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Application of A Hybrid Multi-Criteria Decision-Making (MCDM) Approach for High-Speed Rail (HSR) Alignment Finalization

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***Abstract*— Mumbai-Ahmedabad High-Speed Rail (HSR) project basically is a game-changer in the transport scene in India. Figuring out how to best lay those rails is a serious challenge that combines economics, tech specs, environmental flare and Heisted philosophies, all at the same time. In this paper, we're throwing out a GIS-based decision tool, which uses TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) to score and rank three possible routes for the new HSR corridor. We ran up GIS on key land-use stuff - how dense, for example, are the cities, where are the farms and patches of forest and how close everything is to water bodies. Those spatial details were then bundled with talk of money, safety checks, travel demand forecasts and limits on the environment to make a full decision matrix. TOPSIS helped us to rank the options the further from the "ideal" route, and we put the same weight for each factor. After crunching all that, Route No. 1 came out on top: It increases safety, cuts travel time, increases projected ridership and looks good on the balance sheet in the long run. And what's neat is this route makes use of tunnels in order to keep out of fragile spots like Thane Creek. Basically, our approach of using GIS - integrate TOPSIS added smoothness to the decision-making process - reduce human error, adds transparency to the decision process and provides a method of making decision, which can be copied and easily scalable. All of this also adds on to the growing knowledge on sustainable transport planning, especially spatial analysis intersecting with multi-criteria evaluation. And the best part? The same framework could totally work for other big project like highways, metros or pipelines.**

***Index Terms*— High-Speed Rail, GIS, Route Optimization, TOPSIS, QGIS, Multi-Criteria Decision-Making.**

I. INTRODUCTION

The Mumbai, -Ahmedabad High -Speed Rail (HSR) are one of largest wins as part of infrastructure upgrade of India as it connects some of the key economic hubs of India using state-of-the-art rail tech. I'm honestly blown away by how complex these mega- projects get due to the need to juggle technical, environmental, economic and social factors which are all woven together during the planning phase (Sugimori et al., 2022). Route alignment selection is especially important because it varies construction and operational costs, system efficiency, safety, environmental conservation and public acceptance (Al - Hamasawi et al., 2018; Farooq et al., 2019).

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Classic methods of planning just don't cut it when you're dealing with so many variables and so students/practitioners are increasingly turning to advanced analytical tools (Kumar et al., 2017). In this respect mapping and multi-criteria decision-making techniques (i.e. TOPSIS) could be combined with Geographic Information Systems (GIS) as a potentially serious contribution to help us to evaluate HSR route options in a structured and transparent fashion (Luca et al., 2012).GIS allows us to dig deep into a detailed spatial analysis of the key variable such as land use patterns, forest cover, water bodies, urban density etc. while TOPSIS helps to rank the alternatives systematically based on a weighted criteria like cost, safety, demand and environmental impact (Mondal et al., 2021). Together these tools provide us with a mechanism to increase objectivity and reduce the uncertainties in the selection of an alignment for Mumbai-Ahmedabad corridor. MCDM approaches based on GIS have been widely used for comparative studies for HSR alignments. For example, Turkey, a GIS based AHP model for Erzincan-Trabzon region to estimate the terrain/land use characteristics both in the cost efficient and environmentally sustainable environment in a balance way sensitive analysis [Yildirim and Bediroglu (2019)].Similarly, a two-stage GIS-based railway planning framework in China combined environmental impact assessment and automatic alignment optimization of railway, with improved planning quality and ecological protection (Song et al., 2021). Environmental studies of Mumbai-Ahmedabad HSR have also stressed on the mitigation measures, including tunneling in environment sensitive zones, to reduce ecological disturbance (Sugimori et al., 2022). Decision-support systems also play a role in further aligning the optimization as they can take into account the constraints within construction, geometric needs, and natural barriers (Costa et al., 2016). Numerous studies have been dedicated for HSR corridors evaluation and ranking using performance indicators and MCDM techniques. Approaches that are based on urban planning and economic viability are especially applicable in areas with limited financial capabilities (Hamurcu & Eren, 2018). Hybrid methodologies that integrate AHP with unascertained measure models have been employed to evaluate HSR sustainability on environmental, social and economic dimensions (Zhao & Li, 2016). TOPSIS has been widely accepted in transportation planning because it is effective in dealing with complex decision problems and it has been used for congestion assessments and route selection analyses (Wang and Chen, 2014; Cioca et al., 2021). Recent methodological advances overcome above-mentioned limitations on criterion interdependence and weight uncertainty by means of one cluster analysis and the other composite weighting (Xu et al., 2015). Geographic Information System (GIS) - based TOPSIS-based frameworks further refine the decision-making by prioritizing the alternatives of the routes based on the closeness coefficient and thus serve as a data-driven and transparent procedure for corridor selection (Cioca et al., 2021).High speed rail (HSR) projects have considerably impact on land use dynamics and environmental systems. Particularly, the location of stations has a decisive impact on urban expansion patterns, real estate development and mobility regimes (Song et al., 2014; Farooq et al., 2019). To avoid any negative consequences, alignment choices should avoid ecologically sensitive areas, agricultural areas, and areas with higher population density (Song et al., 2021). GIS plays a critical role in the environmental impact assessment process by conducting spatial assessment of trade-offs between alternative routes (Farooq et al., 2019). Studies that have combined GIS and TOPSIS have evaluated factors like slope, proximity to settlements and existing infrastructure to determine environmentally-suited routes in a transparent way (Yildirim & Bedirogu, 2019). Beyond intercity corridors, in urban rail planning, both macro and micro-level transportation analysis has also been incorporated into the planning of urban rail systems using GIS-based approaches (Ahmed et al., 2020; Çaliday and Atahan, 2023). Applications: Park and ride terminal location analysis with demographic data, accessibility indicators and commuter catchment modelling to help define indices of suitability for priority of investment (Li et al., 2011; Liu et al. 2009; Guo and Shahraki, 2023) Despite understanding the progress made worldwide, the use of GIS-based MCDM tools in Indian HSR planning is low (Sugimori et al., 2022). India has a complex pattern of land-use, an ecological sensitivity and high rates of urbanization, which require context-specific planning frameworks (Sugimori et al., 2022). To fill this gap, the current study used a GIS-based TOPSIS model for the assessment of various alignments of Mumbai-Ahmedabad HSR considering spatially and non-spatially based parameters such as route length, safety, construction feasibility, environmental impact and accessibility for population. The findings are intended to back the sustainable HSR development and offer a replicable framework for future examination of decision-making techniques for projects in India as well as other developing regions (Sugimori et al., 2022).

