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An optimization model of a highway route scheme in permafrost regions

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ABSTRACT

To establish a more realistic and comprehensive algorithm to assist decision makers in optimizing a route in a permafrost regions, the optimal design should be determined and funds should be used more efficiently. In this paper, we used the permafrost subgrade treatment, the permafrost distribution, geological engineering conditions, interference of facilities along the route, route length and 10 other indicators to reflect the factors affecting the selection of route in permafrost regions. An optimization model for highway route scheme was established based on matter element theory by comparing the optimal value of each evaluation program. The weight of each index was determined by an analytical hierarchy process. A case study shows that the optimal model was simple and intuitive, providing a new comprehensive evaluation method for route scheme selection considering the unique geological conditions in permafrost regions.

1. Introduction

Since permafrost is difficult to prevent and handle, it must be considered when constructing highway in the permafrost regions of the Qinghai-Tibet Plateau. It can influence a wide range of scales and lead to a series of highway engineering distresses, such as rutting, roadbed subsidence, and landslides (Wang et al., 2004). It is important to select an optimal route scheme in this area, evaluating the plan for each route in advance and using funds in an efficient manner.

Highway route selection in permafrost regions has been a topic of considerable interest in the field of highway engineering. Domestic and foreign scholars have conducted extensive research in this field, but few meaningful results have been obtained. In terms of route scheme selection theory, many researchers illustrated the theory by the characteristics of permafrost, the permafrost phenomenon and its harmfulness to highway based on the actual case of the Qinghai-Tibet Railway (Yongdong, 2002). Other researchers explained the railway line selection principle by estimating the cost of the geological condition assessment and the corresponding engineering structure (Jin et al., 2009; Shenping, 2009; Wu et al., 2005). However, the theoretical principles only apply the qualitative analysis and cannot directly aid decision makers in making decisions. In this situation, the roadway designers will overly depend on their own experience, which will strongly restrict practical applications. Scholars have proposed route scheme selection models based on various evaluation methods, such as the conventional multi-index comprehensive evaluation method and analytical hierarchy process (a comprehensive evaluation method involving multivariate statistics), which provide the basis for the intelligent selection of the route (Junming et al., 2004; Qing-Fu et al., 2004; Liu and Zhao, 2012). For example, previous studies have established the membership function using fuzzy mathematical theory and have handled the various indices of social and environmental benefits in a non-dimensional manner via the valued statistics method to ultimately derive a dimensionless matrix. The final results of the coordinated development of various highway project indices can be obtained according to the maximum membership degree principle (Zhang (2007)). Previous studies have used the degree of gray correlation to explain the gray information of highway construction project plans and support the decision-making process (Rong-Guo et al., 2004). However, there are some limitations to the above methods. For example, the Delphi method is simple and easy to operate, but the assigned value differs considerably based on different understandings of experts, and the uncertainty and selection of the difficulty level for the fuzzy comprehensive evaluation method make applications extremely difficult.

Since the emergence of GPS technology in the early 1990s,"3S" (GPS, GIS, and RS) technology plays a critical role in highway survey and design. Thus, a digital geometric model can be quickly constructed, and the alignment design can be traced and improved. Moreover, the graphic display is more intuitive, especially during calculations that result in scheme determination (Dan, 1987; Jong and Schonfeld, 2003; Kim et al., 2005; Taniguchi et al., 1999; Yamasaki et al., 2002). With the

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development of computer technology, many methods, such as genetic algorithms, neural networks, and expert systems, have widely been used in the field of scientific research and increasingly important. For example, the combination of the information model and GIS make it possible to partition the geological situation along the route corridor and lay the foundation for the GIS-based route selection (Jha and Schonfeld, 2004; Kang et al., 2012; Kim et al., 2004; Shenyong and Runqiu, 2001; Ping, 2001). The use of a multi-objective highway alignment optimization algorithm, such as the particle swarm optimization algorithm, enables a more intelligent route plan to be established (Yang et al., 2014; Shafahi and Bagherian, 2013). Three-dimensional optimization can assist in alignment design software planning for highway alignment using computers and remote sensing images, which is convenient and can reduce cost. However, the genetic algorithms and particle swarm algorithm based on GIS require a large number of samples that must meet the requirements of a certain purpose. Secondly, the algorithm itself has many defects that prevent it from reaching the optimal solution. Thus, these methods are not suitable for the optimization of highway routes in permafrost regions.

