Criteria Group	Criterion	Weight	Benefit/Cost
Demography	Employment Centers	0.300	Benefit
	Population Density	0.700	Benefit
Land Use	Building Density	0.171	Benefit
	Commercial	0.108	Benefit
	Entertainment	0.098	Benefit
	Green Spaces	0.116	Cost
	Heritage Sites	0.091	Cost
	Industrial	0.051	Benefit
	Land Use	0.364	Categorical
Transportation	Airport	0.117	Benefit
	Parking	0.110	Benefit
	Public Transport	0.150	Cost
	Road Network	0.264	Cost
	Traffic Volumes	0.193	Benefit
	Travel Time	0.166	Benefit
Infrastructure	Bridge Locations	0.099	Cost
	Hospitals	0.311	Cost
	Power Supply	0.172	Cost
	Soil Conditions	0.102	Categorical
	Universities	0.243	Benefit
Topography	Elevation	0.178	Cost
	Slope	0.822	Cost
Environment	Archaeological	0.194	Cost
	Protected Areas	0.444	Cost

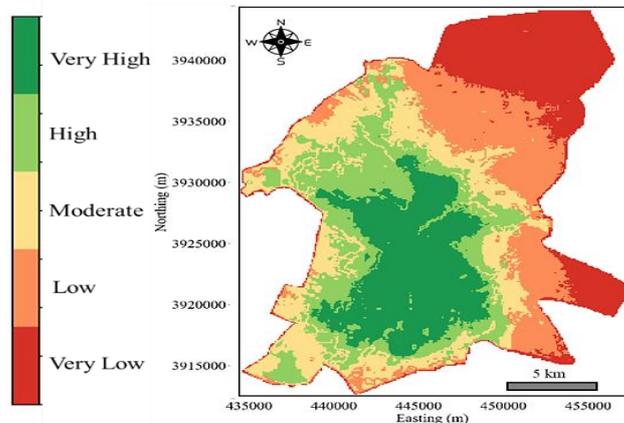


Figure 3. Site suitability map for monorail routes using AHP evaluation.

This outcome is due to the high level of concentration of demographic, land use, and structural factors, which were highly relevant in the AHP analysis. The pattern of spatial distribution analysis indicates that the most efficient monorail lines would go along northsouth line in the middle part of Kirkuk without touching the peripheral parts, which have always been reported to be of low suitability in both classification systems. The variations among classification techniques highlight the significance of the methods used during spatial decision-making. The quantile classification allows preferences to be identified on an alternative basis, on a relative basis, whereas equal-interval classification allows identification of the exact range of the suitability of infrastructure investments.

3.2 Results of Monorail Route Selection and Analysis

3.2.1 Study area characteristics and network analysis

A comprehensive assessment of Kirkuk city statistics indicates that the study area covers 460.89 km², and the city has suitable urban infrastructure for a monorail system, refer to **Table 4**. The existing road network shows significant connectivity, with a total length of 5,533.27 km, comprising 67,663 road segments and 24,872 junctions. This shows that for every km² of the land, there are 12.01 km of roads. The metropolitan network, with an average section length of 81.78 m, has a fine structure that offers many opportunities for future expansion of monorail routing. There are 3,193 points of interest (POI) in the study area, with a density of 6.93 POIs per km². This suggests that a sufficient number of urban activity zones exist, capable of serving as potential stations and meeting future monorail ridership needs, as shown in **(Fig. 4)**.

Table 4. Summary statistics for the study area.

Metric	Value
Study area (km ²)	460.89
Proposed routes	4
Total route length (km)	31.15
Total stations	31
Road network length in study area (km)	5533.27
Road segments in study area	67663
Intersections in study area	24872
Average segment length (m)	81.78
Road density (km/km ²)	12.01
POIs in study area	3193
POI density (per km ²)	6.93

