Multi-Objective Optimization of Hazardous Materials Transportation Routes with the Example of Sodium Metal

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Abstract: This article takes the transportation of dangerous goods as the research background, considers the characteristics of the dangerous goods themselves and the various influencing factors in the transportation process, introduces the index P to measure the safety coefficient, and builds a multi-target one-way transportation route optimization based on safety, time, and cost. The model is solved by the improved grey correlation method, and the optimal path is obtained. At the end of the article, the transport of metal sodium is taken as an example to confirm the safety factor and the feasibility of the model.

Keywords: hazardous materials; path optimization; safety factor; grey correlation method

0. Introduction

With the continuous improvement of China's transportation network and logistics system, the number of dangerous goods transportation is increasing. Due to the large social hazards of dangerous goods, the production area and the demand area are far away. Considering that they have strict requirements for the choice of transportation roads, a safer and shorter time is selected among many feasible roads. The route with lower transportation cost is very necessary.

1. Construction of Mathematical Model

1.1 Background of Mathematical Model Construction

The traffic service network with the distribution center as the core can be assumed as D=(V,A),V is the node set, representing the distribution center and distribution nodes. A is the arc set, representing the road connection between each node. Suppose there are N distribution points in the traffic network, distribution center coordinates are known (x0, y0), distribution node coordinates are (x_i, y_i), distribution vehicle number is m, the vehicle's weight is Q. The weight required for distribution node i is q_i.The distance from distribution point i to distribution point j is d_{ij}.Transportation time is t_{ij}, the total cost is C_{ij},the road passage fee is c_{ij}, safety index is P_{ij}, the maximum distance of distribution vehicle is D, the laytime of distribution node i is t_i.An optimal route is required to ensure the highest safety, shortest total time and lowest total cost of dangerous goods transportation.

1.2 Mathematical Model Construction

The mathematical model of multi-objective one-way dangerous goods logistics path optimization is as follows:

$$\min F_1 = \exp\left\{-\prod_{i,j=0}^{n} P_{ij}\right\} \quad (i \neq j) \tag{1-1}$$

$$\max F_2 = \sum_{i,j=0}^{n} \sum_{k=1}^{m} t_{ij} + \sum_{i=0}^{n} t_i \tag{1-2}$$

$$\min F_3 = \sum_{i,j=0}^{n} C_{ij} \tag{1-3}$$

The definition of time and cost in the objective function:

$$t_{ij} = \lambda_{ij} \frac{d_{ij}}{v} \tag{1-4}$$

$$C_{ij} = c_{ij} + c' \mu_{ij} d_{ij} \tag{1-5}$$

In these formulas,the transport cost per unit path of a vehicle on an ideal road is c', the influence coefficient of road attributes on the transport cost μ_{ij},and the influence coefficient of road attributes on the travelling speed of the transport vehicle is λ_{ij}.

Constraints:

$$\sum_{i,j=0}^{n} d_{ij} \leq D, k = 1,2,...m(i \neq j) \tag{1-6}$$

$$\sum_{i,j=0}^{n} q_i \leq Q, k = 1,2,...m(i \neq j) \tag{1-7}$$

$$0 \leq \lambda_{ij} \leq 1 \tag{1-8}$$

$$0 \leq P_{ij} \leq 1 \tag{1-9}$$

$$\mu_{ij} \geq 1 \tag{1-10}$$

In the above formula,formula 1-1 represents the product of the safety coefficient on each path, which means that the safety coefficient of any section of road on this path will greatly affect the safety of this path.Moreover, the smaller F1 is, the safer this path will be.