On the other hand, extension theory has been widely used in the field of scheme selection and quality assessment. For example, some experts combine critic weight analysis method and extension theory for scheme selection. For example, WanQing-Li established an evaluation model for mine ventilation system that help for determining the optimal solution (Wan-Qing et al., 2013); Zhang, W. et al. applied this evaluation method in construction bidding process, the research results show that this evaluation method was thought to be relatively objective, simple and practical (Zhang et al., 2013). Some others combining the entropy weight method with the extension theory for quality evaluation programs like quality assessment of geological disaster prone regions and comprehensive evaluation of coal and gas outburst risk (Zhang and Liu, 2013; Liu et al., 2013; Zhang et al., 2011). Besides, extension theory is used for the evaluation of ecological environment combined with the simple correlation function extension (Min et al., 2007).

Therefore, this paper establishes an optimization model for route schemes in permafrost regions based on matter element theory, which can summarize the method of optimizing the roadway plan using the extension theory framework and can pave the way for intelligent selection. A quantitative analysis and evaluation are performed using as follows. Firstly, the measurement index and the weight coefficient are determined; then, the program that does not meet the necessary conditions are screened. Using the objects to establish the correlation function and calculate the degree of conformity, the degree of conformity is standardized, the goodness is calculated and a reasonable scheme is selected based on comparison with the value of the evaluation program. The weight of each index was analyzed by using the analytical hierarchy process. Thus, a more realistic and comprehensive algorithm was established to assist the decision makers to select the route scheme in permafrost regions.

2. Analysis of influence factors for route schemes in permafrost regions

Highway route design is an engineering system of decision making and design, which is varied and complex, and covers multiple factors, and multiple levels. This engineering system involves both engineering-scale indices and environmental indicators. The engineering-scale indices refers to some index like the length of the route, subgrade earthwork, permafrost subgrade treatment, and length of bridges and tunnels, while the environmental indicators refer to some index like engineering geological conditions, the permafrost condition, and interference of the facilities along the alignment.

The route length is the actual route length between the start and end points of the route plan. The route length reflects the mileage, fuel consumption, time and other factors. The operating costs of a longer route would increase with the increasing traffic, which will outweigh all of the benefits saved by the short route scheme (Larsen and Turkensteen, 2014).

The earthwork quantity is a major index of highway construction projects. In highway design and route scheme optimization process, the quantity of subgrade earthwork is one of the main technical indices for evaluating the roadway design. In the selection of a route scheme, the earthwork quantity refers to the total number of discarding quantity and fill quantity. Designers often try to avoid debiting soil from the outside highway or waste soil to reduce the occupation of farmland, the cost of the highway and damage to environment.

Permafrost has the composition of solid mineral particles, viscous plastic ice inclusion, liquid-phase water (unfrozen water) and strongly bond water and gaseous inclusions of water vapor and air. Under poor geological and hydrological conditions, water transport phenomena will occur during the freezing process of subgrade soil. Water transfers to the freezing front and is frozen into ice in this process. In the freezing process, frost heave of subgrade soil occurs with the volume expansion because the density of ice is slightly lower than that of water (Li et al., 2010). Thus, frost heave is a factor that must be considered in cold region engineering. Therefore, in the process of highway construction, particularly the construction of a high embankment on permafrost regions, the subgrade will become unstable if reinforcement measures are not taken. This factor should be considered when comparing and selecting a route scheme in permafrost regions. The original heat exchange conditions are changed due to the construction of highway engineering in permafrost regions. As a result, the heat absorption in the roadbed increased due to the change of the heat exchange conditions. The heat accumulation in the roadbed results in an increased temperature in the lower soil layer and thawing of the permafrost, which is the main reason for the destruction of the building materials in permafrost regions (Yu et al., 2015). If the permafrost thaws at a fast rate, the rate of ice melting is higher than the rate of water discharging. Thus, the pore pressure in the soil increases, resulting in instabilities of slopes and various structures. When the buried depth of underground ice layers is shallow, the permafrost will thaw partially and the overlying soil layer will subside under the action of soil mass and the external force due to the influence of various human factors during the construction and operation period, which will cause serious roadbed deformation. As a result, the overlying soil layer will be subside, the roadbed shoulder and slope will crack and decline and the cutting slope will slide. Therefore, the permafrost must be considered when designing highways in cold regions. The effects of permafrost must be considered.

In the process of selecting a routing scheme, we should consider the length proportions of bridges and culverts and their overall performance. If we do not consider the influence of this sector, the route scheme of the work will be biased. The impact of this section on the cost of the project will also be larger. Therefore, the length proportions should be considered when selecting a routing scheme.