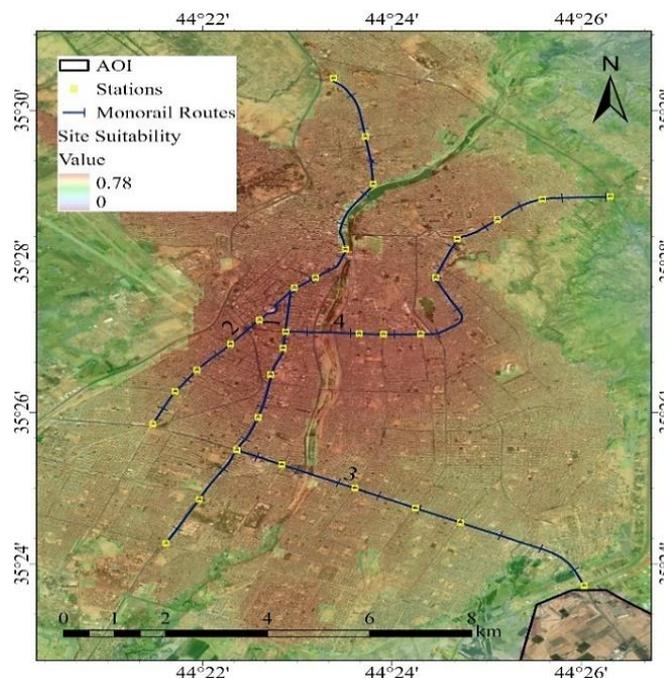


Figure 4. The best alternative monorail routes were selected using the proposed methodology.



3.2.2 Route Performance Analysis

The optimization algorithm identified the four monorail routes, referring to **Tables 5 and 6**, with their peculiarities and indicators of performance. The longest route 0 became the longest one, covering a distance of 12.5 km, with ten well-placed stops connecting major cities. The average suitability measure of this route was 0.66 and the standard deviation was 0.06 which shows that the conditions of the route were the same. as shown in **(Fig. 5)** The elevation profile of Route 0 depicts that the levels of the route are quite different over the land with maximum and minimum height at 288 and 378 m respectively with an average of 335.25 m and a standard deviation of 24.72 m. The successive challenges were therefore categorized as moderate, mean grade of 0.06 and highest grade of 0.32. It was found that route 1 was the shortest (the length of the route was 4.15 km and the stations were 6 in the number) and received the largest average suitability score of 0.70. Topography of the route is also consistent with the elevation ranging between 298 and 342 m and standard deviation of lowest elevation is the lowest among all routes (11.85 m). The topography has an average slope of 0.05 with a maximum grade of 0.22 meaning it is favorable to build and run a monorail. The best suitability position reported by a standard deviation of 0.03 is route 2 that is 6.61 km in length with six stations. It scored however 0.60 on average competency. The path was over flat terrain with little change in elevation of between 29 to 7-320 m with standard deviation of 4.8 m. The mean gradient value of 0.04, the highest grade of 0.20 depict the best topographical conditions on all the studied routes. The length of route 3 is 7.88 km and it has nine stations. The suitability mean score was 0.66, just like route 0. However, in this direction the topography is most diverse, having a range of altitudes of 322 to 393 meters and even a few of the steepest inclinations with the highest gradient of 0.30 as shown in **(Fig. 6)**.

Table 5. Summary statistics of the selected routes for the monorail construction.

Route ID	0	1	2	3
Length (km)	12.5	4.15	6.61	7.88
Suitability (mean)	0.66	0.7	0.6	0.66
Suitability (std.)	0.06	0.06	0.03	0.07
Suitability (min.)	0.55	0.61	0.5	0.5
Suitability (max.)	0.78	0.78	0.66	0.77
Elevation (mean)	335.25	322.88	307.68	349.09
Elevation (std.)	24.72	11.85	4.8	20.6
Elevation (min.)	288	298	297	322
Elevation (max.)	378	342	320	393
Grade (mean)	0.06	0.05	0.04	0.04
Grade (max.)	0.32	0.22	0.2	0.3
Grade (std.)	0.07	0.06	0.05	0.05
Stations	10	6	6	9
Total Cost (USD)	580.10	214.01	312.58	387.35
Cost Per km (USD)	46.40	51.57	47.26	49.13

