

A Multi-Criteria Methodology to Determine the Optimal Highway Candidate

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Abstract: Research on optimization of highway alignment has been quite intensive in two past decades. Determine the best candidate of highway alignment is one of the most complex of highway design stages because the effect of various parameters with different impacts. Hence, in the present study, a multi-criteria analysis methodology is proposed to determine the best highway candidate with the special focus on the cost and safety criteria. The multi-criteria analysis methodology is based upon the analytical hierarchy process technique which systematically transforms the performed calculations for each criterion into a series of simple pairwise comparisons and then determines the weight of each criterion. Provided methodology in current research is not limited to cost and safety criteria and can be upgraded to other criteria. This methodology is carried out for a case study region in western north of Iran and therefore cost and safety criteria are obtained for case study condition.

Key words: Cost category, safety parameter, the best highway candidate, analytic hierarchy process, methodology

INTRODUCTION

There has been a great deal of research effort in recent years in developing methods of determining the optimal candidate of highways. So far several extensive researches have been carried out to determine the optimal alignment in all over the world which is led to the emergence of different models and algorithms. Some of the most important ones are: calculus of variations (Howard *et al.*, 1969), network optimization (Turner and Miles, 1971), dynamic programming, genetic algorithm (Jong, 1998), genetic algorithm and Geographic information system (Jha, 2000), etc. All models which are presented for highway alignment optimization perform alignment optimization only with minimizing the total cost. While determining the best highway candidate is very complex and several parameters can be affected on such as: cost, safety, etc.

Costs are one of important parameters in determining the optimal candidate of highway. Cost parameters are divided into direct and indirect costs. Indirect costs are paid by investments of government and private sector (such as: costs related to highway design, construction, maintenance, air and noise pollution, etc.) and direct costs are paid by highway users after the operation of the highway (such as: vehicle operating costs, loss time costs, toll and parking costs, etc). In this study is considered four categories of cost functions including:

length dependent cost, structural cost, location dependent cost and earthwork cost. The results of each cost category for each highway candidate can express the weight of each highway candidate and also each cost category.

Other significant parameter which plays an importance role in highway alignment optimization is safety. Global statistics indicate that more than 1 million people lost their lives in road accidents annually. According to the latest report by the World Health Organization (WHO), road injuries which lead to death are in the top 10 causes of death in all over the world. The statistics which are provided by WHO show that around 1.3 million people have lost their lives in 2012 in road accidents around the world. A similar statistic also shows that around 25000 people lose their lives in Iran annually because road accidents. According to studies conducted in Iran, main causes of accidents are respectively human factors (70%), road and environmental factors (20%) and the vehicle factor (10%). As stated by statistics, the effect of the road and environmental factors is considerable in road accident occurrences in Iran. With correct routing and use of all effective parameters in determine the best highway candidate such as compulsory point, sea, marshes, rivers, hydrology, geology, faults, landslides, etc., the rate accidents can be reduced (Yunus *et al.*, 2015).

In current paper is provided a new methodology for determining the best highway candidate by using Analytic Hierarchy Process technique with specific focus on cost and safety parameters. The weight of each safety parameters relative to each other is obtained by using questionnaires. But the weight of each highway candidate based on each safety and cost parameter is obtained based on extraction of safety and cost parameters from highway candidates and then using a method which is defined in this paper. Finally, the obtained weights for cost and safety will be used in AHP technique and then the best highway candidate will be obtained based on provided methodology. The best candidate which is obtained based on provided methodology can satisfy all used parameters simultaneously. The investigated cost and safety parameters in current study are based on Iran condition and can be upgraded for other territories.

MATERIALS AND METHODS

Cost category: In this study is considered and upgraded four categories of cost functions including: length dependent cost, structural cost, location dependent cost and earthwork cost. Calculated costs in this paper are estimated by assumption some of the parameters and are approximately. These cost functions are merely for determining comparable weight of costs related to each highway candidates which are needed in the analytic hierarchy process technique. All cost categories used in this study are obtained for case study region which is located in Western North of Iran between two cities Qeydar and Zarrin Rood and can be upgraded for other case studies.

Length dependent costs: In this research, the concept of length dependent costs is the costs which have a direct relationship with decrease or increase of highway length and are divided into three categories as following:

- Pavement costs including sub-base, base and surface of pavement
- Costs related to signs and signals
- Costs associated with safety guards and facility such as guardrail, lighting systems, etc.