Interference refers to the consideration of whether the route scheme interferes with railway, pipeline and other facilities, whether there is a cross and whether the route deviates from the proposed route. The corridor belt that is used for construction in the Qinghai-Tibet Plateau is limited in order to reduce the destruction of permafrost. Thus the different alignment engineering like the Qinghai-Tibet Highway, Qinghai-Tibet Railway, and optical cable communication engineering should be constructed in this narrow corridor belt to reduce their impact on environment. If the different alignments are located closely, the thermal interference phenomenon will occur which will accelerate the thawing of permafrost and the thawing settlement of subgrade. Therefore, the Interference should be considered when selecting a routing scheme.

The influence factors of the route plan in permafrost regions refer to the complex factors influencing the construction and operation of the highway projects considered when a highway is designed in permafrost regions. Comparison and selection of a highway route scheme in permafrost region refer to a comprehensive evaluation of the engineering scale and environmental indicators for a variety of highway projects.

Establishing the influence factors for the route scheme in permafrost regions is the premise and foundation of the research on prediction and evaluation, and it is a process of qualitative analysis and quantitative study. The qualitative analysis refers that the experts or the construction officers determine the weight of influence factors according to their own experience and some other factors like integrity, locality, relevance, and independence, whereas the quantitative research is based on mathematical theory through series of modeling operations or a scientific and rational evaluation factor system. Evaluation systems generally include four basic elements (factor, factor structure analysis, the weight of each factor and the mapping relationship). Therefore, the comparison and selection of the permafrost project can be described as

$$N = f(v, s, w) \tag{1}$$

where v represents the index value of the influence factor, s represents the hierarchical structure, w represents the weight of the index, and f represents the mapping relationship.

The three elements (v, s, w) of this group in the course of the permafrost region route scheme are interrelated and influence each other, forming an organic integrity. The influence factor of the route scheme in the permafrost region is the part v in the formula. The main difficulty of the routing scheme evaluation is the selection of influencing factors. The influencing factor system of the route scheme of the permafrost region is established (Table 1) according to aforementioned analysis.

3. Route scheme optimization model in permafrost regions based on extension theory

This study focuses on the various conflicting factors that must be considered when constructing highways in permafrost regions. The various contradictions described in the first section are difficult to resolve with the traditional engineering methods, which rely mainly on experience; however, the contradictions can be solved easily by extension. Therefore, it will be advantageous to the long-term development of the highway route selection technology to apply extension theory to the highway route scheme in a permafrost region, which also expands the application range of the extension study.

Here, extension theory is extended to aid in deciding how to solve these problems: an extension of the decision-making problems and the extension of the engineering applications, which are also included in the scope of the extension engineering methods. Specifically, the extension decision method has been developed based on the matter element analysis, which uses the mathematical tool of the extension set, analyzes the compatibility of each subsystem of the object, and changes the contradiction problem into a compatible problem by using the matter element transformation to develop the relevant decision-making strategies. The extension decision method does not simply consider the optimization of the relationship among quantities. Its basic realization is to satisfy the requirements of the main system and main target maximumly. For the non-principal system, the requirements are turned into compatible problems by the method of matter element transformation. Then, the best strategy is obtained. Extension decision is a decision-making tool that can be applied to the problem of contradiction and have a variety of features (Zuoyong, 1999; Cai, 1999).

Table 1
Influence factor system of a route plan in permafrost regions.

Class system	Specific factor	Grading unit
Route length	Length	km
Subgrade earthwork quantity	Earthwork volume	m^3
Protective drainage	Cubic capacity	m^3
Treatment of permafrost subgrade	Earthwork volume	m^3
Proportion of bridges and tunnels	Proportion	%
Construction fee	Cost	Billion yuan
Distribution of permafrost	Mileage	km
Engineering geological condition	Disaster degree	1
Snow and ice effect	Influence degree	1
Facilities interference along the line	Interference degree	1

Currently, there are many ways to map the relationship between the factors and things being evaluated. The evaluation of things refers to the consideration of both its positive and negative attributes. Extension of the priority degree evaluation method and combining this method with things of dynamic and variable qualities, using correlation functions to measure things to the extent consistent with all of the features, a comprehensive reflection on the advantages and disadvantages of the things makes the evaluation results more consistent with the actual conditions. According to the characteristics of the evaluation system of route schemes in permafrost regions, this method is used to establish the model of highway route plan selection in permafrost regions.