2. Based on the improved grey relational degree theory solution model

2.1 Calculate the Security Index P

2.1.1 Construction of safety index system

Table 1 safety index system

	Level indicators	**The secondary indicators**	**Level 3 indicators**
Safety index system of dangerous goods transportation A	1.Dangerous goodsB_1	1.1 categories of dangerous goodsC_1	
		1.2 packaging of dangerous goodsC_2	
		1.3 actual load of dangerous goods Real-time monitoring capabilityC_3	1.3.1vehicle running acceleration valueD_1
			1.3.2 temperatureD_2
			1.3.3 humidity valueD_3
			1.3.4 hydrogen concentrationD_4
	2.Environment and property Factors affecting theB_2	2.1 environmental pollution risksC_4	2.1.1 water source areaD_5
			2.1.2 nature conservation areaD_6
			2.1.3areas of historical interestsD_7
			2.1.4 agricultural area (soil)D_8
		2.2 risks of crowd gathering areasC_5	2.2.1 retail investors along the wayD_9
			2.2.2 cluster towns and villages along the wayD_{10}
		2.3 risk of property lossC_6	2.3.1 housing constructionD_{11}
			2.3.2 equipment and facilitiesD_{12}
			2.3.3 crops and livestockD_{13}
	3.Emergency rescue capabilityB_3	3.1 number of emergency rescue personnelC_7	
		3.2 emergency relief materials and equipmentC_8	
		3.3.Accessibility of emergency rescueC_9	
	4.The road factorB_4	4.1 road lengthC_{10}	
		4.2 road capacityC_{11}	
		4.3 road linearityC_{12}	
		4.4 influence of speed limit on vehicle runningC_{13}	

According to GB17914-2013 storage and maintenance technical conditions of inflammable and explosive commodities, the storage condition of metallic sodium in the compartment environment of transport vehicles is that the temperature does not exceed 35℃ and the air humidity does not exceed 80%.The error of temperature monitoring is within 1℃ and that of humidity monitoring is within 4%.A reasonable and effective evaluation system is developed for several indicators of the actual load of dangerous goods.

Table 2 evaluation criteria for real-time indicators of transportation

The evaluation object	**The scope of the monitored value of the evaluation object**	**score**
1.3.1 vehicle running acceleration value	0-1 g	100 points
	1-2 g	80 points
	2-3 g	60 points
	> 3 g	dangerous
1.3.2 temperature	< 20 ℃	100 points
	20-30 ℃	80 points
	30-34 ℃	60 points
	> 34 ℃	dangerous
1.3.3 humidity value	0-20%	100 points
	20% - 50%.	75 points
	50% - 76%.	60 points
	> 76%	dangerous

1.3.4 hydrogen concentration	0-0.5 parts per million	100 points
	> 0.5 PPM	dangerous

2.1.2 Construct the contrast matrix to obtain the weight vectors of each layer index

The weight vector is obtained by constructing judgment matrix and consistency test, and the following weight results are obtained.

Table 3 judgment matrix of A1--B1, B2, B3, B4

a.	B1	B2	B3	B4	W.	AW
B1	1	1/5	1/2	1/5	0.0752	0.3014
B2	5	1	3	1	0.3937	1.5756
B3	2	1/3	1	1/3	0.1374	0.5503
B4	5	1	3	1	0.3937	1.5756

Table 4 judgment matrix of B1 -- C1,C2,C3

B1	C1	C2	C3	W.	AW
C1	1	2	3	0.5296	1.6138
C2	1/2	1	2	0.2970	0.8886
C3	1.3	1/2	1	0.1634	1.00038

In summary, the result of weight vector of each layer is as follows:

The weight vector of a-b is $W_0 = \{0.075, 0.394, 0.137, 0.394\}$;

The weight vector of b1-c is $W_1 = \{0.530, 0.297, 0.163\}$;

The weight vector of b2-c is $W_2 = \{0.540, 0.163, 0.279\}$;

The weight vector of B3-C is $W_3 = \{0.4, 0.4, 0.2\}$;

The weight vector of b4-c is $W_4 = \{0.126, 0.329, 0.329, 0.217\}$;

The weight vector of C3-D is $W_5 = \{0.484, 0.229, 0.207, 0.080\}$;

The weight vector of C4-D is $W_6 = \{0.106, 0.350, 0.350, 0.194\}$;

The weight vector of c5-d is $W_7 = \{0.2, 0.8\}$;

The weight vector of C6-D is $W_8 = \{0.540, 0.163, 0.297\}$.

Weight of transportation risk, transportation cost, and transportation time relative to the overall goal $\omega = \{0.557,0.387,0.056\}$.