The main factor in the costs above-mentioned is highway length although other factors are also involved in determining the costs. For example with increasing length of a highway candidate, costs associated with highway will increase. In the following more detail on each of these costs will be explained.

Pavement cost: One of the costs associated with the length of highway are included by costs based on preparing and implement of sub-base, base, surface and haul which have directly relation with highway length. In current research unit cost related to pavement is defined by upc. Therefore, the costs associated with pavement of highway will be equaled to Eq. 1. In this research unit cost related to highway pavement for all highway candidates are assumed to be constant because these costs are dependent on the length and type and location of highway candidates don't have any effect on determinant of it Eq. 1:

$$C_{len(p)} = L \times upc \tag{1}$$

Where:

- $C_{len(p)}$ = Pavement cost related to length dependent cost
- upc = Unit pavement cost
- L = Length of highway candidate

Costs related to signs and signals: This type of costs is related to cost of supplying and installing traffic signals and guide boards along of highways. In this research unit cost related to sign and signal is defined by usc. Therefore, the costs related to signs and signals of highway will be equaled to Eq. 2. This cost is dependent on factors such as the geometric design of the highway, road type and geographical condition, etc. In this study, given that the general condition of highway candidates are almost identical between two points thus it is assumed that such costs have relationship with highway length directly and its unit cost is assumed to be constant for all candidates:

$$C_{len(s)} = L \times usc \tag{2}$$

Where:

- $C_{len(s)}$ = Signs and signals cost related to length dependent cost
- usc = Unit sign cost
- L = Length of highway candidate

Costs associated with safety guards and facility: This type of costs is related to cost of supplying and installing the middle guards of the highway and guardrail as well as lighting system along of highways. In this research unit cost related to safety guards and facility is defined by uic. Therefore, the costs associated with safety guards and facility of highway will be equaled to Eq. 3. This cost is directly related to the length of the highway candidate thus uic can be fixed for all candidates.

$$C_{len(i)} = L \times uic \tag{3}$$

Where:

$C_{Len(i)}$ = Guards and facility cost related to length dependent cost

uic = Unit installation cost

L = Length of highway candidate

The total cost related to the length of each highway candidate can be defined according to Eq. 4:

$$TC_{Len} = C_{Len(p)} + C_{Len(s)} + C_{Len(i)} \quad (4)$$

Location dependent cost: The final location dependent cost is associated with unit cost of land with different applications in along of highway candidate and area of each one of them (including land located in highway alignment and needed margin of highway). Based on different regulations the needed margin of highways are different, for example Regulations Geometric Design of Iran Roads have determined the width equal to 76 m for highways (total width of highway including width of lanes and needed margin). As regards the highway alignments are a function of Point Intersection (PI) thus location dependent costs can be as Eq. 5 (Maji, 2008):

$$TC_{loc} = \sum_{i=1}^{nlp} uc_i \times af_i \quad (5)$$

Where:

TC_{loc} = Total location dependent cost

uc_i = Unit cost of land parcel in the study area

af_i = Fractional area of land parcel required for the highway Alignment

nlp = Total number of land parcels in the study area

Moreover, land parcels can be divided into two categories in terms of ownership type real ownership (personal) legal ownership (public or private organizations). Unit cost of each one of mentioned type of land parcel in above can be based on different factors as following (Haughwout *et al.*, 2008; Bergeijk, 2012):

- Landuse of land parcel such as: commercial, residential, industrial, agricultural (farmland or gardens) and the National Lands
- Land distance from the boundaries of the city or village

Given the scope of this study which is to determine the optimal highway candidate between two points (two centres of populations) therefore land parcels where are located outside the boundaries of cities or villages are considered. There are different conditions to determine

the unit cost of land in various regions. Urbanism structures in different countries may be have different forms, for example in studied country in this research (Iran) all the landuse for construction a highway between two cities are divided into three categories Industrial lands national lands agricultural lands. Each of these three categories can be under the ownership of one of the modes or which is listed above.

Industrial lands: Today's, industrial lands in urbanism structures are located usually outside of cities boundary and are called industrial towns. In case study region, any highway candidate is not permitted to pass through these areas or in the other word this kind of land parcels are considered as constraint one. Industrial lands are usually under ownership of private sectors.

National lands: National lands are usually under ownership of governments. In this research, the cost related to this type of lands are assumed equal zero if they don't take as part of constraints parameters such as environmental or geographical constraint.

Agricultural lands: Various factors are effective in determine cost of agricultural land such as: amount of water, fertility, distance to existing roads, regional climate and the distance to the city boundaries, etc. In this study, only the effect of the land parcel distance to city boundary is considered.