Everything in the objective world is a union of quality and quantity. Matter element theory overcomes the drawbacks of the quality of the things in mathematics, introduces the concept of basic elements, and finally explains the dialectical relationship between qualitative and quantitative change in formal language (Hongna and Liu, 2010; Jia et al., 2003). The theory describes the characteristics and values of a particular object in an ordered three-tuple (R: an object, a feature, and a quantity).The same thing may have a number of characteristics which is called the multidimensional matter element and can be expressed as an array:

$$R = R_i(N_i, \alpha_i, v_i) = \begin{bmatrix} N_i & \alpha_1 & v_1 \\ & \alpha_2 & v_2 \\ & \cdots & \cdots \\ & \alpha_n & v_n \end{bmatrix} \tag{2}$$

where N_i represents the matter; i is the Unique Sequence Number of the matter; α_i, the factor that affects the evaluation of the matter; v_i, the corresponding value of the factor α_i. Based on the theory of basic elements, the evaluation method of the excellent degree of extension theory can be used to evaluate the quality of things, methods, and strategies. The evaluation steps and procedures of the application of the method are as follows:

1) Determine the measurement index

Highway distress assessment is related to a certain index system. To evaluate the advantages and disadvantages of a program, the evaluation indicators will be determined firstly. The set index is represented by $\alpha = \{\alpha_1, \alpha_2, \cdots, \alpha_n\}$. Firstly, the range of possible value of each index was determined. Then the tolerance range of each index was determined. That is, the classical domain (R_0) and domain (r) of the matter element model were determined.

2) Determine the weight coefficient

The advantages and disadvantages of different programs $(N_j(j = 1, 2, 3, \cdots, m))$ are evaluated, because each index of the evaluation index $(\alpha = \{\alpha_1, \alpha_2, \cdots, \alpha_n\})$ has the weight of points. The weight coefficient can be used to indicate the importance of each evaluation index. The weight of the index that must be satisfied (set asα_1) is recorded as Λ. For other evaluation indices, the weight of [0,1] is assigned to each one according to the degree of importance. $w = (\Lambda, w_2, \cdots, w_n)$, in which we suppose $w_1 = \Lambda$ and others satisfy the equation $\sum_{k=2}^{n} = 1$.

At present, the methods of weight classification are subjective and objective analysis, the expert scoring method, the risk graphic method, gray theory, the analytical hierarchy process and group decision-making. The analytical hierarchy process method (Chang and Taili, 2007) is a combined qualitative and quantitative multi-objective decision analysis method in which the combined weights of the experience of the expert judgments and appropriate mathematical models are determined through calculation. The expert scoring method and other statistical methods are effective for binding up. Thus this paper adopts the analytic hierarchy process method used for weight calculation.

3) First evaluation

After determining the weight coefficient of each measured index, the index (set as α_1) that must be satisfied is screened, and if a removal program (set N_1 not satisfying the program) does not meet the indicator, then the following steps are performed to satisfy the requirements that must be met.

4) Establishing the correlation function ($k_i(x)$)

a. If $a_i(N)$ is represented by an interval X_{0i}, then $k_i(x)$can be described as

$$k_i(x) = -\frac{px, x_{0i}}{|x_{0i}|}, i = 1, 2, 3, \ldots, n \tag{3}$$

where $|X_{0i}|$ is the length of the interval and $p(x, x_{0i})$ is the distance, which indicates the distance between point x and the interval $x_{0i}= \langle a,b \rangle$:

$$\rho(x, x_0) = \left| x - \frac{a+b}{2} \right| - \frac{1}{2}(b-a) = \begin{cases} a-x, & x \le \dfrac{a+b}{2} \\ x-b, & x > \dfrac{a+b}{2} \end{cases} \tag{4}$$

b. If $a_i(N)$ is a collection of some discrete data, for example, a_i indicates the quality of engineering geological conditions, and $a_i(N) = \{$-*Excellent*,*good*,*poor*$\}$, then the $k_i(x)$ can be described as

$$k_i(x) = \begin{cases} a, & x = excellent \\ b, & x = good \\ c, & x = poor \end{cases} \tag{5}$$

The values of a, b, c can be scored based on expert opinion or historical data.

