Research on Yangtze River Waterway Transportation Safety Evaluation Model Based on Fuzzy Logic Theory

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***Abstract*—Waterway transportation accidents may cause great economic losses, casualties and environmental pollution. Traditional comprehensive index method is used to conduct safety assessment with fixed values, and can't reflect the randomness and uncertainty of risk. This paper analyzes several typical factors influencing the Yangtze River waterway transportation safety to identify four indexes for waterway transportation safety evaluation, and then the waterway transportation safety evaluation model is established through the method of fuzzy logic to analyze the Yangtze River waterway transportation accident data from 2002 to 2011. With the accurate evaluation results, this model is reliable. This study can be used to improve the management of Maritime Safety Administration.**

Keywords—waterway transportation; fuzzy logic; safety evaluation

I. INTRODUCTION

Waterway is a complicated system, affected by many factors such as ship performance, crew's quality, natural environment, management factors, etc. Waterway transportation accidents often cause huge economic losses, casualties and environmental pollution. Therefore, it is significant to accurately evaluate the waterway transportation safety. From 1970s to 1980s, scholars at home and abroad have carried out many researches about waterway transportation safety. In past 10 years, fault tree analysis method, fuzzy mathematics, grey theory, artificial neutral network and comprehensive safety assessment theory have been widely used in the analysis of accidents [1-3], but seldom used in waterway transportation safety evaluation [4].

Waterway transportation safety evaluation is a complex work, and the common methods are security index method [5], comprehensive safety index method, etc. Safety index is suitable for coastal basin closed waters, and cannot solve the evaluation about inland water ports and channel overlap at open water, in which the comprehensive safety index method is widely used. However, comprehensive safety index method

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represents the risk value with the fixed value, which can't reflect the uncertainty characteristics of risk.

For the defects of waterway transportation safety evaluation, in this paper, based on the fuzziness concept, fuzzy comprehensive evaluation model of Yangtze River waterway transportation safety is established to carry out the quantitative evaluation of Yangzi River waterway transportation safety.

II. Yangtze River waterway transportation safety evaluation model

A. The evaluation index sets and evaluation sets

There are many factors influencing waterway transportation safety. Therefore, it is a very important to choose the most influential factors as indexes [6]. This paper selects safety evaluation indexes according to three principles: (1) science and objectivity; (2) the measurability and comparability; (3) concise and comprehensive. In waterway transportation safety evaluation system, x_1 represents the number of accident, x_2 represents the number of deaths, x_3 represents the number of sunken ship, and x_4 represents economic losses [7]. The index set is $X=\{x_1,x_2,x_3,x_4\}$.

Domain is evaluation results of experts. According to the current condition of the Yangtze River waterway transportation safety, traffic safety condition can be divided into safe, relatively safe, general and unsafe. Therefore, the evaluation set is $V=$ {safe, relatively safe, general, and unsafe}.

B. The evaluation index weight

In order to reflect the important degree of each index x , Yangtze River waterway transportation safety evaluation indexes will be assigned with a corresponding weight w_i (i=1, 2, 3, 4, $w_i \geq 0, \sum w_i = 1$). The rationality of the weight will affect the accuracy of the established model [8].The methods of determining the weight are Analytic Hierarchy Process (AHP), expert method, etc. A precedence relation matrix is built through statistical expert advice. As shown in Table 1.

TABLE I. 0.1-0.9 scale definition

scale	definition	Instruction
0.5	same important	Comparing the two elements, same important
0.6	a little important	Comparing the two elements, one is slightly more important than the other one
0.7	obviously important	Comparing the two elements, one is obviously important than other one
0.8	very important	Comparing the two elements, one Is more important than the other one
0.9	extremely important	Comparing the two elements, one is extremely important than the other one
0.1 0.2 0.3 0.4	Anti compare	if element x_i compared with element x_j to get the judgment r_{ij} , the judgment that the result of element compared x_j with element x_i is $r_{ji}=1-r_{ij}$

