ADBI Working Paper Series

**OPTIMIZATION OF HIGH-SPEED RAILWAY
STATION LOCATION SELECTION BASED ON
ACCESSIBILITY AND ENVIRONMENTAL IMPACT**

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No. 953
May 2019

Asian Development Bank Institute

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The Working Paper series is a continuation of the formerly named Discussion Paper series; the numbering of the papers continued without interruption or change. ADBI's working papers reflect initial ideas on a topic and are posted online for discussion. Some working papers may develop into other forms of publication.

Abstract

High speed railway (HSR) planners aim to select locations that optimize the overall utility or benefit of HSR stations by satisfying various desirable requirements. Among other factors, accessibility and environmental impact are important considerations for HSR station location selection. The desirable requirements of these two factors include improved access to, and intermodal integration with, existing transportation facilities and services (like airports, train stations, and bus stops); avoidance of environmentally sensitive areas (such as water bodies, wetlands, and forest) and land with higher right-of-way costs; and accommodation of strategic necessities (for example, proximity to city centers and socioeconomic development hubs). This study quantifies the overall utility of an HSR station by analyzing the extent to which a location satisfies these desirable requirements. For this, suitable utility functions were developed and evaluated. To obtain individual utility scores, appropriate weights were assigned based on relative importance. The overall utility of a location was then estimated as the weighted summation of these utility scores. A GIS-based analytical framework was specifically developed for geo-processing, mapping, and visualization of the geospatial data analysis and result representation. This utility-based quantification and identification process would be useful to planners in assessing an area and determining the most suitable station locations for an HSR project. The proposed model was used to identify the potential station locations along the Mumbai-Ahmedabad HSR corridor in India and to compare the obtained results with the planned locations of the project.

Contents

1. INTRODUCTION

High speed railways (HSR) are the rail services that operate at speeds in excess of 200 km/h, on exclusive or grade-separated rights-of-way (European Union 1996). They provide short and competitive travel time between strategically important locations. HSR planners identify regions or major cities that have adequate GDP, population, and ridership potential, and satisfy interstation distance and travel-time requirements (Takeshita 2012). An HSR line is developed by identifying appropriate locations for terminal and intermediate stations, and connecting them with a suitable alignment. Determination of station locations is not always a straightforward problem. In addition to optimizing ridership and travel time, planners aim to select locations that optimize the overall utility or benefit of the stations for the adjacent environment and population. This is achieved by satisfying various desirable requirements such as: improved access to, and intermodal integration with, existing transportation facilities and services (airports, train stations, bus stops, etc.); avoiding environmentally sensitive land parcels (water bodies, wetlands, forest, etc.) and land with higher right–of-way costs; and meeting strategic necessities such as proximity to city centers and socioeconomic development hubs. The existing station location identification process is manual in nature and carried out during the planning stage of HSR development. It involves identification of locations by overlaying maps of the study area with relevant information regarding locations of the transportation facilities, residential population distribution, land-use details, geographic features, etc. This approach indirectly factors in certain desirable requirements but cannot always guarantee a station location with maximum utility because not all feasible locations will be evaluated and no exact quantification of utility is available.

Geographic information systems (GIS), with their advanced mapping, geo-processing, and visualization capabilities, could be used in the spatial analysis of potential station locations. The GIS data, in the form of land use and land-cover maps, property-data maps, and maps showing other facility locations within the study area, could be utilized in the process. A model that quantifies the desirable requirements and presents as a utility score would greatly benefit HSR planners by helping them identify optimal station location within potential HSR regions. Hence, the objective of this paper is to develop a GIS-based HSR station location optimization model. For this purpose, an analytical model is specifically developed to identify a pool of candidate locations for HSR stations by quantifying the desirable requirements. Overall, it helps in identifying the station location with the highest utility. The desirable requirements of HSR station locations are estimated using utility functions and integrated into the GIS-based analytical framework. A real-world case study is presented to demonstrate the efficacy of the proposed model.

2. LITERATURE REVIEW

Station location identification is a facility location decision or analysis problem. The aim of this type of problem is to find the optimal feasible location for a facility that satisfies various predetermined selection criteria. The easiest way to identify feasible locations for stations can be done by using the simplest suitability analysis or map-algebra approach (McHarg and Mumford 1969). The map-algebra approach for a potential location involves measuring some form of accessibility score (and/or available utility value) (Cervero et al. 1999) using distance decay functions (exponential, power, binary, kernel form, etc.) (Kronbak and Rehfeld 2000; Skov-Petersen 2001; Hipp and Boessen 2017) based on the existing residences (or services and facilities) located elsewhere. There are various studies on location decision problems with small numbers of

pre-identified feasible locations (Vorhauer and Hamlett 1996; Baban and Parry 2001; Vlachopoulou et al. 2001). In such studies, no further analysis or modeling was necessary apart from the suitability analysis. However, it becomes difficult to select one alternative over another when problems have large numbers of available feasible locations. Extensive location allocation modeling, apart from the suitability analysis, is necessary in such cases (Murray 2010). These models attempt to find the best facility locations by optimizing one or more objectives (minimum weighted distance, minimax distance, maximum utility, capacity constraint, etc.) (Fisher and Rushton 1979). Researchers obtained the optimal location for a facility by minimizing the maximal service distance required to reach the facility (Church and ReVelle 1974), by maximizing the expected profit of a convenience store in a region (Ghosh and Craig 1984), by maximizing the utility measured as a function of facility attributes and distance to the location (Drezner 1994; Drezner and Drezner 1996), by maximizing the total budget share of retail facilities under budget constraint (Drezner 1998), and by minimizing the weighted distance from demand points to the facility location (Yeh and Chow 1996; Church 1999). Numerous possible combinations should be examined to obtain the best solution to solve these types of problems.