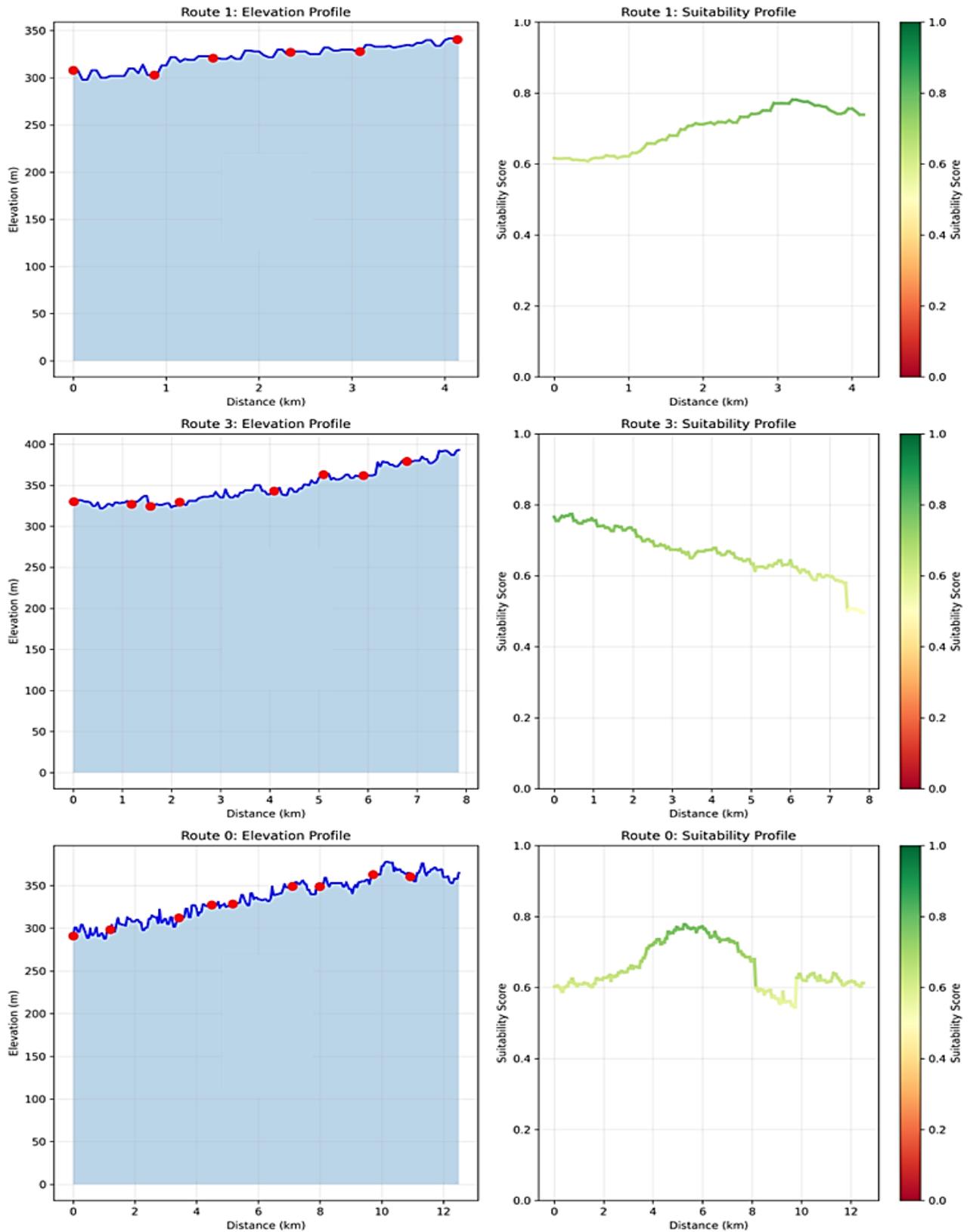


Figure 5. Profile charts of the suitability and elevation of the top three monorail routes.