According to expert scoring, the priority relation matrix R about the number of accidents, the number of deaths, the number of sunken ships and economic losses can be got:

$$R=\begin{pmatrix} 0.5 & 0.7 & 0.6 & 0.4 \\ 0.3 & 0.5 & 0.4 & 0.2 \\ 0.4 & 0.6 & 0.5 & 0.3 \\ 0.6 & 0.8 & 0.7 & 0.5 \end{pmatrix}$$

Though analyzing the priority relation matrix R, it has the following properties:

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$$r_{ii}=0.5,\ i=1,2,\ldots,n \qquad (1)$$

$$r_{ji}=1-r_{ji}, i,j=1,2,\ldots,\ n \qquad (2)$$

$$r_{ij}=r_{ik}-r_{jk}+0.5, i,j,k=1,2,\ldots,n \qquad (3)$$

Therefore, matrix R is fuzzy consistent matrix. The maximum eigenvalue is 1.893, and corresponding feature vector is:

$$\lambda = (-0.5379\ ,-0.3326\ ,-0.4355\ ,-0.6405)$$

After normalized processing, evaluation index weights are:

$$W = (0.275, 0.172, 0.225, 0.328)$$

C. Determining fuzzy relationship matrix and membership

In order to get rid of the effect of different range of indexes, data should be normalized as shown in Eq. 4.

$$\overline{x_i} = \frac{x_i - \min x_k}{\max x_k - \min x_k} \qquad (4)$$

Where $\max x_k$ is the maximum value of the collection $\{x_k\}$; $\min x_k$ is the minimum value of the collection $\{x_k\}$; $\overline{X_i}$ is the dimensionless x_i.

The fuzzy relationship from the index set to evaluation set represents the possibility that each index x_i make evaluation v_i, which is the membership of index. The fuzzy evaluation matrix from index set $X=\{x_1,x_2,x_3,x_4\}$ to evaluation set $V=\{v_1,v_2,\cdots,v_n\}$ is shown as in Eq. (5).

$$K=\begin{pmatrix} k_{11} & \cdots & k_{1n} \\ \vdots & \ddots & \vdots \\ k_{m1} & \cdots & k_{mn} \end{pmatrix} \qquad (5)$$

Where $k_{ij}(i=1,2,\cdots,m; j=1,2,\cdots,n)$ represents that the membership of evaluation v_j for the index x_i in the first level. According to the results of the current study, in waterway transportation safety evaluation, membership function k_{ij} can be obtained by a linear relationship. Waterway transportation safety evaluation can be classified into safe (A), relatively safe (B), general (C) and unsafe (D) as shown in followings:

$$f_A(x)=\begin{cases} 1, x<\lambda_1 \\ \dfrac{\lambda_2-x}{\lambda_2-\lambda_1}, \lambda_1 \le x \le \lambda_2 \\ 0, x>\lambda_2 \end{cases} \qquad (6)$$

$$f_B(x)=\begin{cases} 0, x<\lambda_1 \\ \dfrac{x-\lambda 1}{\lambda_2-\lambda_1}, \lambda_1 \le x \le \lambda_2 \\ \dfrac{\lambda_3-x}{\lambda_3-\lambda 2}, \lambda_2 \le x \le \lambda_3 \\ 0, x>\lambda_3 \end{cases} \qquad (7)$$

$$f_C(x)=\begin{cases} 0, x<\lambda_2 \\ \dfrac{x-\lambda_2}{\lambda_3-\lambda_2}, \lambda_2 \le x \le \lambda_3 \\ \dfrac{\lambda_4-x}{\lambda_4-\lambda_3}, \lambda_3 \le x \le \lambda_4 \\ 0, x>\lambda_4 \end{cases} \qquad (8)$$

$$f_D(x)=\begin{cases} 0, x<\lambda_3 \\ \dfrac{x-\lambda_3}{\lambda_4-\lambda_3}, \lambda_3 \le x \le \lambda_4 \\ 1, x>\lambda_4 \end{cases} \qquad (9)$$

$\lambda_1,\lambda_2,\lambda_3,\lambda_4$ are the threshold values for corresponding safe level, which can be determined by experts or researchers through their researches. In this paper, the threshold values are calibrated through cumulative percentile of statistical method. Putting the normalized indexes into Eq. (6)-(9), the membership for each safety level can be got as in Eq. (10).