Thus according to explanations in three above section Eq. 5 can be upgraded to following equation based on every case study condition:

$$TC_{loc} = \sum_{i=1}^{ngp} \alpha_i \times ugc \times A_{gi} + \sum_{i=1}^{nfp} \alpha_i \times ufc \times A_{fi} \quad (6)$$

Where:

ugc = Unit cost of standard land parcel with garden landuse where is located in near the city boundary based on real estate agents

ufc = Unit cost of standard land parcel with farmland landuse where is ith located in near the city boundary based on real estate agents

A_{gi} = Fractional area of ith land parcel with garden landuse where is located in highway alignment

A_{fi} = Fractional area of ith land parcel with farmland landuse where is located in highway alignment

α_i = An index based on the case study conditions and the distance of land parcel to city boundary

ngp = Number of garden land parcel

nfp = Number of farmland land parcel

α_i can be obtained by using questionnaire (asking question of range of land parcel cost from real estate agents in the region of case study), for example in case study used in this research are acquired the following amount:

- $\alpha \approx 1$ if land parcel be located <2 km from city boundary
- $\alpha \approx 0.85$ if land parcel be located between 2-5 km from city boundary
- $\alpha \approx 0.75$ if land parcel be located >5 km from city boundary

Structural costs: Structural costs are another effective cost to the selection of optimal candidate of highway including cost related to bridges, tunnels, retaining walls, culverts, etc. This cost for various candidates of highway accordance with its geographical situation may be different and should be calculated separately for each candidate. This cost is generally divided into three major categories as following:

- The costs related to bridges
- The costs related to tunnel
- The costs related to retaining wall

In the following each one of the costs related to structure will be investigated more accurately.

The costs related to bridges: Bridges is usually needed when crossing from rivers or valleys or old roads. These regions as well as the dimensions of the bridges can be identified by using the GIS database. Accordance with the regulations geometric design of Iran roads bridges is defined as following.

Bridge: It is a structure with spans over 6 m which allows to path for passing from waterway, valley, power transmission lines, rail or other old roads. Distance between bridge fulcrums in along the bridge center line is called the bridge span. In the multi-span bridge, length of each span should be 3 m or more.

In current research the unit cost related to volume of bridge is considered by ubc and total length of each bridge or culvert (L_b) is obtained from GIS database or other software. Equation 7 shows total cost related to bridges in along of highway candidate:

$$C_{str(b)} = \sum_{j=1}^{Seg} L_{b(j)} \times ubc \quad (7)$$

Where:

$C_{str(b)}$ = Total bridge cost in along of highway candidate
 $L_{b(j)}$ = Length of bridge

ubc = Unit bridge cost based on bridge volume
 seg = Number of bridges in along of highway alignment

The costs related to tunnel: In some cases, prediction of tunnel along the studied candidate is logical and necessary. Selection a tunnel in along a highway candidate can be for reasons such as: economic, reduction of length of highway candidate, protection of road in snowy region, landslide place, avalanche risk, etc. In the highways, tunnels are constructed one-way and the number and width of lanes and road shoulder inside of the tunnel will be identical with outside the tunnel. Using GIS database can be determined position and length of the tunnels in along of highway alignment. In current research unit cost related to tunnel construction is considered by utc and total length of each tunnel (L_t) is obtained of GIS database or other Software. Equation 8 shows total cost related to tunnels in along of highway candidate:

$$C_{str(t)} = \sum_{j=1}^{Seg} l_{t(j)} \times utc \quad (8)$$

Where:

$C_{str(t)}$ = Total tunnel cost in along of highway alignment
 $l_{t(j)}$ = Length of tunnel
 utc = Unit tunnel cost based on tunnel length
 seg = Number of tunnels in along of highway alignment

The costs related to retaining wall: Retaining walls are used for soil motion control and overload of various structures on the road or at the foot of excavation and embankment. These structures are usually constructed in places where the groundwater level is high and the soil is poorly. Retaining walls can be used depending on soil elevation, administrative constraints, type of facility located on soil and climate condition. The location and dimensions of the retaining wall can be determined by using of GIS database or other softwares. In current research unit cost related to construct retaining wall is defined by uwc and total area of each retaining wall (A_w) is obtained of GIS database or other softwares. Equation 9 shows total cost related to retaining wall in along of highway alignment:

$$C_{str(w)} = \sum_{j=1}^{Seg} A_{w(j)} \times uwc \quad (9)$$

Where:

$C_{str(w)}$ = Total retaining wall cost in along of highway alignment
 $A_{w(j)}$ = Area of retaining wall
 uwc = Unit retaining wall cost
 seg = Number of retaining walls in along of highway alignment

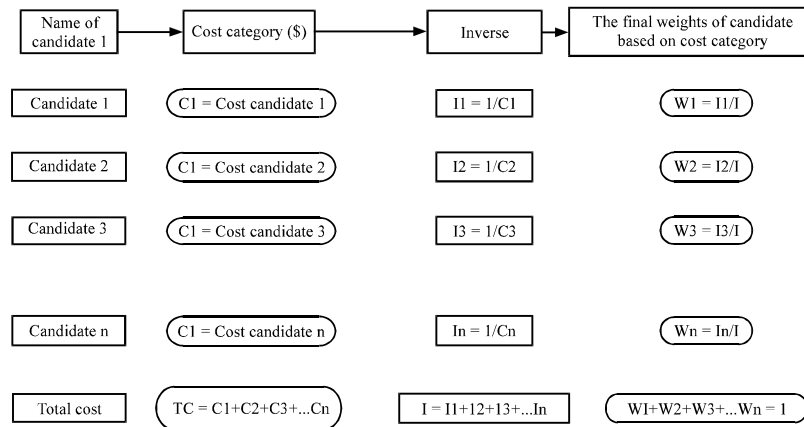


Fig. 1: Flowchart for obtaining weights of each candidate based on each cost category

The total cost related to the structures of the highway can be defined according to Eq. 10:

$$TC_{str} = C_{str(b)} + C_{str(t)} + C_{str(w)} \quad (10)$$

Earthwork costs: Earthwork costs are included by costs related to excavation, embankment and haul. So far many methods have been proposed to calculate this cost. There are two popular methods for calculating earthwork volume: trapezoidal method the average-end area method. Whereas the trapezoidal method offers better precision but it increases computational burden. For planning phase assessment the average-end area method is enough (Jha and Schonfeld, 2004). In current study is also used the average-end area method for earthwork volume of each candidate by using Auto CAD Civil 3D Software. To determine the volume of the earthwork (embankment and excavation) first should be determined grade line (or project line) of the highway candidate. The grade line should be determined so that satisfying the following factors:

- Volumes of excavation and embankment should be equal
- Not exceed from allowable slope

Therefore can be provided various grade lines that satisfy above factors, in other words, the grade line can be changed according to the situation and it is not unique. In current study has been endeavored which grade line only satisfy maximum allowable slope. After determining the volume of earthwork for each candidate the following equation shows the earthwork cost. In this equation it is assumed that cost related to haul is fixed for all candidates and therefore it is ignored:

$$C_E = V_c \times ucc + V_f \times ufc \quad (11)$$

Where:

- C_E = Earthwork cost for each candidate (\$)
- V_c = Total cut volume of each candidate
- V_f = Total fill volume of each candidate
- ucc = Unit cost of cut (\$/m³)
- ufc = Unit cost of fill (\$/m³)

Cost weights: In previous sections are upgraded or created four functions related to highway costs based on case study conditions. All of these cost functions in current study are used in order to determining weights of cost categories for each highway candidate and weights for each cost category. In other word, these cost functions are for obtaining weight of cost categories relative to each other (what is weight of each cost category) as well as for obtaining weight of each candidate based on each cost category.

In current study, it is suggested a method for determining cost weights. For determining AHP weight to each candidate based on each cost category, initially, the cost of each defined candidate based on provided cost functions should be counted. Afterward, the AHP weight of each candidate will be obtained based on following chart (Fig. 1).

AHP weights of all highway candidates should be counted by using above flowchart based on each cost category which is investigated in previous sections. These weights will be used in process of determining the best highway candidate by using Analytic Hierarchy Process technique. To determine AHP weights of each cost category, the provided process in flowchart in Fig. 2 can be used. For using this process, initially should be made the average of each cost category