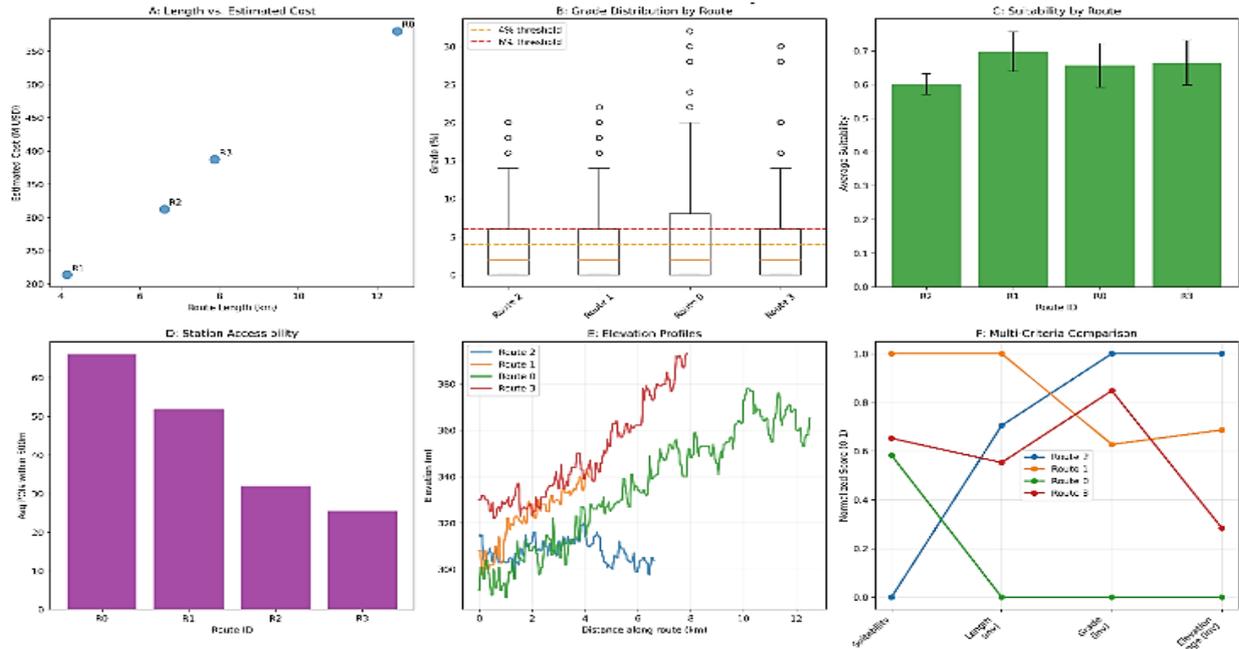


Figure 6. Monorail route performance metric analysis.

Table 6. Summary statistics of the POIs and service area of each selected monorail routes.

Route ID	0	1	2	3
POI count 500m mean	66.1	51.83	32	25.44
POI count_500m std.	56.2	35.59	23.44	22.39
POI count 1km mean	190.9	184.67	100.5	93.11
POI count 1km std.	143.75	101.78	76.24	73.68
Nearest POI dist. mean	59.53	48.05	66.8	115.92
Nearest POI dist. Min.	15.02	28.48	25.57	18.02
Service Area_1km_sum	31.37	18.82	18.82	28.23

3.2.3 Economic Analysis and Cost-benefit Assessment

As illustrated in **Table 7**, economic analysis revealed significant disparities in capital investment requirements along the proposed route. Route 0 requires the highest total funding of \$580.10 million due to its extensive length and varied terrain. Route 0 showed the most competitive cost per kilometer at US\$46.40 million/km, despite its overall higher cost. This shows that producing goods in large quantities can save costs for the company. Route 1 showed the lowest total capital demand, US\$214.01 million, yet it recorded the highest cost per kilometer at US\$51.57 million/km. This suggests that route construction will be more challenging, or shorter routes will require denser infrastructure. Route 2 exhibited an overall economic profile with a total cost of US\$312.58 million and competitive cost per kilometer of US\$47.26 million. The total investment required for Route 3 was US\$387.35 million, with a cost per kilometer of US\$49.13 million, placing it in the average range compared to other options in terms of economic performance. A cost efficiency analysis, which employed bubble size to illustrate the findings, showed that Route 0 performed best in balancing construction costs with route length. In contrast, Route 1 showed an increase in cost per unit despite its lower total distance. Routes 2 and 3 showed



average cost-effective relationships, with Route 2 showing slightly better economic performance for its length as showed Fig. 7.