c. If $a_i(N)$ can be described as an interval set of X_{0i} and $X_i(X_{0i}, X_i)$, then $k_i(x)$ can be described as

$$k_i(x) = \frac{\rho(x, x_{0i})}{\rho(x, X_i) - \rho(x, X_{0i})}, i = 2, 3, \ldots, n \tag{6}$$

where

$$\rho(x, x_{0i}) = \left| x - \frac{1}{2}(a_{0i} + b_{0i}) \right| - \frac{1}{2}(b_{0i} - a_{0i}), \quad i = 2, 3, \ldots, n \tag{7}$$

$$\rho(x, x_i) = \left| x - \frac{1}{2}(a_i + b_i) \right| - \frac{1}{2}(b_i - a_i), \quad i = 2, 3, \ldots, n \tag{8}$$

The best value of the above correlation function lies in the midpoint of the qualified interval X_0. For some indicators, the best value is not at the middle of the qualified zone, but the smaller the better, or the bigger the better, for this type of index correlation function should calculate by the left or right distance. Thus, $k_i(x)$ can be described as follows:

$$k_i(x) = \begin{cases} \dfrac{\rho(x, x_0, X)}{\rho(x, X) - \rho(x, X_0)}, \rho(x, X_0) \ne \rho(x, X) \\ -\rho(x, x_0, X_0) - 1, \rho(x, X_0) = \rho(x, X) \end{cases} \tag{9}$$

The left margin is used to calculate the value of index ρ (a smaller value is better):

$$\rho = \begin{cases} a-x, & x < a \\ \dfrac{b-x_0}{a-x_0}(x-a), x \epsilon a, x_0 \\ x-b, & x \ge x_0 \end{cases} \tag{10}$$

The right margin is used to calculate the value of index ρ (a larger value is better):

$$\rho = \begin{cases} a-x, & x \le x_0 \\ \dfrac{b-x_0}{a-x_0}(x-a), x \epsilon x_0, b \\ x-b, & x \ge b \end{cases} \tag{11}$$

where $X = (a, b)$ represents the positive region, that is the acceptable range of $\alpha_i(N)$. $X = (a_0, b_0)$ is the standard positive region, that is the satisfaction interval of $\alpha_i(N)$.

5) Standardize the correlation degree

The advantages and disadvantages of each participating scheme are compared. In this paper, we normalize the qualified degree calculated by the correlation function that is based on the principle of public degree in comprehensive evaluation theory (Weihua, 2000). The specifications for each program on the evaluation index of the degree of conformity are as follows:

$$k_{ij} = f(x) = \begin{cases} \dfrac{k_i(N_j)}{max k_i(x)}, & x \epsilon x_0, k_i(N_j) > 0 \\ \dfrac{k_i(N_j)}{max|k_i(x)|}, & x \epsilon x_0, k_i(N_j) < 0 \end{cases}, \quad (i = 2, 3, \cdots, n, j = 2, 3, \cdots, m) \tag{12}$$

Therefore, the standard qualification of each program $N_2, N_3, \cdots, N_m$ for each scheme $\alpha_2, \alpha_3, \cdots, \alpha_n$ can be denoted as $k_i = (k_{i2}, k_{i3}, \cdots, k_{im})$, $(i = 2, 3, \cdots, n)$.

6) Computational optimization

Standard qualification of program N_j about each scheme $\alpha_2, \alpha_3, \cdots, \alpha_n$ is denoted as

$$k(N_j) = \begin{bmatrix} k_{2j} \\ k_{3j} \\ \vdots \\ k_{nj} \end{bmatrix}, (i = 2, 3, \cdots, n) \tag{13}$$

Therefore, the goodness of program N_j can be described as

$$C(N_j) = \sum_{i=2}^{n} w_i k_{ij} = [w_2, \cdots, w_n] \begin{bmatrix} k_{2j} \\ k_{3j} \\ \vdots \\ k_{nj} \end{bmatrix} \tag{14}$$

4. Case study

At present, there are five alternative route schemes (K1, K, B5, B5-1, B6) in the permafrost region of the Qinghai Tibet Plateau from the Yamarle River to the Xiushui River, as shown in Fig. 1.The route must cross the Fenghuo Mountains, where the terrain is extremely complex and the accumulated snow in winter is extensive. Moreover, there are various types of permafrost in this region of the Fenghuo Mountains region, which are complicated, changeable, and include thawed areas, permafrost, ice-rich permafrost, saturated soil ice and etc. When selecting the alignment in this area, we must consider the distribution of the permafrost type and the accumulated snow situation, which can reduce the impact of accumulated snow and ice on highway distress. In addition, the alignment selection is also influenced by other facilities, such as the Qinghai-Tibet railway, oil pipelines and power lines. The evaluation process is as follows.