$$K_r = [k_{ij}]_{4\times4} \qquad (10)$$

Fuzzy evaluation matrix can be obtained according to the above weight of indexes.

$$B = W \bullet K_r = \{b_1, b_2, b_3, b_4\} \qquad (11)$$

Normalized vectors can be got by normalizing the evaluation matrix B according to the Eq. (12).

$$f = \{f_1, f_2, f_3, f_4\} \quad (12)$$

Among them:

$$f_i = \frac{b_i}{\sum_{k=1}^{4} b_k} \quad (13)$$

D. The comprehensive fuzzy evaluation model

According to previous research results [7], the values for evaluation set $V = \{safe, \text{relative } safe, general, unsafe\}$ are shown in TABLE II:

TABLE II. Waterway transportation safety classification range

Grade	Safe(A)	Relative Safe(B)	General(C)	Unsafe(D)
interval	80-100	60-80	40-60	0-40
median	90	70	50	20

According to TABLE II, comprehensive evaluation value of waterway transportation safety can be determined as shown in Eq. (14):

$$E = f_1 \times 90 + f_2 \times 70 + f_3 \times 50 + f_4 \times 20 \quad (14)$$

III. The example analysis

According to 2002-2011 Yangtze River waterway transportation accident statistics, the statistics results and dimensionless values of the number of accidents, the number of deaths, the number of sunken ships and economic losses are shown in TABLE III:

TABLE III. 2002-2011 Data comparison of evaluation index about Yangtze River water traffic accident

Times	The number of accidents		The number of deaths		The number of sunken ships		Economic losses	
	Raw data	Dimensionless	Raw data	Dimensionless	Raw data	Dimensionless	Raw data	Dimensionless
2002	98	1	134	1	66	1	265.08	0.59
2003	70	0.65	128	0.95	49	0.68	293.38	0.69
2004	72	0.67	69	0.47	49	0.68	253.4	0.54
2005	66	0.60	78	0.54	39	0.49	297.67	0.70
2006	46	0.35	45	0.27	25	0.23	199.19	0.34
2007	43	0.31	62	0.41	30	0.32	171.21	0.24
2008	46	0.35	45	0.27	38	0.47	276.32	0.63
2009	42.5	0.30	43	0.25	28	0.28	377.99	1.00
2010	22	0.04	28	0.13	19	0.11	157.8	0.19
2011	18.5	0	12	0	13	0	105.8	0

According to the TABLE III, from 2002 to 2011, the four indexes of the Yangtze River waterway transportation accidents are gradually decreasing. Thus the waterway transportation safety level from 2002 to 2011 can be considered to increase year by year, except 2008 and 2009.

In this paper, fuzzy evaluation model is used to evaluate the 10 years' waterway transportation safety level of the

Yangtze River, and membership function thresholds are demarcated by cumulating percentile method with safe (A), relatively safe(B), general(C), unsafe (D), and the demarcating process is shown as following:

Step1: Calculate frequency of the four dimensionless indexes;

Step2: Arrange it from small to large, and then calculate the cumulative frequency of indexes;

Step3: Get the dimensionless values of 15%, 40%, 60%, 80% cumulative frequency by interpolation method, which are set as function threshold of the membership λ.

From 2002 to 2011, the cumulative frequency of evaluation indexes for Yangtze River waterway transportation accidents are shown in TABLE IV:

TABLE IV. 2002-2011 Cumulative frequency distributions of dimensionless data about the Yangtze River waterway transportation evaluation