Table 7. Summary statistics of the economic efficiency of the selected monorail routes.

Route ID	Total Cost (USD)	Cost per km (USD)	Total Time (minutes)	Service area (km ²)
2	312.58	47.26	13.84	18.82
1	214.01	51.57	9.61	18.82
0	580.1	46.4	25.6	31.37
3	387.35	49.13	17.27	28.23

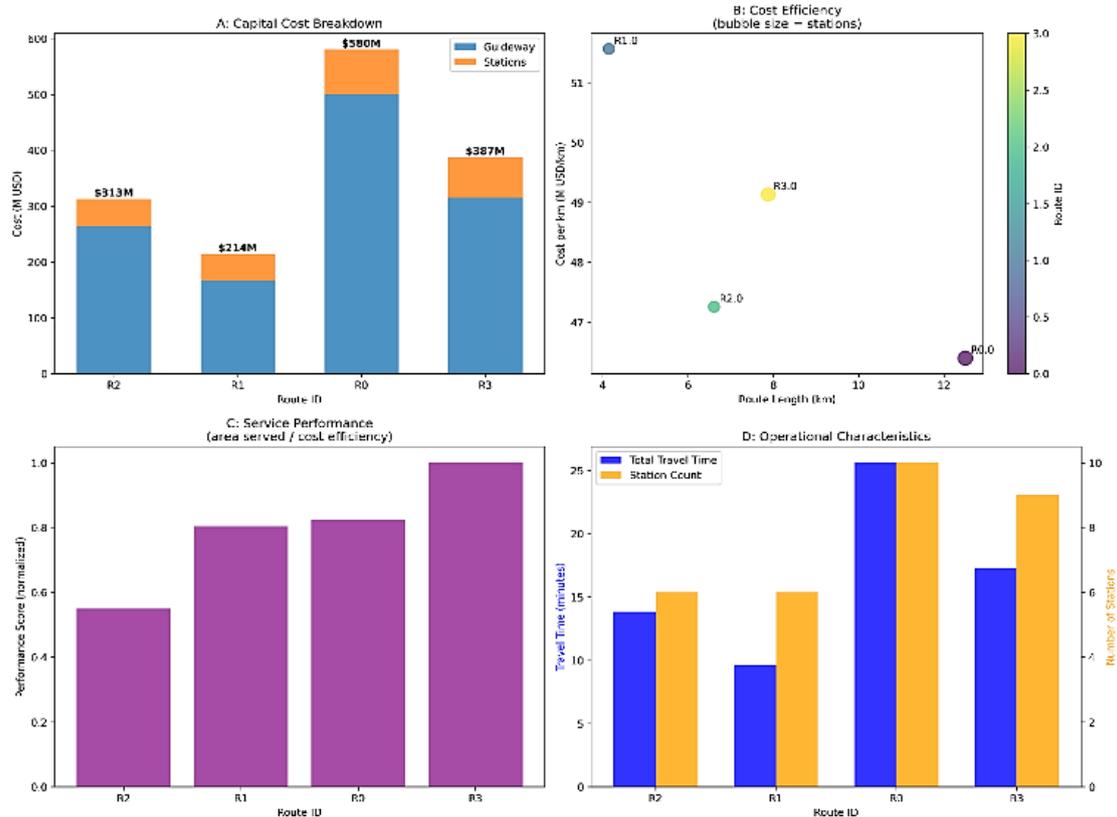


Figure 7. Economic and operation analysis of the monorail routes.