2.1.3 Risk analysis

(1) Dangerous goods B_1

The category of dangerous goods C_3 value is fixed at 80.The vehicle running acceleration value D_1 , temperature value D_2, humidity value D_3 and hydrogen concentration value D_4 are in dynamic changes.Record the changes of each monitoring index value during the experimental simulation transportation and take the average value. The final score is obtained by comparison in Table 2.

$$B_{1i} = \sum_j W_1 * \{C_{1ij}, C_{2ij}, C_{3ij}\} = \sum_j 0.530 * C_{1ij} + 0.297 * C_{2ij} + 0.163 * C_{3ij} \quad (2\text{-}1)$$

In the above formula, the final score value of T_1、T_2、T_3 and T_4 is obtained by comparison in the table 2.The road safety coefficient is obtained:$R_{ij} = \frac{1}{B_{1i}}$

(2) Environmental and property factors B_2

$$B_{2i} = \sum_j W_2 * \{C_4, C_5, C_6\} = 0.540 * C_{4i} + 0.163 * C_{5i} + 0.279 * C_{6i} \quad (2\text{-}2)$$

$$C_{4i} = \sum_j C_{4ij} \sum_j \frac{\left(\alpha_1 \frac{1}{D_{5ij}} * + \alpha_2 * \frac{1}{D_{6ij}} + \alpha_3 * \frac{1}{D_{7ij}} + \alpha_4 * \frac{1}{D_{8ij}}\right) * Q_{1ij} * \frac{1}{R_{ij}}}{Q_{ij}} \quad (2\text{-}3)$$

$$C_{5i} = \sum_j C_{5ij} \sum_j \frac{\left(\beta_1 * \frac{1}{D_{9ij}} + \beta_2 * \frac{1}{D_{10ij}}\right) * Q_{2ij} * \delta * \frac{1}{R_{ij}}}{Q_{ij}} \quad (2\text{-}4)$$

$$C_{6i} = \sum_j C_{6ij} \sum_j \frac{\left(\gamma_1 * \frac{1}{D_{11ij}} + \gamma_2 * \frac{1}{D_{12ij}} + \gamma_3 * \frac{1}{D_{13ij}}\right) * Q_{3ij} * \frac{1}{R_{ij}}}{Q_{ij}} \quad (2\text{-}5)$$

In the above formula, α_1、α_2、α_3、α_4、β_1、β_2、γ_1、γ_2 and γ_3 are all weights in the index system;Q_{ij} is the area of section j of road i;Q_{1ij}、Q_{2ij} and Q_{3ij} are the area that harm the environment, people and property when an accident occurs on section j of road i; The greater the value of $\frac{1}{D_{5j}}$, the higher the risk;δ is the fatal injury rate within the area of the affected people.

(3) Emergency rescue capabilityB_3

$$B_{3i} = \sum_j B_{3ij} \sum_i \frac{\mu_1 * C_{7ij}}{C_{7ij*}} + \frac{\mu_2 * C_{8ij}}{C_{8ij*}} + \frac{\mu_3 * C_{9ij}}{C_{9ij*}} \quad (2\text{-}6)$$

In the above formula, μ_1、μ_2 and μ_3 are the weights in the index system; C_7、C_8 and C_9 are the corresponding index values; C_{7*}、C_{8*} and C_{9*} are the index values when the rescue degree is smooth.

(4) Road factor B_{4i}

$$B_{4i} = \sum_j 0.126 * \frac{1}{C_{10ij}} + 0.329 * C_{11ij} + 0.329 * C_{12ij} + 0.217 * \frac{1}{C_{13ij}} \quad (2\text{-}7)$$

Where, $\frac{1}{C_{10i}}$ indicates that the longer the line, the higher the risk; $\frac{1}{C_{13i}}$ indicates that the higher the speed, the greater the risk;

(5) Total score

$A_i = W_0 *\{B_{1i}, B_{2i}, B_{3i}, B_{4i}\}=0.075*B_{1i}+0.394B_{2i}+0.137B_{3i}+0.394B_{4i}$ (2-8)

2.2 Grey Correlation Analysis Method for Solving Model

In the process of multi-objective optimization of metal sodium road transportation routes, there are usually multiple goals that cannot be reached at the same time. In order to minimize the impact of subjective factors on the choice of route plans, this paper uses an improved gray correlation theory to To solve the above multi-objective route optimization function, the specific steps are as follows:

There are n (n> 1) feasible route schemes, and 3 target values on all feasible routes are required.The eigenvalue matrix of the 3 goals of the n route schemes is:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot \\ a_{n1} & a_{n2} & a_{n3} \end{bmatrix}$$

Where, a_{ij}represents the j target value on the route i.i = 1, 2,..., n.j = 1, 2, 3.