Previous studies assumed possible location of stations as *a priori* information (Bruno et al. 2002; Schöbel 2005; Laporte et al. 2011). Also, the local attribute details of a study area, such as right-of-way cost details, accessibility from existing public transportation facilities, environmental and geographically sensitive locations, and availability of sufficient land for station location, were excluded to simplify the problem (Bruno et al. 2002; Schöbel 2005; Repolho et al. 2013). These simplifications of relevant information could yield sub-optimal results. Certain studies integrated study area information from an urban rail perspective. However, there was no exclusive literature on HSR station locations. Therefore, a methodology to identify a feasible station location would be greatly useful in the HSR planning process. It should include various desirable requirements and constraints to assist in quantifying the desirable requirements by means of utility functions and thus, help in identifying the station location with the most utility. GIS can be particularly useful in developing such a methodology due to its advanced geo-processing, mapping, and visualization capabilities in managing various data types (such as property data, land use and land-cover maps, maps showing other important facility locations, and demographic information). Hence, the aim of this paper is to develop a GIS-based HSR station location identification model that considers relevant desirable requirements and constraints.

3. DESIRABLE REQUIREMENTS AND CONSTRAINTS FOR HSR STATION LOCATIONS

HSR station locations typically need to satisfy certain desirable requirements based on accessibility, environmental concerns, geographic/spatial concerns, and physical requirements and conditions. These requirements can be represented mathematically and used in developing suitable utility functions to check the feasibility of a candidate site location. In this study, the main focus is on environmental and accessibility-based requirements. These desirable requirements, its mathematical representations and utility functions, are stated as follows:

- Stations should avoid environmentally sensitive areas (for example, forests and wetlands), topographically infeasible areas (for example, lakes and rivers), and historically sensitive areas (for example, cemeteries, places of worship, historical

sites, and ruins). Let C_{sa} and S_{if} be the study area and the set of infeasible locations or areas, respectively. Then the feasible set of station locations S_f can be represented as given in equation 1.

$$S_f = \left(C_{sa} \cap \overline{S_{if}} \right) \tag{1}$$

Where, S_f = set of feasible station locations.

A sharp threshold value can be assigned to avoid the environmentally sensitive regions. This type of model is known as isochronic definition (Cervero et al. 1999) or cumulative opportunities measure (Handy and Niemeier 1997). A binary model can be introduced to assign a fixed value of 1 and 0 to the locations which are feasible and infeasible, respectively. Let G_i denote the candidate station location. The binary model can be represented as shown in equation 2.

$$\gamma_i = \begin{cases} 1 \text{ if } G_i \in S_f \\ 0 \text{ if } G_i \in S_{if} \end{cases} \tag{2}$$

- Terminal stations (stations at both ends of the corridor) should be located close to the city center or downtown area of large regional cities to enhance the ridership potential (Menéndez et al. 2002). Let D_i be the distance of candidate station G_i from the downtown area, and D_{Th} be the threshold distance from downtown. This distance should be less or equal to the threshold distance as indicated in equation 3.

$$D_i \leq D_{Th} \tag{3}$$

Sharp threshold value can be used to model the proximity of station locations to downtown area/city center. A binary model can be formulated as shown in equation 4 to assign a fixed value (1 or 0) to the locations closer than the given threshold value.

$$U_{i1} = \begin{cases} 1 \text{ if } D_{ij} \leq D_{Th} \\ 0 \text{ if } D_{ij} > D_{Th} \end{cases} \tag{4}$$

- Stations should avoid locations with extensively developed neighborhoods that have very high right-of-way costs. Since the region encompassing the station locations might have a high variance of land-cost values, a utility function based on a normalized cost (the values would be in the range [1,0]) can be formulated as equation 5.

$$U_{i2} = \left(1 - \frac{C_{ijROW} - C_{iMin\_ROW}}{C_{iMax\_ROW} - C_{iMin\_ROW}}\right) \tag{5}$$

Where,

C_{iROW} =   Cost of land or right-of-way cost for candidate station G_i;
C_{Min_ROW} =   Minimum cost of land or right-of-way cost;
C_{Max_ROW} =   Maximum cost of land or right-of-way cost;

- Stations should be located near existing transportation facilities (such as airports, railways, bus stops, and highways) for ease of accessibility and intermodal integration. Let D_i^m be the distance of candidate station G_i from the existing

transportation facility m, and D_w be the threshold average walking distance, then, as per the accessibility requirements, it is represented as equation 6.

$$D_i^m \le D_w \tag{6}$$

Distance decay functions are commonly used to model accessibility of facilities in spatial analysis (Skov-Petersen 2001). Hence, a utility function can be modeled using equation 6, which assigns the maximum utility value, i.e., 1, on satisfying the accessibility criteria, and a continuously decreasing utility value up to 0, with increasing distance. It is shown in equation 7.

$$U_{i3} = \begin{cases} 1 \text{ if } D_i^m \le D_w \\ \dfrac{1}{e^{\left(\frac{D_i^m}{D_w}-1\right)}} \text{ if } D_i^m > D_w \end{cases} \tag{7}$$

4. PROBLEM FORMULATION

The objective of the study is to optimize station location by satisfying the desirable requirements. A positive utility score can be assigned to each location in the study area, which is estimated using the utility functions developed for each desirable requirement. Relevant weights W_j are assigned to each desirable requirement j. The summation of all weights is equal to 1. Therefore, the utility score for each location would be the weighted summation of positive scores, based on the number and extent of desirable requirements satisfied. The problem can thus be formulated as the maximization of this total utility score for candidate station locations in the study area. The station location identification is thus formulated as a mixed integer programming problem, as shown in equation 8, with constraints in equations 9 and 10.

$$Max \sum_{i=1}^{ng} \sum_{j=1}^{nj} \alpha_i * \gamma_i * W_j * U_{ij} \tag{8}$$