II. Methodology

The methodology that has been used in this study, as shown in Figure 1 and the flowchart, outlines a systematic method of finding the optimal alignment for Mumbai to Ahmedabad high speed rail corridor. The process begins with the delineation of the study area and specification of the pertinent evaluation criteria and goes through extensive data collection. The geographic data is used in the QGIS tool to quantify the land use impacts for proposed routes. These findings are then evaluated with the help of TOPSIS multi-criteria decision-making technique which allows for a data-driven choice of the most feasible and sustainable route.

III. STUDY AREA

India's flagship high-speed rail project, Mumbai-Ahmedabad High-Speed Rail (HSR) runs for around 508 kms passing through the states of Maharashtra and Gujarat. The corridor cuts through a variety of geographic, environmental and urban conditions that makes complex analysis in space important to finding an acceptable alignment. In order for this analysis to be made possible, several spatial data sets were coupled to the QGIS environment. Among these were land use/land cover (LULC) information, high resolution satellite imagery, network of rivers and water bodies, road and highway infrastructures and administrative boundaries. Additional layers (classification) for urban areas, forests, agricultural areas and environmentally sensitive areas were added. Proposed and alternative route alignments were digitized and overlaid upon them to enable their spatial nature to be compared. The resulting geodatabase formed the basis to perform the multi-criteria evaluation technique.