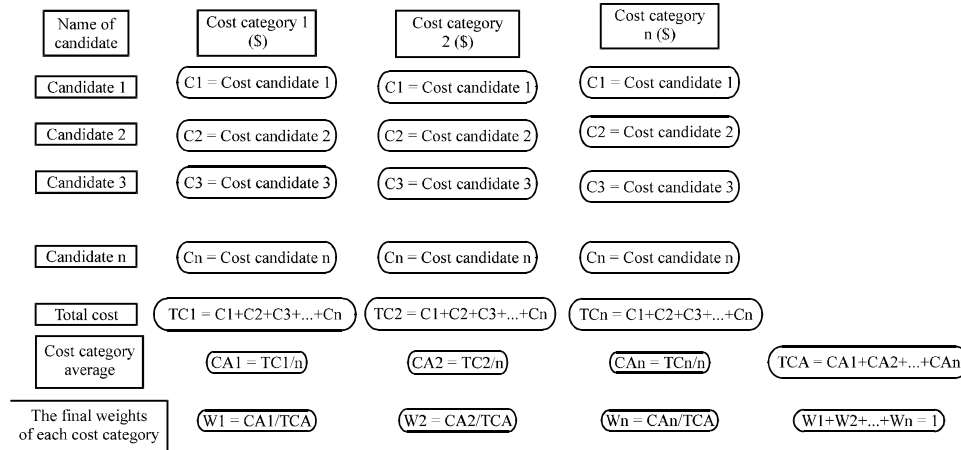


Fig. 2: Flow chart of AHP weight for each cost category

(location dependent cost, earthwork cost, length dependent cost and structural cost) for all candidates and then below process can be used.

These cost categories weights and cost weights of each highway candidate will be used in process of determining the best candidate by using AHP technique.

RESULTS AND DISCUSSION

Safety parameters: Several geometric characteristics of highway alignment can play an importance role in reduction of road accident such as, horizontal curve, vertical curve, horizontal and vertical curve interference, direct path, tunnel, bridge and etc. Effects of these geometric characteristics of highway alignment are investigated in several researches which were carried out by Gupta and Jain (1975), Walmsley and Summersgill (1998), Ahadi and Etemadzadeh (2013), Anastasopoulos and Mannering (2009), Elvik (2000) and Lamm *et al.* (2002) in all over the world. After a comprehensive study on the factors effective in creating road accidents in the study area, the three main parameters have been investigated in current research such as: number of horizontal and vertical curve interference, number of horizontal curve and number of vertical curve. According to importance of highway projects the effective safety parameters which will be used in determining the best highway candidate can be more and more accurate. The weights of each safety parameter in current study were obtained by using questionnaires. Questionnaires were set based on AHP technique. In this research 15 participants who had good experience in highway safety, had been attended for determining the weights of safety parameters. Table 1 shows the final weights of safety parameters which are obtained from questionnaires.

Table 1: Final safety parameters weights based on questionnaires

Criteria name	AHP weight (%)
Number of horizontal curve	18.18
Number of vertical curve	9.09
Number of horizontal and vertical curve interference	72.73

Weight of each highway candidate based on each safety parameters: To determine the weights of each highway candidate based on each safety parameters following chart process can be used. In this method initially should be extracted each safety parameters for each highway candidate and then the weight of each candidate will be obtained by using Fig. 3-6. These AHP weights related to safety parameters and safety parameters weights will be used in process of determining the best candidate by using AHP technique.

Analytic hierarchy process for determining the best candidate: The more of the organizing and analysing on complex decision is provided by Analytic Hierarchy Process (AHP) because it is a structured method. This technique invented by Thomas L. Saaty in 1970s that based on mathematics and psychology and then with the passage of time this method has been extensively studied and refined. In current research is also used this technique to determine the best candidate of highway among several candidate with the special focus on the cost and safety parameters. The weights of each highway candidate related to each cost and safety parameters as well as the weight of each cost and safety parameters are needed for this method. These weights in current research are obtained based on provided equations and flowcharts in and Table 2, respectively. A simple hierarchy of AHP related to provided cost and safety criteria is shown in Fig. 7. Based on concept of AHP in the above hierarchy

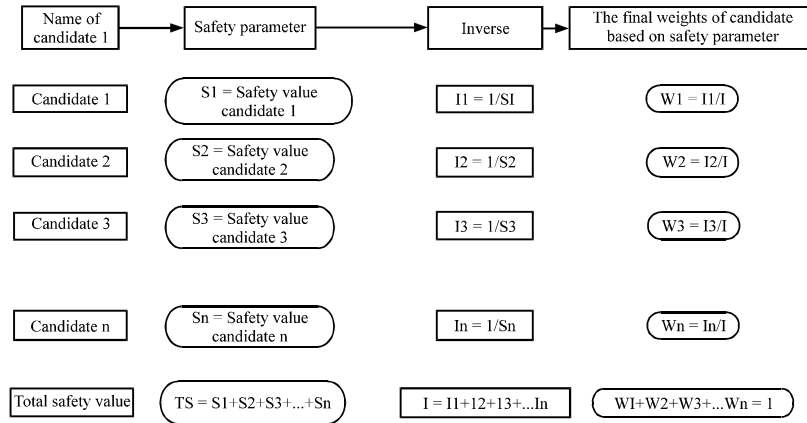


Fig. 3: Flow chart of AHP weight for each candidate based on each road safety parameter