Serial numbers	The number of accidents		The number of deaths		The number of sunken ships		Economic losses	
	Frequency	Cumulative frequency	Frequency	Cumulative frequency	Frequency	Cumulative frequency	Frequency	Cumulative frequency
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.01	0.01	0.03	0.03	0.03	0.03	0.04	0.04
3	0.07	0.08	0.06	0.09	0.05	0.08	0.05	0.09
4	0.07	0.15	0.06	0.15	0.07	0.15	0.07	0.16
5	0.08	0.23	0.06	0.21	0.08	0.22	0.11	0.27
6	0.08	0.32	0.10	0.31	0.11	0.33	0.12	0.39
7	0.14	0.46	0.11	0.42	0.12	0.45	0.13	0.51
8	0.15	0.61	0.13	0.55	0.16	0.61	0.14	0.65
9	0.16	0.77	0.22	0.77	0.16	0.77	0.14	0.80
10	0.23	1.00	0.23	1.00	0.23	1.00	0.20	1.00

Using curve fitting method, the cumulative frequency is y-coordinate, and dimensionless indexes are x-coordinate. Dimensionless cumulative frequency distribution of the four indexes can be drawn. The cumulative frequency approximate curves are shown in Fig.1 and Fig.2:

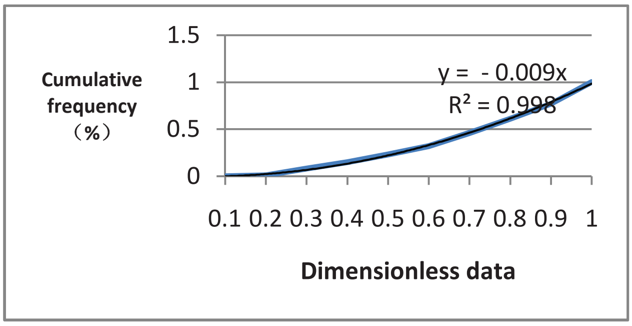

Fig.1. Dimensionless value cumulative frequency of the number of accidents

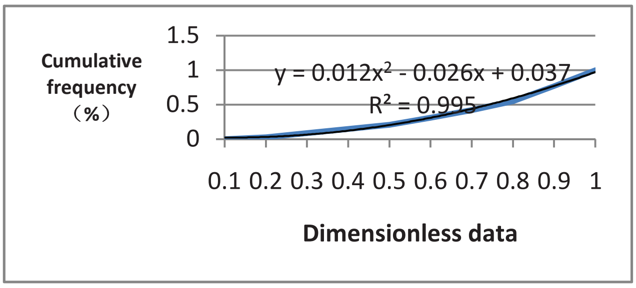

Fig.2. the dimensionless cumulative frequency of the number of deaths

The dimensionless values, which are corresponded with 15%, 40%, 60%, 80% cumulative frequency, can be calculated by interpolation method, and are used as threshold λ of the four safety levels of the number of accidents and the number of deaths. Another two safety thresholds of evaluation indexes can be calculated in the same way. So, dimensionless values are shown in TABLE V:

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TABLE V. 15%、40%、60%、80% dimensionless data corresponded by the index of cumulative frequency

rank	Safe	Relative Safe	General	Unsafe
	15% Digit	*40% Digit*	*60% Digit*	*80% Digit*
The number of accidents	0.4182	0.6532	0.7897	0.9048
The number of deaths	0.4377	0.6724	0.8052	0.9164
The number of sunken ships	0.4190	0.6566	0.7932	0.9081
Economic losses	0.3721	0.6183	0.7656	0.8909

The data in the TABLE V are thresholds of membership function of the four levels (unsafe, general, relatively safe and safe).

$$\lambda_a = \{0.4182, 0.6532, 0.7897, 0.9048\}$$
$$\lambda_b = \{0.4377, 0.6724, 0.8052, 0.9164\}$$
$$\lambda_c = \{0.4190, 0.6566, 0.7932, 0.9081\}$$
$$\lambda_d = \{0.3721, 0.6183, 0.7656, 0.8909\}$$

λ_a, λ_b, λ_c, λ_d represent the membership threshold sets of the number of accidents, the number of deaths, the number of the sunken ships and economic losses.