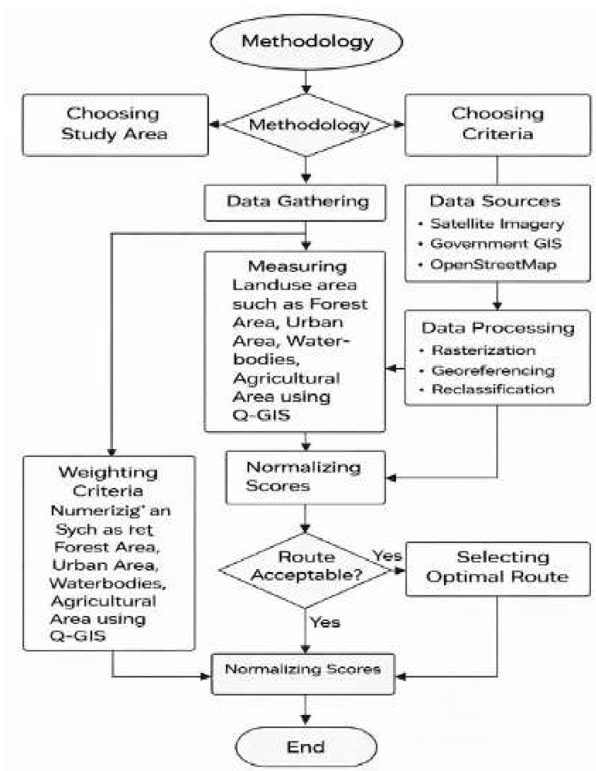

Figure 1. Flow chart for methodology for multi criteria decision analysis

A. Route Evaluation Criteria

The choice of a high-speed rail corridor is a complex issue with many interdependent factors influencing project viability, cost, sustainability and public acceptance. To ensure a comprehensive and rational process of decision-of making 10 key criteria for evaluation of infrastructure projects were identified on the basis of an extensive review of literature, inputs of stakeholders, and practical considerations unique to Indian infrastructure projects, including:

- Travel demand: This is one of the criteria used to predict estimated number of daily travelers on high-speed rail (HSR). Routes that allow access to dense urban centers and larger economic centers are favored, as they will bring higher ridership away from, which will help provide financial sustainability.
- Environmental impact: Alignment ways were rank scored based on how close they are to ecologically-sensitive features (forests, rivers, wetlands, wildlife habitat etc.) Minimizing environmental degradation and meeting regulatory requirements are imperative to long term success of the project.

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Figure 2. HSR Alternative Route 1

Figure 3. HSR Alternative Route 2

Figure 4. HSR Alternative Route 3

C. Route Evaluation Criteria

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- Environmental impact: Alignment ways were rank scored based on how close they are to ecologically-sensitive features (forests, rivers, wetlands, wildlife habitat etc.) Minimizing environmental degradation and meeting regulatory requirements are imperative to long term success of the project.
- Risk of financial and economic risk: This risk is measured in terms of capital and operating expenditures, cost/benefit trade-offs, and financial returns. Routes with lower construction costs and greater expected benefits are given a more favorable ranking.
- Land acquisition risk: It can take a long time to acquire land, the risk of which is hampered by legal, social and compensation matters where the land is in the same area which has a high population density and a high agriculture productivity rate. Routes that minimize displacement and resistance from the public are therefore preferred.
- Construction management risk: Topographical and geotechnical conditions were analyzed with regard to their effect on construction complexity. Routes having steep slopes, water crossing, etc., are considered as routes with a higher level of engineering and scheduling risk.
- Alignment change risk: This criterion considers the risk that realignment will have to take place during the implementation due to unforeseen environmental, legal or socio-political concerns. Stable alignments are preferred because they save time and money.
- Overrun safety: Routes were checked for natural disaster hazards such as flood plains, landslide prone areas and seismic areas. Safer alignments improve resilience and save operational maintenance costs in the long term.

- social sustainability impact: For this type of assessment, it is evaluated how the site may cause displacement, disturbance of local livelihood and how close it is to culturally or historically sensitive sites. Routes that minimize adverse social impacts are given a higher rating.
- Operational and connectivity potential: The level of connectivity interconnection with extant transport networks (highways, airports and urban transit systems) is assessed. Better-connected routes are better accessible and convenient for users.
- Travel Time: Routes were compared for their ability to minimize travel time while balancing cost, safety, and engineering feasibility. Faster routes enhance competitiveness with other transport modes.

D. GIS- Based multi – criteria decision making (MCDM) Framework

All the ten evaluation criteria were spatially modelled in QGIS using thematic raster and vector layers. Data preprocessing in this case entailed reclassification, normalization and overlay analysis to create standardized decision layers.

These layers were integrated by the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) which is widely used in multi criteria decision making (MCDM) to rank alternatives based on how close they are to an ideal solution.

Criterion weights were a combination of expert judgment supported by the literature review to reflect the relative importance of each factor. The integrated GIS-Topis framework helped in ranking the alternative alignments spatially in Favor of finding the most feasible, sustainable, and cost-effective high-speed rail alignment between Mumbai and Ahmedabad.

E. Data Measured using Q-GIS Software

In this project, using QGIS we were able to dig into the data regarding land use and get an idea of how the different high speed rail route options would affect the environment. First of all, we mapped out the proposed routes and loaded up a number of land-use maps - forests, cities, bodies of water, farmland etc. Then we counted how many of each kind of land each of the routes would go through. This provided for us a definite way to objectively compare the environmental impact of each of the routes.