2.3 Determine the standard model

Since all objective functions in this paper are expected to be as small as possible in actual transportation, it is assumed that the "absolutely optimal" objective vector of the gray correlation analysis is set as the standard model: $A_0 = (a_{01}, a_{02}, a_{03})$, $A_0 = max\, a_{ij}$ .Then adding a vector A_0 to the eigenvalue matrix A, and constructing a (n+1) × 3 order target eigenvalue matrix:$A' = (a_{ij})_{(n+1)\times 3}$:

$$A' = \begin{bmatrix} a_{01} & a_{02} & a_{03} \\ a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot \\ a_{n1} & a_{n2} & a_{n3} \end{bmatrix}$$

In the formula,$a_{0j}(j = 1,2,3)$ is the minimum value of the corresponding column in the matrix constructed in 2.1.

2.4 Dimensional Unification of the Target Eigenvalue Matrix

Because the physical meaning of each object in the matrix A' is different, the results obtained by comparison have large errors. In order to ensure the equivalence and homogeneity of each target, the original target eigenvalue matrix needs to be dimensionless and normalized. This paper chooses the following formula for dimensionless processing of data.

$$t_{ij} = \frac{max\, a_{ij} - a_{ij}}{max\, a_{ij} - min\, a_{ij}} \quad \text{(i= 1, 2,..., n + 1;j = 1, 2, 3)} \quad \text{(2-9)}$$

After processing transformation, the original target eigenvalue matrix $A' = (a_{ij})_{(n+1)\times 3}$ is transformed into $M' = (m_{ij})_{(n+1)\times 3}$, and the standard model A_0 is transformed into the standard target center: $A_0 = (1,1,\dots,1)$.

2.5 Calculate the Two Extremes of the Normalized Target Eigenvalue Matrix

According to the formula $\Delta_{ij} = |1 - m_{ij}|$, the target eigenvalue matrix $A' = (a_{ij})_{(n+1)\times 3}$ is processed, and a new $(n + 1) \times 3$order difference information matrix is obtained:$\Delta = (\Delta_{ij})_{(n+1)\times 3}$.The maximum value among all the elements of the matrix Δ_{max} is called the two-pole maximum difference.And the minimum difference isΔ_{min}.The difference information space is denoted as $\Delta_{CR} = (\Delta, \rho, \Delta_{max}, \Delta_{min})$ .Among them, Δ is the difference information of all, which is Δ_{ij} ; ρ is the discrimination coefficient, $\rho \in (0,1)$, and Generally its value is taken as 0.5.

2.5 Calculate the Grey relational and select the route plan

The bullseye coefficient on the j-th target of a_{ij} and a_{0j} is denoted as:$\theta_{0i}(j)_{(n+1)}$

$$\theta_{o_i}(j) = \frac{(\Delta_{min} + \rho\Delta_{max})}{\Delta_{ij} + \Delta_{max}} \quad \text{(2-10)}$$

If the element constructs the bullseye coefficient matrix, then the grey relational degree of the route I is equal to:

Constructing a bullseye coefficient matrix $\theta_{0i}(j)_{n\times 3}$ with the elements as $\theta_{o_i}(j)$, the gray correlation of the i-th route x_{0i} is:

$$x_{0i} = \sum_{j=1}^{n} \theta_{0i}(j)\omega(j) \quad i = 1,2,\dots,n \quad \text{(2-11)}$$

In the formula, the weight of each target is expressed to $\omega(j)$.The routes are sorted according to the gray correlation degree.The greater the correlation degree, the better the corresponding transportation route plan.