Fuzzy sets, which are the memberships of the four evaluations, can be calculated.

$$B_{2002} = (0.0377, 0.2903, 0, 0.6720)$$

$$B_{2003} = (0.0037, 0.6260, 0.1982, 0.1720)$$

$$B_{2004} = (0.2526, 0.6750, 0.0724, 0)$$

$$B_{2005} = (0.3171, 0.5010, 0.1819, 0) \; B_{2006} = (1, 0, 0, 0)$$

$$B_{2007} = (1, 0, 0, 0) \; B_{2008} = (0.6237, 0.3502, 0.0260, 0)$$

$$B_{2009} = (0.6720, 0, 0, 0.3280) \; B_{2010} = (1, 0, 0, 0)$$

$$B_{2011} = (1, 0, 0, 0)$$

The Yangtze River waterway transportation safety evaluation of each year can be got by Eq. (14):

$$E_{2002} = 37.154 \; E_{2003} = 57.503 \; E_{2004} = 73.604 \; E_{2005} = 72.704$$

$$E_{2006} = 90 \; E_{2007} = 90 \; E_{2008} = 81.947 \; E_{2009} = 67.04 \; E_{2010} = 90$$

$$E_{2011} = 90$$

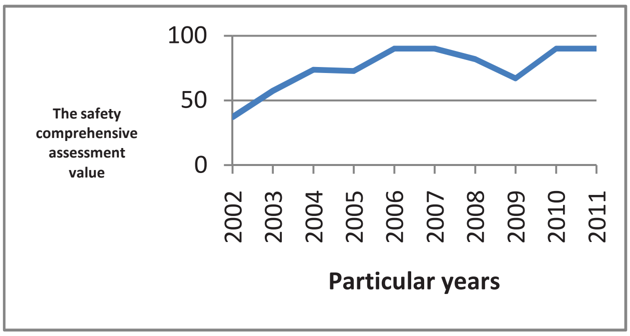

Fig.5. 2002-2011 comprehensive evaluation of the Yangtze waterway transportation safety

According to the results of evaluation, the Yangtze River waterway transportation safety in 2002 is unsafe; the result in 2003 is general; the result in 2004, 2005 and 2009 are relatively safe; others are safe. This shows that the Yangtze River waterway transportation safety has been improved, except 2008 and 2009, which may be caused by the harsh climate. Thanks to cumulative frequency percentile method, the membership threshold in this method can change with the changes of the data.

IV. CONCLUSION

This paper identifies the various safety level thresholds by using cumulative frequency percentile method, then constructs the fuzzy evaluation matrix, finally establishes the Yangtze River waterway transportation safety evaluation model based on the fuzzy logic. Comparing the Yangtze River waterway transportation safety evaluation results of this model with the actual situations, the results are consistent, illustrating that this model is reliable. However, this model is relative, which causes the evaluations' relativity. Future research will be carried on how to establish a model with absolute evaluations.

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REFERENCES

[1] Liang. L, Yuling. T and Wenfeng. H, "The optimal portfolio model based on multivariate T distribution with Fuzzy Mathematics method", *Study in Mathematical Sciences*, 2012, April. 1, PP. 1-5.

[2] Paras. K, Nigam. P and Narotam. K, "Vehicular traffic noise modeling using artificial neural network approach", *Transportation Research Part C*, 2014, 40.

[3] Jakub. M, Floris. G and Pentti. K, "On a systematic perspective on risk for formal safety assessment", *Reliability Engineering and system safety*, 2014, 127.

[4] Jun. L, Li. S and Feng. W, "Review of Maritime Transport Environmental Safety Evaluation", World Shipping, 2005. 8, PP.12-13.

[5] Xianglin. F, Fengchen. W, and Zhaolin. W, "Vessel Traffic Safety Evaluation Method", *Dalian Maritime University*, 1992, PP.337-341.

[6] Jinyu. G, Zhongbin. Z and Qingyun. S, "Study and Applications of Analytic Hierarchy Process", *China Safety Science Journal*, 2008(5), PP.149-153.

[7] Yansheng. H, "Traffic Safety Appraisal Target System of Changjiang River", *Wuhan University of technology*, 2006.

[8] Jibin. L, Yang. X, Liangan. H, Jiazhong L, "Research on the Priorities of Fuzzy Analytical Hierarchy Process", *Systems Engineering - Theory &Practice*, 2006(9), PP.108-112.

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