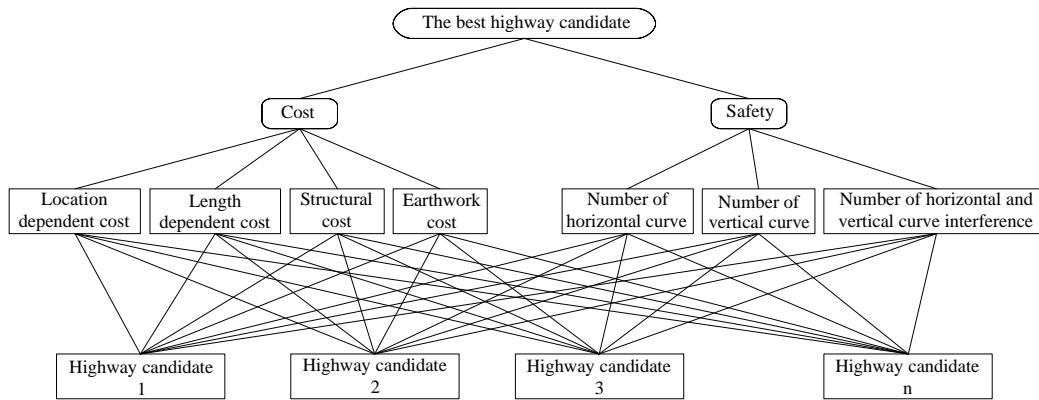


Fig. 4: A simple hierarchy of AHP based on provided cost categories and safety parameters



Fig 5: Case study region in Western North of Iran

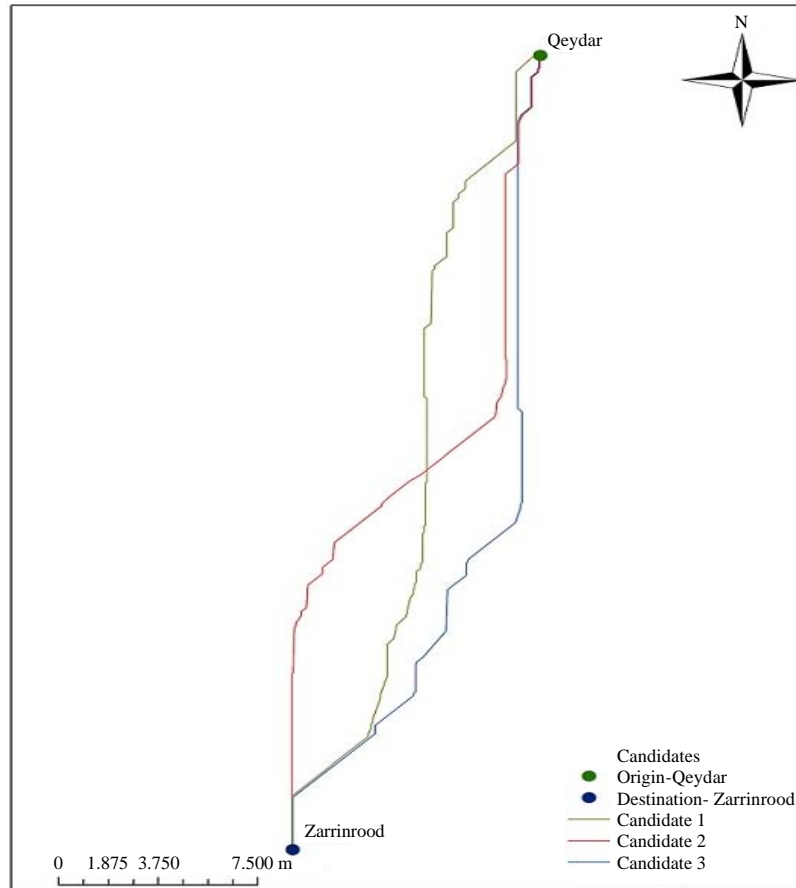


Fig. 6: Three highway candidates between Qeydar-ZarrinRood defined for current example