3.2.4 Accessibility and Service Coverage Analysis

Findings from the accessibility research showed that the proposed routes approved significant differences in terms of station coverage and integration of points of interest. Route 0 showed excellent accessibility to points of interest, with an average of 66.1 POIs within a 500 m radius and 190.9 POIs within 1 km of stations. This suggests strong integration with established urban activity centers. Significant standard deviations of 56.2 and 143.75 indicate significant variation in the density of points of interest along the route. Some stations cater to bustling areas, while others extend their reach to emerging districts. Route 1 showed an average of 51.83 points of interest (POI) within a 500 m radius and 184.67 POIs within a 1 km radius, making it the second most accessible route despite its short length. The reduced standard deviations of 35.59 and 101.78 indicate a more uniform



distribution of points of interest along the route alignment. Route 2 showed a moderate level of accessibility with an average of 32 points of interest (POI) within a 500 m radius and 100.5 within a 1 km radius. In contrast, route 3 showed the lowest reach with mean counts of 25.44 and 93.11. Proximity analysis to the nearest point of interest revealed that Route 1 showed the most favorable average distance, which was 48.05 m. In contrast, Route 3 showed the worst connectivity, with an average distance of 115.92 m to the nearest point of interest. Service area analysis shows that Route 0 has shown the most extensive coverage, covering an area of 31.37 km² in a radius of 1 km. This was largely due to its advantageous position. Routes 1 and 2 cover the same service area of 18.82 km², while Route 3 covers a larger service area of 28.23 km². This shows the effect of route length on geographic coverage.

3.2.5 Multi-criteria Performance Assessment

The multi-criteria analysis shows that there are significant differences in the performance of the four routing options. Relative to the alternative routes, Route 1 shows better outcomes in meeting the eligibility requirements, as well as maintaining time and cost competitive advantage. The route 0 covers a wide geographical area and access to key destinations; It would however require investment in terms of finances to build. Some of the classifications that performed well included route 2 due to acceptable prices and the existence of homogeneous topography among others. Route 3 had a satisfactory performance and access was not cost effective and rather difficult.

The assessment of the grades on all the routes showed that the topographical environment was sufficiently good with most of the areas being in the normal operation ranges of monorail. Still, the sharp inclinations of Routes 0 and 3 can be considered in the future because they may presuppose some additional technical activity to ensure the highest possible level of efficiency and comfort of the passengers in the vehicles. An examination of the elevation map revealed that all roads cross different surfaces that shape the city aspect of Kirkuk. The elevation does not change significantly on Route 2 that could result in the enhancement of the efficiency of the operations and the consumption of less energy. To the contrary, the topography of routes 0 and 3 is more varied, which may result in a more interesting visual experience but an increase in the complexity of the operational processes at the same time.

3.2.6 Operational Efficiency and Travel Time Analysis

Operational analysis showed significant variation in travel time on the proposed route. Route 1 showed the most efficient overall travel time, which was 9.61 minutes, thanks to its shorter length and convenient configuration. Route 2 showed greater efficiency in travel time, requiring only 13.84 minutes against Route 0, which took 25.6 minutes due to wider coverage. Route 3 had a duration of 17.27 minutes, placing it centrally in the travel time range. The relationship between route length and travel time exhibits linear scaling with minor variations due to factors such as station density, slope conditions and speed limits. Analysis of travel time efficiency shows that shorter routes offer faster travel times for certain corridor coverage, while longer routes offer network connectivity, although individual travel durations are extended.

3.2.7 Station Planning and Geographic Distribution

As shown in **Fig. 8**, studies on station planning have indicated that there are differences in strategic decisions on distance and coverage optimization in routes. The design of Route 0,



which had 10 strategically placed stations, made sure that there was full coverage of the main urban centers without any overcrowding of the stations. The spacing between the stations was irregular and the areas with the maximum of 1500 m surpassed and the areas with the minimum of 800 m were under the allowable threshold of 1500 m. The stations of Route 1 were well spaced out in the corridor, whereas the stations of Route 2 were spread evenly on the length of the route. The 9-station design of Route 3 provided the largest coverage; Nonetheless, the large vacancy issues could compromise the effectiveness of the route. Analysis of the geographic distribution indicated that the station locations were able to effectively amass significant clusters of points of interest yet could be constructed in an urban setting. The coverage of the overall service revealed that route 0 and route 3 had better coverage of 1 km service area and route 1 and route 2 covered 500 m service area more densely but less effectively.