3. The Example

In this case, FT company transported 20 tons of sodium metal from Shaoyang to Changsha.Due to the active nature of sodium metal, in order to reduce driving turbulence, it gave priority to the unrestricted expressway during route selection.At the same time, during the driving process, the four factors that affect the temperature and humidity of metal sodium transportation and storage, driving acceleration, and hydrogen concentration are monitored in real time as safety indicators.It is known that there are three best ways to choose from Shaoyang to Changsha.

(1)G60 KungHu expressway - G0421 XuGuang expressway - G5513 ChangZhang expressway

(2)G55 ErGuang expressway - S50 ChangZhi expressway - G0421 XuGuang expressway - G5513 ChangZhang expressway

(3)G60 KungHu expressway - S21 ChangZhu expressway

There is no direct road from Shaoyang to Changsha. In order to calculate the relevant indicators of each path, the path is divided into sections. The schematic diagram can be seen in Figure 1, and the section information is shown in Table 5.

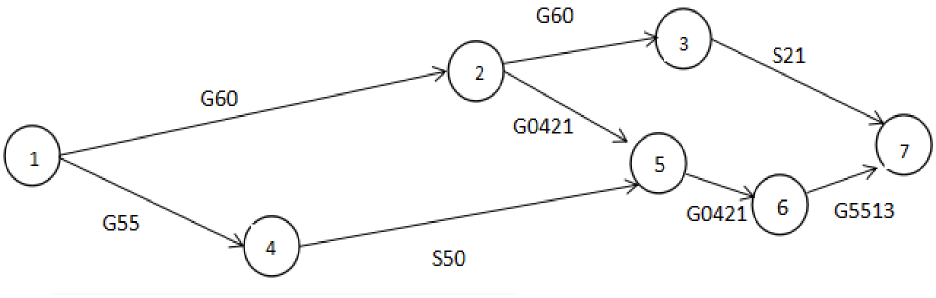

Figure 1 Three transport paths

Table 5 Overview of relevant section information

road	Road width (m)	Path length (km)	Number of lanes	Design speed (km/h)	Highway toll(￥/ km)
1 - 2	21.5	152.8	4	110	1.5
2 - 6	21.5	29.1	4	120	1.4
6 - 7	21.5	16	4	100	1.4
1 - 4	23.5	60.5	4	120	1.4
4 - 5	24	109.1	4	100	1.4
5 - 6	21.5	17.9	4	120	1.4
6 - 7	21.5	16	4	100	1.4
1 - 3	21.5	189.7	4	110	1.5
3 - 7	21.5	21.1	4	120	1.4

Table 6 environment and property composition

path	road	Environmental factors (km^2)				Property factor (10^7yuan)		
		Water area	Nature reserve	Places of interest	Agricultural area (soil)	Housing construction	Equipment and facilities	Crop livestock
path 1	1--2	15	35	8	58	285	84	12
	2--6	7	19	2	37	92	20	5
	6--7	2	2	0	15	31	9	1
path 2	1-4	13	23	3	41	202	64	14
	4-5	32	0	0	37	192	58	10
	5-6	4	12	4	36	31	13	5
	6-7	0	12	5	28	64	20	8
path 3	1-3	2	0	14	138	280	120	34
	3-7	4	10	0	42	76	23	5

Table 7 special population

path	road	The total population of the settlement (people)	Total settlement area (km^2)	The average population density of a settlement (people/km^2)	The total number of people in sparsely populated areas （people）	The area of sparsely populated areas (km^2)	Average population density in sparsely populated areas (people/km^2)
path 1	1--2	77952	32	2436	5871	57	103
	2--6	21288	6	3548	1960	20	98
	6--7	6267	3	2089	2288	8	286
path 2	1-4	82880	35	2368	11256	84	134
	4-5	211840	80	2648	24786	102	243
	5-6	17514	9	1946	1960	20	98
	6-7	41635	11	3785	2356	19	124
path 3	1-3	192504	78	2468	14688	102	144
	3-7	25776	12	2148	8490	30	283

Table 8 emergency rescue capability

path	road	The actual situation			Degree of smooth rescue		
		Number of people rescued (people)	Rescue equipment and supplies (ton)	Accessibility (%)	Number of people rescued (people)	Rescue equipment and supplies (ton)	Accessibility (%)
path 1	1--2	64	10	90	80	15	100
	2--6	29	5	90	45	7	100
	6--7	21	3	85	30	5	100
path 2	1-4	36	4	100	40	6	100
	4-5	20	5	90	42	7	100
	5-6	19	5	90	30	5	100
	6-7	20	4	80	30	5	100
path 3	1-3	53	8	90	60	12	100
	3-7	25	6	85	35	6	100