Subject to

$$\sum_{j=1}^{nj} W_j = 1, \; 0 < W_j < 1 \tag{9}$$

$$0 \le U_{ij} \le 1 \tag{10}$$

Where,

α_i = $\begin{cases} 1 \text{ if location } i \text{ is selected} \\ \quad 0 \text{ otherwise} \end{cases}$

U_{ij} = utility score based on desirable requirement j for location i

W_j = weightage given to requirement j

ng = total number of candidate locations in study area

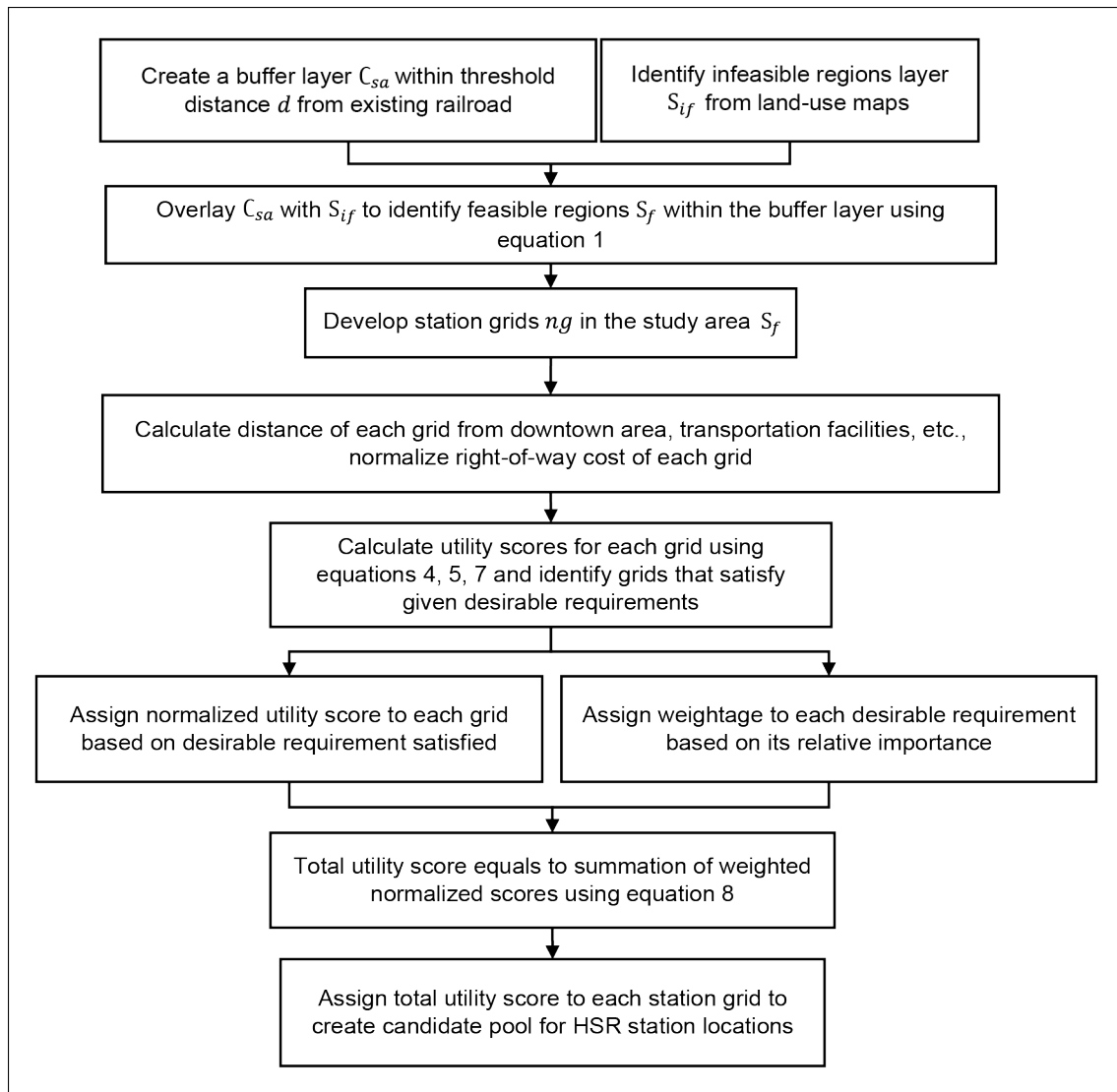nj = total number of desirable requirements for station location

5. METHODOLOGY

Infeasible locations are identified *a priori* and screened out from the study region. Subsequently, the feasible region is divided into grids of sizes equal to station location areas. A positive utility score is assigned to each feasible grid location for each desirable

requirement considered. Relevant weights are assigned to each desirable requirement, based on their relative importance. The total utility score for each feasible station location is thus calculated as the weighted summation of the positive scores assigned to a station location. The various steps of the station location identification process are illustrated in Figure 1. The stations locations that have a total utility score close to 1 are the most suitable for HSR station locations.