1) Selection index

For simplicity, we selected five evaluation indices (the length of the route through accumulated snow a_1, the ice-rich permafrost distribution a_2,the length of the route through high vegetation coverage a_3, interference of facilities along the route a_4 and the length of the route scheme a_5) to evaluate the alternative route schemes, and each index is described as follows:

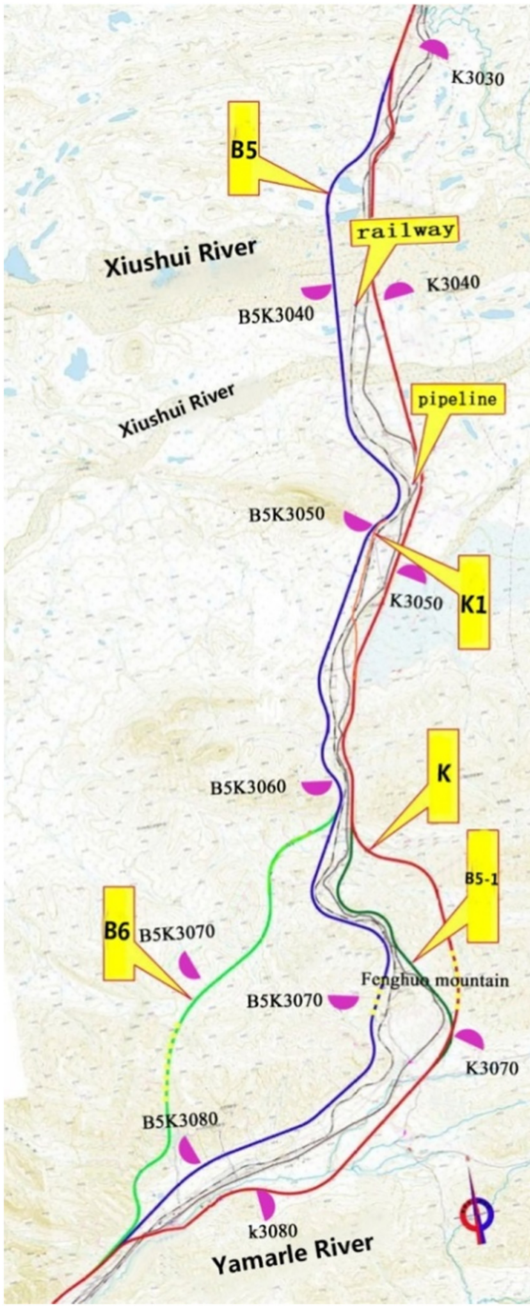

Fig. 1. Alternative route scheme ((K1, K, B5, B5-1, B6)).

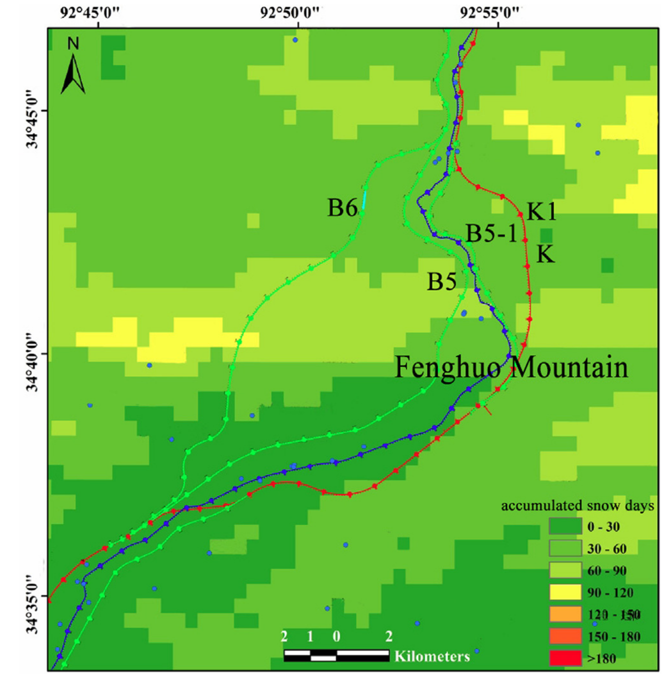

Fig. 2. The spatial distribution characteristics of accumulated snow.