Table 2: Unit cost of each cost parameter

Cost category	Cost parameter name	Unit cost (\$)
Location dependent cost		
	Farming land	10
	Garden	50
	National land	0
	Mix farming land and national land	5
	Mix farming land and garden	30
Earthwork cost		
	Cost of cut	3
	Cost of fill	3
Structural cost		
	Bridge cost based on bridge volume	1000
	Tunnel cost based on tunnel length	10000
	Retaining wall cost	400
Length dependent cost		
	Pavement cost	100
	Sign and signal cost	50
	Safety guards and facility cost	40

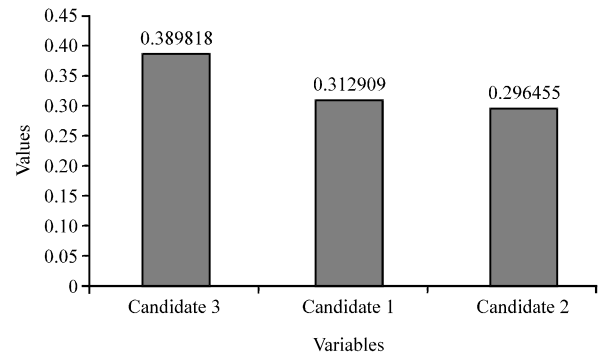


Fig. 7: Final AHP weights of each highway candidate based on provided cost and safety parameters

the first level is called target, second level is criteria and the third level is alternatives of provided model. This method can be carried out by Expert Choice Software. In the next an example is investigated by using provided methodology for determining the best candidate of

highway in case study region. Consistency ratio in current analysis is 0.007 and based on definition of AHP technique it is acceptable.

Example: An example has been provided here to demonstrate how to work with the proposed methodology