Figure 1: Data Preparation and Initial Screening for HSR Station Locations

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┌─────────────────────────────────┐  ┌─────────────────────────────────┐
│ Create a buffer layer C_sa       │  │ Identify infeasible regions layer │
│ within threshold distance d      │  │ S_if from land-use maps           │
│ from existing railroad           │  │                                   │
└─────────────────────────────────┘  └─────────────────────────────────┘
                    │                                    │
                    └──────────────┬─────────────────────┘
                                   ▼
        ┌─────────────────────────────────────────────────┐
        │ Overlay C_sa with S_if to identify feasible       │
        │ regions S_f within the buffer layer using         │
        │ equation 1                                        │
        └─────────────────────────────────────────────────┘
                                   │
                                   ▼
        ┌─────────────────────────────────────────────────┐
        │ Develop station grids ng in the study area S_f    │
        └─────────────────────────────────────────────────┘
                                   │
                                   ▼
        ┌─────────────────────────────────────────────────┐
        │ Calculate distance of each grid from downtown     │
        │ area, transportation facilities, etc.,            │
        │ normalize right-of-way cost of each grid          │
        └─────────────────────────────────────────────────┘
                                   │
                                   ▼
        ┌─────────────────────────────────────────────────┐
        │ Calculate utility scores for each grid using      │
        │ equations 4, 5, 7 and identify grids that satisfy │
        │ given desirable requirements                      │
        └─────────────────────────────────────────────────┘
                    │                                    │
                    ▼                                    ▼
┌─────────────────────────────────┐  ┌─────────────────────────────────┐
│ Assign normalized utility score │  │ Assign weightage to each         │
│ to each grid based on desirable │  │ desirable requirement based on   │
│ requirement satisfied           │  │ its relative importance          │
└─────────────────────────────────┘  └─────────────────────────────────┘
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        │ Total utility score equals to summation of        │
        │ weighted normalized scores using equation 8       │
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                                   │
                                   ▼
        ┌─────────────────────────────────────────────────┐
        │ Assign total utility score to each station grid   │
        │ to create candidate pool for HSR station          │
        │ locations                                         │
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6. CASE STUDY

The proposed Mumbai–Ahmedabad HSR corridor connects Ahmedabad, in the state of Gujarat, with India's economic hub, Mumbai, in the state of Maharashtra. It will be India's first HSR line. In this study, the city of Mumbai is chosen as the case study. The city of Mumbai is a very densely populated city with a well-connected transportation network and variable land cost. It makes Mumbai an interesting location for this case study. The data collection process, type, usage, and sources of data collected for this study are described in the subsequent subsections. The data collected was processed and GIS operations were applied accordingly for further analysis.

Land Use and Land-Cover Map Data. Land-use data in the form of raster maps in GeoTiff format, having 1:250000 resolution, was downloaded from the Bhuvan web portal (2016). The land use and land-cover maps had 18 classifications. These maps were used to identify environmentally sensitive areas, such as forests, rivers, wetlands, and swamps. These land-use categories were extracted in GIS and used as the infeasible layer.

GIS Shapefiles. GIS data in the form of vector shapefiles were downloaded from the Open Street Maps website (2017). This included point shapefiles for locations; transportation points (bus stops, railway stations); polyline shapefiles for railways, highways, and road networks; and polygon shapefiles for buildings, political/ administrative boundaries, and waterbodies. The shapefile showing the administrative boundaries was used to generate a grid layer with user-specified grid size. Figure 2 shows the study area with land-use information, location of the existing transportation points, and planned HSR station.

Figure 2: Study Area with Land Use, Transportation Points, and Planned HSR Station
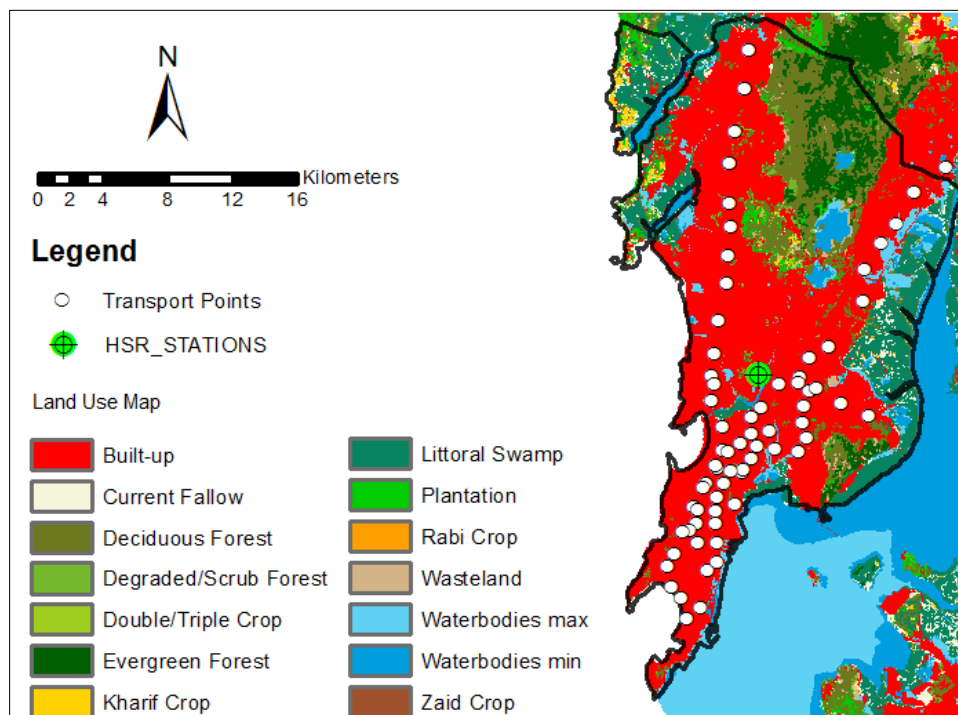
Source: Bhuvan 2016.

Property Data. Urban-land property-cost data was downloaded from property brokerage websites (99acres.com 2017; magicbricks.com 2017). These rates were used to calculate the possible price of land by using equation 11 (Chakravorty 2013).

$$C_{iROW} = (C_{iProp} - C_{CC}) * FSI \qquad (11)$$

Where,

C_{iROW}	=	possible price of land or right-of-way cost for grid G_i;
C_{iProp}	=	cost of property for grid G_i;
C_{CC}	=	construction cost;
FSI	=	floor space index

Vector shape files in the form of points were created throughout the study area using ArcGIS 10.4. The price-of-land data obtained from equation 11 was input as attribute data for point shapefiles at respective locations. This data was then interpolated to get the price of land for urban/built-up areas for the entire study area. Figure 3 represents the raster cost dataset obtained for the study area. Table 1 shows the parameters used in this case study.