a. The length of the route through accumulated snow must not exceed 2 km. The route in the Fenghuo Mountains can easily be impacted by severe weather. The accumulated snow does not thaw easily and can be harmful to highway safety. This paper investigated and analyzed the spatial distribution characteristics of accumulated snow along the Qinghai-Tibet Highway, which is shown in Fig. 2.

b. According to Fig. 2, the average number of accumulated snow days in this region in a whole year is 34, which can easily cause freezing and slipping. The schemes K1, K, B5, and B5-1 cross this section by long tunnels. The length of the route affected by accumulated snow is no more than 0.5 km. In contrast, the highway of B6 scheme in this part constructed directly in the air instead of tunnel, and the length of the route affected by accumulated snow is as high as 2.7 km.

c. The ice-rich permafrost distribution mileage must be as small as possible.

d. The length of the route with high vegetation coverage must be as small as possible. Bases on the information of multi-source remote sensing data, we investigated the distribution characteristics of vegetation coverage along the Qinghai-Tibet Highway, which is shown in Fig. 3.

According to Fig. 3, the average vegetation coverage index in this region is 0.178, with some regions as high as 0.19. The crossing length of scheme K in this section is 0.87 km, which has the greatest impact on the environment.

e. The length of facility interference along the line must be as small as possible. When the distance between the project is <150 m, the mutual thermal interference between the various projects is serious, particularly the serious interference to highway by electric power and the permafrost under the highway caused by the transmission pipeline (Qi-Hao et al., 2012).

f. Length of the alignment: a 20–30 km highway route scheme is optimal, a 30–40 km highway route scheme is not preferable, and a highway route scheme longer than40km cannot be used. The value of the different influence factors of the routing scheme are shown in Table 2.

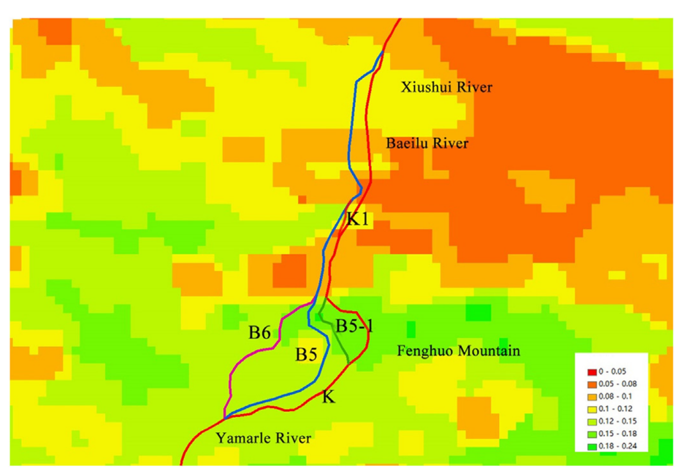

Fig. 3. The spatial distribution characteristics of vegetation coverage.

Table 2
Influence factors and weight table.

Index	B6	K1	K	B5	B5-1	w_i
The length of the route with accumulated snow/k	2.7	0.47	0.43	0.45	0.49	Λ
Ice-rich permafrost distribution/%	15.230	16.587	11.935	13.21	17.526	0.27
The length of the route with high vegetation coverage/km	0.51	0.81	0.87	0.41	0.74	0.34
Facilities interference along the line/1	16.5	1.2	0.7	15.2	14.7	0.21
Route length/km	22.589	28.538	25.000	34.580	37.468	0.18

2) Determine weights

In this example, the length of the route with accumulated snow a_1 is an index that must be satisfied and $w_1 = \Lambda$ such that the other indicators of the weight can meet the conditions $\sum_{k=2}^{5} w_k = 1$, and the weights of the influence factors of the routing scheme evaluation are listed in Table 2 too.

3) Initial evaluation

Program B6 is deleted, for it does not meet the requirements of an index, K1, K, B5 and B5-1 are saved for evaluation. The index a set is changed to $\alpha_2, \alpha_3, \alpha_4, \alpha_5$ accordingly. Therefore, the object to be evaluated is

$$R_2 = \begin{bmatrix} K1 & \alpha_2 & 16.587 \\ & \alpha_3 & 0.81 \\ & \alpha_4 & 1.2 \\ & \alpha_5 & 28.538 \end{bmatrix} R_3 = \begin{bmatrix} K & \alpha_2 & 11.935 \\ & \alpha_3 & 0.87 \\ & \alpha_4 & 0.7 \\ & \alpha_5 & 25.000 \end{bmatrix}$$

$$R_4 = \begin{bmatrix} B5 & \alpha_2 & 13.21 \\ & \alpha_3 & 0.41 \\ & \alpha_4 & 15.2 \\ & \alpha_5 & 34.580 \end{bmatrix} R_5 = \begin{bmatrix} B5-1 & \alpha_2 & 17.526 \\ & \alpha_3 & 0.74 \\ & \alpha_4 & 14.7 \\ & \alpha_5 & 37.468 \end{bmatrix}$$