TABLE I: DATA MEASURED USING Q-GIS SOFTWARE

	Alternative Route 1	Alternative Route 2	Alternative Route 3
Forest area Km2	505.78	505.78	307.78
Agriculture Area Km2	8584.598	9047.06	8207.51
Waterbodies Km	10.72	10.249	7.631
Urban Area Km2	1010.68	1094.78	7.631

F. Application of TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) has its conceptual origin in the first structured approaches to decision-making dating back to the time of Benjamin Franklin in handling and comparing the advantages and disadvantages systematically.

This method later on became a formal multi-criteria decision-making method with TOPSIS, introduced by Hwang and Yoon in 1981. The technique determines the right alternative in question by determining the relative proximity of every option to both ideal and bad ideal solutions and is widely employed in real-world decision problems.

In the planning of high-speed rail (HSR) routes, there are multiple conflicting criteria that need to be assessed at the same time, including safety, cost, environmental impact, and economic benefits. TOPSIS gives you a quantitative and objective way to compare and rank route alternatives so that decisions are based on the results of the analysis of structured data, rather than on a subjective evaluation, or on limited results generated by software tools alone.

Steps in TOPSIS analysis

- Criteria Selection: Key criteria that affect the route selection of HSR were identified such as route length, proximity to water bodies, land use (urban areas, agricultural areas, forest areas, water bodies) and cost feasibility.

  These criteria have been selected which balance route efficiency and environmental and construction constraints.
- Data Normalization: As various criteria are measured in different units (i.e. in meters, rupees, time, speed) the process of normalization is needed to make comparison possible.

The formula for normalization is given in the formula:

$$x_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$$

xij is the value of the j-th criterion for the i-th alternative
m is the total number of alternatives.

- Weighted Normalized Schedule actual decision matrix: Each criterion was assigned a weight as per the relative importance of each criterion as determined by the concerned authority. The weighted normalized matrix was done by multiplying each normalized value with its corresponding weight.
- Ideal and Negative Ideal Solution: The ideal solution is the optimum solution of all the criteria values in an obtained way, and the negative ideal solution is the worst of all the solutions.
- separation measures: The Euclidean distances for each alternative to the ideals and negative ideal solutions was represent the distances form the ideal and negative ideal solutions respectively.

The distances are calculated using the following formulas.

$$s_i^+ = \sqrt{\sum_{j=i}^{n} (x_{ij}^{'} - x_j^+)^\wedge 2} \qquad s_i^- = \sqrt{\sum_{j=i}^{n} (x_{ij}^{'} - x_j^-)^\wedge 2}$$

where Si+S_i^+Si+ and Si−S_i^-Si− represent the distances of the i-th alternative from the ideal and negative ideal solutions, respectively.

- degree of approach to the ideal solutions: the relative closeness of each alternative was calculated as

$$c_i^* = \frac{s_i^-}{s_i^+ + s_i^-}$$

This value, Ci∗C_i^*Ci∗, indicates how close an alternative is to the ideal solution, with a higher value representing a better alternative. The alternative with the highest Ci∗C_i^*Ci∗ value is considered the most optimal route for the railway project

Alternative Evaluation Criteria

The evaluation criteria for comparison of three alternative routes for Mumbai Ahmedabad High-Speed Rail (HSR) corridor have been presented in the table using TOPSIS method. These criteria include a wide variety of technical, environmental, economic and social factors necessary for making holistic decisions. This ultimate comparison sets the basis for finding the best and most sustainable path going forward.

Quantitative values are quantifiable and expressed with a number (e.g. distance, cost, time). Qualitative values are descriptive and are based upon perception or judgement (i.e., safety, comfort, aesthetics).

Some of the values are quantitative while others are qualitative. The challenge is that quantitative values can be measured directly while qualitative values (high safety or low safety) cannot. If qualitative values are to be rendered in a way that they are comparable with one another, they must be assigned points. That's why Safety gets 1 point when it is Highest and 0.5 for alternative route when comparing

Normalized Matrix

Normalization was carried out to bring the diverse criteria measured in different units such as kilometer, square kilometer and million INR on a scale for fair comparison. This step ensures that no single criterion has an undue influence because of its magnitude. The normalized matrix is the basis for the computation of the weighted decision matrix and additional proximity measures that ultimately lead to the selection of the most adequate alignment of routes.