Figure 3: Raster Cost Dataset
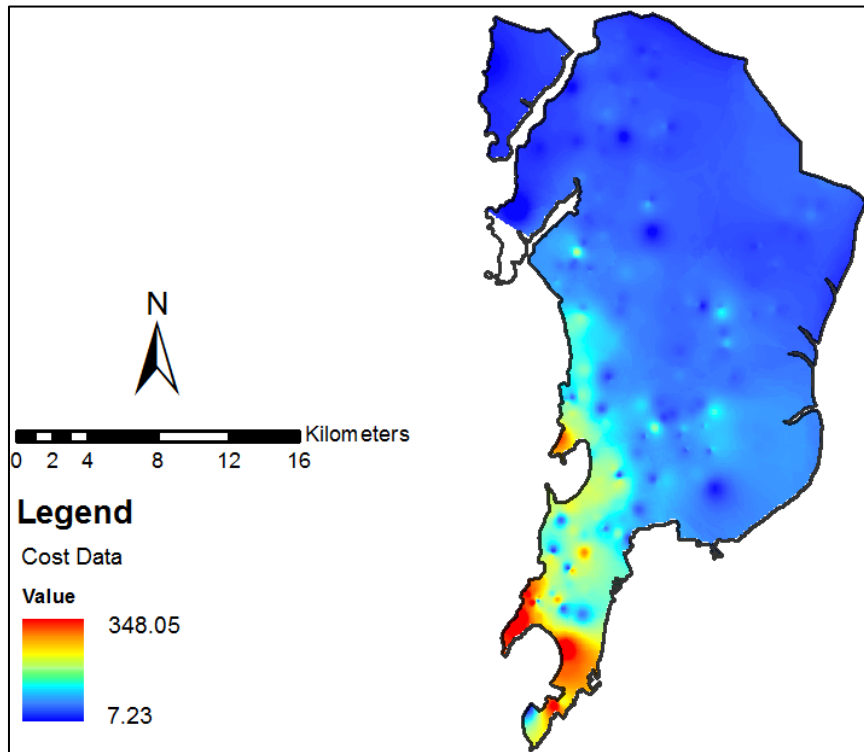
Table 1: Parameters and Corresponding Values

Description	Parameter	Value	Source
Threshold Distance for Buffer Layer	d	13 km	RITES 2013
Grid Size for Station Locations	Ar_G	70 acres, 15.35 acres	Brinckerhoff 2004; JICA 2015
Threshold Average Walking Distance	D_w	400 m	Guerra et al. 2012
Threshold Distance from Downtown Area	D_{Th}	3 km	Assumed

Weightage Assigned for Desirable Requirements. Nine different weightage scenarios were considered in order to determine the effect of the weightage assigned on the utility of a location. Each scenario had a separate set of weightage assignment for the respective desirable requirements. Each of these sets of weightages was then used to evaluate the utility scores. The resulting utility scores were then compared to find the weightage set that maximized the utility score. The most suitable weightage assignment should maximize the total utility for the actual stations selected.

Table 2 shows the weightage assignment for all the scenarios considered in this study. Proximity to city center was given the highest weightage in scenario 1. The next highest weightage was given to cost of land and accessibility to existing transportation points, to avoid land with very costly right-of-way and to have ease of access, respectively. Similar to the base scenario, proximity to city center was assigned the highest weightage in scenario 2. The next highest weightage was given to accessibility to existing transportation points and cost of land. The cost of land was given the lowest weightage. In scenarios 3 and 4, the highest weightage was assigned to accessibility to existing transportation points. The next highest weightage was assigned to cost of land, for scenario 3, and proximity to city center, for scenario 4, respectively. The highest weightage was assigned to cost of land, followed by proximity to city center, for scenario 5, and accessibility to transportation points, for scenario 6, respectively. Proximity to city center was assigned the total weightage, in scenario 7. Similarly, cost of land and accessibility to existing transportation points were assigned the total weightage in scenarios 8 and 9, respectively.

**Table 2: Weightage Assigned for Desirable Requirements**

| Notation	Desirable Requirement	Weightage W_k								
		S1	S2	S3	S4	S5	S6	S7	S8	S9
U_{i1}	Close Proximity to City Centre	0.5	0.5	0.2	0.3	0.3	0.2	1	0	0
U_{i2}	Avoiding High Right-of-Way (ROW) Cost	0.3	0.2	0.3	0.2	0.5	0.5	0	1	0
U_{i3}	Accessibility to Existing Transport Points	0.2	0.3	0.5	0.5	0.2	0.3	0	0	1

7. RESULTS

This section presents the step-by-step geo-processed results obtained when the proposed model was applied to the study area data. Figure 4(a) shows the study area along with the buffer distance at a threshold distance from the existing railroad. Figure 4(b) shows the infeasible regions obtained from the land-use data. When these two data layers were overlaid, the feasible regions of the study area were obtained. Figure 4(c) shows the feasible regions identified from the study area. The station grid locations were then developed from the feasible regions using the grid size mentioned earlier. Figure 4(d) shows the developed grids in the feasible region of the study area. These were the candidate locations for HSR station. Figure 5(a), (b), and (c) show the normalized individual utility scores for the feasible regions of the study area. Individual desirable properties and respective utility score variation can be observed in this figure. Figure 5(a), (b), and (c) show the variation of the utility score for the feasible regions with respect to city center proximity U_{i1}, avoiding high right-of-way cost U_{i2}, and accessibility to existing transportation points U_{i3}, respectively. The total utility score of all the locations in the feasible region of the study area (i.e., weighted summation of the normalized utility scores) was obtained based on the weightage assignment provided in Table 2. It is

displayed in Figure 6(a). The total utility score obtained for the feasible regions was then assigned to each grid location to create a candidate pool for HSR station locations. Figure 6(b) and (c) show the candidate pool for station locations after the scores were assigned to the grids having different grid sizes. Figure 7 shows the variation of the total utility score for the various weightage assignments given in Table 2. Table 3 shows the value of each of the desirable requirement satisfied along with respective individual utility score for the planned HSR station location in Mumbai.