4) Normalized correlation degree

The process of calculating various route plans by using Eqs. (3)–(8) is as follows:

$$k_2(x) = -x, x \geq 0$$

$$k_3(x) = -x, x \geq 0$$

$$k_4(x) = -x, x \geq 0$$

$$k_5(x) = \begin{cases} x-21, & x \leq 25 \\ \dfrac{x-20}{2(x-25)}, & 25 < x \leq 30 \\ \dfrac{x-30}{-10}, & x > 30 \end{cases}$$

5) Calculate the correlation and standard correlation of each route scheme

$$k(R_2) = \begin{bmatrix} K1 & \alpha_2 & -16.587 \\ & \alpha_3 & -0.81 \\ & \alpha_4 & -1.2 \\ & \alpha_5 & 1.207 \end{bmatrix} k(R_3) = \begin{bmatrix} K & \alpha_2 & -11.935 \\ & \alpha_3 & -0.87 \\ & \alpha_4 & -0.7 \\ & \alpha_5 & 4 \end{bmatrix}$$

$$k(R_4) = \begin{bmatrix} B5 & \alpha_2 & -13.21 \\ & \alpha_3 & -0.41 \\ & \alpha_4 & -15.2 \\ & \alpha_5 & -0.458 \end{bmatrix} k(R_5) = \begin{bmatrix} B5-1 & \alpha_2 & -17.526 \\ & \alpha_3 & -0.74 \\ & \alpha_4 & -14.7 \\ & \alpha_5 & -0.746 \end{bmatrix}$$

To compare the different dimensions of the indicators, the results of the standard correlation using Eq. (9) are shown in Table 3.

6) Comparison and selection of goodness

According to the extension theory, the higher the goodness is, the better the scheme is. We can see from Table 3, the goodness of K1 is −0.534, the goodness of K is −0.354, the goodness of B5 is −0.594, the goodness of B5–1 is −0.798, that is C(B5 − 1) < C(B5) < C(K1) < C(K), so scheme K is found to be the best solution to the selection of the permafrost region.

5. Conclusions

Highway route scheme optimization for highway construction is extremely important. If the choice of the program is not reasonable, a poor choice will result in significant loss. Considering the specific climate conditions of the permafrost region, geographical location and other realities, the evaluation method of the excellent degree of extension theory was used to establish a selection model for route schemes in permafrost regions. The main conclusions are as follows:

A comprehensive evaluation index system that is suitable for the selection of highway routes in permafrost regions is established. The engineering scale index and the environmental indicators are analyzed in this part, which reflect the characteristics of route scheme selection in permafrost area.

The highway route scheme optimization model in cold regions is established using the established evaluation index system and the analytic hierarchy process. The method of analytic hierarchy process is used to avoid subjectivity, arbitrariness and inconsistency so that the results are more intuitive and consistent with the actual conditions.

The practical application shows that it is reasonable and feasible to select route schemes in frozen regions by using the optimization model. The method using the correlation function instead of the fuzzy mathematics evaluation needs to determine the difficulty of the membership function. This method also avoids personal subjectivity and arbitrariness and involves easy programming. In addition, as the algorithm is simple and easy to implement, it is a relatively high-quality evaluation method.

Table 3
Optimization evaluation table of route design schemes in the permafrost region.

Index	Weights	Correlation				Standard correlation			
		K1	K	B5	B5–1	K1	K	B5	B5–1
Ice-rich permafrost distribution	0.27	−16.587	−11.935	−13.21	−17.526	−0.946	−0.681	−0.754	−1
The length of the route with high vegetation coverage	0.34	−0.81	−0.87	−0.41	−0.74	−0.93	−1	−0.47	−0.85
Facilities interference along the line	0.21	−1.2	−0.7	−15.2	−14.7	−0.079	−0.046	−1	−0.967
Route length	0.18	1.207	4	−0.458	−0.746	0.302	1	−0.115	−0.187
Goodness						−0.534	−0.354	−0.594	-0.798

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: 10.1016/j.coldregions.2017.03.010. This data include the Google map of the most important areas described in this article.

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