3.1 Integration of Calculation Results

Table 9 synthesis table of calculation results of three paths

	Path 1		Path 2		Path 3	
	The calculated value	After normalization	The calculated value	After normalization	The calculated value	After normalization
B_{1i}	79.4813	0.7948	81.6000	0.8160	81.6000	0.8160
C_{4i}	4.0775	0.4750	5.3800	0.7110	3.4678	0.8271
C_{5i}	3.230	0.1489	1.9627	0.2590	0.4920	0.1174
C_{6i}	1.2753	0.3761	0.2248	0.0300	0.2248	0.0555
B_{2i}	0.3857		0.4345		0.4813	
B_{3i}(average)	0.711		0.7424		0.8279	
B_{4i}(average)	0.5225		0.5237		0.5325	
Total safety index score A	0.5149		0.5404		0.5741	

Note: The capacity score is a fixed value, and this article is set to 0.8.

3.2 Calculation and Analysis of Route Selection

The grey relational degree method introduced above is used to solve the case:

(1) Construction of eigenvalue matrix for optimized targets of metal sodium transportation routes

$$A=\begin{bmatrix}0.5976 & 292.34 & 1.79\\ 0.5825 & 284.9 & 1.9\\ 0.5632 & 314.09 & 1.9\end{bmatrix}$$

(2) Determine the standard mode

The standard mode is: $A_0=(0.5632，284.9，1.79)$ .Add it into the eigenvalue matrix to obtain:

$$A'=\begin{bmatrix}0.5632 & 284.9 & 1.79\\ 0.5976 & 292.34 & 1.79\\ 0.5825 & 284.9 & 1.9\\ 0.5632 & 314.09 & 1.9\end{bmatrix}$$

(3) Conduct dimensional unified processing on matrix data A'

Use (2-9) to perform dimensionless processing on it to obtain a standardized target eigenvalue matrix:

$$M'=\begin{bmatrix}1 & 1 & 1\\ 0 & 0.745 & 1\\ 0.439 & 1 & 0\\ 1 & 0 & 0\end{bmatrix}$$

(4) Calculate the two range and difference information spaces of the M'

According to the formula： $\Delta_{ij}=\left|1-m_{ij}\right|$, process the target eigenvalue matrix: $A'=\left(a_{ij}\right)_{4\times 3}$, and then a new order difference information matrix is obtained:$\Delta=\left(\Delta_{ij}\right)_{4\times 3}$.Accordingly, the difference information space is.$\Delta_{CR}=(\Delta,0.5,1,0)$.

$$T=\begin{bmatrix}0 & 0 & 0\\ 1 & 0.255 & 0\\ 0.561 & 0 & 1\\ 0 & 1 & 1\end{bmatrix}$$

(5) Find the target's center coefficient matrix and calculate the grey relational degree of each path T

$$T=\begin{bmatrix}0.25 & 0.3984 & 0.5\\ 0.3203 & 0.5 & 0.25\\ 0.5 & 0.25 & 0.25\end{bmatrix}$$

By using (2-11) to obtain the grey correlation degree of each path, it can be obtained:$y_{01}=0.3214$, $y_{02}=0.3859$, $y_{03}=0.3893$.

(6) Sort the routes according to the grey relational degree

From the above results, we can get: $y_{03}>y_{02}>y_{01}$,the third route among the three routes is the relatively optimal route, and the sodium should be transported on this route to ensure the highest safety, the most cost saving and the least time.

4 Conclusion

This paper uses the analytic hierarchy process to evaluate the safety factor, and builds a functional model on safety, time, and cost, as well as the gray correlation method to optimize the route of FT ’s metal “sodium” transportation from Shaoyang to Changsha. The optimal path is selected from the three alternative paths. With the further improvement of the transportation network and logistics system, the relevant theories of dangerous goods transportation will surely develop and apply rapidly.

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