Figure 4: (a) Study Area with the Buffer Distance at Threshold Distance from Existing Railroad; (b) Infeasible Regions; (c) Feasible Regions; (d) Developed Grids in Feasible Region of Study Area
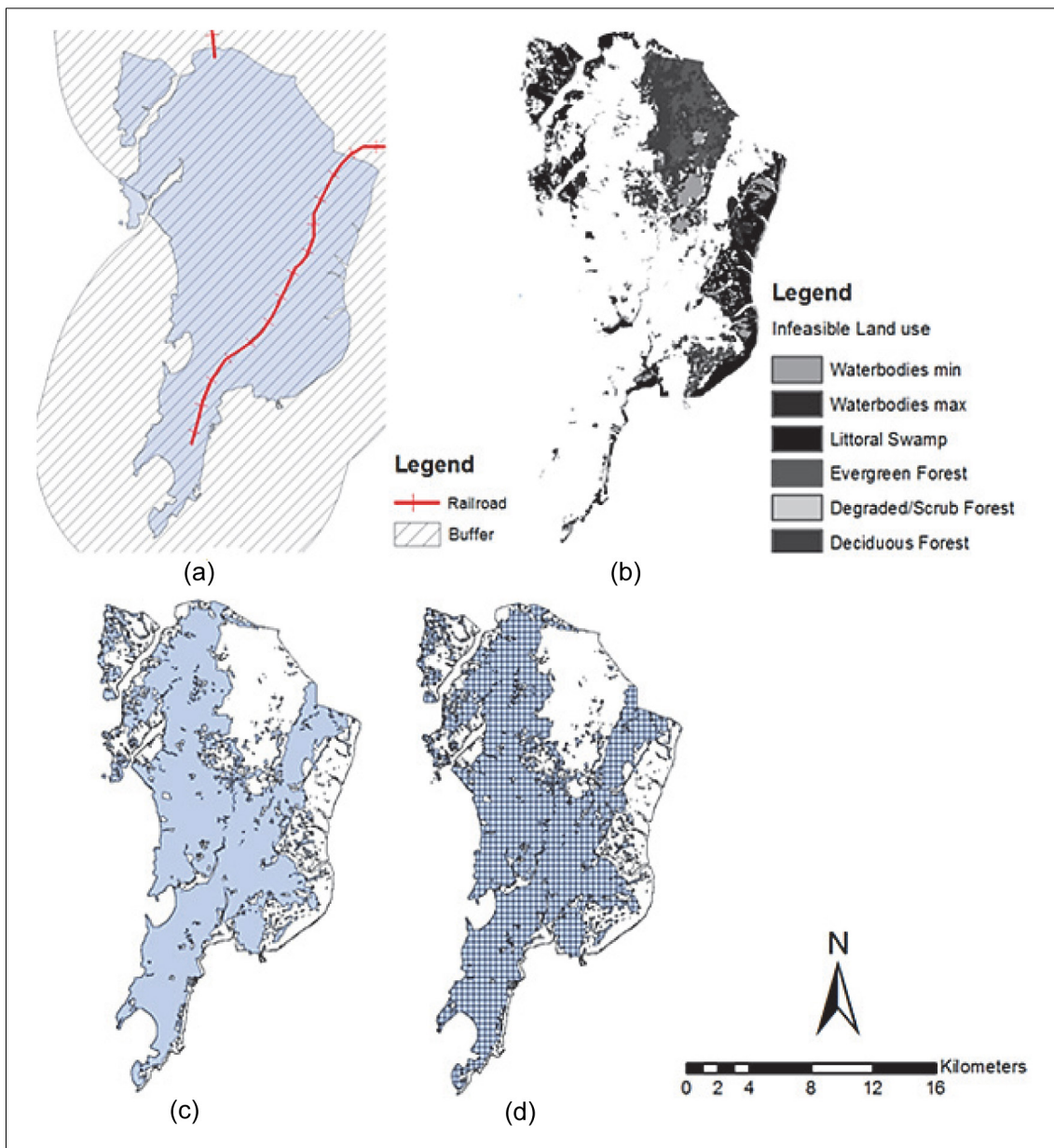
Figure 5: (a) Utility U_{i1} with respect to City Center Proximity; (b) Utility U_{i2} with Respect to Avoiding High Right-of-Way Cost U_{i2}; (c) Utility U_{i3} with Respect to Accessibility to Existing Transportation Points
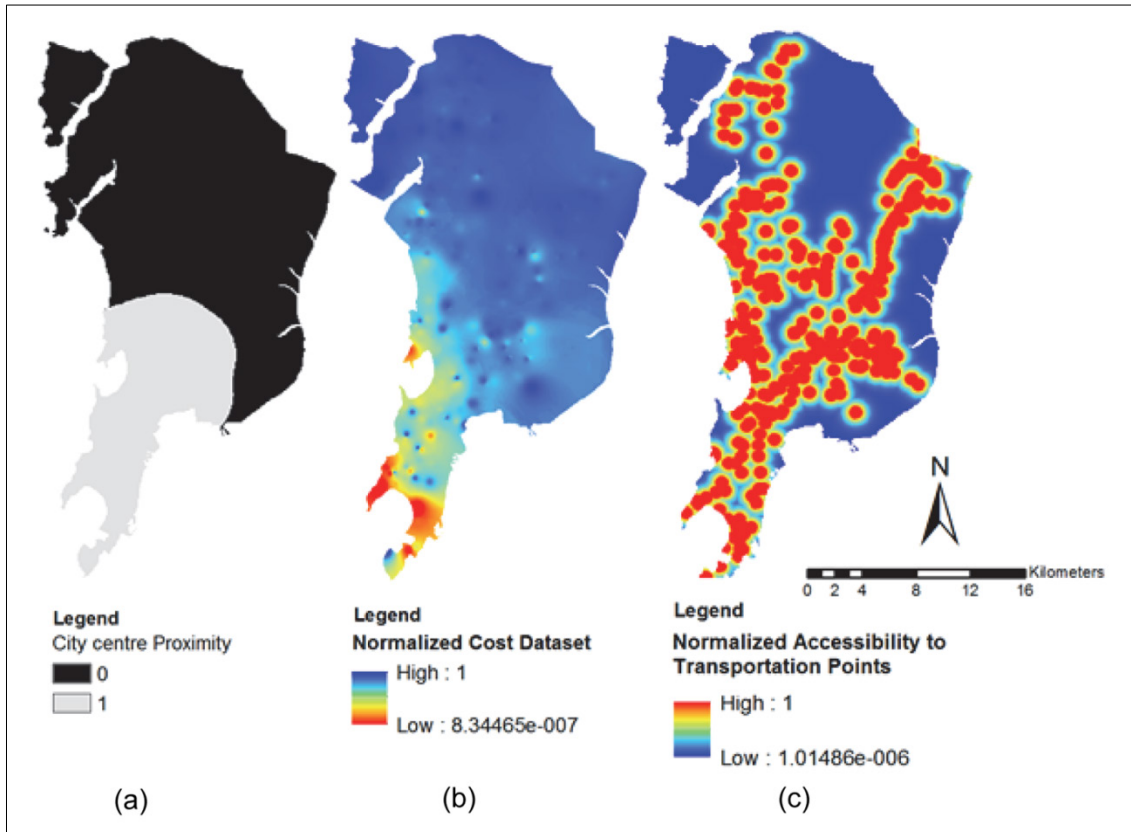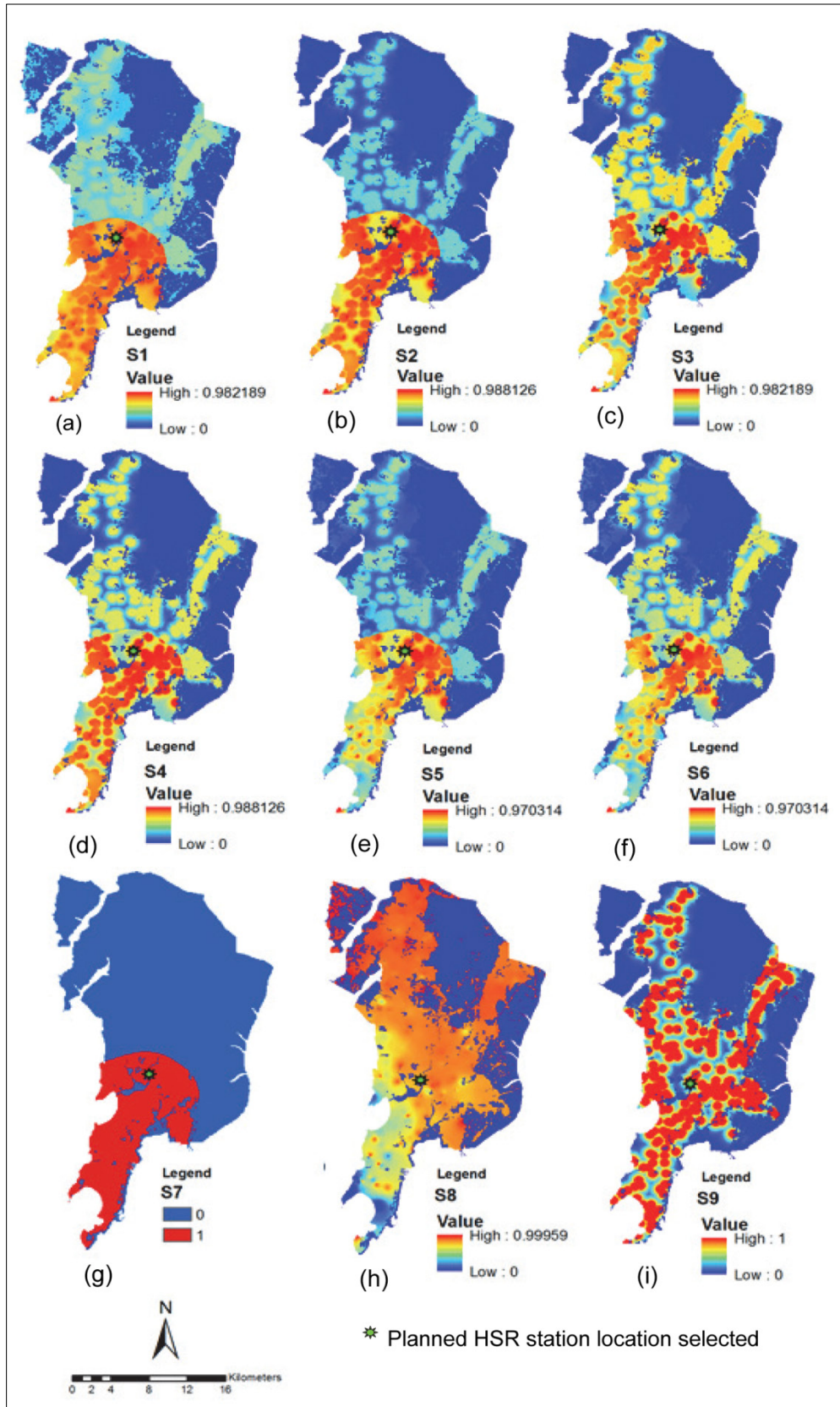