TABLE II: CRITERIA FOR COMPARISON

Sr.no	Criteria	Alternative 1	Alternative 2	Alternative 3
1	Travel demand	40000 PAX/day (2023) 202000 PAX/day (2053)	33000 PAX/day (2023) 168000 PAX/day (2053)	34000 PAX/day (2023) 165000 PAX/day (2053)
2	Urban area	1010.68 Km2	1094.786 Km2	1526.272 Km2
3	Agriculture	8584.598 Km2	9047.06 Km2	8207.51 Km2
4	Forest area	505.78 Km2	505.78 Km2	307.78 Km2
5	Waterbodies	10.72 Km	10.29 Km	7.631 Km
6	Safety	High	High	Low

7	Travel time	a) 2 hours 7 min (spot at 3 stations) b) 2 hours 58 min (spot at all station)	a) 2 hours 7 min (spot at stations) b) 2 hours 58 min (spot at all station)	a) 8 hours 52 min (if travelled non stop)
8	Cost of project (million INR)	709,151	684,194	656,038
9	Land	2.8 ha/Km	3.2 ha/Km	9.3 ha/Km
10	No. of station	12	12	11
11	Complex	33	34	36
12	Natural conservation	Not affected	7 Km long thane creek is affected	Not affected
13	Technical issue	No issue	No issue	Many other local trains are operated on the same route reducing the efficiency of HSR.

TABLE III: EXPRESSION OF QUALITATIVE VALUES IN QUANTITATIVE VALUE

Criteria	Alternate 1	Alternate 2	Alternate 3
Travel Demand	40,000 PAX/day (2023) 2,02,000 PAX/day (2053)	33,000 PAX/day (2023) 1,68,000 PAX/day (2053)	34,000 PAX/day (2023) 1,65,000 PAX/day (2053)
Urban Area	1010.68 Km2	1094.786 Km2	1526.272 Km2
Agricultural Area	8584.598 Km2	9047.06 Km2	8207.51 Km2
Forest Area	505.78 Km2	505.78 Km2	307.78 Km2
Waterbodies	10.72 Km	10.29 Km	7.631 Km
Safety	1	1	0.5
Travel Time	127 min	127 min	532 min
Cost Of project			
(Million INR)	709,151	684,194	656,038
Land requirement	2.8 ha/km	3.2 ha/km	9.3 ha/km
No of station	12	12	11
Complex Structures	33	34	36
Natural Conservation	0	1	0
Technical issue	0	0	1

Normalized Matrix

Normalization was carried out to bring the diverse criteria measured in different units such as kilometer, square kilometer and million INR on a scale for fair comparison. This step ensures that no single criterion has an undue influence because of its magnitude. The normalized matrix is the basis for the computation of the weighted decision matrix and additional proximity measures that ultimately lead to the selection of the most adequate alignment of routes.

Weightage Matrix

In this matrix, every normalized criterion value is multiplied by its respective weight which indicates how much that specific criterion should be considered in the decision-making process. The weights were calculated by applying expert judgment, a review of literature, and project specific priorities. This matrix then combines both, the performance and significance of each criteria allowing a balanced and objective comparison of the three alternative high-speed rail routes.

After Applying Equal Weightage to each Criteria.

1/12=0.0833

TABLE IV: NORMALIZED MATRIX

Criteria	Alternate 1	Alternate 2	Alternate 3
Travel Demand	0.054	0.044	0.046
Urban Area	0.039	0.043	0.059
Agriculture Area	0.048	0.050	0.046
Forest Area	0.054	0.054	0.033
Waterbodies	0.053	0.051	0.038
Safety	0.055	0.055	0.028
Travel Time	0.019	0.023	0.078
Cost of project	0.050	0.048	0.046
Land Acquisition	0.023	0.026	0.075
Land Requirement	0.049	0.049	0.045
No. of Stations	0.046	0.047	0.050

Natural Conservation	0.000	0.083	0.000
Technical Issue	0.000	0.000	0.083

TABLE V: WEIGHTAGE MATRIX

Criteria	Alternate 1	Alternate 2	Alternate 3
Travel Demand	0.645	0.532	0.548
Urban Area	0.474	0.513	0.716
Agriculture Area	0.575	0.606	0.550
Forest Area	0.650	0.650	0.395
Waterbodies	0.642	0.616	0.457
Safety	0.667	0.667	0.333
Travel Time	0.223	0.276	0.935
Cost of project	0.599	0.578	0.554
Land Acquisition	0.274	0.313	0.909
Land Requirement	0.593	0.593	0.544
No of Station	0.555	0.571	0.605
Natural Conservation	0.000	1.000	0.000
Technical Issue	0.000	0.000	1.000