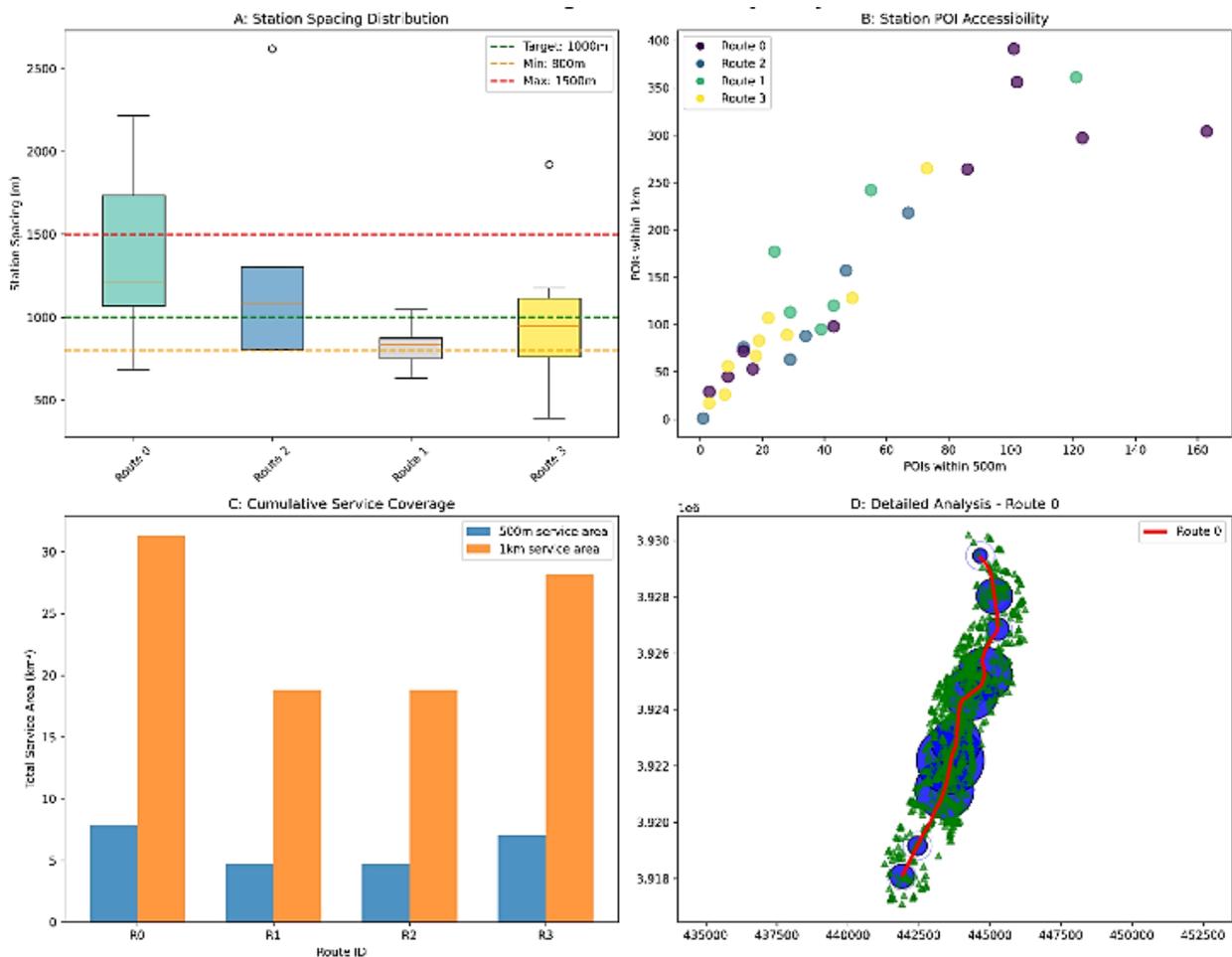


Figure 8. Station planning and accessibility analysis of the monorail routes.