Figure 6: (a) Total Utility Score of All Locations in Study Area; (b) Candidate Pool of Station Locations for Grid Size of 15.35 Acres; (c) Candidate Pool of Station Locations for Grid Size of 70 Acres
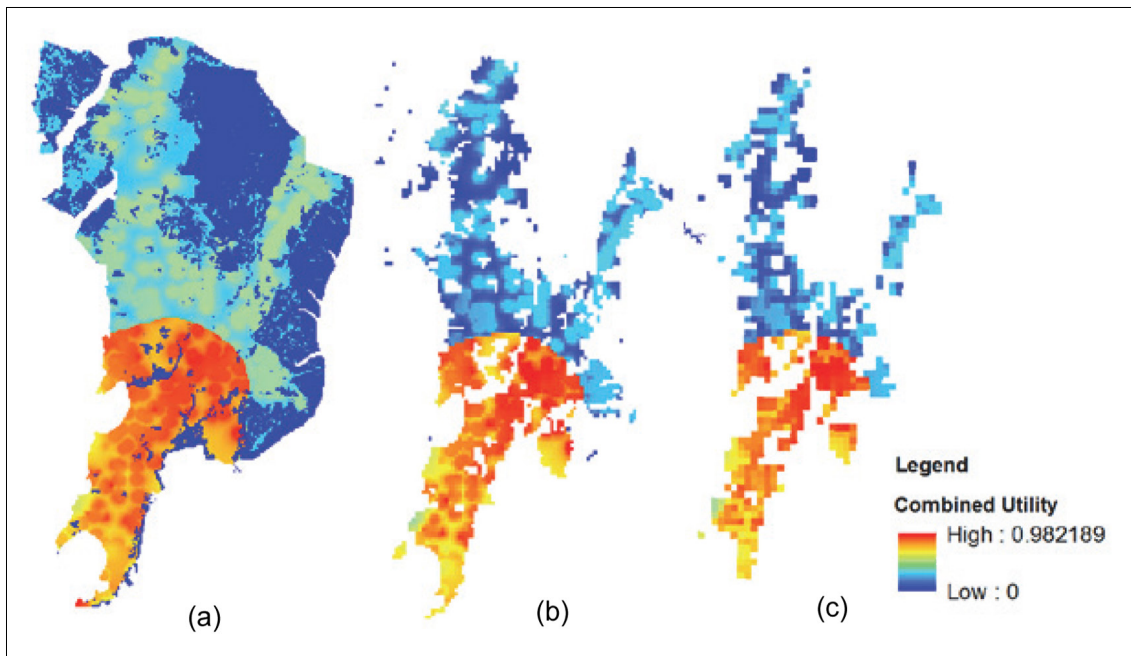
Figure 7: Variation of Total Utility Scores for Different Weightage Assignment for Mumbai