Identification of Ideal negative and Idea Positive Solutions

The table shows the identification of Ideal Positive Solution (best case) and Ideal Negative Solution (worst case) for each evaluation criterion in the TOPSIS analysis. These reference points are the best and worst values among all the alternatives in order to obtain a pattern of comparison. The Ideal Positive Solution is the most desirable solutions i.e. maximum travel demand or minimum cost and the Ideal Negative Solution is the most undesirable solutions. By initializing these extremities means the TOPSIS method measures the distance of each alternative route with respect to ideal situation, which leads to the choice of optimal high speed rail alignment.

TABLE VI: IDEAL NEGATIVE AND POSITIVE SOLUTIONS

Ideal Positive Solution	Ideal Negative Solution
0.054	0.044
0.039	0.059
0.046	0.050
0.033	0.054
0.038	0.053
0.055	0.028
0.019	0.078
0.046	0.050
0.023	0.075
0.049	0.045
0.046	0.050
0.000	0.083
0.000	0.083

Calculation of Separation Measures

The table shows the calculation of separation measures for each of the alternative high speed rail routes by using the TOPSIS method. These measures are the Euclidean distance of each alternative to the Ideal Positive and Ideal Negative Solutions respectively. Separation from the ideal solution shows how far an alternative solution is from the best-case scenario, and the separation from the negative ideal shows how far it is from the least favourable scenario. These values are critical for measuring relative proximity of each route towards the ideal solution, for objective and data-driven ranking of the alternatives.

TABLE VII: SEPARATION MEASURES

	Alternate 1	Alternate 2	Alternate 3
Separation Positive ($Si+$)	0.0264	0.0875	0.1201
Separation Negative ($Si-$)	0.1461	0.1158	0.0872

Relative Closeness to the Ideal Solution

The relative closeness of each alternative route to the Ideal Solution is presented in the table using the TOPSIS method. This value, which varies between 0 and 1, is a measure of how near each route is to a solution that matches with the best possible solution as saw when all evaluation criteria are considered. A higher closeness value means that the route is closer to ideal and further away from worst case condition. These results assist in ranking the three alternatives and aid in selection of the most optimal pathway for the high-speed rail alignment.

TABLE VIII: RELATIVE CLOSENESS TO THE IDEAL SOLUTION

	Alternate 1	Alternate 2	Alternate 3
Relative Closeness to the Ideal Solution	0.847	0.5695	0.4207

From above calculation Following Ranks are Calculated:
Alternative Route 1= 0.847
Alternative Route 2= 0.5695
Alternative Route 3= 0.4207
Alternative Route 1 is on the Highest Rank.

IV. RESULT

Based on 13 criteria, each of which was weighted equally, the ranks resulted from the TOPSIS analysis essays Alternative Route 1 came out to be the best suited alignment for Mumbai-Ahmedabad High-Speed Rail corridor, with highest closeness coefficient (0.847), followed by route 2 (0.5695) and the third option (0.4207). GIS based analysis further proved that Route 1 reduced the environmental impact (particularly near Thane Creek through tunnelling) but ensured better safety and higher ridership potential and also a better economic viability which confirmed the value of combining GIS and TOPSIS for sustainable data-driven infrastructure planning.

V. CONCLUSION

The support of GIS allowed for efficient spatial analysis with less human error, and TOPSIS allowed for a structured decision-making structure. Although there are limitations when it comes to data availability, methodology proved to be practical, repeatable, as well as adaptable to other infrastructure projects such as highways and metro systems to enable more informed and sustainable planning. In this study, TOPSIS was used to evaluate three high speed rail path alternatives based on 13 equally weighted criteria (0.0833 each). The results of the calculated relative closeness values for Alternative 1, Alternative 2, and Alternative 3 were found to be 0.847, 0.5695, and 0.4207, respectively, which resulted in the ranking of Alternative 1, Alternative 2, and Alternative 3, respectively. Thus, Alternative Route 1 was found to be the most conducive alignment for the Mumbai-Ahmedabad High-Speed Rail corridor. The results show the strength of the combination of GIS or TOPSIS to influence the route selection, with Alternative Route 1 exhibiting balanced behavior in terms of both safety, cost, environmental impact, and travel demand analysis with minimized ecological disturbance on the sensitive areas such as Thane Creek through tunnel sections.

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