4. CONCLUSIONS

This research was able to show how geographic information systems can be used in conjunction with multi-criteria decision analysis to enhance the choice of monorail routes in a multi-faceted urban environment. The best option was route 1, having the top terrain adaptability grade of 0.70, shortest average travel time of 9.61 minutes, and the least balanced total capital requirement of USD 214.01 million. The 4.15 km long route was



comprised of six strategically placed stations. The advantages with route 0 are numerous and create a broad network. The coverage of the area in terms of service is unprecedented (the area is 31.37 km²), and access to the locations of interest is outstanding (there are 66.1 POIs in 500 meters). The advantage of Route 0 is that it is beneficial in the long-term development system because it covers a large area and is significant in terms of connections. The combination of different geospatial data streams such as digital elevation models, site suitability analysis and open street map network provides a good representation of the complexities involved in the planning of urban transport. An effective weighted graphing technique balances the distance optimization, construction, terrain and accessibility of the area. Research conducted in the future should make this model more dynamic by adding aspects like population projections, possible land use developments, and incorporation of the existing modes of transportation.

Credit Authorship Contribution Statement

All authors contributed equally to the preparation of this article.

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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منهجية متعددة المعايير قائمة على نظم المعلومات الجغرافية (GIS) لتحسين اختيار مسار المونوريل في مدينة كركوك

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قسم هندسة تقنيات المساحة، الكلية التقنية في كركوك، الجامعة التقنية الشمالية، الموصل، العراق

الخلاصة

تقدم هذه الدراسة منهجية شاملة لتحسين اختيار مسارات المونوريل في مدينة كركوك باستخدام نظام معلومات جغرافية متكامل (GIS) وتحليل متعدد المعايير للقرارات. يهدف هذا البحث بشكل رئيسي إلى تطوير وتطبيق إطار تحليلي كمي قائم على نظم المعلومات الجغرافية (GIS) والتحليل متعدد المعايير، بهدف تحسين الاختيار الموضوعي لمسار المونوريل الأنسب في مدينة كركوك، العراق، من خلال دمج العوامل المكانية والطبوغرافية وإمكانية الوصول وتغطية الخدمة والعوامل الاقتصادية، بما يسهم في دعم التخطيط الحضري المستدام وذو الكلفة الفعالة للبنية التحتية للنقل في سياق إعادة الإعمار في المدن الخارجة من النزاعات. تغطي منطقة البحث 460.89 كيلومترًا مربعًا، بما في ذلك شبكة طرق واسعة بطول 5,533.27 كيلومترًا و3,193 نقطة جذب. طُورت أربعة مسارات مختلفة للمونوريل وقيمت باستخدام بيانات OpenStreetMap المُستمدّة من عملية تسلسل هرمي تحليلي، ونماذج ارتفاعات رقمية، وتحليل ملاءمة الموقع. يعتمد هذا النهج على بناء الرسوم البيانية الموزونة، وأساليب مختلفة لأقصر المسارات، ومجموعة واسعة من مقاييس الأداء، بما في ذلك فعالية التكلفة، وتغطية الخدمة، والظروف الطبوغرافية، وسهولة الوصول. يتضمن تحسين المسار ملاءمة التضاريس (درجات من 0.50 إلى 0.78)، ومستوى الارتفاع (288-393 مترًا)، وحدود الانحدار (الدرجة القصوى من 0.20 إلى 0.32)، ونقاط الاهتمام (POIs) ضمن دائرة خدمة تتراوح بين 500 متر و1 كم. كان المسار 1 الخيار الأمثل لكونه الأكثر توفيرًا (4.15 كم، 214.01 مليون دولار أمريكي)، وأعلى درجة ملاءمة (0.70) وأقصر مدة سفر (9.61 دقيقة). من ناحية أخرى، تمتع المسار 0 بأوسع تغطية للخدمة (مساحة خدمة 31.37 كيلومترًا مربعًا، و66.1 نقطة اهتمام ضمن نطاق 500 متر).

الكلمات المفتاحية: مسارات المونوريل، شبكات الشوارع المفتوحة، نقاط الاهتمام، AHP، نظم المعلومات الجغرافية