Table 3: Variation of Total Utility Scores for Different Weightage Assignment

Desirable Requirement	Desirable Requirement Values	Individual Utility Score	Weightage Assignment	Total Utility Scores
Close Proximity to City Center (Km)	0.36	U_{i1} =1.00	S1	0.930
			S2	0.850
			S3	0.931
Avoiding High ROW Cost (INR Crores per Acre)	87.92	U_{i2} =0.768	S4	0.904
			S5	0.824
			S6	0.884
Accessibility to Existing Transport Points (Walking Distance) (Meters)	300	U_{i3} =1.00	S7	1.00
			S8	0.768
			S9	1.00

It can be observed from Table 3 that the station location selected is at close proximity to the city center (less than 3 km), and is within accessible walking distance from the existing transportation points (within 400 m). Hence, the station location was given the highest possible individual utility score i.e., 1, for both desirable requirements (U_{i1}, U_{i3}). It also can be seen that the right-of-way cost for the selected station location is 87.92 INR crores per acre, which is neither the lowest (0.368 INR crores per acre) nor the highest (300 INR crores per acre) cost. Hence, the utility score U_{i2} was neither 1 nor 0. Further, it shows the variation of utility scores as they pertain to different assigned weightage for the planned HSR station location in Mumbai. It is evident from Table 3 that the station location selected for this case study reports high utility scores for each of the assigned weightage, the lowest being 0.768 for S8, where the right-of-way cost has the highest weightage. This station location completely satisfies two desirable requirements (i.e., accessibility and proximity to the city center) and partially satisfies the third desirable requirement (i.e., right-of-way cost). Also, the selected station location in Mumbai is not on environmentally sensitive land. Hence, it can be concluded that the station locations selected for the given case study should provide high utility to the adjacent population based on accessibility, land cost, city-center proximity, and environmental impact factors.

8. CONCLUSION

HSR station locations are vital, as they provide access to the riders, serve as multi-modal transportation hubs (with connections to regional and local transit), and are prime locations for Transit-Oriented Development. This paper presents a GIS-based analytical model that optimizes station-location specific, desirable requirements. The paper states the desirable requirements for HSR station locations, which include (though not necessarily limited to) improved accessibility and intermodal integration with existing transportation facilities and services, avoidance of environmentally sensitive areas and land with higher right-of-way costs, and other strategic necessities. Suitable utility functions are developed to estimate the utility of a candidate location associated with its respective requirements, which are integrated into the station locations identification process. Appropriate weights are assigned based on relative importance of each requirement. The overall utility of a location is then estimated as the weighted summation of these utility scores. In other words, this study quantifies the overall utility of an HSR station by analyzing the extent to which a location satisfies these desirable requirements, using appropriate utility functions and weightages. These vital components were mostly ignored in previous HSR models.

The developed methodology demonstrates how an available GIS database can be used in the real-world planning stage of the development of an HSR project. Station location identification is modeled and covered in this methodology, which is a primary aspect of HSR development. This utility-based quantification methodology has the capability of easily identifying feasible station locations in the corridor for HSR. Such quantification can be used by the planners for further analysis and station location selection. This study demonstrates the applicability of the methodology in HSR planning, using the city of Mumbai, India as a case study. The results obtained are compared with the planned real-world station location identified for the city of Mumbai and show promising results. The developed methodology is expected to help the planners in station-location identification, in particular, and the overall planning of HSR, in general.

The future scope of work in this methodology could be inclusion of additional socioeconomic requirements relevant for station locations, modeling, and examining subsequent steps of HSR development. These steps include using the configuration of stations to develop an HSR alignment for the corridor.

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