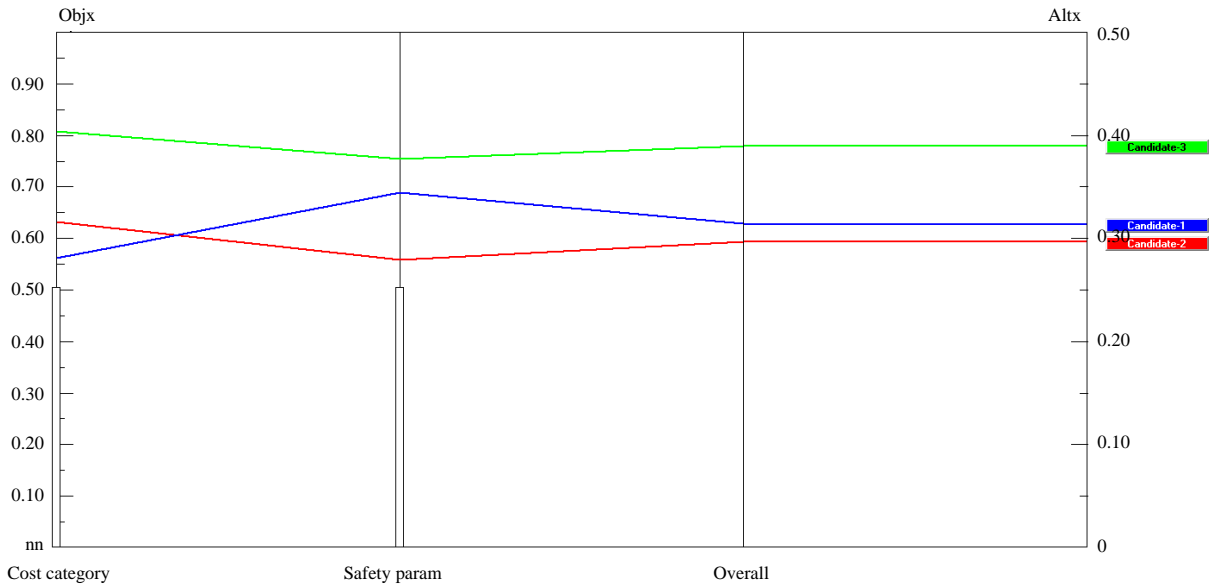


Fig. 8: Sensitivity graph of highway candidates based on their weights

Table 3: Location properties obtained by ArcGIS software for three candidates

Landuse	Alfa	Total area (m ²)	Landuse	Alfa	Total area (m ²)	Landuse	Alfa	Total area (m ²)
Farming land	1.00	102,600	Mix farming land and garden	1.00	15200	Mix farming land and garden	1.00	152000
Garden	1.00	49,400	Mix farming land and garden	0.85	19000	Mix farming land and garden	0.85	15200
Garden	0.85	15,200	Farming land	0.85	209000	Farming land	0.85	212800
Farming land	0.85	212,800	Farming land	0.75	95000	Farming land	0.75	68400
Farming land	0.75	604,200	Mix farming land and garden	0.75	83600	Mix farming land and garden	0.75	110200
Mix farming land and national land	0.75	592,800	Farming land	0.75	1045000	Farming land	0.75	900600
Farming land	0.75	577,600	Mix farming land and national land	0.75	433200	Mix farming land and national land	0.75	737200
Farming land	0.75	125,400	National land	0.75	171000	National land	0.75	630800
Mix farming land and garden	0.75	76000	Farming land and national land	0.75	478800	Farming land	0.75	630800
Farming land	0.75	152000	Farming land	0.85	212800	Garden	0.85	11400
Farming land	0.85	155,800	Garden	0.85	15200	Garden	0.85	53200
Mix farming land and garden	0.85	72,200	Garden	1.00	49400	Farming land	1.00	98800
Mix farming land and garden	1.00	57,000	Farming land	1.00	102600	-	-	-
National land	1.00	11,400	-	-	-	-	-	-
Mix farming land and garden	1.00	83,600	-	-	-	-	-	-

along with validation of this methodology with a real world case study. In this example, three highway candidates are defined between two cities (Qeydar-ZarrinRood located in Western North of Iran (Fig. 8) based on some constraint parameters. The geometric specifications of this case study based on cost categories are shown in Table 2-6 which these are obtained by ArcGIS and Civil 3D Softwares. The final target of this example is to determine the best candidate in terms of cost and safety criteria simultaneously. According to above-mentioned cost specification of these

three highway candidates, the following weights for each highway candidate and each cost category are obtained based upon the provided methodology: Table 7-8 shows the specification these three highway candidates based on provided safety parameters in current research by using ArcGIS Software. According to above-mentioned safety specification of these three highway candidates, the following safety weights for each highway candidate are obtained based upon the provided methodology: the final weights of each safety parameter relative to each other are obtained based on questionnaire which was

Table 4: Specifications of each highway candidate extracted from civil 3D Software

Name of candidate	Total length (m)	Total bridge length (m)	Total tunnel length (m)	Total retaining wall area (m ²)	Total cut volume (m ³)	Total fill volume (m ³)
Candidate 1	42168.3124	143.75	0	0	5,739,088.36	6,477,345.82
Candidate 2	42263.5101	122.85	0	0	2,563,764.95	3,619,957.98
Candidate 3	42243.7760	74.70	0	0	1,012,294.27	1,132,571.51

Table 5: Final weights of each highway candidate based on each provided cost category

Candidate name	Location dependent cost	Earthwork cost	Length dependent cost	Structural cost
Candidate 1	0.3252	0.1154	0.3338	0.2442
Candidate 2	0.3432	0.2278	0.3330	0.2858
Candidate 3	0.3316	0.6568	0.3332	0.4700

Table 6: Final weights of each cost category

Candidate name	Location dependent cost	Earthwork cost	Length dependent cost	Structural cost
Final weight	0.5099	0.3511	0.1371	0.0019

Table 7: Specification of each highway candidate based on provided safety parameters

Name of candidate	Number of horizontal curve	Number of vertical curve	Number of horizontal and vertical curve interference
Candidate 1	47	55	17
Candidate 2	37	64	23
Candidate 3	27	49	17

Table 8: Final weights of each highway candidate based on each provided safety parameter

Name of candidate	Number of horizontal and vertical curve interference	Number of horizontal curve	Number of vertical curve
Candidate 1	0.3651	0.2493	0.3354
Candidate 2	0.2698	0.3167	0.2882
Candidate 3	0.3651	0.4340	0.3764

expressed by Table 1. After determining the final weights of each highway candidate and each cost and safety parameters, all of the obtained weights are inputted into expert choice Software and the final weights of each highway candidate based on cost and safety are outputted by software. The final result is shown by bar chart in Fig. 7. The final result expressed that the best highway candidate can satisfy all of the provided cost and safety parameters simultaneously. Figure 8 shows the sensitivity graph of three highway candidates based on cost and safety parameters.

CONCLUSION

The final result of current study shows that the optimal highway candidate which is obtained by provided methodology can satisfy all the relative parameters in highway alignment optimization based upon their impact simultaneously.

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